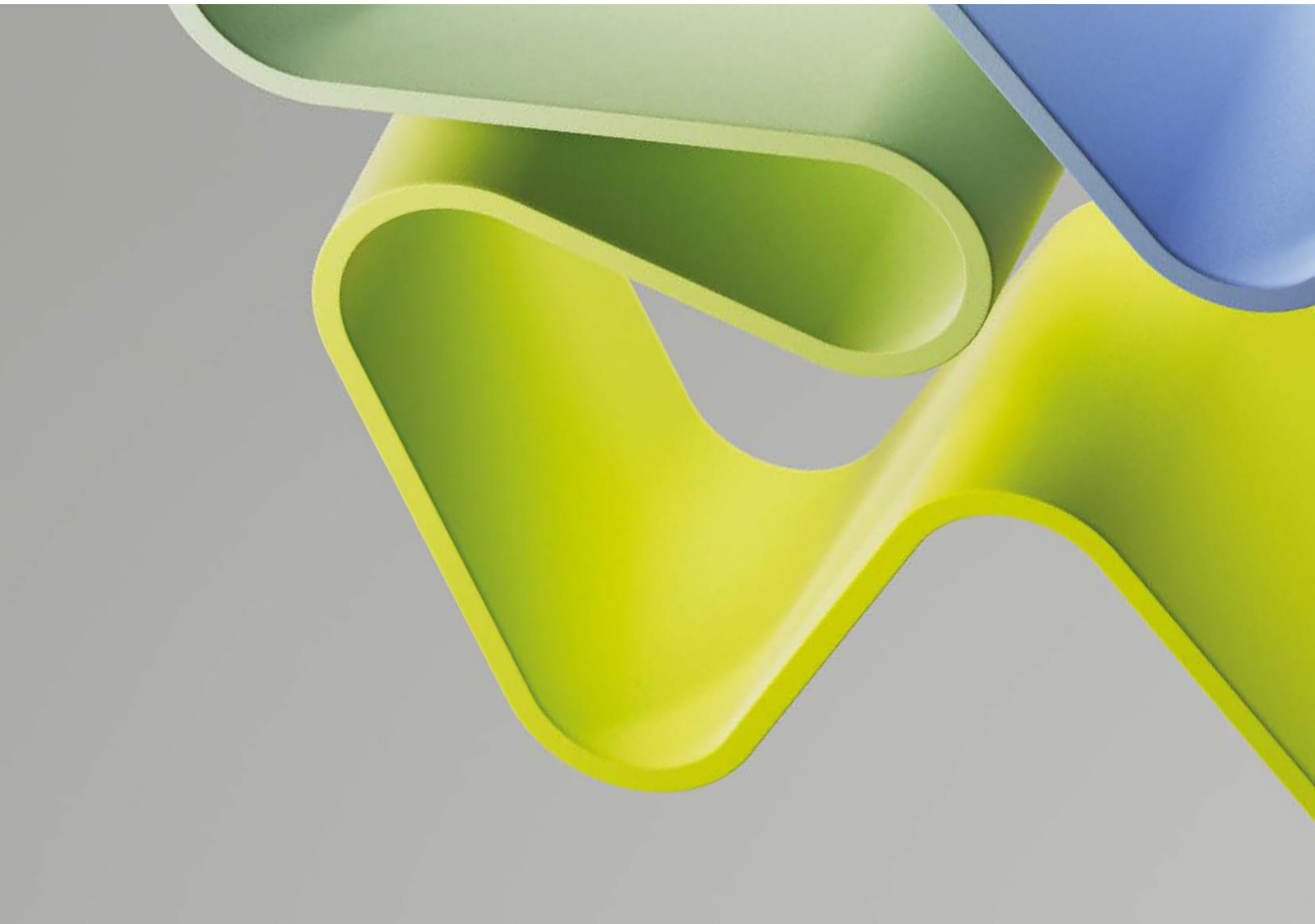
The Research Council of Norway

Evaluation of Natural Sciences 2022-2023

Impact Cases

June 2024



Introduction

Administrative units participating in the Evaluation of Natural Sciences Research in Norway 2022-2023 were invited to submit case studies documenting the societal impact of their research. In this report the impact cases will be presented in the way they were submitted by the institutions using the template for impact cases which was sent to the 28 enrolled administrative units in September 2022 with a deadline in January 2023. Impact cases from the administrative units are presented here.

Definition

The definition of, and model for, societal impact was derived from the 2021 Research Excellence Framework (REF) in the United Kingdom:

Definition of Societal impact: an effect on, change or benefit to the economy, society, culture, public policy or services, health, the environment or quality of life, beyond academia.

Impact includes the reduction or prevention of harm, risk, cost or other negative effects.

Academic impacts on research or the advancement of academic knowledge are excluded. Impacts on students, teaching or other activities both within and/or beyond the submitting institution are included.

Impact includes, but is not limited to, an effect on, change or benefit to:

- *the activity, attitude, awareness, behaviour, capacity, opportunity, performance, policy, practice, process or understanding.*
- *of an audience, beneficiary, community, constituency, organisation or individuals.*
- *in any geographic location whether locally, regionally, nationally or internationally.*

Impact case guidelines

Each case study should include sufficiently clear and detailed information to enable the evaluation committee to make judgements based on the information it contains, without making inferences, gathering additional material, following up references or relying on members' prior knowledge.

Timeframes

- The impact must have occurred between 2011 and 2021.
- Some of the underpinning research should have been published in 2010 or later.
- The administrative units were encouraged to prioritise recent cases.

Maximum number of cases per administrative unit:

For up to 10 researchers: one case; for 10 to 30 researchers: two cases; for 30-50 researchers: three cases; for 50-100 researchers: four cases, and up to five cases for units exceeding 100 researchers.

IG Case 1

Institution: UiT The Arctic University of Norway	
Administrative unit: Department of Geosciences (IG)	
Title of case study: Building up geoscientific expertise in rock avalanches	
Period when the underpinning research was undertaken: 2013-2019	
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2019	
Period when the impact occurred: 2015-2019	

1. Summary of the impact

The main societal impact of this case study was to increase geohazard (avalanche) knowledge to minimize challenges related to safety and values for people, emergency planning, and crisis management in avalanche-prone municipalities in northern Norway. Another impact was to facilitate future recruitment needs for protection against geohazards in the region and contribute to build up of local research and knowledge databases regarding avalanche location/distribution, causes, processes, and future geohazards threats to society. A subsidiary impact is to establish a National Centre of Avalanche Risk Assessment at UiT, which also would include expertise in snow avalanche monitoring and warning.

2. Underpinning research

The underpinning research for the impact of this case study focused on structurally controlled failure mechanisms of unstable mountain (bedrock) slopes in Troms and Finnmark County, northern Norway. By combining and integrating basic geological knowledge with new technology and multiple methods and tools, it advanced the understanding of the behaviour of unstable mountain slopes in a changing climate.

Thorough understanding of triggering factors and failure mechanisms for rockslides was achieved by integrating data from multiple fields, including geological and structural mapping, engineering geology, and rock mechanics, and by using advanced new research techniques/tools to study rock slope weakening over time before developing into a catastrophic rockslide. Methods/tools applied include drone-photogrammetry, remote sensing techniques (LiDAR, GPS measurements), InSAR-data from satellite and ground-based radar to separate and link spatial variations in rock strength, extensometer, crack meter and laser beams to refine and monitor rock avalanche scenarios, meteorological data, and numerical modelling.

The key research discoveries show that inherited structures and mechanical weak zones in bedrocks of steep mountain slopes create a recurring pattern of anisotropy that may cause mass instability and rock-slope failure. More detailed findings are that: i) rock mechanical strength corresponds to varying lithology and structure in the bed rock; ii) lowering of rock strength occurs in lithological weakness zones in unstable mountain slopes; iii) areas of lower strength may be intrinsic or linked to external rockslide processes (e.g., groundwater flow and weathering), or a combination of those; and iv) quantification and mechanical testing of unstable rock masses and rock material strengths, rock structure and microstructure can be used to evaluate how rockslide lithology and strength impact the generation of sliding zones in large unstable mountain slopes.

Our geohazard case studies were carried out by several researchers at from IG at UiT The Arctic University of Norway in collaboration with researchers at NORUT/NORCE, the Geological Survey of Norway (NGU), the Norwegian Water Resources and Energy Directorate (NVE), The Norwegian

Public Roads Administration (Statens vegvesen), Troms and Finnmark County, NORSAR, municipalities in northern Norway (e.g., Kåfjord, Nordreisa, Lyngen, Balsfjord, Karlsøy), Norwegian Geotechnical Institute (NGI), consultant companies (e.g., Norwegian Geotechnical Institute, Multiconsult), etc., and several PhD and M.Sc. students in close collaboration with public actors.

Names of key researchers during the case period 2013-2019:

Prof. Steffen G. Bergh (UiT, 2013-2019), Post. Doc. Louise Vick (UiT, 2016-2019; Dr. Louise Vick continued as researcher at IG and was appointed through direct hire to an associate professor position at IG in 2021 to keep a highly competent colleague among the faculty to ensure continuation of related research and education activities as Steffen Bergh retired at the end of 2022), Ass. Prof. Geoff Corner (UiT, 2013-2019), Prof. II Lars Harald Blikra (NVE, 2014-2019), Prof. II Anne Hormes (2017-2019), Prof. II Helena Alexanderson (Lund University, 2019), PhD student Harald Ø. Eriksen (UiT, NORUT, 2013-2016), Researcher Tom Rune Lauknes (NORUT, 2013-2016), Researcher Line Royet (NORUT, 2018-2019), Researcher Martina Bøhme (NGU, 2015-2019).

3. References to the research

Eriksen, H. Ø., Lauknes, T. R., Larsen, Y., Corner, G. D., Bergh, S. G., Dehls, J. F. & Kierulf, H.P. 2017: Visualizing and Interpreting Surface Displacement Patterns on Unstable Slopes Using Multi-Geometry Satellite SAR Interferometry (2D InSAR). *Remote Sensing of Environment. 191,* 297–312

Eriksen, H.Ø., Bergh, S.G., Larsen, Y., Skrede, I., Kristensen, L., Lauknes, T.R., Blikra, L.H., & Kierulf, H.P. 2017: Relating 3D Surface Displacement from Satellite- and Ground-Based InSAR to Structures and geomorphology of the Jettan Rockslide, Northern Norway. *Norwegian Journal of Geology*. 97, 233-253.http://dx.doi.org/10.17850/njg-403

Eriksen, H. Ø., Rouyet, L., Lauknes, T. R., Berthling, I., Isaksen, K., Hindberg, H., Larsen, Y. & Corner, G.D. 2018: Recent acceleration of a rock glacier complex, Adjet, Norway, documented by 62 years of remote sensing observations. *Geophysical Research Letters, 45*, 8314–8323. https://doi.org/10.1029/2018GL077605

Eckerstorfer, M., Eriksen, H.Ø., Rouyet, L., Christiansen, H.H., Lauknes, T.R. & Blikra, L.H. 2018: Comparison of geomorphological field mapping and 2D-InSAR mapping of periglacial landscape activity at Nordnesfjellet, northern Norway. *Earth Surf. Process. Landforms* 43, 2147–2156. DOI: 10.1002/esp.4380

Vick, L. M., Böhme, M., Rouyet, L., Bergh, S. G., Corner, G. D., & Lauknes, T. R. 2020: Structurally controlled rock slope deformation in northern Norway. *Landslides* 17, 1745-1776. https://doi.org/10.1007/s10346-020-01421-7

Vick, L.M., Bergh, S.G., Höpfl, S., Percival, J. & Daines, E.B. 2020: The Role of Lithological Weakness Zones in Rockslides in Northern Norway. International Society for Rock Mechanics and Rock Engineering Source ISRM International Symposium - EUROCK 2020, 14-19 June, ISRM-EUROCK-2020-197, ISBN: 978-82-8208-072-9

Vick, L.M., Mikkelsen, M., Corner, G.D., Kjellman, S.E., Trønnes, L., Hormes, A., Allaart, L. & Bergh, S.G. 2022: Evolution and temporal constraints of a multiphase postglacial rock slope failure. Geomorphology, 398, 108069. https://doi.org/10.1016/j.geomorph.2021.108069

4. Details of the impact

By combining and integrating basic geological knowledge with advanced technology and multiple new methods, the results of this case study have a number of impacts that are highly relevant for societies both at a regional, national, and international scale. This is because unstable mountain slopes can directly affect residences in landslide-prone municipalities, critical infrastructure (e.g., roads and other supply infrastructure), as well as the environment (e.g., diversion or damming of rivers due to blocking from landslides).

Integrating geological, geophysical, and engineering work on the behaviour and anisotropy of unstable rock masses and structurally controlled rear ruptures is new and ground-breaking in geohazards research. Thus, our case study contributes directly to improved monitoring systems for more precise early warning and in consequence, for a better safety, preparedness, and resilience of local societies in northern Norway in the future. Further, it helps to improve existing hazard analysis recommendations used in Norway for slope deformations.

Concrete examples of impacts are when researchers at UiT and their master and PhD students became directly involved with protection design, e.g., based on the study of impact dynamics from rockfalls and snow avalanches in coastal mountainous areas in northern Norway. Examples include Svarthola on the island of Senja, an unprotected stretch of road that experiences a high frequency of mass movements at a tunnel portal, and similar risky avalanche areas along coastal roads on the Lofoten islands, and the Kåfjord municipality in Troms and Finnmark County. Louise Vick and her students recently also reconstructed and provided public input of a major quick clay landslide at Kråkenes in Alta municipality, Troms and Finnmark County, where the E6 road above the previous landslide area slipped out towards the fjord Furthermore, many previous students at IG are currently employed at institutions like The Norwegian Public Roads Administration (Statens Vegvesen) and several consultant companies in Tromsø (Multiconsult, Barlindhaug, etc.). Their work contributes directly to safer and more reliable roads and transportation, and thus to the creation of values in northern Norway.

A follow-up impact is ongoing effort to establish an internationally competitive research and education hub for geohazards in Tromsø, under the lead of UiT. The purpose of the centre is to improve the understanding of causes and consequences of geohazards, as well as preventing, predicting and adapting to them. It shall be a centre where competencies from UiT, as well as the public, private and institute sectors are integrated to fill knowledge gaps. Competencies currently present at UiT include mapping, hazard and risk analysis, consequence analysis; spatial planning and regulations; preparedness planning, risk and disaster management, security; behaviour and decision-making; monitoring, warning systems and mitigation; physical processing and modelling of landslides and avalanches. There is an urgent need to obtain funding to appoint a coordinator to start the work.

In addition to being recognised as a valuable collaborator for various case studies and research projects (see above), Dr. Louise Vick's work was also recognised through the award of the Else Ragnhild Neumann Award for women in geosciences (https://www.mn.uio.no/ceed/english/about/news-and-events/news/2021/else-ragnhild-neumann-award-winner-2021.html).

5. Sources to corroborate the impact (indicative maximum of ten references)

IG Case 2

Institution: UiT The Arctic University of Norway	
Administrative unit: Department of Geosciences (IG)	
Title of case study: Research Centre for Arctic Petroleum Exploration (ARCEx)	
Period when the underpinning research was undertaken: 2013 - 2021	
Period when staff involved in the underpinning research were employed by the submitting institution: 2013 - 2021	
Period when the impact occurred: 2014 - 2021	

1. Summary of the impact

ARCEx was a national consortium consisting of 9 academic partners and 6 user partners. About 250 peer reviewed publications were published, and some studies received prestigious awards. The impact of the centre can be summarized as follows: (1) the geological research was used by partners to increase the precision when assessing geological settings and conditions, (2) the environmental risk assessment was used to suggest response scenarios in case of an unwanted spill, and (3) the technological research paved the way for passive eco-friendly exploration techniques. ARCEx implied high-quality researcher training and collaboration across disciplines and geographical distances.

2. Underpinning research

The Research Centre for Arctic Petroleum Exploration (ARCEx) was established in order to address a set of key cross- and multi-disciplinary challenges in petroleum research and development in the Arctic. The overarching research goal for ARCEx was to reduce all kinds of risk connected to petroleum activities. This can be further broken down for the three main pillars (geology, environment, technology) as follows: the geological research activity aimed to reduce the risk for not locating areas containing prospective petroleum resources, the environmental research activity aimed to reduce the operational risk, and the technological research activity aimed to reduce the risk for invoking environmentally harmful, inaccurate and incorrect measurements and analysis. Thus, the research activities in the three research pillars were highly interwoven and interconnected, providing a collective, coordinated and coherent approach to solve the overarching research goal of ARCEx in a holistic manner.

The geological research was mainly carried out in Work packages (WPs) 1&2 where the main research topics were tectonics and basin formation, uplift and subsidence, and erosion and sedimentation. In particular, research was carried out to show when and how the sedimentary basins of this region formed, and how this is linked to deeper structures. Also, the question of when and how deep the maximum burial was for the different organic rich intervals of the Barents Sea sedimentary succession was addressed, since this is crucial to assess the potential for the existence of hydrocarbons.

The environmental risk assessment research was organized in WP3. The main research topics were concentrated on marine ecosystems, the sensitivity of Arctic key species, and risk assessment and management. In particular, we achieved deep insight into how Arctic key species (from plankton via fish to sea mammals) respond to anthropogenic activities and pollution, and we have developed a thorough understanding of the baseline ecology in the Barents Sea.

Technological research was carried out in WP4. The main research has focused on developing new ways to ensure eco-safe exploration in vulnerable areas, how to perform seismic on ice and snow, and the development of optimal data analysis and numerical models suitable for

Arctic conditions. In particular, we have achieved results that provide explorational constraints that maximize data quality and minimize environmental impact.

Key researchers in ARCEx associated with the Dept. of Geosciences from 2015 to 2021:

Prof. Alfred Hanssen (2015-2021), Assoc. prof. Sten-Andreas Grundvåg (2015-2021), Prof. Jan Sverre Laberg (2013-2021), Prof. Steffen Bergh (2013-2021), Assoc. Prof. Tom Arne Rydningen (2015-2021), Adjunct Assoc. Prof. Stig-Morten Knutsen (2015-2021), Adjunct Prof. JoLynn Carroll (2013-2021), Adjunct Prof. Jan Inge Faleide (2013-2018), Adjunct Prof. Sverre Planke (2018-2021), Postdoc. Amando Lasabuda (2018-2021), Postdoc. Mathias Bockwoldt (2020-2021), PhD stud. Amando Lasabuda (2015-2018), PhD stud. Ana Sofia Aniceto (2014-2018), PhD stud. Fredrik Wesenlund (2017-2021), PhD stud. Jean-Baptiste Koehl (2015-2018), PhD stud. Julian Janocha (2020-2021), PhD stud. Renate Paulsen (2018-2021), PhD stud. Andreas Hagset (2018-2021), PhD stud. Dimitrios Ktenas (2013-2019), PhD stud. Maximilian Weber (2020-2024), PhD stud. Rowan Romeyn (2018-2021), PhD stud. Stine Bjordal Olsen (2019-2021)

3. References to the research

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Helland-Hansen, W., Grundvåg, S.A. (2021): The Svalbard Eocene-Oligocene (?) Central Basin succession: Sedimentation patterns and controls. *Basin Research,* 2020(33,1), pp. 729-753. DOI: 10.1111/bre.12492.

Kristensen, T.B., Rotevatn, A., Peacock, D.C.P., Henstra, G.A., Midtkandal, I. and Grundvåg, S.-A. (2016): Structure and flow properties of syn-rift border faults: the interplay between fault damage and fault-related chemical alteration (Dombjerg Fault, Wollaston Forland, NE Greenland). *Journal of Structural Geology*, 2016(92), pp. 99-115. DOI: 10.1016/j.jsg.2016.09.012.

Lasabuda, A.P., Johansen, N.S., Laberg, J.S., Faleide, J.I., Senger, K., Rydningen, T.A., Patton, H., Knutsen, S.M., Hanssen, A. (2021): Cenozoic uplift and erosion in the Norwegian Barents Shelf – A review. *Earth-Science Reviews*, 2021(217), article 103609. DOI: 10.1016/j.earscirev.2021.103609.

Paulsen, R., Birchall, T., Senger, K., Grundvåg, S.A. (2022): Seal characterization and integrity in uplifted basins: Insights from the northern Barents Shelf. *Marine and Petroleum* Geology, 2021(139), 105588. DOI: 10.1016/j.marpetgeo.2022.105588.

Romeyn, R., Hanssen, A., Ruud, B. O., and Johansen, T. A. (2021): Sea ice thickness from air-coupled flexural waves. *The Cryosphere*, 2021(15), pp. 2939–2955. DOI: 10.5194/tc-15-2939-2021.

Wesenlund, F., Grundvåg, S.-A., Sjøholt, V.E., Thiessen, O., Pedersen, J.H. (2022) Multi-elemental chemostratigraphy of Triassic mudstones in eastern Svalbard: Implications for source rock formation in front of the World's largest delta. *The Depositional Record*, 2022(00), pp. 1-36. DOI: 10.1002/dep2.182.

4. Details of the impact

ARCEx has served as a coordinator for high-north oriented research in Norway since its inception in 2013. The volume of research that has been produced is massive, and most of the results have been published in high-impact scientific journals (in total about 250 peer-reviewed publications). This benefits society at large. Furthermore, ARCEx has played a significant role for the R&D and innovation strategies of the partners. In addition, for the smaller companies in the consortium, ARCEx has to some extent served as their *de facto* R&D department.

The research activities in environmental risk assessment are in many ways "license to operate" for Arctic operations. The user partners have collaborated extensively through ARCEx, and the summary of this research are concrete best practices that are implemented by our partners. This can be regarded as a positive ripple effect both for the environment and for the society.

The networks among user partners and academia have been vastly strengthened. This may lead the industry to achieve improved access to relevant competence and research personnel. Also, the collaboration may play a role for the recruitment of qualified and highly skilled personnel who have completed their research training.

As expressed by one of the major industry partners in the midway evaluation of ARCEx: "Equinor is actively contributing to developing petroleum resources in Arctic areas, especially on the Norwegian Continental Shelf to provide energy to growing markets in a safe and profitable way. The ARCEx activities are contributing significantly to meet these objectives. There is a strong industry support and collaboration in all the ARCEx projects."

A direct effect of the midterm evaluation was that we required all new PhD projects to include at least one co-supervisor from industry. As a result, several of our early career personnel have spent short and longer-term stays with industry partners and relevant authorities. Our observation is that even short-term visits are of importance for the students, and it allows for bilateral information exchange and sharing of knowledge and experience that would otherwise be very difficult to achieve. In particular, PhD students with co-supervisors from industry partners have used the opportunity to gain valuable industry input and views on their research projects. The centre management saw a multitude of positive side effects of this kind of personnel exchange. In particular, we observed that it was very motivating for the early career scientists to experience how the industry partners actually work, and how they utilize the knowledge developed though ARCEx.

A distinct contribution that should be highlighted, is that we have achieved new and improved estimates of the past glacial erosion rates in the Barents Sea. This work has been published in a massive review paper in a high-impact journal, and we have observed that the results of the paper are highly regarded by the user partners and by the international scientific community.

With integration in mind, we see that the complete geological picture of the Barents Sea can now be compiled from the many publications written by ARCEx scientists. This, with the addition of publications containing new chemical analyses of the source rock and the caprock properties can bring the energy companies closer to unravelling the enigma of petroleum resources in the Barents Sea.

We maintain that ARCEx has produced significant positive ripple effects and value creation based on public investments, and with an impact that reaches far beyond the energy sector.

5. Sources to corroborate the impact

ARCEx Final Report:
https://www.forskningsradet.no/contentassets/3317066f14d84c2c95349870483cb442/arcex---final-report-2022.pdf

ARCEx Annual Reports from 2014 to 2020:
https://arcex.no/?page_id=1812

ARCEx Midterm Evaluation:
https://www.forskningsradet.no/siteassets/publikasjoner/1254032234293.pdf

IG Case 3

Institution: UiT The Arctic University of Norway	
Administrative unit: Department of Geosciences (IG)	
Title of case study: Detection and monitoring of subsurface fluids for de-risking CO_2 sequestration and geohazard detection	
Period when the underpinning research was undertaken: 2011-2021 (ongoing)	
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2021(ongoing)	
Period when the impact occurred: 2017-2021(ongoing)	

1. Summary of the impact

In the Center of Excellence CAGE we have developed 3D/4D seismic technology that allows to detect and monitor subsurface fluid migration at ~10 times the resolution of conventional seismic systems. The knowledge of these processes greatly enhances an understanding and risk assessment of CO_2 storage and the likelihood of CO_2 leakage. This system can detect very low quantities (as low as ~1 t) of CO_2 in the overburden of a storage reservoir. Such an understanding provides reassurance to the public and regulators that any risks associated with CCS activities are understood, thereby contributing to the safe and environmentally sound storage of CO_2 and increasing public confidence.

2. Underpinning research

Since 2001, UiT has co-developed a 3D seismic acquisition system for high-resolution 3D seismic imaging, called P-Cable system. In 2009, the Research Council of Norway granted funding to procure a full-scale P-Cable system for UiT within its 'National Infrastructure' program. The increases in resolution facilitate a much better target identification and achieve a much more accurate imaging of subsurface structure. Such high-resolution subsurface structure studies are crucial for understanding geosphere-biosphere interactions, environment and energy, future potential CO_2 storage and European Large-Scale Infrastructure (ESFRI) ocean observatory site investigations (EMSO: European Multidisciplinary Seafloor Observations), particularly in the underexplored Arctic regions, a vast area with potentially large implications for global carbon fluxes and climate.

We have studied many aspects of subsurface fluid leakage and gas seepage into the water column including the detailed architecture of leakage structures and their governing geological processes and mechanisms. We have also shown that we can detect small quantities of fluids and gases in the shallow seafloor that may pose a geohazard for offshore installation, e.g. offshore wind farms. Data acquired with the P-Cable system has led to outstanding new research results that have been published in high-impact journals (Science, Nature) or have a high number of citations over a short period of time.

The P-Cable system has allowed CAGE to establish a new research field: 4D time-lapse high-resolution seismic studies of natural geological processes. We are the only group in the world who are working in this fore-front research field. A cornerstone step has been achieved by documenting the repeatability of P-Cable 3D seismic data based on 4D time-lapse seismic data from three different geological settings on the Norwegian and Svalbard margins. Part of this 4D seismic development was driven through EU projects in the FP7 and H2020 program where theoretical work proved the feasibility of this approach using high-resolution 3D seismic data. We subsequently demonstrated that the P-Cable system may develop into an important tool for monitoring the shallow overburden of offshore CO_2 storage. This system can detect very low quantities (as low as ~1 t) of CO_2 in the overburden of a storage site.

Names of key researcher during the case period (2011-2023):
Prof. Stefan Bünz (UiT, 2011-2023), Prof. Jürgen Mienert (UiT, 2011-2017), Assoc. Prof. Andreia Plaza-Faverola (UiT, 2013-2023), Researcher Sunil Vadakkepuliyambatta (UiT, 2011-2021), PhD student/Post.doc Malin Waage (UiT, 2015-2022), PhD student/Post.doc Kate Waghorn (UiT, 2014-2022), PhD student/Post.doc Sunny Singhroha (UiT, 2014-2022)

3. References to the research

Bünz, S., Polyanov, S., Vadakkepuliyambatta, S., Consolaro, C. and Mienert, J., 2012. Active gas venting through hydrate-bearing sediments on the Vestnesa Ridge, offshore W-Svalbard. *Marine Geology*, 332, pp.189-197.

Andreassen, K., Hubbard, A., Winsborrow, M., Patton, H., Vadakkepuliyambatta, S., Plaza-Faverola, A., Gudlaugsson, E., Serov, P., Deryabin, A., Mattingsdal, R. and Mienert, J., 2017. Massive blow-out craters formed by hydrate-controlled methane expulsion from the Arctic seafloor. *Science*, 356(6341), pp.948-953.

Panieri, G., Bünz, S., Fornari, D.J., Escartin, J., Serov, P., Jansson, P., Torres, M.E., Johnson, J.E., Hong, W., Sauer, S. and Garcia, R., 2017. An integrated view of the methane system in the pockmarks at Vestnesa Ridge, 79 N. *Marine Geology*, 390, pp.282-300.

Waage, M., Bünz, S., Landrø, M., Plaza-Faverola, A. and Waghorn, K.A., 2019. Repeatability of high-resolution 3D seismic dataHigh-resolution 4D seismic data. *Geophysics*, *84*(1), pp .B75-B94.

Waage, M., Portnov, A., Serov, P., Bünz, S., Waghorn, K.A., Vadakkepuliyambatta, S., Mienert, J. and Andreassen, K., 2019. Geological controls on fluid flow and gas hydrate pingo development on the Barents Sea margin. *Geochemistry, Geophysics, Geosystems*, *20*(2), pp.630-650.

Waage, M., Singhroha, S., Bünz, S., Planke, S., Waghorn, K.A. and Bellwald, B., 2021. Feasibility of using the P-Cable high-resolution 3D seismic system in detecting and monitoring CO_2 leakage. *International Journal of Greenhouse Gas Control*, *106*, p.103240.

4. Details of the impact

The P-Cable infrastructure is essential to support Norwegian research within marine geosciences. This fore-front technology has allowed UiT to become a world leader in 3D seismology. The infrastructure constituted a key technology for research within SFF CAGE and other EU-funded or industry-funded projects, where it has led to several publications in high-impact journals like Nature and Science. Particularly, it has helped a research group at SFF CAGE to establish a new research field: 4D time-lapse seismic studies of natural geological processes.
The P-Cable infrastructure has benefitted UiT and collaborating institutions and it has instigated more collaboration on projects amongst these institutions. The significance of the data products for Norwegian lead proposals to International Ocean Discovery Program (IODP) cannot be understated. New knowledge provided the scientific basis for two IODP drilling legs (IODP Expeditions 396 (2021) and Expedition 403 (scheduled for 2024)). In each case, the high-resolution 3D seismic data offers full, detailed view of the subsurface allowing the planning of drill site with great precision. In their review of these proposals, IODP has lauded the quality and superiority of the high-resolution 3D seismic data for drill planning with respect to both achieving the science objectives and ensuring safe drilling operations.

This system can detect very low quantities (as low as ~1 t) of CO_2 in the overburden of a storage reservoir. It constitutes cost-effective technology amongst a suite of other subseafloor, seafloor and water-column monitoring technologies that were developed within an associated EU project to address CO_2 leakage risks. Together, these technologies are products with commercial value and socioeconomic impact. Carbon capture, utilisation and storage (CCUS) has gained significant momentum over the last few years as countries have recognized its potential to mitigate carbon emission. Several geophysical companies have recognized the potential of high-resolution 3D and 4D seismic imaging and developed similar commercial systems for a rapidly expanding CCUS landscape.

Furthermore, government agencies and other stakeholders have realized the potential for further development at even higher resolution. UiT is engaged in utilizing the technology for detailed subsurface geotechnical investigations and geohazard analysis within offshore wind farm projects towards renewable energy and the energy transition. The availability and proliferation of this technology will also have an impact on research activities related to the sustainable use of the seabed and ecosystem-based management of marine environment under government programs for the exploration and exploitation of deep-sea minerals and in support of solving the challenges set forth in the UN decade of the ocean initiative and the European Commission Green Deal.

5. Sources to corroborate the impact

IG – Case 4

Institution: UiT – The Arctic University of Norway	
Administrative unit: Department of Geosciences (IG)	
Title of case study: Carbon-cryosphere-ocean interactions in the Arctic	
Period when the underpinning research was undertaken: 2013-2021 (ongoing)	
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2021(ongoing)	
Period when the impact occurred: 2016-2021(ongoing)	

1. Summary of the impact

Research on carbon-cryosphere-ocean interactions in the Arctic has been perfomed in the Center of Excellence CAGE: Understanding climate, carbon cycling, and ocean processes, linked to ice-sheet dynamics, are crucial for sustainability planning over societally relevant timescales. Past deglaciation events of the Arctic represent an important analogue for contemporary and future processes associated with cryospheric meltdown and Arctic climate amplification. Knowledge gained through the development of empirical and modelling investigations has enhanced context and understanding that has fed into (inter)national policy, public discourse, and national resource management.

2. Underpinning research

The development of a numerical ice-sheet model of the growth and deglaciation of the last Eurasian ice sheet represents the culmination of a long history of empirical investigations constraining its development and chronology. This new tool developed within CAGE has provided a quantitative framework to explore the interactions of the ice sheet with various Earth systems during the last cryospheric meltdown and its role in the carbon cycle.

A shifting research approach that closely integrates empirical data with numerical modelling techniques has enabled new avenues for exploring the interaction of the cryospheric processes such as uplift/erosion/isostasy with fluid flow from deeper hydrocarbon systems, gas hydrate cycling, and the regulation of methane emissions from the subsurface upon deglaciation. These processes, that have been active over longer geological timescales through the Quaternary, play a key role for explaining the observed distribution and scale of natural seepages of gas and oil across the deglaciated domain of the Eurasian Arctic today.

Utilizing marine sediment records, we have constrained the efficiency of Arctic Ocean carbon sink linked with change in ice sheets during the last deglaciation, shifting from a prominent CO2 source to the atmosphere during the last deglaciation towards today's mode of being a prominent sink.

Investigations on the present-day ice sheets and ocean provide a broader environmental context on the pace and magnitude of ice-ocean interactions and the role they play in the carbon cycle. Linking these observations to the paleo record provides a long-term view for the future environmental changes.

Names of key researchers during the case period 2013-2023:

Prof. Karin Andreassen (UiT, 2013-2023), Associate Prof. Monica Winsborrow (UiT, 2014-2023), Researcher Henry Patton (UiT, 2013-2023), Prof. Alun Hubbard (UiT, 2013-2023), Researcher Mohammed Ezat (UiT, 2013-2023), PhD student/PostDoc Pavel Serov (UiT, 2013-2023), Researcher Sunil Vadakkepuliyambatta (UiT, 2013-2021), Prof. Stefan Bünz (UiT, 2013-2023), Prof. Jemma Wadham (UiT, 2019-2023), Prof. Tine Rasmussen (UiT, 2013-2023), PhD/PostDoc Alexey Portnov (UiT, 2013-2017), Researcher Rune Mattingsdal (Norwegian Petroleum Directorate, 2016-2023)

3. References to the research (indicative maximum of six references)

Andreassen, K., Hubbard, A.L., Winsborrow, M., Patton, H., Vadakkepuliyambatta, S., Plaza-Faverola, A., Gudlaugsson, E., Serov, P., Deryabin, A., Mattingsdal, R., Mienert, J., Bünz, S. 2017. Massive blow-out craters formed by hydrate-controlled methane expulsion from the Arctic seafloor. *Science 356*, 948-953. https://doi.org/10.1126/science.aal4500

Ezat, M., Rasmussen, T.L., Honisch, B., Groeneveld, J., DeMenocal, P. 2017. Episodic release of CO2 from the high-latitude North Atlantic Ocean during the last 135 kyrs. *Nature Communications 8*, 1-10. https://doi.org/10.1038/NCOMMS14498

Kishankov, A., Serov, P., Bünz, S., Patton, H., Hubbard, A.L., Mattingsdal, R., Vadakkepuliyambatta, S., Andreassen, K. 2022. Hydrocarbon leakage driven by quaternary glaciations in the Barents Sea based on 2D basin and petroleum system modelling. *Marine and Petroleum Geology 138*, April 2022, 105557. https://doi.org/10.1016/j.marpetgeo.2022.105557

Patton, H., Hubbard, A.L, Andreassen, K., Auriac, A., Whitehouse, P.L., Stroeven, A.P., Shackleton, C., Winsborrow, M., Heyman, J., Hall, A.M. 2017. Deglaciation of the Eurasian ice sheet complex. *Quaternary Science Reviews*, 148-172. https://doi.org/10.1016/j.quascirev.2017.05.019

Portnov, A.D, Vadakkepuliyambatta, S., Mienert, J., Hubbard, A.L. 2016. Ice-sheet-driven methane storage and release in the Arctic. *Nature Communications 7*, 10314. https://doi.org/10.1038/ncomms10314

Serov, P., Mattingsdal, R., Monica Winsborrow, M., Patton, H., Andreassen, K. In Review 2023. Widespread natural methane and oil leakage from submarine Arctic reservoirs. In Review in *Nature Communications.* Available at Reseach Square: https://doi.org/10.21203/rs.3.rs-1225012/v1

4. Details of the impact

Our results and datasets have directly influenced the approach and data acquisition of the national seabed mapping programme, MAREANO, at NGU, IMR and Kartverket to constrain and monitor seafloor leakage of hydrocarbons.

Our results, expertise and infrastructure have led to a joint collaboration with the Norwegian Petroleum Directorate to develop a geological model that explains the hydrocarbon leakages across the Barents Sea wider area. A direct consequence of the surveying of hydrocarbon leakage in areas currently exploited by national industry is the identification of leakage associated with hydrocarbon wells. This discovery has opened dialogues with industry on safe-practice methods to (re)seal wells in the Arctic.

This research into Arctic carbon cycling dynamics is a forefield topic of relevance for the international community, demonstrated by the contributions of the research group to various international forums for guiding policy decisions. For example, research outputs have been cited in the latest IPCC report AR6, and CAGE researchers are leading and contributing to the Polar Chapter of the Global Carbon Project, RECCAP2. This EU-coordinated project for the first time quantifies the impact of ice sheets on the present-day global carbon cycle. CAGE researcher, Alun Hubbard, also gave three keynote talks and multiple interviews at COP26 in Glasgow 2021 on glacier and ice sheet melt driving rapid global sea-level rise, how Arctic sea-ice loss is fueling extreme weather events, and the ticking time-bomb of future Arctic methane release in a warming world.

As well as for policy makers there exists a high interest from the public into research demonstrating the linked changes of the cryosphere and carbon cycle, as demonstrated by the significant impacts of the outreach projects that have stemmed from this research. At the local level this includes the creation of new exhibitions at the Tromsø Science Center and at the Tromsø University Museum. Our research has also had an international reach through its focus in documentaries such as ‘Ice on Fire’ and ‘Frozen Planet’, as well as in the popular science book ‘Ice Rivers’.

As an indicator to the extent of this research impact is its establishment as a priority at national funding level. New multi-million NOK investments are being made in infrastructure at UiT, for example with the establishment of a unique lab to establish Arctic-tailored methods for reconstructing climate and ocean changes, and the ICe Oceans and cliMate (ICOM) laboratory at the Department of Geosciences, that is designed to conduct low temperature advanced and cutting-edge experimental research on microbiology and biogeochemical cycles from the ice to ocean.

Lastly, the newly funded national Center of Excellence iC3 at the Department of Geosciences, UiT, to start in 2023 will generate a lasting impact around ice-sheet-carbon-climate interactions over the next 10 years.

This section should provide a narrative, with supporting evidence, to explain:

- How the research underpinned (made a distinct and material contribution to) the impact;
- The nature and extent of the impact.

The following should be provided:

- A clear explanation of the process or means through which the research led to, underpinned or made a contribution to the impact (for example, how it was disseminated, how it came to influence users or beneficiaries, or how it came to be exploited, taken up or applied).
- Where the submitted administrative unit's research was part of a wider body of research that contributed to the impact (for example, where there has been research collaboration with other institutions), the case study should specify the particular contribution of the submitted administrative unit's research and acknowledge other key research contributions.
- Details of the beneficiaries – who or what community, constituency or organisation has benefitted, been affected or impacted on.
- Details of the nature of the impact – how they have benefitted, been affected or impacted on.
- Evidence or indicators of the extent of the impact described, as appropriate to the case being made.
- Dates of when these impacts occurred.

5. Sources to corroborate the impact (indicative maximum of ten references)

www.cage.uit.no?

IG Case 5

Institution: UiT- The Arctic University of Norway	
Administrative unit: Department of Geosciences (IG)	
Title of case study: MinExTarget - Enhanced Use of Heavy Mineral Chemistry in Exploration Targeting	
Period when the underpinning research was undertaken: 2020 – 2021(ongoing)	
Period when staff involved in the underpinning research were employed by the submitting institution: 2015-2021(ongoing)	
Period when the impact occurred: .2021 - ongoing	

1. Summary of the impact

The main aim of the project is to develop an innovative methodology for more efficient exploration of metals, including metals needed for the green energy transition. The project has resulted with creation of a start-up company (MinExTarget Oy), as well as with education of a new generation of experts in the mineral exploration sector. In terms of the education, particular impact was made through the research-based education of several Master students, including a student (Johan Hilmo; see reference list) who, after gaining his master's degree at UiT/IG, joined LKAB, Sweden, and contributed to recent finding of the largest known REE mineral deposit in Europe.

2. Underpinning research

Population growth, accompanied with a rapid development of high technologies and urgent needs for the Green Energy Transition, exponentially increases the global demand for metals and drives a need for discovery of new mineral deposits. Whereas undiscovered mineral deposits are partly or completely buried and reside deeper in the crust, the development and implementation of new exploration techniques is needed. The MinExTarget project aims at developing and introducing a new exploration tool, which provides better targeting capacities in the early stages of mineral exploration. Recognition and interpretation of geochemical and mineralogical anomalies that have been inherited from primary metallic mineral deposits in sediments are widely used tools in mineral exploration. The new, innovative concept of the project is that the primary sources of those anomalies can be better targeted and qualified by the determination of associations and concentrations of trace elements together with stable and radiogenic isotope compositions in selected types of heavy mineral grains, taking geological, mineralogical and geochemical characteristics of the primary mineralization into consideration. The project is founded on the broad expertise of the MinExTarget consortium, including the expertise of the UiT/IG project participants. The underpinning research relevant for the MinExTarget project combines the research in fields of: 1) geochemistry of mineral deposits (Dr. Sabina Strmic Palinkas, Dr. Yulia Mun), 2) structural geology and tectonics (Prof. Steffen Bergh, Harald Hansen); and 3) sedimentology (Prof. Matthias Forwick).
Whereas underpinning research in fields of structural geology and tectonics, as well as sedimentology has been conducted at UiT/IG since the 1970's, geochemistry of mineral deposits was introduced as a new research and education discipline at UiT/IG from 2015.

Sabina Strmic Palinkas (associate professor, project coordinator at UiT), Steffen Bergh (professor), Matthias Forwick (professor), Yulia Mun (postdoctoral researcher), Harald Hansen (PhD student)
.
The project has been funded by EIT Raw Materials and is led by the Geological Survey of Finland (GTK). The funding period is 01.01.2020-31.12.2023.

1. **References to the research**

Hilmo, J. 2021: The geochemical signature of Cu mineralisation preserved in stream sediments from the Alta-Kvænangen Tectonic Window, Northern Norway. Master's thesis, UiT Norges arktiske universitet; https://munin.uit.no/handle/10037/21928.

Mun, Y., **Strmic Palinkas S.**, Kullerud, K., Nilsen, K. S., Bekker, A. 2020: Evolution of metal-bearing fluids at the Nussir and Ulveryggen sediment-hosted Cu deposits, Repparfjord Tectonic Window, northern Norway. *Norwegian Journal of Geology/Norsk Geologisk Forening*, *100*(2); https://doi.org/10.1785/njg100-2-5.

Mun, Y., **Strmic Palinkas S.**, **Forwick, M.,** Junttila, J., Pedersen, K., Sternal, B., Neufeld, K., Tibljaš, D., Kullerud, K. 2020: Stability of Cu-sulfides in submarine tailing disposals: A case study from Repparfjorden, Northern Norway. *Minerals* 10(2); https://doi.org/10.3390/min10020169.

Paulsen, H.K., **Bergh, S.G.**, **Strmic Palinkas, S.**, Karlsen, S., Kolsum, S., Ulvik Rønningen, I., Armitage, P.E.B., Nasuti, A. 2021: Palaeoproterozoic foreland fold-thrust belt structures and lateral faults in the West Troms Basement Complex, northern Norway, and their relation to inverted metasedimentary sequences. *Precambrian Research* 362, 106304; https://doi.org/10.1016/j.precamres.2021.106304.

Sahlström, F., **Strmic Palinkas, S.**, Dundas, S.H., Sendula, E., Cheng, Y., Wold, M., Pedersen, R.B. 2022: Mineralogical distribution and genetic aspects of cobalt at the active Fåvne and Loki's Castle seafloor massive sulfide deposits, Arctic Mid-Ocean Ridges. *Ore Geology Reviews*, 105261; https://doi.org/10.1016/j.oregeorev.2022.105261.

4. Details of the impact

The MinExTarget project has been contributing to the research-based education of a new generation of experts in the mineral exploration sector through an active involvement of Master and PhD students in the project activities, as well as through organization of short-courses. So far 4 Norwegian Master students have completed their Master projects as a part of the MinExTarget project. Two students were from UiT (Sondre Simonsen, 08/07/2021; Johan Hilmo, 08/07/2021) and two students were from the University of Bergen, but supervised from UiT (Trond Fjellet, 09/09/2021; Frida Forsberg, 09/09/2021). All 4 students have got relevant jobs, and one of them (Johan Hilmo) actively participated in recent discovery of the European largest REE deposit. In addition, more than 70 Norwegian and international students participated in the short-course «Fingerprinting techniques in mineral exploration - Discover the mineral potential of Fennoscandia and Northern Europe» organized at UiT/IG and given online in the period from 14-18.06.2021.

5. Sources to corroborate the impact

- https://eitrawmaterials.eu/short-course-fingerprinting-techniques-in-mineral-exploration/

- https://lkab.com/en/press/europes-largest-deposit-of-rare-earth-metals-is-located-in-the-kiruna-area/

IKJ-NTNU Case 1

Institution:
Administrative unit: Department of Chemistry NTNU (IKJ-NTNU)
Title of case study: Sustainable food production in aquaculture
Period when the underpinning research was undertaken: 2016 - 2023
Period when staff involved in the underpinning research were employed by the submitting institution: 2015 - 2023
Period when the impact occurred: 2019 to date

1. Summary of the impact (indicative maximum 100 words)
This section should briefly state what specific impact is being described in the case study.

Aim of the research in the SFI CtrlAQUA has been to achieve through novel solutions a support for further expansion of Norwegian aquaculture, thereby securing Norway's position as the world-leading supplier of aquaculture expertise, technology, and sustainable seafood. Within this main goal this Case describes impact linked to processes taken in use by the aquaculture industry on recommendations to secure good water quality and fish health as well as more cost-efficient process for microbial management strategy for nitrifying bioreactors in closed or semi-closed aquaculture systems with variable salinity.

2. Underpinning research (indicative maximum 500 words)

The Norwegian Government and Atlantic salmon industry have a strategy to increase the aquaculture production and sustain Norway role of being the world leading producer of sustainable seafood. However, there are concerns related to the challenges in salmon aquaculture, including e.g., sea lice, infectious diseases, escapees, loss of fish transferred to open sea-cages, water quality etc. To reach the envisioned goal of growth, a strong research-driven innovation effort is required to ensure minimal environmental impact and fish mortality, challenges that are limiting large-scale increases in production. The aim of the CtrlAQUA Centre was to provide the needed solutions by innovating technology and knowledge necessary for using closed-containment systems (CCS), during strategic parts of the salmon production cycle. Main impact was to achieve reliable, controllable, and efficient production of salmon in CCS providing a realistic solution for the aquaculture industry. Maintaining good water quality is a crucial part of CCS management that requires use of water recirculation and water treatment. In this Case we describe impact from only parts of the extensive research that have been carried out in the SFI consortium. The consortium has brought together a diverse group of national and international academic institutions, major aquaculture industry in Norway as well as both national and international research institutes. This have included research and development partners (NOFIMA, NORCE, University of Bergen, NTNU, University of South-Eastern Norway, University of Gothenburg, The Conservation Funds), technology suppliers (Create View, Pure Salmon, Kaldnes, Atlantium Illuminating Water Quality, Aquafarm Equipment, FishGlobe, FiiZK), farming companies (MOVI, CERMAQ; Grieg Seafood, Lerøy), and pharmaceutical companies (PHARMAQ and PARMAQ Analytics). NOFIMA has been the coordinator of the SFI. Department of chemistry NTNU has especially been involved in the Technology Department of the SFI, and main role have been to give recommendations to the industry based on research carried out during experiments in the consortium concerning factors that can affect the water quality and to achieve more reliable sensor data to on water quality to secure fish health. We have also together with NOFIM and Kruger Kaldnes Veola been involved in and supporting research leading to recommendations taken in use by the aquaculture industry to achieve more cost-efficient process for microbial management strategy for nitrifying bioreactors in closed or semi-closed aquaculture systems with variable salinity. Our role has also been on sensor development itself to achieve suitable sensor systems for chemical parameters (copper, zinc, iron) not earlier monitored automatically in aquaculture. Through the period from 2016 and until the now IKJ have been supporting the industry to achieve more reliability sensor data through avoid biofouling of sensor systems monitoring chemical parameters crucial for the water quality, developed more sustainable cost-effective handling of nitrate as well as aspect connected to organic matter in recirculating system in CCS and how it might be affected by treatment processes.

Key researchers

Only those affiliated with Department of Chemistry is listed:
2015 to date: Øyvind Mikkelsen Professor, Leader of the project SENSOR in the Tech. Dep. in the SFI, researcher in the project, main supervisor of 4 PhD affiliated to the project, supervisor of master students in the project
2017 to date: Alexandros Asimakopoulos Associate Professor researcher in project, Co-supervisor of PhD student
2016 – 2021 Shazia Aslam Postdoc, researcher, co-supervisor master students
2016 to 2021: Rudolf Schmid Associate Professor, researcher in project, Co-supervisor of Phd
2016 to data: Murat van Ardelan Professor Supervisor of master students affiliated to the project
PhD students; Ingrid Naterstad Haugen, Xiaoxue Zhang, Patricia Aguilar Alarcon, Sharada Navada (Industry PhD)
Several master students was successfully involved in contextual learning through master projects carried out in direct collaboration with consortium partners / research Institutes and industry partners.

3. References to the research (indicative maximum of six references)

1. Alarcon, P.A., Zherebker, A., Rubekina, A., Shirshin, E., Simonsen, M.A., Kolarevic, J., Lazado, C.C., Nikolaev, E.N., Asimakopoulos, A.G., Mikkelsen, Ø. (2022). Impact of ozone treatment on dissolved organic matter in land-based recirculating aquaculture systems studied by Fourier transform ion cyclotron resonance mass spectrometry, Science of The Total Environment, 843:157009. https://doi.org/10.1016/j.scitotenv.2022.157009

2. Alarcon, P.A., Gonzalez, S.V., Simonsen, M.A., Borrero-Santiago, A.R., Sanchís, J., Meriac, A., Kolarevic, J., Asimakopoulos, A.G., Mikkelsen, Ø. (2020). Characterizing changes of dissolved organic matter composition with the use of distinct feeds in recirculating aquaculture systems via high-resolution mass spectrometry, Science of The Total Environment, 749:142326. https://doi.org/10.1016/j.scitotenv.2020.142326

3. Navada, S., Sebastianpillai, M., Kolarevic, J., Fossmark, R.O., Tveten, A-K., Gaumet, F., Mikkelsen, Ø., Vadstein, O., (2020) A salty start: Brackish water start-up as a microbial management strategy for nitrifying bioreactors with variable salinity. Science of the Total Environment. 739:139934 https://doi.org/10.1016/j.scitotenv.2020.139934

4. Navada, S., Vadstein, O., Gaumet, F., Tveten, A-K., Spanu, C., Mikkelsen, Ø., Kolarevic, J. (2020) Biofilms remember: Osmotic stress priming as a microbial management strategy for improving salinity acclimation in nitrifying biofilms. Water Research. 176: 115732. https://doi.org/10.1016/j.watres.2020.115732

5. Aslam, S.N., Navada, S., Bye, G.R., Mota, V.C., Terjesen, B.F., Mikkelsen, Ø., (2019) Effect of CO2 on elemental concentrations in recirculating aquaculture system tanks. Aquaculture 511: 734254. https://doi.org/10.1016/j.aquaculture.2019.734254

6. Zhang, X., Årstøl, E., Nymark, M., Fages-Lartaud, M.R., Mikkelsen Ø. (2022). The Development of Polydimethysiloxane/ZnO–GO Antifouling Coatings. J Clust Sci 33, 2407–2417. https://doi.org/10.1007/s10876-021-02165-7

4. Details of the impact (indicative maximum 750 words)

As part of the multidisciplinary consortium collaborating in the SFI, it is the overall contribution of all sub-projects together that generates the significant impact and overall, of the frame of the Centre. Starting point for the SFI was concerns about challenges in salmon aquaculture. A sustainable aquaculture salmon industry needs to be optimized both with respect to the environmental, economic, and social pillars. A crucial aspect in salmon aquaculture is water quality, especially for closed and semi-closed compartment systems using water recycling and water treatment. Successful CCS or S-CCS aquaculture have impact on all the three pillars of sustainability. Main role of Department of Chemistry through the lifetime of the SFI been especially related to water quality, with impact to fish health and in the prolongation of this the productivity. Knowledge about water quality is also vital for the environmental aspects connected to waste and energy/costs for water treatment. One important cost driver in CCS and S-CCS is handling of harmful compounds potentially building up in the water over time. Significant step in the treatment process is use of biofilters that degrades organics and convert ammonia to nitrates. Through the actual research activity new knowledge on the dynamics of starting up the biofilter in different salinities have been achieved, this have resulted in more efficiently processes in converting ammonia to nitrates. This has a direct positive impact on the process by substantially reducing the freshwater consumption, which have an economic impact by reducing the energy required for pumping and temperature regulation. Impact of this reach has already been adapted by the aquaculture industry and suppliers of biofilter systems. Research behind this impact has been achieved by a series of experiments carried out in collaborations with partners in the CtrlAqua SFI. Main contributors have been Kruger Kaldnes (Veola), NOFIMA and Department of Chemistry NTNU, and involved an Industry PhD student from Kruger Kaldnes hosted at our department. Further Department of Biology at NTNU was strongly involved. Research activity gave in-depth insight in the nitrification process in biofilms under varying salinities. Research has also included studies of the impact of salinity on biofilm microbial communities and how microbial strategies may be utilized to improve bioreactor design and management. Economic impact for the aquaculture salmon industry has been achieved as well as scientific impact through several scientific papers in high quality international journals that despite their recent publication dates have received good citing index (>30). The presence of organic matter is also a significant part of the water quality, that up to data have been a “black box” in aquaculture. Organic matter may accumulate in recirculating aquaculture systems resulting in negative effect on water quality, fish health directly or through degradation products generated by water treatment process (e.g., ozonation), as well as putting higher loads and costs on the water treatment process. A significant research activity has therefor been devoted to organic matter. The different sources of natural organic matter accumulated in the system have been studied and through applying non-targeted analyses using high-resolution mass spectrometry techniques to decipher for the first time the molecular composition of dissolved organic matter in recirculating CCS/S-CCS with Atlantic Salmon and its transformation during the water treatment processes. Scientific impact achieved from this research is completely new understanding of how dissolved organic matter impacts the water quality through use of advance analytical chemistry. Main contributors in this research have been our department, NOFIMA and international research collaborators also outside the SFI Consortium (Catalan Institute for Water Research (Spain), University of Girona (Spain), Skolkovo Institute of Science and Technology (Russia), Department of Physics, Lomonosov Moscow State University (Russia), Laboratory of Clinical Biophotonics, Scientific and Technological Biomedical Park, Sechenov University (Russia). The mention research activity along with additional research activity from our department using nanotechnology for developing antifouling coatings to prevent biofilm formation on sensor systems as well as automatic sensor system for trace metal monitoring in CCS/S-CCS have formed impact and potential impact on several levels:

Scientific impact: publications of results in open access high quality international journals

Economic impact/industry impact: new and cost-efficient process for microbial management strategy for nitrifying bioreactors in closed or semi-closed aquaculture systems

Educational impact: several master projects in collaboration with private industry and research institutes (as requested in the Long-term plan for research and education), based on contextual learning which have impact on the educational activity at department to align with NTNU strategy.

Social impact: part of research generating more sustainable food production that aligns with EU SDGs.

5. Sources to corroborate the impact (indicative maximum of ten references)

https://www.forskningsradet.no/siteassets/publikasjoner/2019/midway-evaluation-of-17-centres-for-research-based-innovation-sfi-iii.pdf (page 38 - 47)

https://ctrlaqua.no/news/events/phd-defense-of-patricia-aguilar-alarcon/

https://ctrlaqua.no/news/events/phd-defense-xiaoxue-zhang/

https://ctrlaqua.no/news/2021/03/03/a-vegetarian-with-a-phd-in-fish/

https://thefishsite.com/articles/many-students-being-educated-in-ctrlaqua

https://ctrlaqua.no/news/2022/05/09/meet-three-ctrlaqua-students/

https://ctrlaqua.no/news/2022/03/23/phd-in-quality-of-sensors/

https://www.rastechmagazine.com/the-salmon-doctor-is-in/

https://www.kyst.no/ctrlaqua-sfi-doktorgrad-kr/doktorgrad-viser-oppsiktsvekkende-resultater/185154

https://www.fiskeribladet.no/tekfisk/grumsete-vann-i-ras-produksjon-av-fisk/2-1-832210

IKJ-NTNU Case 2

Institution:
Administrative unit: Department of Chemistry NTNU (IKJ-NTNU)
Title of case study: Thermodynamic driving forces / Applications of porous layers for PEM Fuel cells and CO_2 sequestration
Period when the underpinning research was undertaken: 2017 to date
Period when staff involved in the underpinning research were employed by the submitting institution: 2017 to date
Period when the impact occurred: 2017 to date

1. Summary of the impact (indicative maximum 100 words)
This section should briefly state what specific impact is being described in the case study.

This Case is from the Centre of Excellence PoreLab where Department of Chemistry is partner. The case relates to research and impact connected to applications of porous layers for PEM Fuel cells and CO2 sequestration.

2. Underpinning research (indicative maximum 500 words)

PoreLab is a Norwegian Center of Excellence created in 2017 and situated at the Norwegian University of Science and Technology (NTNU) in Trondheim, and the University of Oslo (UiO). The Centre is organised into groups but there is a strong emphasis towards collaboration across these groups. Research fellows from different groups are co-located to encourage this. Main aim of reaches is to advance the understanding of flow in porous media. Starting from a sound basis in physics the goal is to achieve a better description of flows that range from geological to biological and technological. Impact is strongly scientifically, but also for applications in industry and society. PoreLab consists of seven main research themes, where Department of Chemistry especially are involved and responsible for “Thermodynamic driving forces” and “Applications”. The objectives of the latter research theme “Applications” is: **a)** design more efficient electrochemical systems such as batteries and systems with ion-selective membranes. **b)** describe moisture migration in insulation materials. **c)** enhance the understanding of biological systems. **d)** study porous materials for transport and storage of hydrogen. Knowing under what conditions a liquid phase can seep through a solid phase containing voids and how the effective macroscopic transport parameters are influenced by the microscopic geometric structure of the medium are basic problems of enormous impact in basic science and engineering. Among important impact is outcome on porous layers for PEM Fuel cells and CO2 sequestration.

Key researchers

Only those affiliated with Department of Chemistry is listed:

2021 to date: Øivind Wilhelmsen, Professor PI Research Theme, research, supervisor PhDs

2017 to date: Dick Bedeaux, Professor emeritus, research, supervisor PhDs

2017 to date; Signe Kjelstrup, Professor and Professor emeritus from 2022, former PI Research Theme, research, supervisor PhDs

2017 to date: Bjørn Hafskjold, Professor and Professor emeritus from 2021

2017 to date; Eirik Grude Flekkøy, Professor research, supervisor PhDs

PhD candidates: Kim R. Kristiansen, Astrid F. Gunnarshaug, Sebastian Everard Nordby Price, Olav Galteland, Michael Rauter, Vegard Jervell + additional PhD affiliated at other Departments but co-supervised by staff at Department of Chemistry.

3. References to the research (indicative maximum of six references)

1. Bråten, Vilde; Zhang, Daniel Tianhou; Hammer, Morten; Aasen, Ailo; Schnell, Sondre Kvalvåg; Wilhelmsen, Øivind (2022) Equation of state for confined fluids. Journal of Chemical Physics 2022; Volum 156.(24) s 16 (244504). DOI: http://dx.doi.org/10.1063/5.0096875

2. Hansen, A., Sinha, S., Bedeaux, D., Kjelstrup, S., Gjennestad M.Aa., Vassviket V.M. (2018) Relations Between Seepage Velocities in Immiscible, Incompressible Two-Phase Flow in Porous Media. Transp Porous Med 125, 565–587 (2018). https://doi.org/10.1007/s11242-018-1139-6

3. Hafskjold, Bjørn; Bedeaux, Dick; Kjelstrup, Signe; Wilhelmsen, Øivind. (2021) Theory and simulation of shock waves: Entropy production and energy conversion. Physical review. E 2021 ;Volume E104. p. 18 – DOI: http://dx.doi.org/10.1103/PhysRevE.104.014131

4. Rauter, Michael Tobias; Schnell, Sondre K.; Kjelstrup, Signe. (2021) Cassie-Baxter and Wenzel States and the Effect of Interfaces on Transport Properties across Membranes. Journal of Physical Chemistry B 2021 s. 11- DOI: http://dx.doi.org/10.1021/acs.jpcb.1c07931

5. S. Kjelstrup, E. Magnanelli (2020) Efficiency in the process industry: Three thermodynamic tools for better resource use. Trends in Food Science & Technology. Volume 104, October 2020, Pages 84-90. https://doi.org/10.1016/j.tifs.2020.08.010

6. Li, Jie; Arbizzani, Catia; Kjelstrup, Signe; Xiao, Jie; Xia, Yong-yao; Yu, Yan; Yang, Yong; Belharouak, Ilias; Zawodzinski, Thomas; Myung, Seung-Taek; Raccichini, Rinaldo; Passerini, Stefano (2020) Good practice guide for papers on batteries for the Journal of Power Sources. Journal of Power Sources 2020; 452. s.1-4 – 15 March 2020, 227824 Doi: https://doi.org/10.1016/j.jpowsour.2020.227824

4. Details of the impact (indicative maximum 750 words)

Evaluation impact for this case is related to the main goal for Centres of Excellence that are to "..to achieve ambitious scientific goals through collaboration..." *and* "…research at the centers must be innovative and have great potential for boundary-breaking results that move the international research front." Significant scientific impact is therefore expected, and tge Case review research activity where Department of Chemistry has played a major role in the SFF. The research has been going on from 2017 and will continue until 2027. To illustrate the scientific impact the paper from A. Hansen, S. Sinha, D. Bedeaux, S. Kjelstrup. M. Aa. Gjennestad and M. Vassvik on "Relations between Seepage Velocities in Immiscible, Incompressible Two-phase Flow in Porous Media" has become the most downloaded paper ever in Transport in Porous Media, the main journal in porous media research, since 1986. Through the research it was reported how certain easily overlooked symmetries in immiscible two-phase flow in porous media lead to new equations constraining how the two fluids move. The ultimate goal of this work is to present a complete theoretical description of immiscible two-phase flow in the limit where the porous medium may be seen as a continuum, i.e. the scales where relative permeability theory today reigns.

Adsorption has made porous materials like zeolites and metal organic frameworks (MOFs) candidates to store hydrogen or capture CO_2 or methane to combat global warming. Therefore, part of our research is dedicated to describing heat and mass transport into these porous media by understand the interplay between adsorption, desorption and other transport mechanisms like diffusion and convection. The scientific impact of the research is illustrated with an extensive number of papers in high quality journals (see ref 1 in form below by search of involved staff from our department). Further several PhDs have been educated or are in progress, and our activity have contributed to achieve significant impact to achieve both goals in the "Long-term plan for research and education 2018 – 2028" to develop research groups of excellent quality as well as contributing to achieving goals in the updated "Long-term plan for research and education 2023 – 2032) to achieve goals within the thematic research areas of climate, environment, and energy, by conducting research directly applicable for understanding and achieve e.g., more efficient CO_2 separation from natural gas, renewable energy, and efficient fuel cells.

5. Sources to corroborate the impact (indicative maximum of ten references)

Journal Publications – PoreLab

The energy conversion in active transport of ions (pnas.org)

How tiny water droplets form can have a big impact on climate models (phys.org)

(Invited) Modelling Electrochemical Cells with Porous Electrodes. The Proton Exchange Membrane Fuel Cell - IOPscience

The North Sea as a Platform for Clean Energy Transition - SINTEF / The North Sea as a platform for the Clean Energy Transition - regjeringen.no

European Federation of Chemical Engineering - "Michael L. Michelsen" Award (efce.info)

Three young researchers awarded - The Norwegian American

PoreLab Annual Reports – PoreLab

[IKP] [Case 1]

Institution: Norwegian University of Science and Technology – NTNU
Administrative unit: Department of Chemical Engineering / Institutt for kjemisk prosessteknologi – IKP
Title of case study: SFI iCSI
Period when the underpinning research was undertaken: 2015-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2015 – present
Period when the impact occurred: 2015 – present

1. Summary of the impact (indicative maximum 100 words)

iCSI - industrial Catalysis Science and Innovation (iCSI) – is a Centre for Research-based Innovation (SFI) which *impact is a more competitive and sustainable (Norwegian) chemical process industry*. Jointly with the industry (Yara, KA Rasmussen, Dynea, Inovyn and Topsøe) and research partners (University of Oslo, SINTEF Industry) this has been achieved by

- ✓ Establishment of fundamental insights on industrially relevant catalysis
- ✓ Education of candidates (MSc, PhD, postdoc.) who move on to realize the green transition

iCSI's duration is 2015-2023 but due to the fundamental and educational nature, the impact will endure well beyond its completion.

2. Underpinning research (indicative maximum 500 words)

The underpinning iCSI research described below has

- ✓ involved PhD students and postdoctoral fellows funded by iCSI, with MSc students affiliated,
- ✓ demonstrated close collaboration and co-publishing with the iCSI industrial partners,
- ✓ provided key experimental and theoretical research methodology development and fundamental chemical and physical insights to the catalysis critical to the industrial partners' business.

Only research activities at NTNU Department of Chemical Engineering are described below. However, similar impact has been achieved by UiO and SINTEF and there has also been significant collaboration between the research partners.

Polyvinylchloride (PVC), produced by polymerization of the monomer vinyl chloride (VCM), is the third-most widely produced plastic and a key product to Inovyn at its Rafnes/Herøya (Norway) and other sites. VCM production, including ethylene oxychlorination, was introduced in the 1950's and is a mature process where high plant reliability and continuous improvement of energy and raw material efficiency are still required to reduce CO_2 emissions and remain competitive. Ethylene oxychlorination reaction involves reduction, oxidation, and hydrochlorination steps. IIA4 in iCSI has addressed the highly dynamic nature of the $CuCl_2$ catalysts and its effects on the activity, selectivity, and stability, by operando transient kinetic studies. A multiscale approach has been developed, combing the operando kinetic study by following the spatial and time-dissolved catalyst oxidation state changes, DFT-based microkinetic modeling of the whole catalytic cycle, and reactor modeling and simulation, to provide fundamental insights of the process [1-4]. Through this, better catalyst support and promoters were proposed for the industrial catalyst to improve the performance. By tuning the spatial Cu oxidation state, the CO and CO_2 selectivity has been significantly reduced. A novel kinetic model has been developed to accurately predict the Cu oxidation state and its response to the reaction and has been applied to optimize the catalysts and reactors of the industrial process.

In methanol partial oxidation to formaldehyde over silver catalyst, Dynea (process operator and technology licensor) and KA Rasmussen (catalyst producer) are the industrial partners. The main target is to understand how the formaldehyde selectivity can be increased and the complete oxidation to CO_2 can be supressed to reduce methanol cost and environmental impact. Application of an annular reactor concept to the reaction system demonstrated unprecedented formaldehyde selectivity (96%) and new mechanistic and kinetic insights at industrially relevant conditions [5]. But notions in literature claiming complex effects of oxygen dissolution in and restructuring of the silver as important to the surface chemistry were strengthened and directs further research.

Nitric acid is a commodity chemical with an annual global production of 65 Mtonnes. Yara operates 3 nitric acid factories in Porsgrunn (Norway) and several others. The main target has been to explore catalytic oxidation of NO to NO_2 to increase nitric acid output and heat recovery, and to reduce plant CAPEX. Several catalysts have been identified as active at industrial conditions. Ru, Pt and MnO_2-based catalysts show promising low-temperature catalytic activity for NO oxidation [6]. In situ X-ray absorption spectroscopy and X-ray diffraction have been applied at demanding reaction conditions to give new insight into the active state of the catalysts.

Key researchers:

Professor and iCSI Director Hilde Johnsen Venvik, Department of Chemical Engineering, NTNU

- Lise Meitner Guest Professor, Department of Chemical Engineering, Lund University, Sweden
- Council Secretary, European Association of Catalysis Societies (EFCATS)
- Methanol partial oxidation to formaldehyde, experimental and theoretical methods; (in situ/operando) x-ray photoelectron spectroscopy, surface science, electron microscopy characterization, density functional theory calculations.

Professor De Chen, Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- List of scientists with highest publication points in Norway 2017-2020
- Oxychlorination/VCM, experimental and theoretical methods; (in situ/operando) UV–vis–NIR, kinetic investigations, (micro)kinetic modeling, reactor modeling, density functional theory calculations, catalyst development.

Professor Magnus Rønning, Department of Chemical Engineering, NTNU

- Vice Dean for Research, Faculty of Natural Sciences, NTNU
- NO oxidation, experimental and theoretical methods; (in situ/operando) x-ray absorption spectroscopy, x-ray diffraction, Raman spectroscopy, IR spectroscopy, catalyst synthesis.

Professor Edd Blekkan, Department of Chemical Engineering, NTNU

- NO oxidation, experimental and theoretical methods; (in situ/operando) SSITKA and microcalorimetry, in situ mass analysis, catalyst development

Associate professor Jia Yang, Department of Chemical Engineering, NTNU

- Methanol partial oxidation to formaldehyde, experimental and theoretical methods; (in situ/operando) SSITKA and microcalorimetry, in situ mass analysis, kinetic investigations

Adjunct Associate Professor Kumar Rout (2019-2022), Dept. Chemical Engineering, NTNU

- Oxychlorination/VCM, experimental and theoretical methods; (in situ/operando) UV–vis–NIR, kinetic investigations, (micro)kinetic modeling, reactor modelling.
- Main affiliation: SINTEF Industry (2016-2021), Quantafuel (2021-22)

Adjunct Professor David Waller (2021-) Department of Chemical Engineering, NTNU

- Synthesis gas, ammonia and nitric acid production. Catalyst characterization, synthesis, development, testing and implementation.
- Main affiliation: Yara

Adjunct Associate Professor Ingeborg Helene Svenum, Dept. Chemical Engineering, NTNU

- (in situ/operando) x-ray photoelectron spectroscopy, surface science, density functional theory calculations.
- Main affiliation: SINTEF Industry

3. References to the research

[1] Rout, Kumar Ranjan; Fenes, Endre; Baidoo, Martina Francisca; Abdollahi, Reza; Fuglerud, Terje; Chen, De, **Highly Active and Stable CeO_2-Promoted $CuCl_2/Al_2O_3$ Oxychlorination Catalysts Developed by Rational Design Using a Rate Diagram of the Catalytic Cycle**, *ACS Catalysis,* 2016, 6, 7030-7039

[2] Hongfei Ma, Guoyan Ma, Yanying Qi, Yalan Wang, Qingjun Chen, Kumar R. Rout, Terje Fuglerud, and De Chen: **Nitrogen-Doped Carbon-Assisted One-pot Tandem Reaction for Vinyl Chloride Production via Ethylene Oxychlorination**. *Angewandte Chemie International Edition*, 2020, 59, 49, 22080-22085

[3] Ma, Hongfei; Sollund, Erling S.; Zhang, Wei; Fenes, Endre; Qi, Yanying; Wang, Yalan; Rout, Kumar Ranjan; Fuglerud, Terje; Piccinini, Marco; Chen, De: **Kinetic modeling of dynamic changing active sites in a Mars-van Krevelen type reaction: Ethylene oxychlorination on K-doped $CuCl_2/Al_2O_3$**. *Chemical Engineering Journal,* 2021, 407, 128013

[4] Ma, Hongfei; Wang, Yalan; Zhang, Hao; Ma, Guoyan; Zhang, Wei; Qi, Yanying; Fuglerud, Terje; Jiang, Zheng; Ding, Weiping; Chen, De: **Facet-Induced Strong Metal Chloride−Support Interaction over $CuCl_2/\gamma\text{-}Al_2O_3$ Catalyst to Enhance Ethylene Oxychlorination Performance.** *ACS Catalysis* 2022, 12, 8027-8037

[5] Stine Lervold; Rune Lødeng; Jia Yang; Johan Skjelstad; Kristin Bingen; Hilde Johnsen Venvik: **Partial oxidation of methanol to formaldehyde in an annular reactor**, *Chemical Engineering Journal*, 2021, 423, 130141

[6] Salman, Ata ul Rauf; Enger, Bjørm Christian; Auvray, Xavier; Lødeng, Rune; Menon, Mohan; Waller, David; Rønning, Magnus, **The Catalytic oxidation of NO to NO_2 for nitric acid production over a Pt/Al_2O_3 catalyst**, *Applied Catalysis A, General*, 2018, 564,142-146

4. Details of the impact (indicative maximum 750 words)

The iCSI research activities were initiated during 2015-16. At NTNU Department of Chemical Engineering, we became heavily involved in industrial process with huge economic and environmental impact, i.e. the production of VCM, nitric acid and formaldehyde. The associated catalytic steps, oxychlorination, ammonia and NO oxidation, and methanol partial oxidation are also notoriously experimentally difficult, involving a wide range of challenges with respect to, e.g., reactant and product stability, thermal precision, chemical quantification, equipment corrosion, as well as laboratory safety. We have continuously worked to solve these challenges and have introduced new or improved methods and protocols.

The iCSI industrial partners have been intimately involved to define the research questions, develop the methodology, and to interpret and learn from the results. This has been demanding, but highly rewarding and inspiring. As shown and explained above, they have been willing to explore fundamental chemical aspects of their existing (oxychlorination, methanol-to-formaldehyde) or prospect (NO oxidation, one-pot VCM) catalytic process technologies, and to publish many of the results. They have also received the affiliated PhD students for short industrial exchanges. To us, such long-term funding and industrial collaboration, in the preferred way of research, yielding also our most prestigious and rewarding results. In parallel, the insights have been used by the industrial partners to increase yields, reduce energy consumption, promote licencing or develop/prospect new technologies.

Three internationally renowned scientists in the field of catalysis with industrial experience have been involved in iCSI as scientific advisors: Prof. Graham Hutchings (Cardiff University); Prof. Enrique Iglesia (UC Berkeley), and Prof. Alessandra Beretta (Politecnico de Milano). Their role has been to participate at our seminars with presentation of recent research at the international forefront and to advise the iCSI candidates. This has inspired and challenged the iCSI team to reach beyond the targets set by ourselves.

10 PhD candidates (2 women) and 3 postdoctoral fellows (all women) are or have been affiliated with iCSI at NTNU Department of Chemical Engineering. 4 of the PhD degrees have already been defended. 18 Master theses (2016-22) have been carried out in affiliation with the iCSI PhD and postdoc research. SINTEF research scientists and industrial researchers have been involved in the supervisor teams, and the candidates have also collaborated with other researchers and students in the group or elsewhere (including international collaboration and visitors). As an example could be highlighted the collaboration between Prof. Tronconi (Politecnico de Milano) and Prof. Chen, leading to a second paper in Angewandte Chemie Int Ed, for which the methodology developed for oxychlorination was applied to obtain new insights one the selective catalytic reduction of NOx by ammonia.

The completed iCSI PhDs have immediately been recruited to highly relevant R&D positions at Equinor, Inovyn and NTNU. Another 23 postdoctoral fellows (8 women) have performed research and 31 PhD candidates (9 women), have or are about to defend their theses in the catalysis group with funding from other projects running in parallel with iCSI (2016-2023), with another 70 master theses affiliated. These are also highly attractive in industry and research after their training in the group, and alumni PhD/postdoc employers include Yara, Dynea, Equinor, Cenate, Freyr, Morrow, Aker Solutions, Aker Carbon Capture, Cambi, Hydrogen Mem-Tech, NAMMO, ReSiTech, BYD, INEOS, IFE, NTNU, SINTEF, TU Delft, Kwame Nkrumah University of Science and Technology. A prominent responsibility in their new jobs is to enable the significantly reduction in climate and environmental impact of the industrial operations required for the green transition.

Hosting a centre like iCSI with its close collaboration with industry partners makes the catalysis community at NTNU and the affiliated research institutions attractive to international students and researchers. In 2021, the master’s students, PhD candidates, postdocs and guest researchers within or affiliated with iCSI at NTNU represented in total 18 countries. Non-Norwegians made up more than 50% of this group of employees and students. In addition, there are typically 5-10 exchange PhDs for shorter stays and 3-5 international exchange master’s students every year.

The industrial partners have significantly revised their strategies since the development of the of the iCSI grant proposal in 2013-14. Strong emphasis on changing or offering technology to enable the green transition is a joint feature of their ambitions. We are therefore delighted that most of them (4/5) have committed to continue the collaboration in a new Centre grant proposal to be developed during 2023-24, as well as via other (smaller) instruments. In addition, we have a range of other industrial partners that may be relevant to the new Centre.

5. Sources to corroborate the impact (indicative maximum of ten references)

i. iCSI webpage with link to 2015-21 Annual Reports on the front page. All research activities are described, all publications and presentations are listed and each year highlight a different main achievement. All postdoctoral fellows, PhD candidates and Master students (iCSI and other projects) are listed, as well as international guests.

ii. Statements on impact provided by the industrial partners in conjunction with the Midway-Evaluation of the Centres for Research-based Innovation (SFI) (**Confidential document attached separately**)

iii. Licensing:
   - 2019: Dynea anounces a new Formaldehyde Plant Contract
   - 2020: Dynea announces a new Formaldehyde Plant Contract
   - 2022: Dynea's 2nd Silver Formaldehyde Conference

iv. iCSI Scientific Advisory Committee on the iCSI webpages

v. Publication resulting from collaboration between Prof. Tronconi (Politecnico de Milano) and Prof. Chen (NTNU catalysis), leading to a second paper in Angewandte Chemie Int Ed:
Wenshuo Hu; Tommaso Selleri; Federica Gramigni; Endre Fenes; Kumar R. Rout; Shaojun Liu; Isabella Nova; De Chen; Xiang Gao; Enrico Tronconi: **On the Redox Mechanism of Low-Temperature NH3-SCR over Cu-CHA: A Combined Experimental and Theoretical Study of the Reduction Half Cycle**, *Angewandte Chemie*, 2021,133(13),7273-7280

vi. KinCat Annual report 2021 with full account of PhD Alumni of the group.

vii. Links to selected strategic announcements of the iCSI industrial partners
   - YARA
   - Inovyn
   - Topsøe
   - Dynea
   - K A Rasmussen

viii. Examples of new projects granted or in development with the iCSI or other industrial partners:
   - *Fast discovery of new functional materials for greening industry.* Research Council of Norway Innovation project (IPN) granted to YARA with the NTNU and SINTEF catalysis group (KinCat) as the research partners
   - *Decomposed ammonia for carbon-free power generation* (DECAMMP). Research Council of Norway Collaborative Project to Meet Societal and Industry-related Challenges (KSP) granted to SINTEF Energy with NTNU, SINTEF Industry, Total Energies, Siemens Energy, Johnson Matthey as partners.
   - *SILVERADO – the Silver catalyst Dynamics in Operando.* Research Council of Norway Knowledge-building Project for Industry (KPN) research grant proposal in development with KA Rasmussen and Dynea as partners. To be submitted February 2023.

[IKP] [Case 2]

Institution: Norwegian University of Science and Technology - NTNU
Administrative unit: Department of Chemical Engineering / Institutt for kjemisk prosessteknologi – IKP
Title of case study: SFI SUBPRO
Period when the underpinning research was undertaken: 2015-2023
Period when staff involved in the underpinning research were employed by the submitting institution: 2015-2021
Period when the impact occurred: 2015-2021

1. Summary of the impact

SUBPRO is a Centre for Research-based Innovation (SFI) within subsea production and processing, hosted and led by the Department of Chemical engineering (IKP).

SUBPRO's impact is to establish a strong and solid growing ground for innovations in the Norwegian subsea and offshore industry.

This impact has been achieved along these main axes:

i. Education of highly competent workforce for the Norwegian industry.
ii. Creation of a new dedicated academic research environment with high-quality research in subsea production and processing (largest activity in the world)
iii. Research-based innovations for offshore and subsea assets.
iv. Spin-off research projects, and strong national and international network

SUBPRO runs 2015-2023. Due to the fundamental and educational nature, the impact will endure well beyond its completion.

2. Underpinning research

The underpinning SUBPRO research described below has

- involved PhD students and postdoctoral fellows funded by SUBPRO, with MSc students affiliated
- was performed in close collaboration with the SUBPRO industrial partners and the partner departments at NTNU
- provided key experimental and theoretical research methodology development and fundamental chemical and physical insights to knowledge and technology for subsea systems critical to the industrial partners' business.

From 2015-2021 consortium consisted of industry partners (Equinor, Lundin, Neptune Energy, Total Energies, Aker BP, Aker Solutions, DNV, Kongsberg Digital, Technip FMC, ABB), and the research partners in the NTNU Departments of Geoscience and Petroleum, Mechanical and Industrial Engineering, and Engineering Cybernetics.

The samples of the underpinning research described below were performed at IKP (21PhD students and 5 postdocs). Similarly, the other departments in the consortium contributed with research of similar significance. All research problems were developed and worked on in collaboration with the industry partners.

At IKP, the SUBPRO research focused on optimal operations, and subsea separation (process concepts and fluid characterization). By optimizing operation, the companies can operate more economically, with a smaller environmental footprint. Several PhD/postdoc projects focused on aspects related to production optimization, including methods for implementing optimal operation with simple control structures [1], estimating unmeasured variables (flow-rates) in multiphase flow [2] by combining knowledge-based and machine learning approaches.

Besides there has been a strong research activity (12 PhD at IKP) to better understand how emulsions of water and oil behave, this has been done in an advanced microfluidic analysis method. This has led to a better understanding of how droplets coalesce, to determine the coalescence behavior of droplets of different droplet sizes [3]. A deeper understanding of droplet breakage in turbulent flows, together with resulting droplet size distributions, was studied using high-speed cameras and automated image analysis [4].These fundamental research results lead to a better system understanding that enables the industry to design more efficient separators, and reduce cost.

New methods and processes for treating produced gas were investigated, including study of the properties of solvents for H_2S removal [5]. The solvent properties were studied on a wide range of temperatures and pressures, and the insight from these experiments can be used for developing simulation tools that have a high accuracy. Other methods for treating/dehydrating natural gas involve membranes, which can achieve a high separation efficiency and in very compact designs. Novel processes including membrane contactors have been studied in simulations and in experimental set-ups. [6]. Besides cleaning the produced gas, these technologies are highly relevant for our partners due to the green energy transition, where CO_2 and other harmful gases are captured.

Key researchers:

Professor and SUBPRO Director Sigurd Skogestad, Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- List of scientists with highest publication points in Norway 2017-2020
- Advanced process control, control structure design and plantwide control, optimal operation of process systems, modelling for control, robust control, PID control and distillation columns.

Professor and SUBPRO Deputy Director Johannes Jäschke, Department of Chemical Engineering, NTNU

- Optimization-driven methods for optimal operation and control strategies, real-time optimization and predictive control, quantitative data methods for optimization and control of process systems, modelling, numerical optimization and control

Professor Hugo Jakobsen, Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- Multiphase reactive flow modeling, numerical methods in computational fluid dynamics (single- and multiphase flows), Population Balance Modeling, fluid particle breakage and coalescence

Professor Liyuan Deng, Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- Gas separation membranes, membrane contactors, separation process design

Professor Gisle Øye, Department of Chemical Engineering, NTNU

- Colloid chemistry and interfacial phenomena within Produced Water Management, Enhanced Oil Recovery and synthesis of nanostructured materials

Professor Hanna Knuutila, Department of Chemical Engineering, NTNU

- List of scientists with highest publication points in Norway 2017-2020
- Acid gas removal using absorption technology, solvent development, and experimental characterization, including solvent stability and solvent degradation studies, thermodynamic and absorption kinetics modeling, and process modeling/simulations

Professor Magne Hillestad, Department of Chemical Engineering, NTNU

- Systematic methods for process design, process operation and design, modeling and simulation of process systems, model predictive control

Professor Jannike Solsvik, Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- Turbulent flow and scale-up of (bio-)chemical processes, Rheology, (Direct) numerical simulations, Bubble hydrodynamics, Bubble-liquid mass transfer, Breakup, Turbulence theory, Stirred tank & bubble column, Population balance equation

3. References to the research

[1] D. Krishnamoorthy, K. Fjalestad, S. Skogestad, Optimal operation of oil and gas production using simple feedback control structures, 2019, Control Engineering Practice, Volume 91, 104107, ISSN 0967-0661, https://doi.org/10.1016/j.conengprac.2019.104107

[2] T Bikmukhametov, J Jäschke, Combining machine learning and process engineering physics towards enhanced accuracy and explainability of data-driven models, 2020, Computers & Chemical Engineering 138, 106834 https://doi.org/10.1016/j.compchemeng.2020.106834

[3] M. Dudek, D. Fernandes, E. H. Herø, G. Øye, Microfluidic method for determining drop-drop coalescence and contact times in flow, 2020, Colloids and Surfaces A: Physicochemical and Engineering Aspects, Volume 586, 124265, ISSN 0927-7757, https://doi.org/10.1016/j.colsurfa.2019.124265

[4] E.H. Herø, N. La Forgia, J. Solsvik, and H.A. Jakobsen. "Determination of Breakage Parameters in Turbulent Fluid-Fluid Breakage." 2019, Chemical Engineering & Technology 42, no. 4, 903-909. https://doi.org/10.1002/ceat.201800610

[5] Eirini Skylogianni, Ingvild Mundal, Diego D.D. Pinto, Christophe Coquelet, Hanna K. Knuutila, Hydrogen sulfide solubility in 50 wt% and 70 wt% aqueous methyldiethanolamine at temperatures from 283 to 393 K and total pressures from 500 to 10000 kPa, 2020, Fluid Phase Equilibria, Volume 511, 112498, ISSN 0378-3812, https://doi.org/10.1016/j.fluid.2020.112498

[6] M. Ahmadi, A. Lindbråthen, M. Hillestad, L. Deng, Subsea natural gas dehydration in a membrane contactor with turbulence promoter: An experimental and modeling study, 2021, Chemical Engineering Journal, Volume 404, 2021, 126535, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2020.126535.

4. Details of the impact

Norwegian companies have been in the forefront of developing and implementing subsea technology for many decades, and the purpose of starting up SUBPRO in 2015 was to bring the academic community in Norway to a similar top international level in selected areas of subsea technology and use this as a basis for further innovation in the industry.

SUBPRO's impact is to establish a strong and solid growing ground for innovations in the Norwegian subsea and offshore industry.

This impact has been achieved along these main axes:

i. Education of highly competent workforce for the Norwegian industry.
ii. Creation of a new dedicated academic research environment with high-quality research in subsea production and processing (largest activity in the world)
iii. Research-based innovations for offshore and subsea assets.
iv. Spin-off research projects, and strong national and international network

The impact along these axes places Norway, and its subsea and offshore industry in a strong position to meet future challenges that arise as the society moves towards a zero-emission society.

Axis i. Education of highly competent workforce for the Norwegian industry.
The research in SUBPRO is carried out by PhD students and postdocs, supervised by Professors and experts from the industry partners. This has led to the education of a very highly qualified workforce. At IKP the center led to education of 21 PhDs, 5 postdocs and 43 Master students. For SUBPRO in total, the numbers are 36 PhDs, 10 postdocs, and more than 90 Master Students that are skilled and willing to work in the sector. Today the graduated PhDs and postdocs work in Equinor, Wood, Prysmian Group, Aker Solutions, Vysus Group, DNV, Jotun, RISE PFI, Worley Origo Process, Aibel, OneSubsea, TNO, BASF, ABB, Conundrum, Cybernetica, as well as in academia and in research institutes.

Axis ii. Creation of a new dedicated academic research environment with high-quality research in subsea production and processing (largest activity in the world)
SUBPRO represents the largest coordinated research activity on subsea production and processing in the world. SUBPRO is well known in the field, and researchers from other parts of the world have visited the centre. For example, the internationally distinguished Prof. L.T. Biegler from Carnegie Mellon University (USA) spent 3 months at IKP as Onsager Professor, and other students and researchers have spent time at the centre (see Axis iv).

The SUBPRO research activity has so far led to 127 peer-reviewed scientific journal and conference publications in this field, that contribute towards closing important scientific gaps (e.g. deeper understanding of fundamental droplet breakages and coalescence phenomena, and systematic ways of realizing more economic operations). The research has attracted international attention, and Researchers associated to SUBPRO have been awarded prestigious prizes, such as the Chorafas Prize, and been invited for prestigious keynote lectures at international conferences (E.g., IFAC Adchem, Dycops)

The centre also contributed to interdisciplinary collaboration among chemical engineers and colleagues at petroleum engineering, and mechanical engineering. This resulted in co-publication of several scientific articles, and activities to set up common subsea separation lab facilities.

Axis iii. Research-based innovations for offshore and subsea assets.
In collaboration with industrial partners, selected research results performed by PhD students and postdocs have been further matured into innovation projects (3-6 months). Here the research results were applied to an industrial case and further developed as proof of concept, or prototype software. For example, one project by Liu et al developed an algorithm that determined well placement and trajectories in a few minutes, for which experts in one of the partner companies required weeks. Other innovation projects included lab-experimental testing of production optimization methods and developing novel digital twins for a subsea compressor, in collaboration with Equinor and Aker Solutions.

Axis iv. Spin-off research projects, and strong national and international network
SUBPRO centre was instrumental in generating new spin-off activities, that brought together companies and universities, also those not directly involved in the centre. In the IKP-led project *AutoPRO*, a collaboration between IKP, the Dept. of mechanical and industrial engineering, Aker BP and 3 Chinese universities was established to research methods for autonomous operations.
Another project, *Safety 4.0*, was based directly on the PhD work of a SUBPRO student. It developed a novel safety a framework for standardized demonstration, and it involved companies and universities that were not part of SUBPRO.

Two INTPART mobility projects with universities in Brazil were anchored in the centre, with 12 students visiting IKP for 3-12 months, and NTNU professors teaching short courses in Brazil, besides several more students visiting the other NTNU departments in the centre.

Our industrial partners have significantly revised their strategies since the start of SUBPRO in 2015. Reaching net zero emissions (scope 1-3) in the next decades has become a common ambition of the sector. To reach this challenging goal while remaining profitable requires more efficient processes and new technology. We are therefore delighted that SFI partners (and some new) have agreed to work towards continuing our collaboration towards a new initiative (SUBPRO-Zero), which extends the current scope of SUBPRO to include carbon-neutral technologies such as Blue Hydrogen and Blue Ammonia. This initiative is intended to lead to a new Centre grant proposal in the next years. In addition, we have a range of other industrial partners that may be relevant to the new Centre.

The long-term funding nature of a center was a very important success factor to realize the achieved impact. It allowed us to have several PhD and postdoc projects to build upon each other and to thus realize more ambitious research results and spin-off projects. Moreover, the long-term cooperation with industry during these years proved to be an excellent arena for building strong relationships and trust between actors in academia and industry. These relationships will be useful for initiating future research activities.

5. Sources to corroborate the impact (indicative maximum of ten references)

i. SUBPRO website with link to 2015-21 Annual Reports on the About page. All research activities are described, all publications and presentations are listed. All postdoctoral fellows, PhD candidates and Researchers (SUBPRO and other projects) are listed, as well as international guests.

ii. SUBPRO project on the webpage of the Research Council of Norway

iii. Statements on impact provided by the industrial partners in conjunction with the Midway-Evaluation of the Centres for Research-based Innovation (SFI) (**Confidential document attached separately**)

iv. Excellence awards in SUBPRO:
- NTNU Natural Science Award (Krishnamoorthy)
- EFCE Excellence Award in Recognition of Outstanding PhD Thesis on CAPE (Krishnamoorthy)
- Chorafas prize List of Chorafas Prize winners (Krishnamoorthy (in 2020))
- Lars Onsager Professorship (Biegler)

v. New projects granted or in development with SUBPRO or other industrial partners:
- Safety 4.0 https://www.dnv.com/research/energy/safety-40-project-description.html
- AutoPRO Research Coucil of Norway Project data base information.
- *BN-SOC 1 & 2.* Research Council of Norway webpage
  - Brazilian-Norwegian Subsea Operations Consortium I
  - Brazilian-Norwegian Subsea Operations Consortium II
- *SUBPRO*-Zero initiative https://www.ntnu.edu/subpro-zero

[IKP] [Case 3]

Institution: Norwegian University of Science and Technology – NTNU
Administrative unit: Department of Chemical Engineering / Institutt for kjemisk prosessteknologi – IKP
Title of case study: Development and Production of Covid-19 test kits
Period when the underpinning research was undertaken: 2011 – Present
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 – Present
Period when the impact occurred: May 2020 – Present

1. Summary of the impact (indicative maximum 100 words)

Due to lack of reagents for corona-tests in the early phase of the pandemic, Departments of Chemical Engineering, and Clinical and Molecular Medicine at NTNU, developed a new corona-test method based on magnetic nanoparticles. The tests were developed, validated patented, and put into use in Norwegian hospitals in less than two months during Spring 2020, corroborating how long-term basic research can spearhead vital solutions for the society during crisis.

The project produced millions of tests for use in Norway, Denmark, India, Brazil and Nepal, and resulted in establishment of a Particle Engineering Research Centre and the spin-off company Lybe Scientific.

2. Underpinning research (indicative maximum 500 words)

The Covid-19 test method developed by NTNU is based on silica coated magnetic nanoparticles, that capture genetic material (RNA) from the coronavirus. The particles used in this test method was developed by researchers at the Department of Chemical Engineering.

The project went through three phases:

- Development phase (March – April 2020) – the synthesis of the particles was developed, the resultant particles characterized and thereafter validated in combination with lysis buffer for finalizing the chosen recipe.
- First production phase (May – July 2020) – upscaling the production of particles, providing to the Norwegian healthcare system and internationally.
- Second production phase (Aug – Dec 2020) – further optimization of the recipe to target customer bases internationally to supply to markets still coping with shortage of tests, while simultaneously evaluating the future path of the invention.

The development of the magnetic nanoparticles was made possible by a long-term research portfolio at the department within controlling the formation mechanisms of nanoparticles with an intent to influence their resultant physico-chemical properties such as size, morphology, magnetic properties, optical properties among others for instance for biomedical applications (2011 – present). There has also been extensive work on characterizing these particles by using state-of-the-art facilities such as NTNU Nanolab and other core facilities.

Worthy of mention, is the department’s active research collaboration with TU Delft, Netherlands, on development of silica coated iron oxide nanoparticles with encapsulated DNA as hydrological tracers for water management (2018 – present). Although these nanoparticles were synthesized for hydrological applications, the synthesis protocols formed the basis for development of the magnetic particles in the corona test project.

Another important aspect of the fast turnaround time and remarkable impact on society was the ease with which two cross-disciplinary research groups at two different departments at NTNU collaborated and worked seamlessly in this project. This was possible due to their previous long-term experience of having worked in interdisciplinary projects. Prof Magnar Bjørås' group at the Department of Clinical and Molecular Medicine is expert within the field of genomics and contributed to the development of the lysis buffer, which is an integral component of the NTNU corona test.

After the test method was developed, it was required to upscale the production method and establish a professional production facility to be able to meet the requirement for Covid-19 tests in the society. Based on existing chemical engineering knowledge at the department, especially with regards to particle growth and aggregation, reactor design and upscaling (2011 – present), the project was, within a few months, able to establish a fully operational production facility with the capacity of producing magnetic nanoparticles required for production of a million Covid-19 test kits per week.

The innovation is a result of understanding the important transition from fundamental to applied research and the vision to develop a solution to a challenge - in this case, the shortage of test kits. The knowledge and competence developed over the years through basic research resulted in the fast pace converting of a laboratory innovation into a diagnostic product, helping ease the burden of the pandemic.

Key researcher (at IKP):

- Sulalit Bandyopadhyay, PostDoc (2018-2021) and Associate Professor (2021-present), Department of Chemical Engineering, NTNU
  - Nanoparticle synthesis, functionalization and applications in biomedicine and environmental resource management.
  - Recycling of batteries using hydrometallurgical routes.

- Jens-Petter Andreassen, Associate professor (2003-2012) and Professor (2012-present), Department of Chemical Engineering, NTNU
  - Established a research group in industrial crystallization and solid-liquid separation (2003-present)
  - Industrial crystallization of pharamceuticals
  - Biomineralization
  - Prediction of solids precipititation in natural gas tie-ins
  - Fundamentals of crystal growth and particle enlargement

3. References to the research (indicative maximum of six references)

1. Bandyopadhyay, Sulalit. "Fabrication and Application of Nanomaterials." (2019), Book, McGraw-Hill. ISBN 9781260132236.

2. Bandyopadhyay, Sulalit. "Smart and Multifunctional Core-Shell Nanoparticles (NPs) for Drug Delivery." (2016). Doctoral Thesis at NTNU, 2016:294.

3. Sharma, Anuvansh, Jan Willem Foppen, Abhishek Banerjee, Slimani Sawssen, Nirmalya Bachhar, Davide Peddis, and Sulalit Bandyopadhyay. "Magnetic nanoparticles to unique DNA tracers: effect of functionalization on Physico-chemical properties. (2021). Research Article. https://doi.org/10.1186/s11671-021-03483-5

4. Beck, Ralf, and Jens-Petter Andreassen. "Influence of crystallization conditions on crystal morphology and size of CaCO3 and their effect on pressure filtration." (2012). Research Article. https://doi.org/10.1002/aic.12566

5. Jenssen, Ina Beate, Seniz Ucar, Ole Morten Dotterud, Oluf Bøckman, and Jens-Petter Andreassen. "Investigating the effects of process parameters on the filtration performance of ferric hydroxide in a continuous MSMPR reactor." (2021). Research Article. https://doi.org/10.1016/j.hydromet.2021.105594

6. Aas, P.A., Hagen, L., Erlandsen, S.E., Bjørås, M., Ottesen, V., Sharma, A., Bandyopadhyay, S., Methods and products for isolating nucleic acids. (2020). Patent. WO 2021/198502 A1.

4. Details of the impact (indicative maximum 750 words)

The main impact from this project has been that the Department of Chemical Engineering, together with the Department of Clinical and Molecular Medicine at NTNU, has been able to produce and deliver ~ 6.5 millions of Covid-19 tests to the Norwegian hospitals, and in addition export tests to Denmark, India, Brazil and Nepal, and in this way contribute to increased testing and hence a safer society during the Covid-19 pandemic. The Department of Chemical Engineering has in this work been responsible for the development and production of the silica coated magnetic nanoparticles. The work got extensive media coverage in NRK, TV2, VG, Dagbladet, Teknisk Ukeblad, Gemini / Norwegian SciTEch News etc. and won several innovation awards/prizes (NFR, NTNU, NTNU Faculty of Natural Sciences) – See Section 5 for references.

During the Covid-19 test project, the Department of Chemical Engineering hired 25 people (students that just had finalized their masters/PhDs or took a break from their masters/PhDs to work on this project). These people have now moved on to other jobs carrying with them a valuable experience from starting up and operating a production facility in a very short time, and in a time of crisis.

With a basis in the technology developed, validated, and patented during this project, the inventors, together with NTNU TTO (Technology Transfer Office), decided in 2021 to establish a spin-off company in Trondheim called Lybe Scientific AS. The company has now 8 employees, a revenue of 15 million NOK annually and is working towards extending their product portfolio in the field of medical diagnostics.

On the academic side, the Department of Chemical Engineering established a research centre called Particle Engineering Centre in the spring of 2021, with an objective to advance the scientific and technical knowledge within fundamental and applied particle engineering research. Currently 28 PhDs, Postdocs, Researchers and 15 master students are associated with the centre, performing research within a wide range of applications, varying from nanomedicine to environmental applications like recirculation of batteries, CO_2 capture and water treatment. The centre cooperates with companies like Hydro, Lybe Scientific, SINTEF, Glencore Nikkelverk, Elkem, etc and arrange a Particle Engineering Day every year where the ongoing research is presented.

Following the success story of the corona project and the extensive media coverage, new national and international research collaborations have nucleated over the past two years, where particle engineering projects are being carried out at the department. One noteworthy collaboration is between the centre and Prof. Bjørås' group at the Department of Clinical and Molecular Medicine, which jointly are running projects on more than 8 mutually co-operating research themes. This research has generated ~9 innovations over the last two years, some of which have been licensed to external companies and some are under evaluation for patenting or being followed up with more research work. In addition, NTNU is collaborating with Lybe Scientific on an IPN project that aims to deliver the next generation diagnostic products in nucleic acid extraction industry.

New research projects have also started between NTNU and TU Delft within nanoplastic detection using gold nanoparticles. Extensive research collaboration within use of nanoparticles for biosensing is ongoing between NTNU and IIT Madras, India, through an Indo-Norwegian research project. This research collaboration is further supported through mobilities under Global Erasmus Mobility program. A research project on developing polymer brushes on magnetic nanoparticles has started with NC State University recently.

In addition, the department has also established a Particle Engineering Core Facility in May 2021, which offers access for researchers to high end equipment and knowhow for characterization of particles in dispersion. In just 1.5 years, the Core Facility has got a lot of internal users from NTNU and cooperate extensively with external users like Lybe Scientific, SINTEF, Equinor and Thermo Fisher.

The development of the corona test method within a short time was the result of many years of fundamental research within particle engineering and the translation of this basic research into a diagnostic product during the pandemic. The successful execution of the project not only helped in easing the burden of the pandemic by supplying test kits nationally and internationally, but also led the foundation for the establishment of a research centre and a core facility and the birth of a new start-up company.

5. Sources to corroborate the impact (indicative maximum of ten references)

1. Article in NRK: NTNU-metode er avgjørende: Nå kan så å si alle koronatestes
2. Article in Dagbladet (incl. video): Her reddes Norges testkapasitet
3. Articles in Gemini / Norwegian SciTech News: Not enough test – we'll make them and Start-up takes NTNU's Covid technology to new markets and applications

4. NFR Innovation Prize 2021 (Info about the award in English)
5. NTNU's Award for Innovation and cooperation with employment 2021
6. NTNU NV Faculty Innovator of the Year Award 2021

7. Spin-off company Lybe Scientific AS was established in 2021
8. IPN project with Lybe Scientific AS

9. Particle Engineering Centre was established in 2021
10. Particle Engineering Core Facility was established in 2021

[IKP] [Case 4]

Institution: Norwegian University of Science and Technology - NTNU
Administrative unit: Department of Chemical Engineering / Institutt for kjemisk prosessteknologi - IKP
Title of case study: CO_2 Capture
Period when the underpinning research was undertaken: 2011 - present
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 – present
Period when the impact occurred: 2011 – present

1. Summary of the impact (indicative maximum 100 words)

Over the years, the Department of Chemical Engineering has had many research projects within CO_2 capture funded by the Research Council of Norway, the industry, and the European Union. Our work has concentrated on studying CO_2 capture from various industrial off-gases, like CO_2 removal from flue gases, biogas upgrading, natural gas sweetening, and blue hydrogen production, covering thus both low-pressure and high-pressure applications. The department has built an internationally strong reputation with extensive experimental and modeling capabilities within three capture technologies: absorption, membranes, and adsorption. The long-term research has led to patents, a spin-off company, licensing of the technologies and participation in numerous EU projects.

2. Underpinning research (indicative maximum 500 words)

The CO_2 capture technology research at the Department of Chemical Engineering has mainly focused on three technologies: absorption, membrane, and adsorption. The overall research focus has been on developing energy efficient, low OPEX and CAPEX technologies to reduce the overall cost of CO_2 removal.

The absorption research team has worked with all steps of process development for absorption-based CO_2 capture. The team has, over the years, developed capabilities within the theoretical screening of new absorbents by use of computational chemistry, experimental screening, testing of environmental properties, characterization of equilibrium, thermal properties, transport properties, kinetics, solvent degradation, and degradation mechanisms. Promising solvent candidates have been piloted to provide data for model validation. Further, testing and evaluation of new technologies (like UV-light for nitrosamine decomposition) is part of the experimental activities. The experimental work has supported modeling activities ranging from simple physical property models to rigorous kinetic and thermodynamic models based on the electrolyte NRTL and extended UNIQUAC model frameworks. Also, models describing aerosol-based solvent emissions and solvent degradation models have been developed, addressing some of the current key challenges in the industry. Further, the use of process models and simulators to optimize and develop new process concepts have been some of the key activities. The research portfolio also includes the development of machine learning models to support process and property modeling and techno-economical assessments.

The membrane research team has conducted extensive research on gas separation membranes and processes, with a focus on CO_2 separation applications, covering membrane material development, transport mechanisms, tailoring of membranes for specific separation processes, and optimization of processes through experimental studies as well as modelling and process simulation. In particular, the team has a high reputation internationally in the field of CO_2 facilitated transport membranes, both in terms of fundamental research of the mechanisms and the advancement of the separation concept, and is a pioneer in the industrialization of membranes in CO_2 capture. A very successful example of CO_2 separation membranes developed by the team is the fixed-site-carrier (FSC) membranes. The membrane research team has also strong expertise in the development of membrane contactors in close collaboration with the absorption team.

The adsorption research team has worked on two axis: development of moving bed carbonate looping concept (MBCL) and low-temperature sorbent-based CO_2 capture. The MBCL concept development has aimed to develop post-combustion CO_2 capture technology with high energy efficiency, low OPEX and CAPEX, and low cost of CO_2 removal, using a compact reactor. The focus has been on process intensification, i.e., by developing an optimized process design, cheaper solid sorbents, compact reactor, and easy operation. As a concrete example, the research has lead into the development of a stable CO_2 acceptor, and production has been scaled to the kilograms range. The work on CO_2 capture by low-temperature sorbents focuses on a temperature swing process using a solid sorbents, where the high capacity solid sorbents with grafted amine are used. Sorbents developed show high stability in the presence of steam, oxygen and high-temperature CO_2, and extremely low regeneration energy.

Key researchers:

Professor Hanna Knuutila, Department of Chemical Engineering, NTNU

- Leader of NTNU Energy Team CCUS
- Leader Gemini Centre CO_2 Impact
- List of scientists with highest publication points in Norway 2017-2020
- Acid gas removal using absorption technology, solvent development and experimental characterization, including solvent stability and solvent degradation studies; thermodynamic and absorption kinetics modeling, and process simulations

Professor Emeritus Hallvard F. Svendsen (professor until 2016), Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- CO_2 removal using absorption technology; solvent development and characterization; thermodynamic, kinetics and aerosol modeling

Professor Liyuan Deng, Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- Gas separation membranes, membrane contactors, separation process design

Professor Emerita May-Britt Hägg (professor until 2017), Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- Gas separation membranes, separation process design

Professor De Chen, Department of Chemical Engineering, NTNU

- Stanfords list of World's Top-cited scientists 2021
- List of scientists with highest publication points in Norway 2017-2020
- Moving bed carbonate looping concept (MBCL) and low temperature sorbent based CO_2 capture

Professor Jana P. Jakobsen, Department of Chemical Engineering, NTNU

- CO_2 capture technologies and CO_2 transport, modelling, development of a methodology and robust computational tools for integrated assessment of CO_2 capture technologies

Professor Magne Hillestad, Department of Chemical Engineering, NTNU

- Systematic methods for process design, process operation and design, modeling and simulation of process systems, model predictive control

Researcher Ardi Hartono, Department of Chemical Engineering, NTNU

- Solvent development and characterization for chemical absorption; thermodynamic and kinetics modeling

Researcher Arne Lindbråthen, Department of Chemical Engineering, NTNU

- Membrane technology development; manufacturing of carbon molecular sieve membranes from polymer solution optimization for spinning to testing of the finished membrane fibers when mounted in a module.

3. References to the research (indicative maximum of six references)

The references are chosen to show the spread of the activities and illustrating the collaboration between the key researchers.

1. Kim, T.-J., Vrålstad, H., Sandru, M., **Hägg, M.-B**., Separation performance of PVAm composite membrane for CO2 capture at various pH levels, Journal of Membrane Science, 2013, 428, pp. 218–224. https://doi.org/10.1016/j.memsci.2012.10.009

2. Ansaloni, L., Rennemo, R., **Knuutila, H.K., Deng, L.**, Development of membrane contactors using volatile amine-based absorbents for CO_2 capture: Amine permeation through the membrane, Journal of Membrane Science, 2017, 537, pp. 272–282. https://doi.org/10.1016/j.memsci.2017.05.016

3. **Svendsen H.F**., Majeed H., **Knuutila H.K., Hillestad, M**., Evjen S., Mejdell T., Einbu A. Hjarbo K.W., Haugen G., Hoff K.A. Aerosol growth in CO_2 absorption with MEA, modelling and comparison with experimental results. International Journal of Greenhouse gas control, Volume 109, 2021, 103390. https://doi.org/10.1016/j.ijggc.2021.103390

4. Carranza Abaid, Andres; **Svendsen, Hallvard Fjøsne; Jakobsen, Jana Poplsteinova**. (2023) Thermodynamically consistent vapor-liquid equilibrium modelling with artificial neural networks. Fluid Phase Equilibria. Volume 564. https://doi.org/10.1016/j.fluid.2022.113597

5. **Hartono, Ardi;** Ahmad, Rafiq; **Svendsen, Hallvard Fjøsne; Knuutila, Hanna K**. New solubility and heat of absorption data for CO_2 in blends of 2-amino-2-methyl-1-propanol (AMP) and Piperazine (PZ) and a new eNRTL model representation. Fluid Phase Equilibria 2021 ;Volum 550. https://doi.org/10.1016/j.fluid.2021.113235

6. Chen, Qingjun; Wang, Siyu; Rout, Kumar Ranjan; **Chen, De.** Development of Polyethylenimine (PEI)-impregnated mesoporous carbon spheres for low-concentration CO2 capture. *Catalysis Today, Volume 369, p 69-76,* 2020, https://doi.org/10.1016/j.cattod.2020.06.016

7. Usman, Muhammad; **Hillestad, Magne; Deng, Liyuan**. (2018) Assessment of a membrane contactor process for pre-combustion CO_2 capture by modelling and integrated process simulation. International Journal of Greenhouse Gas Control. volum 71. https://doi.org/10.1016/j.ijggc.2018.02.012.

4. Details of the impact (indicative maximum 750 words)

Based on the research on CO_2 capture at the department, more than 260 articles in scientific journals have been published since 2011. The teams have more than 10 patents. The patenting has led to technology licensing. Some of the membrane technology-related patents are licensed to Air Products and Aqualung Carbon Capture AS, while the research on CO_2 capture by low-temperature adsorption technology has been licensed into Inrigo As.

The publication and solvent development work has been highly dependent on external funding and collaboration with industry, national and international research organizations (like SINTEF). The key researchers have actively participated in EU projects since FP6, followed by FP7 and H2020 projects. Since 2011 the teams have participated in 8 EU projects and coordinated one (iCAP, 2011-2014). Additionally, we have been part of two ERA-ACT projects and more than 12 national projects (NRF and GASSNOVA). The team has also been part of all the large FMEs within CO_2 capture in Norway (BIGCCS, BIGCO$_2$, and NCCS).

The research teams have actively been part of bringing CO_2 capture technologies to higher TRL levels, for example:

- Two solvent systems have been developed by the absorption team together with SINTEF in EU projects, and have been taken to a demonstration scale. In the EU project CESAR, the solvent system CESAR1 was developed. This solvent system is now taken to TRL 8 in an EU project AURORA (2023-2026). Similarly, in the FP7 project, HiperCAP, a solvent system was developed that was demonstrated in a refinery environment (TRL6) in the follow-up H2020 project REALISE (2018-2023).
- The membrane team has demonstrated the membrane process for CO_2 capture using their pilot membrane modules at coal-fired power and cement plants and is now installing processes for CO_2 capture for shipping and exhaust gas streams from turbines of various industrial processes.
- With the support of GASSNOVA, a moving bed carbonate looping concept (MBCL) has been developed by the adsportion team together with SINTEF and FTG (Fjell technology) since 2017. The project developed and built a radial flow moving bed reactor with heat exchange, and a cold flow MBCL reactor consisting of a multi-channel carbonator, calciner MBR and riser was also built and tested.

Educational outcomes of the research activities include more than 60 PhD defences since 2011. Further, more than 100 master thesis students have been educated within CO_2 capture technologies, and more than 20 postdoctoral fellows and career researchers have received their training at IKP on CO_2 capture.

Due to the long-term focus on experimental capabilities, our absorption and membrane laboratories are part of ECCSEL ERIC, a pan-national research infrastructure opening our facilities for researchers outside Norway.

The teams have also contributed to developing and organizing some of the main conferences on CO_2 capture technologies. For example, Professor Hallvard Svendsen is a cofounder of the Trondheim Conference on CO_2 Capture, Transport and Storage (TCCS). He was after that a member of the scientific committees for conferences from TCCS1 to TCCS 6. Over the years several professors have been the technical committee chair in TCCS conferences (Hägg TCCS-6, Svendsen TCCS-7, Knuutila TCCS-10 to TCCS-12. Other participation in the organization of CO_2-relevant conferences includes being a member of the Scientific Committee for Greenhouse gas control technologies (GHGT8, GHGT9, GHGT10) and post-combustion CO_2 capture conferences organized by IEAGHG (PCCC1 and PCCC2).

In 2020 a Gemini centre, CO_2 Impact, focusing on the development of absorption-based CO_2 capture technologies, was established between NTNU, SINTEF and USN (University of South-Eastern Norway) to ensure continuous focus on the further development of the absorption technologies and long-term research.

Finally, the team members have also received several awards for their contribution to the field. Professor Hallvard Svendsen received Statoil Price for Outstanding Scientific Research and in 2011 the Greenman Award in 2014 given by the GHGT Conference Series given to individuals who had made a significant contribution to the field of CO_2 removal, storage, and utilization. Professor May-Britt Hägg got the SINTEF and NTNU CCS Awards in 2017 for her long-lasting research on membranes, including both the development of membrane materials and membrane separation processes with a focus on CO_2 capture.

Based on the research on carbon molecular sieve membranes, a spin-off company from was established in 2008 with the support of the NTNU Technology Transfer Office (TTO). The name of the company is MemfoACT (= Membranes for Advanced Clean Technology). This company won 3 prizes for creativity and innovation in 2009/2010, and additionally one in 2011. The company concluded in 2014/2015.

In 2021, Aqualung Carbon Capture AS was established. The company uses technology that has been developed by the membrane research team at our department, and they are currently working together on a project for further developing the membranes for commercialization by deploying pilot units at industrial partners sites. The project is funded by the RCN.

5. Sources to corroborate the impact (indicative maximum of ten references)

1. Gemini article: 5 millioner til forskning på karbonfangst
2. Aqualung Carbon Capture: Technology and Info about NTNU researchers
3. Patent licensed to commercial company in 2021 Aqualung Carbon Capture AS
4. Moving Bed Carbonate Looping (MBCL), joined invention by Fjell Technology Group AS, NTNU and SINTEF, 2019, title to the primary patent: Pellets of sorbent suitable for carbon dioxide capture
5. Gemini Centre CO_2 Impact
6. REALISE H2020 project where IKP is a partner
7. Greenman Award to Hallvard Svendsen
8. CCS award to May-Britt Hägg
9. Article in Energi og Klima on CO_2 capture: En innføring i CCS
10. Blog post about solvents for CO_2 capture: When little things have a big impact

NTNU-DMSE 1

Institution: NTNU
Administrative unit: Department of Materials Science and Engineering (DMSE)
Title of case study: FFF – Pyrometallurgical Research
Period when the underpinning research was undertaken: 1990 - 2015
Period when staff involved in the underpinning research were employed by the submitting institution: 1990 – 2022
Period when the impact occurred: 2015 -2022

1. **Summary of the impact** (indicative maximum 100 words)

The Ferroalloy Industry's Research Association (FFF) is an association which, on behalf of its members, shall initiate, implement, and coordinate research aimed at the ferroalloy industry's processes and products. The main goal of FFF is to further develop environments and activities that recruit and train professionals, preferably at PhD level, and who can solve research tasks of vital importance to the industry as a whole.
Basic research, as well as applied research and innovation are brought together covering the five subject areas of social sciences, humanities, technology, natural sciences and medicine and health.

2. **Underpinning research** (indicative maximum 500 words)

FFF has been the representing organ for the pyrometallurgical participation in joint research efforts together with other process industry from EXPOMAT and PROSMAT in the early years in parallel with large project like BioCarbon, Carbomat, and GasFerroSil, directed at specific pyrometallurgical challenges. This has contributed to the fact that the industry today has environmental toxins under control. They have also cut their greenhouse gas emissions by 40% since 1990, while Norway's total emissions have only decreased by 1% in the same period.

Environmental issues: Examples regarding environmental standards and process-related Health, Environment and Safety (HES) work are the Promiljø project (2006-2010) and the FUME project (2009-2014). Promiljø has the objective to reduce environmental impact of ferroalloy plants by: Process optimization and control, Monitoring of emission sources of gas and particulate matter, Reduction of material and energy losses, Investigate end-of-pipe emission reduction, Development of instrumentation for emission monitoring, Exhaustive measuring campaigns of plants work atmosphere (e.g.: dust, PAH, PCDF/PCDD, heavy metals) & Emissions at end-of-pipe), Simulation and model development of combustion processes and pyrolysis, Investigate different NOx-reduction techniques, CFD-simulation of distribution/reduction of dust in the working environment, Evaluation of emission reduction methods.

The FUME project focused on the internal plant environment by development of competence in the area of “fugitive” emissions of materials (gas, dust/particles etc.) to the internal and external environments as well as low and high temperature energy losses from the Norwegian ferroalloys industry. The know-how that is built-up is applied to reduce emissions: through direct process improvements based on a fundamental understanding of emission generation mechanisms, through improvement of equipment for emission reduction and capture with respect to the working environment, to better utilize low- and high temperature waste energy in integrated process solutions (district household heating, fish farming, bio-refineries etc.)

Process equipment and operation: Major changes in core equipment (Furnaces) can only happen in connection with major revamps involving excavations and relining of the furnace. Several such excavations have been coupled to FFF-projects and have provided valuable insight in the internal characteristics of the process.

Names of the key researchers and what positions they held at the *administrative unit* at the time of the research:
Johan Kristian Tuset, Professor; Halvard Tveit, Adjunct Professor; Jafar Safarian, PhD candidate. Øystein Grong, Professor; Tor Lindstad, Adjunct Professor; Leiv Kolbeinsen, Professor; Sverre Olsen, Professor; Merete Tangstad, Professor; Terkel Rosenqvist, Professor Emeritus, Gabriella Tranell, Assistant professor.
It is important to remember that researchers from industry and research institutes like Sintef also have participated in these activities.

3. **References to the research** (indicative maximum of six references)

Schei, Anders; Tuset, Johan Kristian; Tveit, Halvard. : Production of high silicon alloys. Tapir Akademisk Forlag 1998 (ISBN 82-519-1317-9) Book 363 pp.

Safarian-Dastjerdi, Jafar; Grong, Øystein; Kolbeinsen, Leiv; Olsen, Sverre E.: A Process Model for the Carbothermic Reduction of MnO from High Carbon Ferromanganese - The Model. *ISIJ International* 2006; Volume 46.(8) pp 1120-1129

Olsen, Sverre E.; Tangstad, Merete; Lindstad, Tor: Production of Manganese ferro alloys. Tapir Akademisk Forlag 2007 (ISBN 978-82-519-2191-6) Book 247 pp

Rosenqvist, Terkel; Eriksen, Jan Martin; Crespo, Eloy: Equilibrium between Liquid Fe-Ti-O Slags and Metallic Iron. *Steel Research International* 2007; Volume 78.(9) pp 671-675

Sævarsdottir, Gudrun A.; Bakken, Jon Arne; Sevastyanenko, Victor G.; Gu, Liping: High-Power AC Arcs in Metallurgical Furnaces. *High Temperature Material Processes* 2011 ;Volume 15.(3) pp 205-225

Nørstebø, Vibeke Stærkebye; Midthun, Kjetil Trovik; Bjørkvoll, Thor; Kolbeinsen, Leiv: Use of Natural Gas with High CO2 Content in an Integrated Industrial Park. *ISIJ International* 2012; Volume 52.(8) pp 1439-1446

Safarian-Dastjerdi, Jafar; Tranell, Gabriella; Tangstad, Merete: Thermodynamic and Kinetic Behavior of B and Na Through the Contact of B-Doped Silicon with Na2O-SiO2 Slags. *Metallurgical and Materials Transactions B* 2013; Volume 44.(3) pp 571-583

4. **Details of the impact** (indicative maximum 750 words)

In 1989 and before the pyrometallurgical research in Norway was partly funded by The Norwegian Technical and Scientific Research Council (NTNF) based on project applications from the individual ferroalloy companies together with scientists from NTH (later known as NTNU) and SINTEF. The projects addressed short term industrial issues, and their main result were detailed reports on experimental work and discussions of the obtained results relative to existing theory. Presentations based on such projects were given at Conferences, but publications in International Journals were exceedingly rare. Some master students participated in these projects, but on the doctoral level very few examples of involvement are found.

NTNF issued a signal that if this industry wanted to apply for projects in the years to come, they would need to cooperate: "NTNF would no longer consider project A from a company in fjord 1 relative to project B from a company in fjord 2 – especially if the projects A and B had strong similarities and overlapping goals". Education of professionals in the area, especially at PhD level, should also be addressed in the research project applications. The response from the industry was to set down a committee of four, including one professor from Department of Metallurgy, NTH, to suggest the path forward.

The impact of FFF project activities cannot be covered in full detail here, but a few examples are given below. In general, many the FFF projects would never be conducted internally - i.e., that a mix of open academic and proprietary research seems more optimal in terms of cost, time consumption and result. Knowledge developed through the FFF work has been a "standby resource" in cases where acute problems or challenges have occurred e.g., in form of new/changed environmental standards. The FFF collaboration has led to a large and rapidly growing amount of knowledge that "the clever and vigilant" can use, but which does not represent any leakage of trade secrets.

In 2015 the FFF-board formulated a strategy plan for the continuation of the pyrometallurgical research, and they also decided to cooperate with other research institutions and industrial companies in applications for Research Centers, and SFI Metal Production and FME HighEFF are the clearest examples of this so far.

On this basis the fact that since its instigation more than 70 PhDs have been educated in FFF-projects, and in addition to financing the industry is also supporting the individual PhD students by participation in advisory committees, co-authoring papers, and taking the role as future users of their findings. One important factor is that since the PhD candidates come with different backgrounds, e.g., Pyrometallurgy, Chemical Engineering, Physics, Computational Fluid Dynamics, Cybernetics, Material Flow Analysis, etc., and applying this to the challenges provided by the industrial processes involved, the education of PhDs has provided transfer-rable competence both to the industry and to the pyrometallurgical research in general.

In the next section the four PhDs from SFI Metal Production finalizing their work in 2022 are listed together with a few other publications and reports.

SFI Metal Production has 26 associated projects, and one of them is DeMaskUs led by Professor Gabriella Tranell. This project is a good example of the diversity of research carried out in the “FFF-spirit”.

In the ferroalloy and SiC industry, emissions of ultrafine, oxide-based dust originating from different production processes, have been documented. The origin and health effect of these particles is, however, not well known. The DeMaskUs project, a collaboration between the ferroalloy industry, SiC-industry, SINTEF, NTNU, UNN, STAMI and St. Olavs hospital, is divided in three main work packages (WP):

WP 1: *Dust formation mechanisms and kinetics* - aims to develop a fundamental understanding of the nanosized dust formation mechanisms and the characteristic properties of these particles

WP 2: *Protection and human behavior* - seeks to a) identify a selection of Respiratory Protection Equipments (RPEs) with optimal characteristics for the exposure conditions in the smelter industry b) identify psychological factors that interfere with actual use/non-use of RPEs and suggest intervention strategies that better facilitate desired behavior.

WP 3: *Neuroinflammatory health effects* - seeks to i) establish a human in vitro cell model, ii) adopt protocols for alloy particle preparation, dispersion and exposure of cells in vitro, iii) investigate cellular uptake of the particles, and iv) examine biomarkers of inflammation and oxidative stress after exposure of the cells to well characterized respirable alloy particles.

The project includes 2 PhD and 1 Post Doc for recruitment to industry and the research area.

As a direct effect of DeMaskUs, corporate standard procedures are revised, e.g., with new routines in procurement of masks to ensure good fit for different face shapes. To ensure that operators use the right dust masks, fit testing must be conducted continuously. From a plant OHS-perspective, the respiration fit testing and intervention are the most important project results. The course ("Dust and Health") was seen as highly relevant and the videos and other material from the course have been distributed to OHS-staff to be used in the future. The practical recommendations are implemented widely, for example through internal HSE days at the plants where researchers from DeMaskUs continues to participate. The fundamental research results on particle generation are important as all dust reducing process improvements are based on scientific knowledge. The cell viability tests confirm that keeping occupational exposure low does prevent negative health effects.

5. Sources to corroborate the impact (indicative maximum of ten references)

Børset, Marit Takla; Kolbeinsen, Leiv; Tveit, Halvard; Kjelstrup, Signe: Exergy based efficiency indicators for the silicon furnace. *Energy* 2015 ;Volume 90. s. 1916-1921

Kolbeinsen, Leiv (2017) Keynote Lecture: The Importance of Silicon to Society The 11th meeting of the Society And Materials conference, SAM-11, Trondheim, Norw*ay.*

Billy, Romain Guillaume. Monitoring and simulating material cycles and emissions at multiple scales: Case studies for aluminium. Doctoral theses NTNU 2022

Hassanabadi, Massoud. Characterization of Alumina Based Ceramic Foam Filters (CFFs) – An Experimental and Modelling Approach. Doctoral theses NTNU 2022

Solem, Cathrine Kyung Won. Parametric Study of Molten Aluminium Oxidation in Relation to Dross Formation at Laboratory and Industrial Scale. Doctoral theses NTNU 2022

Myklebust, Håkon A Hartvedt Olsen. Fume Formation and Measurements in the Metal-Production Industry. Doctoral theses NTNU 2022

Engh, Thorvald Abel; Sigworth, Geoffrey K.; Kvithyld, Anne. *Principles of Metal Refining and Recycling.* Oxford University Press; Book 2021

The following three reports give a brief overview of the Norwegian metallurgical industry, their emissions, waste, and by-products. The reports are written by students of material science for the general public and also review how the industry is trying to reduce emissions and waste.

Part 1 Companies and Production
Part 2 Emissions and Energy
Part 3 Waste and by-products

NTNU-DMSE 2

Institution: NTNU
Administrative unit: Department of Materials Science and Engineering (DMSE)
Title of case study: Screw extrusion
Period when the underpinning research was undertaken: 2001 – 2022
Period when staff involved in the underpinning research were employed by the submitting institution: 200x - 2022
Period when the impact occurred: 2008 - 2022

1. Summary of the impact (indicative maximum 100 words)

A new metal continuous screw extrusion (MCSE) method has been developed at the PhysMet group at NTNU over the last 10-15 years (Original patent WO 2008/063076, 2008). The idea is to go from granular material to a finished product in one continuous operation, without remelting. Recycling of metal scrap, imposes a large reduction in energy consumption (90% compared to remelting) and limited material waste. Closed-loop recycling of end-of-life high-power transmission lines by MCSE has shown great potential, with engagement from the industry. Production of metal composites is a different application, which is currently explored, ranging from production of Al-Si master alloys, utilizing silicon powder from wafer cutting to produce a Si-rich Al-Si master alloy, to production of welding wires, where inoculants are mixed into the welding wire during screw extrusion.

2. Underpinning research (indicative maximum 500 words)

Between 2005 and 2008 a new continuous metal extrusion method was developed at the PhysMet group at NTNU, and a worldwide patent was approved by Werenskiold et al. in 2008 (Ref. 1 below). Since then, 18 master and 2 PhD projects (Kristian G. Skorpen (2018); Geir Langelandsvik (2021)) in the Physical Metallurgy group have been dedicated to different aspects of the technology and the apparatus itself as well as exploring the potential applications of the screw extruder to make new materials and examine the properties of these materials.

In short, the concept of metal continuous screw extrusion (MCSE) is as follows: Metal feedstock in the form of granules, chips, or other fragments is gradually fed into the steel screw housing. A continuously rotating Archimedes steel screw then transports the material forward until it reaches a preheated conical extrusion chamber. When the temperature in the extrusion chamber reaches the sticking friction temperature of the material, the granules begin to consolidate, which gradually turns into smearing, and eventually "kneading", as more material is added and the temperature increases due to friction. As a consequence, the entire extrusion chamber ultimately consists of a plug of somewhat viscous (but still solid) metal. As even more material is added, the temperature and pressure in the extrusion chamber become sufficiently high to extrude the material through the die at the end of the chamber (usually T >550 - 450°C and P >100–500 MPa). The total extrudability depends on parameters such as die opening, screw geometry, frictional conditions, feedstock form and of course, the inherent material properties of the extrudate. MSE is a continuous process by nature as long as new material is added and the process reaches steady state. It is emphasised that metal screw extrusion has a very complex material flow. This flow has partly been revealed by Widerøe and Welo (Ref. 5 below) using contrast materials, although not all aspects were for practical reasons possible for investigation.

An analytic model by Skorpen et al. (Ref. 4 below) has been proposed to describe the material flow and accumulated strain. In this model the MCSE process is divided into four segments (as described above), where each segment contributes to the total strain. The model includes parameters related to the material flow combined with geometry descriptions of the setup. Further, strain evolution equations for known severe plastic deformation processes (ECAP, HPT, etc.) are adjusted and implemented in the strain model. Granule feeding rate and screw rotation speed are the most influencing parameters for the accumulated strain. Data applied from screw extrusion of an Al-5%Mg alloy using an extrusion die temperature of ~410°C and relatively low feeding rate, showed a total accumulated strain ~15 in the current prototype set-

up for a 10 mm diameter profile. For comparison, classical ram extrusion with similar geometrical in- and output, i.e. billet of diameter 95 mm extruded into a 10mm diameter rod, achieves an equivalent strain of 4.5.
The characteristics of the MCSE process open up for new innovations for metal processing and the related products. They also facilitate new opportunities for scientific investigations that have not been possible before.

Names of the key researchers:

Professor Hans Jørgen Roven († 20.09.2022)
Adjunct Professor Oddvin Reiso (Hydro&NTNU (retired 12/2021)
Adjunct Professor Trond Furu (NTNU&Hydro)
PhD Kristian Skorpen (2012-2018)
PhD Geir Langelandsvik (2016-2021)
Professor Nils Ryum († 17.01.2014)

3. References to the research (indicative maximum of six references)

1. J.C. Werenskiold, L. Auran, H.J. Roven, N. Ryum, O. Reiso. Screw extruder for continuous extrusion of materials with high viscosity. Patenet WO 2008/063076, 2008 https://patents.google.com/patent/US9616633B2/es

2. G. Langelandsvik, M. Grandcolas, K.G. Skorpen, T. Furu, O.M. Akselsen, HJ Roven, HJ. Development of Al-TiC Wire Feedstock for Additive Manufacturing by Metal Screw Extrusion. MDPI Metals, vol. 10, issue 11. Article Number1485. https://doi:10.3390/met10111485

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4. K.G. Skorpen, H.J. Roven, O. Reiso. A physical based empirical model for the accumulated strain in novel Metal Continuous Screw Extrusion (MCSE). J. Mater. Process. Technol. 2020, 116670. https://doi:10.1016/j.jmatprotec.2020.116670

5. F. Widerøe, T. Welo, T. Using contrast material techniques to determine metal flow in screw extrusion of aluminium. J. Mater. Process. Technol. 2013, 213, 1007–1018. https://doi:10.1016/j.jmatprotec.2012.11.013

6. G. Langelandsvik, T. Furu, O. Reiso, H.J. Jørgen Roven. Effects of iron precipitation and novel metal screw extrusion on electrical conductivity and properties of AA1370 aluminium. Materials Science & Engineering B 254 (2020) 114505. https://doi.org/10.1016/j.mseb.2020.114505

7. Skorpen, Kristian Grøtta. Screw Extrusion of Light Metals: Development of materials, characterization and process analysis Doctoral thesis NTNU 2028. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2565656

8. G. Langelandsvik, M. Grandcolas, K.G. Skorpen, T. Furu , O.M. Akselsen, H.J. Roven . Development of Al-TiC Wire Feedstock for Additive Manufacturing by Metal Screw Extrusion. Metals 2020, 10(11), 1485; https://doi.org/10.3390/met10111485

4. Details of the impact (indicative maximum 750 words)

Since the screw extruder technology was first patented in 2008, a number of 18 master and 3 PhD projects in the Physical Metallurgy group at NTNU have been dedicated to different aspects of the technology and the apparatus itself as well as exploring the potential applications of the screw extruder to make new materials and examine the properties of these materials. The major volume of research has been conducted towards aluminium and its alloys, but other metals such as titanium can be manufactured by screw extrusion. As compared to conventionally produced extruded products it has been demonstrated that extrudates with similar or even improved mechanical and functional (electrical) properties can be made by the screw extrusion technology (Ref. 6).

The metal screw extrusion technology clearly opens a lot of new possibilities including solid state recycling and production of metal composites. Recycling of metal scrap, such as profile scrap, metal shavings from machining and granular material from commercial metal recycling imposes a large reduction in energy consumption (only 1/1090% compared to of what is required for recycling via remelting) and close to no material waste. Closed-loop recycling of end-of-life high-power transmission lines by metal screw extrusion has shown great potential, with engagement from the industry.

Production of metal composites is a different application, ranging from production of Al-Si master alloys, utilizing Silicon powder from wafer cutting to produce a Si-rich Al-Si master alloy, to production of innovative and novel aluminium welding wires, where inoculants are mixed into the welding wire during screw extrusion.

Concerning the latter application, the process seems pertinent for mixing particles into the extruded matrix as was first shown by Skorpen et al. [7], and later by Langelandsvik for TiC nanoparticles in Al filler wires (FWs) [8]. Other fabrication routes such as Accumulated Roll Bonding (ARB), and particularly in-situ salt-melt reaction, have been utilized in other studies to incorporate TiC nanoparticles in Al FWs. However, MCSE can potentially offer several advantages compared to these methods: (1) solid state particle incorporation eliminates the difficulties seen in liquid state processing (i.e., fading and sedimentation), (2) the MCSE process is very energy efficient, and the entire fabrication route can be made both continuous and fully automated, (3) the feedstock material can be made from commercial Al alloys, and (4) the principle can very likely be expanded to incorporate new and potentially superior grain refining particles in the future.

The screw extruder, now located at NTNU is a second generation, medium scale experimental extruder. This apparatus has paved the way for a new full scale pilot extruder recently built at Hydro Aluminium at Sunndalsøra .

Further improvements of the screw extruder technology and its applications are currently explored in the RCN Green Platform project AluGreen (with Hydro Aluminium as the project manager), IPN AlPakka and the Center for Research based Innovation project, SFI PhysMet - Centre for Sustainable and Competitive Metallurgical and Manufacturing Industry (RCN P.no. 309584).

5. Sources to corroborate the impact (indicative maximum of ten references)

1. Adjunct Professor, NTNU / Research manager Hydro Trond Furu
2. Professor Torgeir Welo, Department of Mechanical and Industrial Engineering, NTNU
3. Professor Geir Ringen, Department of Mechanical and Industrial Engineering, NTNU
4. Adjunct Professor NTNU / Research manager SINTEF, Mohammed M’hamdi
5. PhD Harald Vestøl, Independent consultant
6. PhD Stig Tjøtta, Research manager Hydro

NTNU-DMSE 3

Institution: NTNU
Administrative unit: Department of Materials Science and Engineering (DMSE)
Title of case study: Current efficiency in electrowinning
Period when the underpinning research was undertaken: 2011 - 2022
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-2022
Period when the impact occurred: 2015-2022

1. Summary of the impact (indicative maximum 100 words)

Several research projects funded by NFR and Norwegian electrochemical industries have been accomplished by members of the group. In several projects we have studied the fundamental properties of electrode reactions having impact on key parameters such as the current efficiency for metal deposition and kinetics for evolution of chlorine and oxygen on alternative anodes during electrowinning of zinc, nickel, copper and cobalt from aqueous electrolytes. Similar studies have been performed in molten salt electrolytes related to electrowinning of aluminium. Factors affecting energy consumption, energy efficiency and carbon footprint in industrial electrowinning processes have been emphasised in several projects.

2. Underpinning research (indicative maximum 500 words)

<u>Current efficiency for aluminium deposition</u>

The current efficiency is a very important parameter for industrial processes as it affects the energy consumption and product quality. In the aluminium electrowinning process, the current efficiency for aluminium deposition in industrial cells is typically in the range from 90 - 94 %. The loss in current efficiency is strongly linked to the fact that aluminium is soluble in the electrolyte. Metal solubility is a general phenomenon in molten salts. In molten cryolite based electrolytes dissolved Na must be considered in addition to dissolved Al. It is known that the subvalent species AlF_2^- is formed as well as dissolved Na, the latter being responsible for a small contribution to electronic conductivity which will limit the obtainable current efficiency. The metal solubility is ~0.06 wt% Al in industrial electrolyte compositions. The solubility decreases by increasing content of AlF_3 and decreasing temperature. The back reaction between dissolved metals (Al and Na) and the anode product CO_2 is responsible for the major loss in current efficiency. The rate of the back reaction is controlled by diffusion of dissolved metals (Al and Na) through the diffusion layer near the cathode. The current efficiency is therefore closely linked to the solubility of dissolved metals in the electrolyte.

<u>PFC formation during aluminium electrowinning</u>

The carbon footprint during electrowinning is mainly due to the anode process; the formation of CO_2 as the primary anode product and the formation of PFC gases (CF_4 and C_2F_6) during anode effect. However, in many countries generation of electricity is the main source for CO_2 emissions.

Aluminium electrowinning takes place by passing a constant current through the cells. If the amount of dissolved alumina in the electrolyte decreases, polarisation will increase to sustain the reaction, eventually rising so far that other anode reactions become possible. Two possible anode products are the perfluorocarbon (PFC) gases CF_4 and C_2F_6. The phenomenon is termed anode effect (AE) and traditionally when this occurs the voltage can raise to levels of 20 V or higher, and the current distribution over the anodes become erratic.

<u>Inert oxygen evolving anodes for copper electrowinning</u>

Copper electrowinning worldwide is carried out in a sulfate electrolyte using lead anodes for oxygen evolution. It is believed that lead may not be possible to use in the future because it is poisonous.

An important part of the project was to study the electrochemical behaviour titanium based anodes with coatings of IrO_2 and Ta_2O_5, so-called dimensionally stable anodes or DSA. Experiments were conducted in sulfate solutions at low pH where the main anode process will be oxygen evolution. The main purpose of these studies was to develop a new anode for oxygen evolution during zinc and copper electrowinning at Boliden and Glencore. Permascand is a major manufacturer of anodes. The idea is to replace lead anodes currently used in this industry, to solve environmental issues related to lead. Also, a new DSA may give lower overpotential and lower energy consumption and much longer service life. The only issue working against DSA is the high cost. Similar anodes with a different coating have been in industrial use for chlorine evolution for several decades.

The research was carried out since 2011.

Prof. Geir Martin Haarberg, Prof. Svein Sunde, Prof. Frode Seland, Assoc. Prof. Espen Sandnes

3. References to the research (indicative maximum of six references)

1. Geir Martin Haarberg, Joseph P. Armoo, Henrik Gudbrandsen, Egil Skybakmoen, Asbjørn Solheim, and Trond Eirik Jentoftsen: "Current efficiency for aluminium deposition from molten cryolite-alumina electrolytes in a laboratory cell", TMS Annual Meeting 2011, San Diego, CA, Collected Proceedings of the 140th Annual Meeting and Exhibition. "Light Metals 2011", ISBN 978-1-11082-935-0, pp 461 - 463.
2. Kenji Kawaguchi, Geir Martin Haarberg, and Masatsugu Morimitsu: "Suppression of PbO_2 Deposition on Nano-structured IrO_2-Ta_2O_5/Ti Anodes in Acidic Solutions", ECS Transactions, 50, pp. 75-85 (2013).
3. H. Åsheim, T.A. Aarhaug, A. Ferber, O.S. Kjos, G.M. Haarberg: "Monitoring of continuous PFC formation in small to moderate size aluminium electrolysis cells", "Light Metals 2014", TMS, ISBN 978-1-11888-908-4, pp. 535-540 (2014).
4. Åsheim, H., Aarhaug, T.A., Sandnes, E., Kjos, O.S., Solheim, A., Haarberg, G.M.: "A laboratory study of partial anode effects during aluminium electrowinning", ECS Transactions, 69(15), pp. 1-12 (2015).
5. Wenting Xu, Geir Martin Haarberg, Svein Sunde, Frode Seland, Arne Petter Ratvik, Erik Zimmerman, Takayuki Shimamune, and Torjus Åkre: "Electrochemical Behaviour of Industrial IrO_2-Ta_2O_5 Anodes for Copper Electrowinning", ECS Transactions, 75 (37), pp. 23 - 35 (2017).
6. . W. Xu, G.M. Haarberg, S. Sunde, F. Seland, A.P. Ratvik, E. Zimmerman, T. Shimamune, J. Gustavsson, T. Åkre: "Calcination temperature dependent catalytic activity and stability of IrO_2 – Ta_2O_5 anodes for oxygen evolution reaction in aqueous sulfate electrolytes", J. Electrochem. Soc., 164 (9) F895-F900 (2017).

4. Details of the impact (indicative maximum 750 words)

Current efficiency for aluminium deposition

Relatively small additions of LiF had a positive effect on CE, also in highly acidic melts. Lowering the superheat was also found to improve the CE. More reliable results were obtained for the effect of current density on the current efficiency. The effect of mass transfer on the CE was also investigated.

A novel method for producing aluminium based alloys have been proposed and investigated in lab experiments where oxides of alloying elements were added to the electrolyte and co-deposition of metals such as silicon, manganese and titanium took place. Also in these experiments the current efficiency for alloy deposition was determined. Implementation of this method has started by running trial experiments in industrial cells.

PFC formation during aluminium electrowinning

PFCs are unwanted from an environmental standpoint as they possess high global warming potential and long lifetimes, making them potent greenhouse gases. Additionally they impede the industrial process by passivating the anodes and increasing the total power consumption. The existence of PFCs not related to the traditional anode effect in industrial aluminium production cells has been documented for a wide range of technologies in recent years. Industrial measurements have shown that PFC production can begin at one anode during normal cell potentials and propagate to the full cell given the right conditions. To experience the phenomenon in the laboratory, a system with more than one anode was designed. Normal voltage anode effect or partial anode effect may occur when one anode starts to draw less current than the other anodes. PFC gas evolution may happen on this one anode since all anodes in parallel are assumed to have the same potential. Lack of distribution of dissolved alumina may be the indirect cause for partial anode effect. Today emissions from anode effects are reported only based on regular anode effects, but partial anode effects may account for an additional 70 % of PFC emissions from this process.

Inert oxygen evolving anodes for copper electrowinning
Controlled laboratory experiments were carried out by using conventional electrochemical studies in a three electrodes set-up. Effects of changing several key parameters were studied. Important parameters are calcination temperature, pretreatment (sandblasting), amount of catalyst and coating method. Accelerated tests of candidate anodes were also conducted in electrolysis experiments. Good catalytic activity and long service life are the most important criteria for assessment of the DSA electrodes. Low calcination temperature improves the catalytic activity but cuts down the lifetime. A medium range calcination temperature seems to be a better option for industrial type DSA electrodes.
During electrowinning of zinc MnO_2 precipitation on the lead anode represents an additional problem. Laboratory studies were performed to look into the electrochemical formation of MnO_2. These studies are ongoing.

5. Sources to corroborate the impact (indicative maximum of ten references)

1. T. Morishige, G. M. Haarberg, H. Gudbrandsen, E. Skybakmoen, A. Solheim, and T. Takenaka: "Effect of Composition and Temperature on Current Efficiency for Aluminium Electrolysis from Cryolite-Based Molten Alumina Electrolytes", ECS Transactions, 77(11) 997-1002 (2017) .
2. Henrik Åsheim, Thor A. Aarhaug, Woichech Gebarowski, Espen Sandnes, Asbjørn Solheim, and Geir Martin Haarberg: "Partial Anode Effect in a Two-Compartment Laboratory Alumina Reduction Cell", Light Metals 2017, ISBN 978-3-319-51540-3, pp. 525 - 532 (2017).
3. W. Xu, S. Sunde, F. Seland, A. P. Ratvik, E. Zimmerman, S. Holmin, J. Gustavsson, Åsa Afvander, T. Åkre, and G. M. Haarberg: "Sandblasting effect on performance and durability of Ti based IrO_2 –Ta_2O_5 anode in acidic solutions", Electrochimica Acta, 295, pp. 204 – 214 (2019).
4. Xu, W., Haarberg, G.M., Seland, F., Sunde, S., Ratvik, A.P., Holmin, S., Gustavsson, J., Afvander, Å., Zimmerman, E., and Åkre, T.: "The durability of the thermally decomposed IrO_2 - Ta_2O_5 coated titanium anode in a sulfate solution", Corrosion Science, 150, pp. 76 -90 (2019).
5. Peng Cui, Bo Qin, and Geir Martin Haarberg: "The Behavior of Additives LiF, MgF_2 and KF on Current Efficiency in Aluminium Electrolysis", Journal of The Electrochemical Society, 166 (13), pp. D559-D563 (2019), doi: 10.1149/2.0431913jes
6. Åsheim, H., Eidsvaag, I.A., Solheim, A., Haarberg, G.M., Sandnes, E.: "The Influence of Polarisation on the Wetting of Graphite in Cryolite-Alumina Melts", Minerals, Metals and Materials Series, pp. 608-619 (2020)
7. Awayssa, O., Haarberg, G.M., Meirbekova, R., Saevarsdottir, G.: "Electro-chemical production of Al–Mn alloys during the electrodeposition of aluminium in a laboratory cell, Electrochemistry Communications, 125, 106985 (2021)
8. Saevarsdottir, G., Awayssa, O., Meirbekova, R., Haarberg, G.M.: "Direct Production of Aluminum Manganese and Silicon Alloys in Aluminum Reduction Cells: A Laboratory Test", Minerals, Metals and Materials Series, 2022, pp. 402–410

IFY-NTNU case number 1

Institution: NTNU
Administrative unit: Department of Physics
Title of case study: Combining educational research with development in school and university
Period when the underpinning research was undertaken: 2014-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2014-2023 (entire group is transferred from other departments 2018)
Period when the impact occurred: 2015-2023

1. Summary of the impact

This case describes the impact our research in science education combined with development has had on teaching in schools, teacher proficiency and on key factors affecting and supporting teachers' work. The case mainly includes two projects, KreTek and ReleQuant. KreTek has investigated how programming can be combined with subject learning and students' creativity in lower secondary school. ReleQuant has researched upper secondary physics students' understanding of theories of relativity and quantum physics with its epistemological consequences. Both projects have contributed to research-based and systematically tested teaching resources, which have an impact on the quality of teaching in schools. The impact also includes improved teacher competence by means of courses and other kinds of dissemination to teachers, as well as improved professional competence for those teachers participating in the projects. Results from the project have also influenced curricula, textbooks and other resources developed outside the project by other agents.

2. Underpinning research

This case presents our research combined with development in science education that has an impact on educational policy (curricula) nationally, teacher competence and resources available for teachers to improve their teaching of physics, chemistry, general science and technology. The case draws on the project KreTek (RCN 2019-2022) managed by our research group at NTNU, but also on ReleQuant (RCN 2015-2019) managed by the University of Oslo with NTNU as partner. KreTek and ReleQuant have in common that research is combined with development in systematic ways with the aim of contributing to general theoretical knowledge as well as improving teaching and learning. Both projects have Design-Based Research (DBR) as a methodological frame, and collaboration with practitioners, in our case teachers, is crucial.

The involvement of teachers has been fortified in KreTek with constructive results with regards to teacher competence and the developed products, a process that in turn has been subject to research published internationally. The project has produced research insights on conditions for teachers' active involvement in DBR projects in collaboration with researchers (Bungum & Sanne, 2021). This illustrates how our research and its impact do not always follow a linear process from pure research through a product to an impact. The process is often more complex and iterative; the products, its development and its impact are in themselves subject to research, which in turn leads to improved products in line with DBR methodology. The research in ReleQuant and KreTek has elicited teachers' challenges in the teaching of quantum physics (Bungum, Henriksen, Angell, Tellefsen & Bøe, 2015) and teachers' views on challenges and opportunities for incorporating creativity in science and mathematics in schools (Johansen, Mogstad, Gajic & Bungum, 2022). Combined with review of research literature, these results have contributed to research-based teaching resources in digital form freely available for teachers. In turn, classroom research on teaching where these resources are used has led to empirical and theoretical insights on student conceptions, teaching methods and teachers' challenges as well as improvement of the resources (Bungum, Bøe & Henriksen, 2018; Henriksen, Angell, Vistnes & Bungum, 2018; Huseby & Bungum, 2019; Bungum & Mogstad, 2022).

Some of our activities do, however, follow a more linear process. This is the case for research on students' conceptions in chemistry that has had direct impact on new national curricula for chemistry in upper secondary school. The development of a Chemistry Concept Inventory (CCI) provided a tool for investigating students' alternative conceptions in chemistry (Eggen, Persson, Jacobsen, Hafskjold, 2017). Research results produced by means of this tool revealed widespread alternative conceptions relating to chemical bonds, and also other concepts central when studying chemistry (e.g. Aakre, Persson, Lein & Eggen, 2020). These results formed part of the knowledge base during the development on new national curricula in Norway, both in general science (from 2020) and upper secondary chemistry (from 2023). The curriculum goals/objectives were formulated in line with knowledge produced in the CCI project.

On university level, results from research on students' learning experiences through collaboration in conceptual learning labs (Mellingsæter 2014) has had direct impact on how physical learning areas were designed at own institution. Furthermore, research on digital education in our project VfK ('Video for Kvalitet') has fundamentally transformed how digital educational videos are designed, locally at NTNU but also elsewhere.

Key researchers and their positions:

From NTNU and our research group:

- Berit Bungum, professor (associate professor until 2015)
- Erik Mogstad, assistant professor
- Astrid Johansen, assistant professor
- Per-Odd Eggen, associate professor
- (Rolf) Jonas Persson, associate professor
- Magnus Strøm Kahrs (previously Mellingsæter)

The researchers in our group transferred collectively from Department of teacher education to Department of physics in 2018 as part of an organizational reorganization. Still, we report results from before 2018 since they were produced by the same group, now belonging to the Department of physics, without changing position.

For KreTek research and CCI, these colleagues from other departments at NTNU contributed:

- Bojana Gajic, associate professor (KreTek)
- Anders Sanne, associate professor (KreTek)
- Iselin Grav Aakre (CCI)

For the research in ReleQuant, the following are key researchers at University of Oslo:

- Ellen Henriksen, professor (associate professor until 2015)
- Maria Vetleseter Bøe, associate professor
- Carl Angell, professor

2. References to the research

Aakre, I., Persson, R.J., Lein H.L. & Eggen, P.O. (2020). First-year university students' perception of chemical bonding and bond energy. Nordic Journal of STEM Education 4(2), 12-30. https://www.ntnu.no/ojs/index.php/njse/article/view/3300

Bungum, B., Bøe, M. V., & Henriksen, E. K. (2018). Quantum talk: How small-group discussions may enhance students' understanding in quantum physics. Science Education, 102(4), 856-877. https://doi.org/doi:10.1002/sce.21447

Bungum, B., Henriksen, E. K., Angell, C., Tellefsen, C. W., & Bøe, M. V. (2015). ReleQuant - Improving teaching and learning in quantum physics through educational design research. NorDiNa, 11(2), 153-168. https://journals.uio.no/nordina/article/view/2043

Bungum, B., & Mogstad, E. (2022). Building and programming a weather station: Teachers' views on values and challenges in a comprehensive STEM project. Research in Science & Technological Education, 1-17. https://doi.org/10.1080/02635143.2022.2103108

Bungum, B., & Sanne, A. (2021). Conditions for the Active Involvement of Teachers in a Design-Based Research Project. Designs for Learning, 13(1), 44-54. https://doi.org/http://doi.org/10.16993/dfl.169

Eggen, P.-O.; Persson, R. J.; Jacobsen, E. E.; Hafskjold, B. (2017). Development of an inventory for Alternative Conceptions among students in chemistry. LUMAT: International Journal on Math, Science and Technology Education 2017 ;Volum 5.(1), 1-11. https://doi.org/10.31129/LUMAT.5.1.115

Henriksen, E. K., Angell, C., Vistnes, A. I., & Bungum, B. (2018). What Is Light? Students' Reflections on the Wave-Particle Duality of Light and the Nature of Physics [journal article]. Science & Education, 27(1), 81-111. https://doi.org/10.1007/s11191-018-9963-1

Huseby, A., & Bungum, B. (2019). Observation in quantum physics: challenges for upper secondary physics students in discussing electrons as waves. Physics Education, 54(6), 065002. https://doi.org/10.1088/1361-6552/ab3694

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Mellingsæter, M. S. (2014). Engineering students' experiences from physics group work in learning labs, Research in Science & Technological Education, 32(1), 21-34. https://www.tandfonline.com/doi/full/10.1080/02635143.2013.853033

Persson, R.J.; Wattengård, E.; Lilledahl, M.B. (2019) The effect of captions and written text on viewing behavior in educational videos. *LUMAT: International Journal on Math, Science and Technology Education* 7(1). https://journals.helsinki.fi/lumat/article/view/1262

4. Details of the impact

Impact on curricula

The national curriculum is a main governmental tool to manage what is taught in schools and how. The influence on curricula may be hard to trace, but it is likely that the resources and research produced by ReleQuant have influenced the current curriculum (K20) implemented 2020 with its focus on 'quantum objects' i upper secondary physics. In similar ways, the research on student conceptions in chemistry in our group has probably had impact in how chemical bonds are addressed in the curriculum for chemistry I upper secondary school (grade 13).

Impact on textbooks in physics and teacher education

While the nationally curriculum is the tool that formally regulates the content of school subjects, the textbooks are often more influential in what is actually being taught and how. Results from ReleQuant on student conceptions and challenges in learning quantum physics are highly visible in the most used textbook, Ergo, for upper secondary physics. The influence is substantial in how the textbook introduces the problems that led to development of quantum physics and in how it brings conceptual problems of quantum physics to students' attention.

In physics teacher education, the textbook 'Fysikkdidaktikk' (Angell et al., 2011, revised 2019) is widely used. The results from ReleQuant has substantially influenced this textbook's content about teaching and learning of modern physics. This means that the research in ReleQuant has impact on virtually all new educated physics teachers for upper secondary school in Norway from 2019 onwards.

Impact on widely used teaching resources
The impact on the teaching resources produced by KreTek and ReleQuant is described in the foregoing since it forms part of the combined research and development. One very concrete example is how we found that the concept of observation creates challenges for students because they tend to understand observation as seeing (Huseby & Bungum, 2019). Then, of course, the way that observation influence electrons behaviour in the double-slit experiment appears even more mystical than it is. This insight from research led to concrete amendment of the digital resources where we now focus explicitly on observation as interaction. This finding also evoked interest internationally and is described in the teacher magazine Classroom physics published by Institute of Physics. Also, products from KreTek evoked international interest, and one of our developed teaching design is published in the teacher magazine Science in School. This means that our work may also influence how science and physics are taught in other countries. On university level, research in our group has had impact on the design of learning areas as well as digital learning resources.

Impact on teacher competence and forms of teaching in schools and university
The impact of our research on teacher competence occurs through a range of teacher courses, conferences for teachers and through contributions on journals for teachers. Some indicators of impact are numbers of teachers participating in events and the number of students using resources as part of their education.

In KreTek, we have reached teachers corresponding to ca 400 course participations (some digitally due to the pandemic) in the period 2020-2022. Furthermore, for the content of the curriculum related to programming, the microcontrollers micro:bit is extensively used by teachers in lower secondary schools. The company Fybicon is a main commercial supplier of this equipment for Norwegian schools, and on their web page they refer to KreTek (as the only reference of this kind) for teaching ideas, without any commercial bonding to the project. This indicates that our resources are generally seen as having high quality and are applicable for teachers.

In the resources from ReleQuant on the platform viten.no, also number of student users can be traced and correspond to ca 500 individual students every year from 2016. This means that, annually, up to 20% of all physics students in final year of upper secondary school learn modern physics by means of resources produced by the project and informed by our research. The resources have been widely disseminated to teachers through courses and conferences, and in magazines for teachers, for example Bungum, Bøe & Henriksen (2017).

Locally, physics education research has had substantial impact on the design of educational videos and physical learning areas.

Conclusion
In sum, our research has significant impact on the content and quality of science, physics and chemistry teaching in schools and university.

5. Sources to corroborate the impact

KreTek resources: www.ntnu.no/skolelab/kretek/ressurser

ReleQuant resources on quantum physics and general relativity available from www.viten.no (published 2015 and revised 2022, the revision is updated based on new research results and adapted to the new curriculum)

Description of research results from ReleQuant in the magazine Classroom physics: https://spark.iop.org/sites/default/files/media/documents/ClassroomPhysicsDecember2021Web.pdf

KreTek resources presented in the magazine Science in School: https://www.scienceinschool.org/article/2022/design-build-smart-lamp/

Contribution from ReleQuant in Naturfag, magazine for teachers:
Bungum, B; Bøe, MV & Henriksen, EK (2017). Kvantesnakk: Korleis kan diskusjonar i smågrupper støtte elevar si læring? Naturfag. ISSN 1504-4564. 2017(2), s. 50–53.
https://www.naturfag.no/binfil/download2.php?tid=2196058

Textbook for physics teacher education: Angell, Bungum, Henriksen, Kolstø, Persson, & Renstrøm (2019). Fysikkdidaktikk. Cappellen Damm.
https://www.cappelendammundervisning.no/_fysikkdidaktikk-9788202623357

Ergo (textbook for upper secondary physics), grade 13: https://www.adlibris.com/no/bok/ergo-fysikk-2-9788203344015,

Fybicon (commercial provider of equipment), referring to KreTek resources: https://www.fybikon.no/programmering/koding/micro-bit/micro-bit-go-v2-club-10-pakning-forelopig-utsolgt

Video for Kvalitet (VfK): https://www.ntnu.no/skolelab/video-for-kvalitet

The national curriculum for science, grade 11:
https://www.udir.no/lk20/nat01-04/kompetansemaal-og-vurdering/kv77?lang=nob

The national curriculum for chemistry, grade 12:
https://www.udir.no/lk20/kje01-02/kompetansemaal-og-vurdering/kv532

The national curriculum for physics, grade 13:
https://www.udir.no/lk20/fys01-02

NTNU-IFY case number 2

Institution: NTNU
Administrative unit: Department of Physics (IFY)
Title of case study: Microfluidics-based fabrication of hydrogels and hydrogel characterization for innovations in tissue engineering and regenerative medicine.
Period when the underpinning research was undertaken: 2014-2019
Period when staff involved in the underpinning research were employed by the submitting institution: 1996 - present
Period when the impact occurred: 2020 --

1. Summary of the impact

The ability to fabricate homogenously sized micro-scale hydrogels beads require control of the gel formation process, such as the gel precursor sample geometry, kinetics of pre-gel component mixing and their gelling. Microfluidic is an especially suitable fabrication technique for this purpose. When combined with novel methods to control gelation, it allows development of new materials and technologies with applications in biomedical research such as tissue engineering. Based on the research performed at Section for Biophysics and Medical Technology (BIOPHYS), Department of Physics, NTNU, a new method to make ionically crosslinked hydrogels was developed. This method is being further developed by the startup company ClexBio, aiming at commercializing engineered human tissue implants.

2. Underpinning research

Ionically crosslinked hydrogels based on polymers such as alginate, chitosan, polygalacturonates, and others are an important class of materials within pharmaceutical and biomedical industries. Research at the BIOPHYS, Department of Physics, NTNU resulted in a discovery (patented US Patent 10,988,583) of a novel method to form ionically crosslinked hydrogels [1,2]. The method termed CLEX involves using competitive displacement of chelated ions to control the release of the crosslinking ions and facilitate the formation of the hydrogel [4]. Crucially, this method solves several problems encountered during formation of microscopic hydrogels constructs, for example as aided by microfluidic devices [2,3]. Crosslinking kinetics of ionically crosslinked hydrogels is typically very difficult to control since it is governed by the rapid binding of gelling ions to the ionotropic polymer. As a consequence, traditional gel formation strategies perform poorly in microfluidic devices. Other strategies, based for example on the pH change, have been employed. However, these are typically not compatible with encapsulation of living microorganisms and cells. The CLEX method allows an unprecedented control of the gelling kinetics and is biocompatible and can easily be implemented in microfluidic devices [2].

The undertaken research was a part of several project supported by RCN and others, where the two following is the most instrumental in the establishing the CLEX protocol: RCN 214607: *Mineralized, hierarchical, bioinspired materials for tissue engineering (project leader P. Sikorski, 2013-2017); Nano- and microscale control of alginate interactions and assembly (NTNU funded, 2012-2016, project leader B.T. Stokke.* These projects investigated microfluidic technology, control of ionic hydrogel formation to yield monodisperse gel beads with user controlled mean size in the range 50 micrometer and below, controlled hydrogel dissolution, development of hydrogel based composites, and material characterization.

D.C. Bassett and A.G. Håti played a main role in developing and testing of the CLEX hydrogel formation method [1,4] and implementing it in microfluidic technology [2]. Microfluidic technology developed at NTNU by AGH, BT Stokke and collaborators at Harvard Univ was essential in exploiting the CLEX process for molding gel beads and fibers.

- **Personnel at BIOPHYS:** PhD candidate AG Håti (2012 - 2016), Post. Doctoral researcher DC Bassett (2014-2019), Prof. P Sikorski, Prof. BT Stokke.
- **Experimental infrastructure at BIOPHYS and NTNU:** NTNU Nanolab, microfludics infrastructure, microscopy facilities and cell laboratory at BIOPHYS.
- Expertise and research in biophysics of biomaterials, biopolymers and microdevices at BIOPHYS.

3. References to the research

[1] Competitive ligand exchange of crosslinking ions for ionotropic hydrogel formation. DC Bassett, AG Håti, TB Melø, BT Stokke, P Sikorski. Journal of Materials Chemistry B 4 (37), 6175-6182. **2016**

[2] Versatile, cell and chip friendly method to gel alginate in microfluidic devices. AG Håti, DC Bassett, JM Ribe, P Sikorski, DA Weitz, BT Stokke. Lab on a Chip 16 (19), 3718-3727. **2016**

[3] Microarrays for the study of compartmentalized microorganisms in alginate microbeads and (W/O/W) double emulsions. AG Håti, NB Arnfinnsdottir, C Østevold, M Sletmoen, G Etienne, E Amstad, BT Stokke. RSC Advances 6, 114830-114842. **2016**

[4] Local Structure of Ca^{2+}Alginate Hydrogels Gelled via Competitive Ligand Exchange and Measured by Small Angle X-Ray Scattering. K Yamamoto, Y Yuguchi, BT Stokke, P Sikorski, DC Bassett. Gels 5 (1), 3. **2019**

All references have been published in leading journals in the fields of biomaterials, lab on a chip and hydrogel research. They have accumulated a significant number of citations from international groups.

4. Details of the impact

The CLEX method combined in with NTNU's research on microfluidic and hydrogel technologies have opened a range commercial applications that will in the future will be able to address real life clinical problems. This technology is being developed further and commercialized by the company ClexBio, founded by two former researchers associated with BIOPHYS.

ClexBio

ClexBio was co-founded in 2020 by former PhD candidate at BIOPHYS, Armend G. Håti, PhD and Manuel Schweikle, PhD who has collaborated with the BIOPHYS research group at NTNU during his PhD. The CLEX technology forms the technological basis of the company's innovative and proprietary tissue engineering approach that has been developed since the foundation of the company. The company currently has 7 full-time employees. Alongside the competence developed at NTNU, the team brings highly relevant experience from the biotech industry and expertise in cell biology, tissue culture automation, and translational research from the Harvard Weitz Lab, Yale University, the Wake Forest Institute for Regenerative Tissue Engineering, Weill Cornell Medical College, and Zimmer Biomet. In addition to the scientific and societal achievements, it has also provided high impact on the career of young scientists.

To date, the company has raised $2.3M in venture financing and $3M in non-dilutive grants. Investors include a member of the global boards of directors of Roche and Clariant, several Partners and Senior Partners at McKinsey & Co in the US and Canada, and family offices and senior business leaders from healthcare, private equity and other industries based across North America, Europe and Asia.

ClexBio aims to commercialize the world's first tissue-engineered vein graft consisting purely of human extracellular matrix (ECM) as a therapy for severe Chronic Venous Insufficiency (CVI), that due to deep venous reflux, represents an enormous burden to healthcare systems across the globe with an estimated 2.4 million patients suffering from the condition in the US, plus an estimated additional ~15 million in other global markets. Today, no effective treatment exists for the 500,000-600,000 patients that suffer from venous ulcers due to reflux in the US (and more across the globe), and high recurrence rates cause a total of ~$30 billion in direct costs every year in the US healthcare system alone.

ClexBio's grafts are grown by healthy human cells rendering the resulting material a biocompatible scaffold for permanent tissue regeneration. The removal of the production cells after ECM formation allows the grafts to be used in any patient and makes for cost-efficient, scalable and centralized production using one cell-source. Uniquely, the company's proprietary technology VivoSet allows the creation of complex tissue structures enabling the production of vein grafts with functional valves, which is not possible to achieve with existing state-of-the-art tissue engineering technologies. Due to the removal of cells, the product will likely be classified as a medical device class II by the FDA. Pursuing a 510k pathway will allow for rapid acceleration and market entry in the US, as compared to products with a biologics or med device class III/ PMA classification.

The product is currently undergoing pre-clinical testing in animals in collaboration with world-class CROs and interim results are showing very promising results on safety. Upcoming trials will test for function and lay the groundwork for first-in-human trials. The company partners closely with leading vein surgeons in the US and Europe on the development of the product and the surgical intervention. Given the large addressable market of CVI due to deep venous reflux and the complete lack of durable and effective endovascular therapies, it can be expected that ClexBio, with its unique positioning, will be able to capture significant market share and become a dominant commercial actor in the space. The company's vein graft solution has an estimated annual peak sales potential of $500 million - 1.1 billion.

5. Sources to corroborate the impact

Since the company's foundation, ClexBio's novel tissue engineering approach has been developed based on the foundation of the CLEX technology namely within two IPN projects.

The completed IPN project "BioMatrix" (RCN project no. 314027) in partnership with NTNU and SINTEF focussed on the bioactive functionalization of CLEX microgels to unlock their potential as 3D cell culture and tissue engineering scaffolds. Namely, the project resulted in the commercial CYTRIX cell micro-encapsulation kit that is currently globally distributed by the UK-based microfluidic company Sphere Fluidics [5,6] the company's innovative VivoSet technology that is utilized to produce the world's first tissue-engineered vein grafts for CVI patients and is currently undergoing patent application.

The ongoing IPN project "SuperVene" (RCN project no. 332280) in partnership with Swiss life science engineering experts CSEM builds on BioMatrix and the VivoSet technology and develops the required tissue culture hardware and processes to produce tissue-engineered vein grafts in a reproducible and industrially scalable way [7].

The early traction and potentially huge impact of the developed tissue engineering technology enabled the company to attract interest of globally leading healthcare VCs [8], recruit a global top-level board of directors [9], and recently win the DNB Nordic Healthcare Prize 2022 [10].

[5] https://spherefluidics.com/store/cytrix-microfluidic-hydrogel-kit/, webpage of the commercial CYTRIX microfluidic cell encapsulation kit.

[6] https://www.businesswire.com/news/home/20210607005345/en/Sphere-Fluidics-and-ClexBio-introduce-CYTRIX-Microfluidic-Hydrogel-Kit, press release for the launch of the

CYTRIX kit.

[7] https://www.csem.ch/press/supervene-the-new-treatment-for-venous-insufficiency , press release announcing the SuperVene project with CSEM.

[8] https://eqtfoundation.com/christmas-calendar/01-dec-clexbio/, feature on ClexBio on the EQT Foundations website.

[9] https://www.businesswire.com/news/home/20220630005855/en/ClexBio-Announces-New-Appointments-to-Board-of-Directors, press release announcing the company's board of directors.

[10] https://www.dnb.no/en/business/a-z/healthcare-conference/winner-of-dnb-healthcare-prize, DNBs press release about ClexBio winning the 2022 Nordic Healthcare prize of NOK 1M.

NTNU-IFY case number 3

Institution: NTNU	
Administrative unit: Department of Physics (IFY), Material physics/TEM research group	
Title of case study: Physics applied to Aluminium alloy development	
Period when the underpinning research was undertaken: 2011-2021	
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-2021	
Period when the impact occurred: 2011-2021	

1. Summary of the impact

This case study shows how fundamental physics, method development and industrial needs have been interacting over long time. Using several transmission electron microscopy (TEM) techniques, the TEM research group has during the last 20 years improved the understanding of the physics taking place at the atomic scale in age-hardenable aluminium alloys. Improvements of properties as thermal stability, strength, and corrosion are obtained by nanoscale studies of nucleation, phase stabilization and precipitation. The work was done in collaboration with scientists in SINTEF Industry (within the TEM Geminicentre) and other departments at NTNU in close contact with Norwegian aluminium industry. This work has led to growth and careers of young scientists.

2. Underpinning research

Aluminium production (Hydro and Alcoa) represents one of Norway's important exports and is based on high technology. Underlying the success is the fundamental aspect of understanding and controlling material properties through nanoscale structure.

Age hardenable aluminium alloys are used in marine, aerospace, and automotive construction applications. The popularity relates to low cost, ease of fabrication and machinability, and to a combination of attractive materials properties, like high strength, low weight, good formability, and corrosion resistance. Tuning of alloy composition can produce a combination of properties desirable to the automotive industry, where the high strength-to-weight ratio allows for production of lighter vehicles with better fuel efficiency and hence reduced emissions. Several companies in Norway produce car parts (Benteler, Steertech and Raufoss Technology). Furthermore, understanding of recycled aluminium is important for sustainability and to achieve a circular economy.

Many aluminium alloys are heat treatable, and aging creates a high density of nanometer-sized semi-coherent and metastable precipitates with surrounding strain fields which obstruct dislocations. The precipitates are formed in the Al host lattice from solid solution. The total alloying addition typically amounts to a few at%. Depending on alloy composition and thermo-mechanical processing, morphology, number, size, and type of metastable precipitates will vary. A fundamental understanding of the underlying physics (structure, phase stability, interfaces, coherence) is needed to be able to optimize of the precipitate microstructure for properties.

Our research group in Department of Physics at NTNU and SINTEF in Trondheim, has over a long period worked together with the Norwegian light metal industry on nanoscale studies of aluminium alloys. We use transmission electron microscopy (TEM) and diffraction to learn more about aluminium alloys and the correlation between micro/nanostructure and properties. By TEM we can map the atomic structure of clusters and precipitates and predict how they develop. From this we can design new alloys or optimize chemical compositions of existing alloys to get desired properties for given applications.

The underpinning research is twofold –

I) Advanced TEM techniques. Advanced experimental characterization techniques, such as (aberration-corrected and quantitative) high-resolution high-angle annular dark-field scanning TEM (HAADF-STEM), give atomically resolved images which make it possible to solve precipitate crystal structures.This is combined with spectroscopic techniques like electron dispersive spectroscopy (EDS) and electron energy loss spectroscopy (EELS) which give information about atomic elements in the precipitates. Moreover, diffraction techniques, like scanning precession electron diffraction (SPED) and nanobeam diffraction are necessary tools which give the required statistics and complementary information. This research is highly dependent on access to and continuously upgrades of the national infrastructure NORTEM. Technique development can be initiated from the fundamental side by academics or from industrial needs. The group is an active contributor to open-source Python packages and contributes to generic method developments. The experimental findings are often supported by ab initio calculations (density functional theory) and electron interaction simulations (dynamical scattering theory).

II) Materials understanding. The characterization is combined with a deep physical understanding of solid-state phenomena in materials, like diffusive phase transformations, behavior of vacancies, metastable phases, interface structures, lattice coherency and thermal energy dissipation. Moreover, this is a multiscale issue. While fundamental property-structure relations often start at the atomic scale, the challenge is to understand the contexts and translate to the macroscopic scale. The group's work is often on the lower (atomistic) scale, but we must interact with stakeholders and scientists working on micro/macro industrial scale.

The work has been continuously going on through the whole period, supported by several types of projects (co) funded by the Norwegian Research Council and (Norwegian) aluminium industry:

- 176816 Nucleation control in Aluminium (IPN-BIA, 2007 - 2012)
- 193619 Japanese-Norwegian Al-Mg-Si project (BILAT, 2009 - 2014)
- 219371 RolEx- 6xxx Alloy Development for Rolling & Extrusion (IPN-BIA, 2012-2017)
- 221714 Fundamentals of precipitation in Al alloys (FRINATEK, 2013 - 2017)
- 237885 SFI CASA/Structural analysis (2015–2023)
- 237900 SFI Manufacturing (2015-2023)
- 247598 FICAL-Fundamentals of IGC in Aluminium (KPN-BIA, 2015 – 2020)
- 247783 AMPERE-Al at elevated temperatures (KPN-BIA, 2015 - 2020)
- 287965 Al precipitation project with Japan (INTPART I&II, 2016-2019, 2019-2023)
- 294933 SumAl - Solute clustering in Aluminium (KPN-BIA, 2019 – 2024)

Key researchers and their positions:

Randi Holmestad (Professor, principal investigator)
Sigurd Wenner (PhD student 2010-2014, now in SINTEF)
Jon Holmestad (PhD student 2011-2015, now in SINTEF)
Takeshi Saito (PhD student 2011-2014, now in Hydro, Singapore)
Eva Anne Mørtsell (PhD student 2012-2016, now in Hydro Metals, Sunndal)
Emil F. Christiansen (PhD student 2015-2019, now at NTNU)
Jonas K. Sunde (PhD student 2016-2020, now in Hydro Extrusions, Oslo)
Adrian Lervik (PhD student 2016-2020, now in Hydro, Oslo)
Jonas Frafjord (PhD student 2016-2020), now at NTNU)
Tina Bergh (PhD student 2016-2021, now at NTNU)
Elisabeth Thronsen (PhD student 2018 -2022, now in SINTEF)
In addition, comes MSc students. Central names from SINTEF are Calin Marioara and Sigmund Andersen in addition, Knut Marthinsen from Department of Materials Science, NTNU.

3. References to the research

Fredrik A. Martinsen, Flemming J.H. Ehlers, Malin Torsæter & Randi Holmestad, Reversal of the negative natural aging effect in Al–Mg–Si alloys (2012) Acta Materialia, 60, 17 6091, https://doi.org/10.1016/j.actamat.2012.07.047.

Calin D. Marioara, Sigmund J. Andersen, Jostein Røyset, Oddvin Reiso, Sverre Gulbrandsen-Dahl, Tor-Erik Nicolaisen, Inge-Erland Opheim, Jan Fredrik Helgaker & Randi Holmestad Improving Thermal Stability in Cu-Containing Al-Mg-Si Alloys by Precipitate Optimization. Metall Mater Trans A 45, 2938–2949 (2014). https://doi.org/10.1007/s11661-014-2250-0

Takeshi Saito, Calin D. Marioara, Sigmund J. Andersen, Williams Lefebvre & Randi Holmestad Aberration-corrected HAADF-STEM investigations of precipitate structures in Al–Mg–Si alloys with low Cu additions (2014), Philosophical Magazine, 94:5, 520, https://doi.org/10.1080/14786435.2013.857051

Sigmund J. Andersen, Calin D. Marioara, Jesper Friis, Sigurd Wenner & Randi Holmestad, Precipitates in aluminium alloys (2018) Advances in Physics: X, 3:1, https://doi.org/10.1080/23746149.2018.1479984

Jonas K. Sunde, Calin D. Marioara, Antonius T.J. van Helvoort & Randi Holmestad, The evolution of precipitate crystal structures in an Al-Mg-Si(-Cu) alloy studied by a combined HAADF-STEM and SPED approach (2018), Materials Characterization,142, 458, https://doi.org/10.1016/j.matchar.2018.05.031.

Takeshi Saito, Eva A. Mørtsell, Sigurd Wenner, Calin D. Marioara, Sigmund J. Andersen, Jesper Friis, Kenji Matsuda & Randi Holmestad, Atomic Structures of Precipitates in Al–Mg–Si Alloys with Small Additions of Other Elements (2018) Advanced Engineering Materials, 20, 1800125, https://doi.org/10.1002/adem.201800125

Adrian Lervik, Elisabeth Thronsen, Jesper Friis, Calin D. Marioara, Sigurd Wenner, Artenis Bendo, Kenji Matsuda, Randi Holmestad & Sigmund J. Andersen, Atomic structure of solute clusters in Al–Zn–Mg alloys (2021), Acta Materialia, 205, 116574, https://doi.org/10.1016/j.actamat.2020.116574.

4. Details of the impact

We have selected 3 areas where we describe the impact in more detail.

I) Commercial impact. The research done in the TEM research group over the years through several competence and industry projects, has resulted in higher competence on alloy design and strengthened the innovation potential for Norwegian aluminium industry. The most concrete example is a patent of a new alloy used for car parts: The ‘Nucleation control’ IPN project with Hydro and Steertech resulted in a patent of a high temperature stable aluminium alloy. High temperature stability is very important in automotive components to maintain strength, also when they are exposed to higher temperatures (like close to engines). The patent was filed in 2011 and granted in 2019, while the paper came out in 2014 and is listed above. It was demonstrated that good thermal stability in Al-Mg-Si-Cu aluminum alloys correlates with a high density of fine lath-shaped, Cu-containing, disordered L phase precipitates. Alloys optimized for the L phase have a high Mg/Si ratio and contain copper. The alloys retained hardness above 90 HV after 3 weeks over-aging at 473 K (200 °C). Further improvement was achieved by substituting Si by Ge in one alloy. HAADF-STEM showed that at peak-hardness conditions, the L phase coexisted with more common needle-shaped precipitates, often with Cu-enriched interfaces. The alloy is today used by the company Steertech in Raufoss to produce 12 million steering columns a year, which have been a quadrupling in the last 4 years. Steertech stated in 2019 that *`TEM has resulted in new contracts and customers and played a major role in quadrupling the production volume over the last 10 years'.* Other companies like Hydro, Benteler and Raufoss Technology have stated the same - that the TEM work and alloy development done in the TEM research group have been and will be a key factor for their competitiveness in several business markets. This is proven by the fact that the TEM group over years has been and still is supported by the industry in a large number of projects (as listed above). The group is also asked to participate in several Innovation Centres (SFIs) to do characterization at the lower scale.

II) Academic impact and method development. The research group has through many years built up a high competence and ownership in the field of micro/nanostructure characterization of aluminium alloys. This has led to international recognition in the academic community. Members of the group are regularly invited to international microscopy and materials conferences. PhD students and young researchers have won career awards at international meetings. Furthermore, a long-lasting collaboration (through bilaterial and INTPART projects) with Japanese researchers have proven our international status.
New technological breakthroughs for TEM instruments (like aberration correction and direct electron detectors) have been utilized to study precipitates in aluminium alloys. With the advent of aberration correction, the high resolution HAADF-STEM technique (also called Z contrast) showed extremely useful to solve atomic structure of precipitates with heavier elements (like Cu and Zn) and revealed atomistic details. However, this could not give the statistics needed (for the billon of precipitates existing in automotive parts). The need for more statistically significant methods made us develop the SPED technique for studies of aluminium alloys, which has proven very useful to study dynamic phase development. Here, we have set up the technique on the NORTEM infrastructure, using new direct electron detection and handling big data. Analyses of the big data sets are done using and developing open-source Python libraries, incorporating supervised machine learning. The group has contributed significantly to several open-source Python packages, such as Hyperspy, Pyxem and Orix.

III) Impact on young careers During the period 2011-2021, the group educated 15 MSc students and 12 PhD students within aluminium alloys. As seen in in the list given in point 2, most of the PhD students have started to work in Hydro, SINTEF and NTNU, still contributing to the field of aluminium alloys and/or materials characterization. The competence they built up has therefore come to use in Norwegian light metal industry. The industry always emphasizes the importance of knowledge and high competence as a competitive advantage and is very satisfied with the candidates from the TEM research group. Fundamental physics knowledge has proven to be a very good basis for more applied materials skills.

5. Sources to corroborate the impact

Since much of the work done in IPN projects for the aluminium industry, the innovation results are protected intellectual property, so we do not have much direct references except for the scientific papers. However, as a part of the NORTEM II infrastructure proposal (which was granted 90 MNOK in 2021), Steertech stated in 2019 that `*TEM has resulted in new contracts and customers and played a major role in quadrupling the production volume over the last 10 years'.* Other companies like Hydro, Benteler and Raufoss Technology have stated the same - that the TEM work and alloy development done in the TEM research group have been and will be a key factor for their competitiveness in several business markets. This is also proven by the fact that the TEM group over years has been and still is supported by the industry in a large number of projects (as listed above). The group is also asked to participate in several Innovation Centres (SFIs) to do characterization at the lower scale.

This patent was granted in 2019: CD Marioara, SJ Andersen, S G-Dahl, J Holmestad, R Holmestad, TE Nicolaisen, IE Opheim, O Reiso & J Røyset, C22C21/08 High temperature stable 6xxx aluminium alloy, Filed 2011-03-30, Granted 2019-05-08, https://patentimages.storage.googleapis.com/f7/00/1b/421f449ebe207e/EP2553131B1.pdf)

Over the years, a few articles have been published in the Norwegian technical weekly Magazine Teknisk Ukelbald:

April 2013: https://www.tu.no/artikler/prover-a-forsta-styrken-til-aluminium/234725/
September 2013: https://www.tu.no/artikler/monterer-nytt-supermikroskop-ved-ntnu/234431/
2014: https://www.tu.no/artikler/dette-skrapet-er-gull-verdt-for-industrien/230374/
2019 https://www.tu.no/artikler/forskning-norsk-forskning-pa-nanoniva-bidrar-til-at-aluminium-kan-brukes-i-alt-fra-biler-til-glidelaser/467205/

The research magazine for NTNU and SINTEF has published about us:
Gemini 2020: https://gemini.no/2019/10/sikrere-biler-bygg-starter-nano-niva/
Gemini 2021: https://forskning.no/fysikk-kjemi-materialteknologi/hvorfor-blir-noen-legeringer-sterkere-i-romtemperatur/1839830 English: https://www.sintef.no/en/latest-news/2021/why-do-some-alloys-become-stronger-at-room-temperature/

CASA News: https://sfi-casa.no/emil-christiansen-has-received-early-career-researcher-award/
CASA News: https://sfi-casa.no/the-art-of-modelling-aluminium-atoms/

The TEM Geminicentre is publishing Annual reports which can be found on this page: https://www.ntnu.edu/temgemini/about

NTNU-IFY case number 4

Institution: NTNU
Administrative unit: Department of Physics (IFY)
Title of case study: Transfer of the advanced laser technology to Norwegian industry
Period when the underpinning research was undertaken: 2011 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 - 2021
Period when the impact occurred: 2012-2023

1. Summary of the impact

The case mainly includes two large EU projects - ERA-NET MARTEC Maritime Laser Radar (MLR) NFR project No 203772/O70, COST project No oc-2013-2-16637 “Advanced Fibre Laser and Coherent Source as tools for Society, Manufacturing and Life Science”- as well as the three NFR projects, including FRITEK project No 191614 “Ultra-short pulsed Tm-doped fiber systems”, NANOMAT N219686 “Advanced Cr-doped II-VI materials for medical lasers” and ENERGIX project No 255003 Laser based kerf-less technology for exfoliation of thin Si layers and wafering of Si ingots (KerfLessSi). In all these international collaborative projects the Laser Physics Group was a critical partner responsible for development of the new laser technology that has been patented by the group members as a result of these projects. The first technology of Tm-fiber laser system born as a result of those EU projects was patented by the NTNU group back in 2013, with the worldwide PCT patent issued in 2019. The NTNU spin-off company ATLA Lasers AS has been created in 2012 and the NTNU technology has been transferred to ATLA that continued developing and patenting of this technology. The three worldwide PCT patents resulting from the above projects could lead to the maturing of the technology to the product prototype state that has been for the first time exhibited in the international Laser Exhibits in 2018 and 2019. Currently the technology is being tested by the industrial partners, e.g. ESKO Kongsberg Precision Systems and IPG Photonics for fine material processing.

Results from the project have also influenced introduction of this particular technology by the other largest laser/photonics companies worldwide, such as IPG photonics, where the laser technology initially invented by the NTNU team has been introduced and produced since 2012 covering the 100 BNOK market of lasers for material processing worldwide.

2. Underpinning research

This case presents our research combined with development in the fundamental laser physics studies at the Laser Physics Group at NTNU that has an impact on industrial, educational and fundamental science development both nationally and internationally. It contributed to the education and employment of the highly qualified laser engineers for Norwegian and European industry and academics. Inevitably the research based education also contributed to the competence and resources available for teaching of physics, and photonics related subjects. The case draws on the FRITEK project “Ultra-short pulsed Tm-doped fiber systems” (2009-2014), NANOMAT N219686 “Advanced Cr-doped II-VI materials for medical lasers” and ENERGIX project #255003 Laser based kerf-less technology for exfoliation of thin Si layers and wafering of Si ingots (KerfLessSi) – all three managed by our research group at NTNU, but also on the two EU projects - ERA NET project MLR in MARTEC programm, managed by the Kongsberg Seatex AS with NTNU as partner, and COST project oc-2013-2-16637 “Advanced Fibre Laser and Coherent Source as tools for Society, Manufacturing and Life Science”. In the latter project NTNU group was a member of the Management Board and the leader of the Work Group “Laser Sources”.

- **FRITEK project No 191614 “Ultra-short pulsed Tm-doped fiber systems”**

The project laid foundations for the novel technology of broadly tunable ultra-short pulse fiber laser based on internal (inside amplifier) Raman self frequency conversion (patent from 2013).

It further led to the development of compact all-fibre power-scalable sub-picosecond commercially attractive systems for remote sensing, LIDAR, medical and scientific applications. Together with the outcomes of ERA-NET project MARTEC it formed the basis for the spin-off company ATLA Lasers AS

- **ERA-NET MARTEC Maritime Laser Radar (MLR). NFR pr. N203772/O70**

The main outcome of the project was a new and advanced laser technology for the kerf-loss-free cost- effective laser micro-processing of thin silicon layers, wafers and related solar cells with femtosecond mid-infrared (2-3 micron) fiber based lasers developed jointly at NTNU and ATLA lasers (NTNU spin-off), in collaboration with SINTEF and the small and large material processing laser tool industry (TRUMPF) as well as other international partners.

- **NANOMAT N219686 "Advanced Cr-doped II-VI materials for medical lasers"**

The strength of the project was in its multidisciplinarity, with the competencies ranging from laser physics, laser technology, nonlinear optics to materials, including materials for lasers, nonlinear-optics and spintronics. Within the IFY ecosystem the group has a strong experimental basis and the top laboratory equipment, including two MBEs and a fiber tower for advanced materials development, an ultrafast laser lab as well as a laser/optical characterization lab as an integral part of the development of advanced active and passive optical components, building and characterization of the laser system. Together with our specific and exceptionally high laser competence the unique infrastructure and top research attract also other industrial partners both in Norway (besides Kongsberg SEATEX we collaborate with FFI in Oslo, ESKO Precision in Kongsberg, Norsk Electrooptics and NORSUN) as well as internationally (we collaborate with large European company TRUMPF and US company IPG Photonics) as well as academic partners (TU Vienna, NIST in Boulder Colorado, Stanford, Caltech, Southampton, Ecole Polytechnique, Lund University etc.). All this resulted not only in publication of the results of the project in the top journals and acknowledgement with the IEE prize of the specific NTNU laser technology which has been developed in this project and laid foundation to the NTNU spin-off ATLA Lasers AS, but also in taking on board of this mid-IR laser technology by the largest in photonics industry multi-billion company IPG Photonics, currently routinely producing these type of lasers. The other companies, including Norwegian companies are actively using these lasers for specific applications in material processing, sensing and environmental monitoring, telecommunications and biomedicine.

Key researchers and their positions:

From NTNU and the Laser Physics research group:

- Irina Sorokina, professor (professor 2007 - now)
- Ursula Gibson (professor 2007 – 2021)
- Vlad Dvoyrin, PostDoc (2010-2014)
- Dmitry Klimentov, Research Fellow (2011-2015)
- Nikolai Tolstik, Researcher (2012-2022)

For the industrial research in FRITEK and Nanomat, the following are key researchers at Kongsberg Seatex and ATLA Lasers AS: Jon Klepsvik (NTNU researcher until 2005)

3. References to the research

Patents:

- **Fiber Amplifier, V. Dvoyrin and I. T. Sorokina**

A family of PCT patents was granted in the US, UK, EU and Japan in 2019-2021. As an example, please see US Patent #US20150288131A1 from 2014
https://patents.google.com/patent/US20150288131A1/en?inventor=Sorokina&oq=Sorokina

The patent describes an optical system that includes a fiber amplifier with an optically active doped fiber, a source of seed pulses, and a pump source. The doped fiber is doped with one or more active element(s) selected such that the seed pulses are amplified in intensity. The doped fiber has a negative (anomalous) group velocity dispersion in the region from the wavelength of the seed pulses to a threshold wavelength at which the magnitude of the optical loss of the doped fiber is greater than a gain due to stimulated Raman scattering. The invention (transferred to ATLA Lasers AS through NTNU TTO) enabled a new product/laser system that allows to electronically tune the wavelength in the broad wavelength range between 2 and 2.5 microns in a compact diode-pumped Tm-fiber laser. The patented effect of tuning is based on the phenomenon of induced self-frequency shift that for the first time has been observed at LP group inside the femtosecond fiber amplifier (previously Raman scattering and self-frequency shift could be observed only in passive nonlinear fibers – not in amplifier).

- **Laser Crystal**

A family of PCT patents granted in the US, UK, EU and Japan. WO2015059309A1. WIPO (PCT). As an example, please see US patent #US10218146B2 from 2014: https://patents.google.com/patent/US10218146B2/en?q=Laser+Crystal&inventor=Sorokina&oq=Sorokina+Laser+Crystal

The patent provides a method of optimising an optical system of a mode-locked laser oscillator or a regenerative, multi-pass or single pass amplifier. The method may include the steps of identifying crystallographic axes of an active laser gain medium crystal, cutting the crystal, and orienting the crystal in the optical system in a predetermined orientation relative to a propagation vector of a laser pulse depending on the required output of the optical system.The invention enabled (together with the patent 3 below) a new product – a compact Cr-ZnS femtosecond laser and supercontinuum source that can be used for ultra-sensitive measurements of the hazardous gases in the atmosphere and in liquids. Thus the LP work in collaboration with ATLA lasers AS contributed not only to the fundamental research of the group, but also to a new product that has been used by EQUINOR in the industrial project to measure <1% of water in oil and vice-versa – a very important task for the Norwegian oil and gas industry. The patent also was provided by ATLA lasers for the further research in frames of UNLOCK project currently conducted by the group.

- **Graphene-Based Optical Sub-system, I. T. Sorokina**

A family of PCT patents granted in the US, UK, EU and Japan. WO2015059309A1. WIPO (PCT) granted in 2021. As an example, please see US patent #US20160268760A1 from 2014. https://patents.google.com/patent/US20160268760A1/en?q=Graphene+mirror&inventor=Sorokina&oq=Sorokina+Graphene+mirror

The present disclosure provides an optical sub-system for a passive, mode-locked laser optical system. The optical sub-system may include a graphene-based saturable absorber and an optical device configured to control dispersion properties of the laser optical system. The graphene-based saturable absorber may be supported by the optical device.

Research articles:

- Roland A. Richter, Nikolai Tolstik, Sebastien Rigaud, Paul Dalla Valle, Andreas Erbe, Petra Ebbinghaus, Ignas Astrauskas, Vladimir Kalashnikov, Evgeni Sorokin, and Irina T. Sorokina, "Sub- surface modifications in silicon with ultra-short pulsed lasers above 2 µm", JOSA B, 37, 2543-2556 (2020) https://doi.org/10.1364/JOSAB.396074 (2019).
- R. Richter, N. Tolstik, and I.T. Sorokina, "Efficient high-energy Raman soliton generation in Tm:doped large mode area fiber amplifier", Optics Express, v.30, p. 3329-3344 (2022) https://doi.org/10.1364/OE.446612

The paper describes the Tm-doped all-fiber MOPA based on a LMA active fiber generating Raman solitons tunable in the range 1970-2300 nm directly from the LMA fiber. By tuning the chirp of the input pulse we reached more than 90 % energy transfer efficiency to Raman soliton. Solitons with 125 fs duration and up to 24 nJ energy are demonstrated in LMA fiber amplifier. We show experimentally that Raman solitons experience both amplification and absorption in active fiber components of the laser system and that the energy of a Raman soliton generated in an LMA fiber amplifier is limited by the soliton area theorem.

- All-laser-microprocessed waveguide Cr:ZnS laser. E. Sorokin, A. A. Bushunov, N. Tolstik, A. A. Teslenko, E. Einmo, M. K. Tarabrin, V. A. Lazarev, and I. T. Sorokina.

Optical Material Express, v. 12, pp. 414-420 (2022). https://doi.org/10.1364/OME.452026

The paper reports proof-of-concept of an operational laser active medium with a depressed cladding waveguide manufactured in the volume of a Cr^{2+}:ZnS single-crystalline sample and antireflection microstructures fabricated on its facets exclusively by femtosecond laser processing techniques. This allowed us to achieve transmittance from 2-8 µm, approaching a maximum of over 90% near 2.5 µm, and lasing at 2275 nm at the average output power of 20 mW for the absorbed pump power of 500 mW with the slope efficiency of 5.5 %. This demonstration opens a route towards industrial fabrication of compact integrable laser sources and sensors based on II-VI materials. The paper is of high industrial relevance and already two companies (IPG Photonics and Kongsberg SEATEX) are supporting our research in UNLOCK project towards integrated laser sources in the mid-IR. The paper uses the patent 2.

- Multi-Kilowatt Peak Power Nanosecond Er-Doped Fiber Laser. V. V. Dvoyrin, D. Klimentov, J. O. Klepsvik, I. V. Mazaeva, I. T. Sorokina, IEEE Photon. Technol. Lett. **28**, 2772-2775 (2016). doi: 10.1109/LPT.2016.262034

The paper describes the laser technology that was developed by the group in the ERA-NET Martec project MLR and further transferred to Kongsberg Seatex as the main user company in this project. The prototype was later successfully tested for LIDAR applications at Kongsberg Seatex and introduced as a product.

- Mid-infrared dual-comb spectroscopy with 2.4 µm Cr2+:ZnSe femtosecond lasers. B. Bernhardt, E. Sorokin, P. Jacquet, R. Thon, T. Becker, I. T. Sorokina, N. Picqué, T. W. Hänsch, Appl. Phys. B **100**, 3-8 (2010). doi: 10.1007/s00340-010-4080-0

The paper describes the first a proof-of-principle experiment of frequency-comb Fourier-transform spectroscopy with two Cr2+:ZnSe femtosecond oscillators directly emitting in the 2.4 µm mid-infrared region – molecular fingerprint region that is so important for atmospheric LIDARS and sensing in general. We used two Cr:ZnSe lasers developed in LP group and later commercialized through ATLA Lasers. The acetylene absorption spectrum in the region of the $\nu1+\nu15$ band, extending from 2370 to 2525 nm, could be recorded within a 10 µs acquisition time without averaging with 12 GHz resolution. The methodology allows to achieve the record (up to now) sensitivities of 200 ppt for e.g. HF molecules. As such, it is very interesting for broad environmental sensing use. This was the first application of double-frequency comb to mid-IR and stimulated a large amount of works worldwide, further extending this approach to other industrially relevant lasers such as silicon micro-resonators. The double-frequency comb methodology based on Cr:ZnSe/ZnS lasers was transferred to ATLA Lasers AS.

4. Details of the impact

Impact on industry

The projects have been supported by the industry from the start. Just as an example, one of the inventions studied in Nanomat project and patented by Irina Sorokina (see patents above) – a new class of compact tunable mid-Infrared ultra-short pulsed Cr:ZnS and Cr:ZnSe – goes back to 2006/2007 when an IEE IEE Snell Premium Award 2004 (together with E. Sorokin, S. Mirov, V. Gapontsev) awarded for “development of broadly tunable and microchip Cr:ZnSe lasers and their applications”. Being a President and CEO of the multibillion laser company IPG Photonics, Dr. V. Gapontsev, in 2012 has introduced this laser (Cr:ZnS and Cr:ZnSe)at IPG Photonics as a product, together with Tm-fiber lasers (another patent). Both types of lasers are also products of ATLA Lasers AS. They are currently at the stage, when the technology has went through the initial stages of technology development and are entering the 10 BEUR fine material processing market, with a potential to cover a not less attractive environmental sensing and biomedical markets. For more details please, see Innovations section of the the Laser Physics Group website: https://www.ntnu.edu/physics/research/laser-physics

The fine laser material processing market enabled by this new class of mid-IR lasers developed in 2011-2021 at the Laser Physics Group of NTNU is attracting growing interest and is 10.48 BEUR growing with 10%CAGR (***Strategies Unlimited report 2020***). Historically, lasers in this market have been characterised by expensive components, bulky products, and until recently, low output power among the newer, more promising technologies. Compact microchip and waveguide lasers offer real potential to deliver compact and more scalable technologies to expand the market in new applications, particularly in bio-imaging and sensing, where the market now is >5.1 BEUR/10% CAGR (***Strategies Unlimited report 2020***).

The fact that a small spin-off company, together with such large partners as IPG Photonics and Kongsberg Precision Systems are entering such big markets is not least due to the large industrial value of the new mid-IR ultrafast laser technology developed by the group. For example, FRITEK project No 191614 and ERA NET Martec project N203772/O70 have both been co-funded by the Kongsberg Seatex, ENERGIX Project No255003 has been supported by the large German concern TRUMF and ATLA lasers, the current projects UNLOCK and MIR are supported not only by Kongsberg and ATLA, but also by the Norwegian company Kongsberg Seatex, Norsun and CERN. Another NTNU employee prof. Ursula Gibson has also established a small company producing nonlinear silicon based Bragg grating devices. Thus, the two NTNU spin-off companies together with patents and current support of ATLA Lasers AS by the other Norwegian industry on the way towards direct introduction of the laser technology as a product highly sought after by the material processing and sensing industries.

Impact on society
As a member of the management Board and a Work Group leader "Laser and Coherent Sources" in COST project oc-2013-2-16637 "Advanced Fibre Laser and Coherent Source as tools for Society, Manufacturing and Life Science" the Laser Physics Group leader Irina Sorokina has personally directly contributed to the promotion of laser science and technology and bridging the gap between science and industry. As a Chair of the Meetings Board of the OPTICA (Optical Society of America – the largest international professional society in optics and photonics in the USA) Irina has established a number of new laser conferences and attracted more than 1 Mln USD and established the largest in the field Laser Congress. Another NTNU employee prof. Ursula Gibson has been also in the leadership of OPTICA in the role of the President of OPTICA (in 2018-2019), indirectly promoting also the Norwegian laser and optics science and industry. Thus, the technology has indirectly impacted the society in a profound way. More information can be found on the group website here: https://www.ntnu.edu/physics/research/laser-physics

Impact on education
The Laser Physics Group has strongly contributed to the optics education in Norway in general by introducing several courses on the Master and PhD level, and having introduced optics fundamentals into important courses as Energy and Environmental Physics TFY4300 and Energy Resources FY2290.

Impact on laser competence in Norway
The Laser Physics Group is contributing to education and through ATLA Lasers AS also helps employment of laser engineers at the Norwegian Lasers and Optics industry. More information can be found on the group website here: https://www.ntnu.edu/physics/research/laser-physics

5. Sources to corroborate the impact

Popular presentation explaining the industrial and societal impact of the developed technology at the TEDEX conference in Arendal, Norway in November 2021:
https://www.youtube.com/watch?v=6Gx55kA_Yds&t=460s

Photonics 21 website on the importance of our lasers for the industry:
https://www.photonics21.org/ppp-services/photonics-for-industry.php

Explanation of processes the laser material processing covers:
https://www.ipgphotonics.com/en/applications/materials-processing

UiS_IER Impace Case 1

Institution: University of Stavanger
Administrative unit: Department of Energy Resources
Title of case study: The National IOR Centre of Norway (NIOR)
Period when the underpinning research was undertaken: 2013-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2021
Period when the impact occurred: 2014-present

1. Summary of the impact (indicative maximum 100 words)

The impact of 8 years of research within the NIOR can be summarized in terms of a few key points. The centre has:

1. Helped train a large number of Ph.Ds and Post-docs with highly relevant and internationally sought expertise in IOR.
2. Has led to new insights and worldwide applicable knowledge and tools which will help the oil industry to meet its current and future challenges.
3. Has helped make Norway a leading nation for IOR.

The success of the NIOR paved the way for the application and establishment of a new national research centre, NCS2030, which is aimed to run from 2022-2029.

2. Underpinning research (indicative maximum 500 words)

The industry views exchanged during regular technical and board meetings, targeted workshops, annual conferences, and delivery forums contributed to keeping high level of relevance of the Centre activities towards applications and operational settings. The individual user partner's needs have been addressed through company visits and their specific feedback. Based on this mutual collaboration, we defined four main categories of deliverables: 1) Methods & Mechanisms, 2) Upscaling, 3) Field Application, and 4) Education & Dissemination. Within these categories, we specified concrete deliverables from every project involved; knowledge and tools that can contribute to environmentally friendly and cost-efficient methods for improved oil recovery. During the last years of the Centre, key researchers and industry specialists have met on a regular basis in topic-specific discussion forums, "Delivery Forums", to create added value from working across themes and tasks. Four delivery forums were formed: 1) Wettability and Smart Water EOR, 2) Polymer, 3) Field application and 4) Upscaling. These topics largely reflect the Centre's research focus for the last eight years. The mandate of the forums was to define deliverables from the Centre and to ensure that both scientific and applied deliverables were reached.
The Delivery Forums were effective arenas for research dissemination and getting feedback from user partners with focus on the industrial needs. Multi-disciplinary research was effective and impactful, in our case connecting disciplines from pore to core to field scales.

The knowledge generated in the Centre has been organised in an online archive at the University website easily accessible to partners and interested parties. Furthermore, the Centre gave rise to several initiatives within education, research, and innovation. The recently awarded Petrosenter NCS2030 was granted by The Research Council of Norway in December 2021 and will, with a similar collaboration between academia and industry as in the IOR Centre, focus on research topics within sustainable subsurface utilization to facilitate the energy needs and climate goals via research and education. The development of software and simulation tools in the Centre has also seen the spin-off of an innovation project with industry partners that will investigate commercialization options. The Subsurface Academy is an initiative by the University of Stavanger within the education aspect, which focuses on preserving subsurface competence and extending it to cope with future energy challenges. Related to this initiative, a newly granted project funded by the Norwegian Directorate for Higher Education and Skills, started in January 2022. It has 5 industry partners and will investigate how the university can best support the challenges of the future in the energy sector.

In accordance with the commitment to the Research Council of Norway, the IOR Centre established an arena for collaboration for the national (and international) IOR research community by arranging an annual conference. IOR NORWAY has been held annually since 2014, with around 300 participants from home and abroad each year. The conference has distinguished itself internationally, and in 2017 it was arranged in collaboration with European Association of Geoscientists and Engineers (EAGE). In 2020, the conference was held together with the International Wettability Symposium, a symposium established in the USA.
A large part of the activities of the Centre involved the education of about 30 PhD candidates and Postdocs, and numerous master and bachelor students, who together with researchers have been contributing to delivering and disseminating research results in the research community and to the broader audience. International cooperation has been a key component of the Centre with mobility of students and researchers in Europe (Denmark, France, Germany, Italy, the Netherlands), North America and Asia. Contacts with other similar national and international centres, through projects, mutual visits, annual IOR Norway conferences, contact meetings organised by The Research Council of Norway, student activities were important both for improving Centre performance and for stimulating better research results and creating larger networks.

The Centre management at the Centre end (2021) consisted of: Ying Guo, IER-UiS (director), Tina Puntervold, IER-UiS (assistant director and Theme 1 leader), Sissel Opsahl Viig, IFE (director of field implementation), Aksel Hiorth, IER-UiS (director of academia and research), Svein Skjæveland, IER-UiS (advisor) and Randi Valestrand, NORCE (research director and Theme 2 leader). Former members of the Centre management included: Merete Vadla Madland, IER-UiS (director 2013-2019); Kristin Flornes, NORCE (assistant director 2013-2016) and Geir Nævdal, NORCE (Leader Theme 2 2013-2016).
Research task leaders at the Centre's end in 2021 were 1) Arne Stavland, NORCE ,2) Udo Zimmermann, IER-UiS, 3) Espen Jettestuen, NORCE, 4) Aksel Hiorth, IER-UiS, 5) Tor Bjørnstad, IFE, 6) Ove Sævareid, NORCE and 7) Geir Nævdal, NORCE.

3. References to the research (indicative maximum of six references)

Six references to research from the NIOR performed by IER staff:

- I. Piñerez, T. Puntervold, S. Strand, P. Hopkins, P. Aslanidis, H. S. Yang, et al., Core wettability reproduction: A new solvent cleaning and core restoration strategy for chalk cores. Journal of Petroleum Science and Engineering 2020 Vol. 195 Pages 107654, DOI: https://doi.org/10.1016/j.petrol.2020.107654
- Nermoen, A., Korsnes, R. I., Hiorth, A., and Madland, M. V. (2015), Porosity and permeability development in compacting chalks during flooding of nonequilibrium brines: Insights from long-term experiment. *J. Geophys. Res. Solid Earth*, 120, 2935– 2960. doi: 10.1002/2014JB011631.
- Lohne, A., Nødland, O., Stavland, A. *et al.* A model for non-Newtonian flow in porous media at different flow regimes. *Comput Geosci* **21**, 1289–1312 (2017). https://doi.org/10.1007/s10596-017-9692-6
- Andersen, P.Ø., Wang, W., Madland, M.V. *et al.* Comparative Study of Five Outcrop Chalks Flooded at Reservoir Conditions: Chemo-mechanical Behaviour and Profiles of Compositional Alteration. *Transp Porous Med* **121**, 135–181 (2018). https://doi.org/10.1007/s11242-017-0953-6
- T. Puntervold, A. Mamonov, I. D. Piñerez Torrijos and S. Strand, Adsorption of Crude Oil Components onto Carbonate and Sandstone Outcrop Rocks and Its Effect on Wettability, Energy & Fuels 2021 Vol. 35 Issue 7 Pages 5738-5747, https://doi.org/10.1021/acs.energyfuels.0c03003
- Hong, A.J., Bratvold, R.B. & Nævdal, G. Robust production optimization with capacitance-resistance model as precursor. *Comput Geosci* **21**, 1423–1442 (2017). https://doi.org/10.1007/s10596-017-9666-8

4. Details of the impact (indicative maximum 750 words)

The main objective and vision of the centre was «to contribute to the implementation of cost-efficient and environmentally friendly technologies for improving oil recovery on the Norwegian Continental Shelf.» To meet the objective the Centre conducted research on oil recovery at multiple length scales and conveyed competencies from several scientific fields (among others, geology, geophysics, reservoir chemistry, material science, computational engineering and methods, advanced mathematics, and physics). The activities included both experimental and modeling work complementing each other.

The research work was performed in seven different tasks: 1) core scale, 2) nano/submicron scale, 3) pore scale, 4) upscaling, 5) tracer technology, 6) reservoir simulation, 7) field scale evaluation. In the Centre, extensive experimental and modelling work related to several topics has been developed and performed. To capture and document these workflows, the Centre has written eleven Recommended Practices within the topics of core preparation, Smart Water EOR experiments, modelling and upscaling, polymer experiments, modelling and upscaling, adding 4D seismic data to history matching, ensemble-based optimization for EOR processes, tracers for inter-well and single well Sor-monitoring, and environmental risk assessment of IOR solutions. Each of the eleven documents gives a state-of-the-art recommendation of how the user partners can apply tools and perform workflows to secure the most optimal results. The recommended practices have been made publicly available, and can be found in the following link: https://ebooks.uis.no/index.php/USPS/catalog/category/IER

In addition to the recommended practices, four modelling software for different scales have been developed, “Open porous media” (OPM) and “IORSim” for field scale simulations, “IORCoreSim” for core scale simulations, and “BadChimp” for pore-scale simulations.

The report from the mid-term evaluation stated: «The combination of work at different scales is excellent. This means that as well as defining the benefits of different EOR treatments empirically, the underlying mechanisms can be understood: so leading to a firm theoretical basis for subsequent modelling and optimization work.» Moreover, the centre meets with the scientific ambitions and goals, by a qualitatively and quantitatively high scientific production and output.

The research team has published almost 200 journal papers in the duration of the Centre and has given more than 700 presentations as conference contributions or scholarly presentations. The details of most of these are available in the Cristin database, registered under the National IOR Centre of Norway, project number 230303. Several researchers in the team have received awards related to their contributions in the field of petroleum during the Centre lifetime; examples are the NPD IOR Award which Geir Evensen won in 2020, and for which Svein M. Skjæveland was nominated in 2018, and the SR Bank’s Innovation Award 2017, which was won by Arild Lohne and Oddbjørn Nødland.

5. Sources to corroborate the impact (indicative maximum of ten references)

In a report by Rystad Energy on the effects of The Research Council of Norway’s targeted activities within petroleum The National IOR Centre of Norway was mentioned in the report stating that long-term research funding pays off. Link: https://www.forskningsradet.no/contentassets/66c1b5cc03054f0e9fe39194cdfbdb60/20200109_effekter-av-marettede-aktiviteter-innen-petroleum_underlag.pdf

UiS_IER Impact Case 2

Institution: University of Stavanger
Administrative unit: Department of Energy Resources
Title of case study: LoCRA
Period when the underpinning research was undertaken: 2013-2022
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2022
Period when the impact occurred: 2013-present

1. **Summary of the impact** (indicative maximum 100 words)

The impact from our 10+ years research activities extends from young M.Sc.'s, PhD's and Postdoctoral researchers career development, researchers competence strengthening, and knowledge to the end users in the area of geological evolution of the Lower Cretaceous of the Greater Barents Sea region, exploration opportunities of this mostly underexplored time interval and region (https://wp.ux.uis.no/locra/).
The project consortium has contributed to all partners with new knowledge and deliverables to the user partners and the Norwegian Petroleum Directorate, which resulted in improved subsurface understanding for de-risking exploratory targets. The study is a pioneer project aiming to integrate detailed analysis into a unified framework that can be expanded into the North American, Greenland, and Kara Sea basin evolution. The research partners have strengthened their position both nationally and internationally providing high quality research and educated personnel in subsurface competence that currently works both in industry and academia. The consortia paved the way to a new project named JuLoCRA (https://wp.ux.uis.no/julocra/) which focuses into the link between the Cretaceous and Jurassic which still produces relevant results.

2. **Underpinning research** (indicative maximum 500 words)

The main goal of the LoCRA project was to improve the basin configuration and fill of the Lower Cretaceous basins in the high Arctic as input to prediction of coarse grained siliciclastic wedges as plays on the Norwegian Continental Shelf in order to reduce exploration risk and ultimately value creation for the Norwegian Society. To meet this ambition and produce as much impact as possible, the main focus areas included better understanding of the basin evolution, stratigraphy, structural styles, depositional setting and paleogeography in the Greater Barents Sea including Svalbard, Franz Josef Land, the northern Norwegian Sea, and on- and offshore East Greenland and their relation to the North American arctic basins. To obtain a refined paleogeography of the Early Cretaceous basins and its coastlines, an improved plate tectonic reconstruction was carried out. Main research areas included plate reconstructions, sequence stratigraphic framework, regional mapping, and other related studies such as detailed sub-basin evolution, petrophysical evaluations, outcrop analogues, and geochemistry as part of the JuloCRA project. An integrated approach where PhDs and postdoctoral researchers working together with multidisciplinary backgrounds resulted in leading edge results a unified geological framework and understanding.

The project was initially planned for 4 years, but due to the large interest of the industry (up to 22 companies) for understanding the Lower Cretaceous interval and the unified approach proposed, the project had extra funding. Therefore, the project expanded its activities and continues with a new project named JuLoCRA, which still produces results with an ongoing PhD finishing in spring of 2023, 10 years after the start the of the original project.

Main project investigator at IER: Prof. Alejandro Escalona. In addition, Prof. Udo Zimmermann, Prof. Carita Augustsson, Prof. Nestor Cardozo, 5 Phds, 2 postdoctoral researchers and more than 10 BSc and MSc students work in the project

3. References to the research (indicative maximum of six references)

The best manner to highlight key references, are those by the young researchers (Phds and Postdocs) that resulted from the consortia which today are working in academia or industry applying the competence gained. Six examples are:

- Grundvåg, S., D. Marin, B. Kairanov, K. Sliwinska, H. Nøhr-Hansen, M. E. Jelby, A. Escalona, and S. Olaussen, 2017, The Lower Cretaceous succession of the northwestern Barents Shelf: Onshore and offshore correlations: Marine and Petroleum Geology, v. 86, p. 834-857, doi: 10.1016/j.marpetgeo.2017.06.036.
- Kairanov, B., A. Escalona, A. Mordasova, K. Sliwinska and A. Suslova, 2018, Lower Cretaceous tectonostratigraphic evolution of the northcentral Barents Sea: Journal of geodynamic, doi: 10.1016/j.jog.2018.02.009.
- Kayukova, A. V., and A. A. Suslova, 2015, A Seismostratigraphic Analysis of the Lower Cretaceous Deposits of the Barents Sea to Reveal Petroleum Perspectives: Moscow University Geology Bulletin, v. 70, p. 104-109
- Marin, D., A. Escalona, S. Grundvåg, S. Olaussen, S. Sandvik, and K. Sliwinska, 2017, Unraveling key controls on the rift-climax to post-rift fill of marine rift basins: insights from 3D seismic analysis of the Lower Cretaceous of the Hammerfest Basin, SW Barents Sea: Basin Research, doi: 10.1111/bre.12266
- Sæbø Serck, C., J. I. Faleide, A. Braathen, B. Kjølhammer, and A. Escalona, 2017, Jurassic to Early Cretaceous basin configuration(s) in the Fingerdjupet Subbasin, SW Barents Sea: Marine and Petroleum Geology, v. 86, p. 874-891, doi: 10.1016/j.marpetgeo.2017.06.044
- Arlebrand, B. A., Augustsson, C., Escalona, A., Grundvåg, S. and D. Marin, 2021, Provenance, depositional setting and diagenesis as keys to reservoir quality of the Lower Cretaceous in the SW Barents Sea. Marine and Petroleum Geology. ISSN 0264-8172. v. 132. DOI: 10.1016/j.marpetgeo.2021.105217

3. **Details of the impact** (indicative maximum 750 words)

The overarching impact of the project is knowledge building, training of young professionals and the delivery of a hands-on database that results in reduce exploration risk therefore increase value creation for the Norwegian society.

The project was created during an increased exploration activity of the Barents Sea, particularly in the Norwegian sector, but with interest in the cross-border understanding with the Russian sector. Further, the understanding of new play concepts such as Lower Cretaceous wedges played a fundamental role. Many of these wedges have been drilled during the research period of the project where both data from the project and input from the results were utilized to improve existing exploration models. Previous unification of geological models and processes between the North American Arctic and the Norwegian-Russian Arctic basins have been limited to country boundaries, and limited knowledge about the neighboring regions have been exchanged. The novel unification of a stratigraphic framework and integrated paleogeography that includes surface and subsurface geology served as a basis for developing an improved basinal framework of the entire Arctic, as well as a better understanding of the Cretaceous and its petroleum potential which allows increased subsurface knowledge and risk reduction in the evalauiton of exploratory prospects for the Lower Cretaceous interval.

Annual meetings with all sponsors to present results and plans for the following year with follow up individual visits provided good discussions to guide and improved the research. This resulted in new project ideas and access of proprietary or new data acquisition that increased the quality of the results and competence building of both the research and industry partners. In several occasions, industry used the ongoing results to de-risk exploration prospects and exploration wells were drilled based on the competence achieved.

A main project delivery occurred in 2018, where a digital and hard copy atlas was provided to the companies, and a full digital database which included all maps, raw and analysed data from cores and chemical analyses, plate tectonic model, GIS, etc. Both the report and database were built for easy access and utilization of the companies, such that they could load the GIS databased and subsurface surfaces and data points produced by the project among others and have immediate utilization of the results in their internal systems, support decision making and reduce risk. Further, education of new professions and the master, PhDs and Postdoc level that are currently part of the working force in both industry and academia.

Finally, the project built a frame and experience at the administrative unit for establishing successfully funded industry projects that have impact both in academia and industry. In these regards, the industry and academic network, and the administrative and project management experience built via the LoCRA project, facilitated the development of new industry consortia at the administrative unit.

5. Sources to corroborate the impact (indicative maximum of ten references)

The project is an industry sponsored project. For corroborating the impact, it is recommended to contact the NPD or the sponsors directly. However, many of the sponsoring companies have merged or do not exist, or personnel have changed positions or do not belong to the same organizations anymore. At the moment, we can only direct to the project webpage https://wp.ux.uis.no/locra/; if necessary, it is recommended to contact Prof. Escalona to recommend names that may provide a reference to the project.

UiT_IK_1_OptiZyme

Institution: UiT The arctic university of Norway	
Administrative unit: Department of chemistry	
Title of case study: Optimization and Application Development of Marine Cold-adapted DNA Polymerases	
Period when the underpinning research was undertaken: 2013 - 2016	
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2023	
Period when the impact occurred: 2016 - 2021	

1. Summary of the impact (indicative maximum 100 words)

The research started with the OptiZyme project dealing with enzymes, i.e., DNA polymerases, for use in isothermal nucleic acid amplification technologies, an emerging but still young technology. Underlying results, experience of working with cold-adapted enzymes, a good planning of the project and the execution thereof made OptiZyme a success. Besides resulting in several forms of scientific output, the project and the experience gained from it let to the funding of further projects between 2016-21, thereby extending application range of cold-adapted polymerases and leading to additional filed patents and license agreements.

2. Underpinning research (indicative maximum 500 words)

Enzymes are proteins that catalyze and thus accelerate chemical reactions. DNA polymerases are enzymes that catalyze the synthesis of deoxyribonucleic acid (DNA) and participate in DNA replication and repair.

They are used in molecular biology applications and molecular diagnostics and are the workhorses in the polymerase chain reaction (PCR). The PCR technology has a high potential but requires the use of repeated high precision temperature cycling. In contrast, in the emerging Isothermal Amplification (IA) methods nucleic acid amplification takes place at constant (moderate) temperatures and has no need for temperature cycling or enzymes stable at high temperatures. IA methods are now increasingly being used but the toolbox of polymerases used here is still limited and cold-adapted DNA polymerases in particular have not been commercially exploited for this purpose.

“Optimization and Application Development of Marine Cold-adapted DNA Polymerases - OptiZyme” was a 3-year Proof-of-Principle project founded by the BIOTEK 2021 program from the Research Council of Norway. Key researchers of the project were Dr. Atle N. Larsen (project leader) and Dr. Yvonne Piotrowski (principal researcher). The project was undertaken from October 2013 to September 2016. Its main goal was to further develop preliminary characterized marine cold-adapted polymerases for improved efficiency and applicability in present and future isothermal amplification technologies by use of rational design studies and molecular evolution.

The polymerase genes have been identified based on bioprospecting (of the arctic region) and originate from psychrophilic genomic and metagenomic sources. Recombinant production, purification and characterization of the DNA polymerases of interest have earlier been established at the SFI Centre for Marine bioactives and drug discovery (MabCent). In the course of the project, a medium-throughput platform for production, purification and characterization of enzyme variants generated by semi-random mutagenesis have been established.

All in all, 1000 enzyme variants have been screened. Fifteen of these have been subjected to large-scale protein production and purification to confirm the improved activities measured during the screening process. Finally, five variants that performed better than state-of-the-art commercial enzymes have been sequenced to identify the mutations and characterized in detail. One variant stood out and showed an increase in the desired activity by more than 2-fold which surprisingly was caused by a single mutation, i.e., a substitution of only one amino-acid residue. Introducing this substitution in homologues DNA polymerases led to the same effect and thus also confirmed the findings.
3. References to the research (indicative maximum of six references) Key outputs of the research performed during the OptiZyme project are: Publication: Characterization and engineering of a DNA polymerase reveals a single amino-acid substitution in the fingers subdomain to increase strand-displacement activity of A-family prokaryotic DNA polymerases, Piotrowski et al., BMC Mol Cell Biol. 2019 Aug 9;20(1):31. doi: 10.1186/s12860-019-0216-1. Disclosure of invention to UiT: Supreme strand-displacement polymerase with proficient processivity from a marine cold-adapted *Psychrobacillus* sp., Atle N. Larsen et al., submitted to UiT – The Arctic University of Norway in June 2015 Patent: Larsen A.N., Piotrowski Y. ”Position based increase in application relevant properties”. International Patent Application, WO2019115834A1, 2018
4. Details of the impact (indicative maximum 750 words) The direct impact to society of the Optizyme project is the launch of the IsoPol™ and IsoPol™ SD+ enzymes for use in isothermal nucleic-acid amplification technologies at ambient temperature by AZT in 2016-2017. Additionally, the OptiZyme project had a substantial impact on the following work of the researchers involved und thus also for the Department of Chemistry. A lot of new knowledge has been gained on how to work with cold-adapted enzymes and in particular complex enzymes such as DNA polymerases. Also following new ideas for applications of the by then well-known cold-adapted DNA polymerases four more projects have been granted and undertaken • 2016 - 2018 – MDxPol – Marine DNA polymerases as tools for next generation Molecular Diagnostic solutions (FORNY2020 – The Research Council of Norway, 2 years) • 2016 - 2021 – MarSynth – Marine DNA modifying enzymes for synthetic biology (BIOTEK2021 – The Research Council of Norway, 4 years) • 2017 - 2018 – Marine DNA polymerases as engines for Single Cell Genomics (Mabit – industrial R&D program for Marine Biotechnology in Northern Norway, 1 year) • 2019 - 2020 – ChimPol – Chimeric DNA polymerases as enzymatic drivers for single cell genomics (Mabit – industrial R&D program for Marine Biotechnology in Northern Norway, 1 year) The MarSynth project resulted in three patents filed internationally in October 2020 and three license agreements between UiT – The Arctic University of Norway and ArcticZymes Technologies ASA signed in December 2022. By being able of receiving more funding based on the success and the experience from the OptiZyme project also seven researchers/technicians in addition to the key researchers could be employed throughout the years part time contributing to the projects but also deepening and expanding their own skills. Many of the personal educated through the projects are today working in the industry.
5. Sources to corroborate the impact (indicative maximum of ten references)

Product description of IsoPol™: https://arcticzymes.com/products/enzymes/isopol-dna-polymerase/

Product description of IsoPol™ SD+: https://arcticzymes.com/products/enzymes/isopol-sd/

MarSynth patents:

- Method and Kit for assembly of multiple DNA fragments at room temperature (WO 2021/064115 A1)
- Marine DNA Polymerase I (WO 2021/064108 A1)
- DNA Polymerase and DNA Polymerase derived 3'-5' Exonuclease (WO 2021/064106 A1)

Press release December 8th by AZT on license agreement with UiT based on the MarSynth results: https://arcticzymes.com/arcticzymes-technologies-exclusively-licenses-novel-dna-assembly-technology/

UiT_IK_2_Amicoat AS

Institution: UiT The Arctic University of Norway
Administrative unit: Department of Chemistry
Title of case study: Amicoat AS
Period when the underpinning research was undertaken: 1994-to date
Period when staff involved in the underpinning research were employed by the submitting institution: 1994-to date
Period when the impact occurred: 2014-to date

1. Summary of the impact (indicative maximum 100 words)

Founding of a company commercializing antimicrobial technology for medical devices

2. Underpinning research (indicative maximum 500 words)

The impact is based on fundamental research that has been ongoing for more than 25 years at the Department of Chemistry. This research has been supplemented by collaborations from the Faculty of Health and the University hospital of Northern Norway.

The research has been directed towards antimicrobial peptides, to elucidate their exact mode of action on microorganisms, to understand their medicinal chemistry, potential toxic effect on humans and to derive principles for the utility of antimicrobial peptides to limit the infection risk caused by the use on medical devices. The research started with the discovery of lactoferricin and has continued through efforts in medicinal chemistry to the definition of the pharmacophore for this class of molecules. Using the pharmacophore model, we have designed ultrashort molecules that retains all the unique properties of the antimicrobial peptides in a small molecule framework enabling the inclusion of important pharmacological properties such as stability against degradation and enhanced bacterial selectivity. More than 25 masters degrees and more than 10 PhD-degrees has been produced throughout the project, and has put UiT at the forefront of antimicrobial peptide research and is an important foundation for the Centre of new antimicrobial strategies (CANS) at UiT.

The antimicrobial peptide technology is now being commercialized by Amicoat AS who has refined our fundamental research into products that are being produced in multi-kg batches and incorporated into medical device products including central venous catheters, urinary catheters, encephalic shunt catheters, sutures, and bandages for advanced wound care.

As the peptide technology is being realized by a commercial entity, the fundamental research on this class of molecules has continued at UiT in the form of large interdisciplinary projects like DigiBiotics headed by a professor at the department of chemistry.

 John S. Mjøen Svendsen (1994-), Øystein Rekdal (1994-2005), Lars H. Vorland (1994-2008)
 Any relevant key contextual information about this area of research.

3. References to the research (indicative maximum of six references)

Morten B Strøm, Bengt Erik Haug, Merete L Skar, Wenche Stensen, Trine Stiberg, John S Svendsen,The pharmacophore of short cationic antibacterial peptides, 2003, Journal of medicinal chemistry, doi.org/10.1021/jm0340039

Johan Isaksson, Bjørn O Brandsdal, Magnus Engqvist, Gøril Eide Flaten, John S Mjøen Svendsen, Wenche Stensen, A synthetic antimicrobial peptidomimetic (LTX 109): stereochemical impact on membrane disruption, 2011, Journal of medicinal chemistry doi.org/10.1021/jm200450h

John S Mjøen Svendsen, Thomas M Grant, David Rennison, Margaret A Brimble, Johan Svenson, Very short and stable lactoferricin-derived antimicrobial peptides: design principles and potential uses, 2019, Accounts of chemical research
doi.org/10.1021/acs.accounts.8b00624

Stensen Wenche; Haug Bengt Erik; Rekdal Oystein; Svendsen John Sigurd, Antimicrobial compounds, 2008, **US8598114B2**,

Adela Melcrova, Sourav Maity, Josef Melcr, Niels AW de Kok, Mariella Gabler, Jonne van der Eyden, Wenche Stensen, John SM Svendsen, Arnold JM Driessen, Siewert-Jan Marrink, Wouter H Roos, Lateral membrane organization as target of an antimicrobial peptidomimetic compound, 2023, bioRxiv

Bengt Erik Haug, Ketil André Camilio, Liv Tone Eliassen, Wenche Stensen, John Sigurd Svendsen, Kristel Berg, Bjarte Mortensen, Guillaume Serin, Jean-Francois Mirjolet, Francis Bichat, Øystein Rekdal, Discovery of a 9-mer cationic peptide (LTX-315) as a potential first in class oncolytic peptide, 2016, Journal of Medicinal Chemistry,
doi.org/10.1021/acs.jmedchem.5b02025

4. Details of the impact (indicative maximum 750 words)

When you enter a hospital, the risk of acquiring a healthcare associated infection (HAI) during your stay approach 10%. An HAI will obviously affect you, requiring extra treatment and extended hospitalization, but otherwise you may regard the incident as a harmless nuisance. That is, given you are young and fit, and the infection is treatable. The global antimicrobial resistance crisis makes the latter point less and less likely, and in an ageing society even the former point has a diminishing likelihood. Already today, HAI creates a high societal burden, in the US alone the Centers for Disease Control and Prevention (CDC) has estimated the annual direct cost of HAI to be 28.4 billion $ with an additional cost caused by increased mortality and lost work output to 12 billion $/y. In Europe the numbers scales slightly differently, but the estimated direct cost of 8 billion €/y is still substantial.

The highest frequency of HAI is associated with the use of invasive devices, in particular central lines, urinary catheters, and ventilators. There is a large effort in reducing the infection risks of invasive devices. HAI is also a major driver for antimicrobial resistance, making the proliferation of HAI into a global health issue. Given the magnitude of the HAI problem, many initiatives have been introduced. Anything from improved hygiene in the invasive procedures all the way to antibiotic medical devices, but none of them have been sufficiently successful in slowing down the problem with HAI.

If the infection rate on indwelling devices could be halved, an estimated sum of 2 – 4 billion €/y could be saved in Europe alone. The antimicrobial peptide research at UiT has proved its potential in contributing to reduce the infection risk caused by indwelling medical devices. The antimicrobial peptides are in many ways uniquely well situated for application in medical devices. The peptides are broad spectrum, rapid acting, with short range of action limiting potential systemic effects, and research performed at Amicoat has proven that central venous catheters cannot be colonized by the normal Gram+ or Gram- bacteria for more than a month in an experimental setting simulating continuous blood flow. This unusual efficacy has resulted in several major producers of catheters are evaluating the Amicoat technology in their future products.

Apart for the obvious societal advantages connected to reduced infection risk in critical care, Amicoat employs a staff of 11 persons, of whom 7 are working in R&D in both Tromsø and in the Oslo area.

5. Sources to corroborate the impact (indicative maximum of ten references)

Impact case guidelines

Each case study should include sufficiently clear and detailed information to enable the evaluation committee to make judgements based on the information it contains, without making inferences, gathering additional material, following up references or relying on members' prior knowledge. References to other sources of information will be used for verification purposes only, not as a means for the evaluation committee to gather further information to inform judgements.

Timeframes

- The impact must have occurred between 2011 and 2021
- Some of the underpinning research should have been published in 2010 or later
- The administrative units are encouraged to prioritise recent cases

Page limit

Each completed case study template will be limited to **five pages** in length. Within the annotated template below, indicative guidance is provided about the expected maximum length limit of each section, but institutions will have flexibility to exceed these so long as the case study as a whole remains no longer than **five pages** (font Arial size 10,5 or similar). Please write the text into the framed template under the sections 1–5 below. The guiding text that stands there now, can be deleted.

Maximum number of cases permitted per administrative unit

For up to 10 researchers: one case; for 10 to 30 researchers: two cases; for 30-50 researchers: three cases; for 50-100 researchers: four cases, and up to five cases for units exceeding 100 researchers.

Naming and numbering of cases

Please use the standardised short name for the administrative unit, and the case number for the unit (1,2,3, etc) in the headline of the case. Each case should be stored as a separate PDF-document with the file name: [Administrative unit short name] [case number]

Publication of cases

RCN plans to publish all impact cases in a separate evaluation report. By submitting the case the head of the administrative units consents to the publication of the case. Please indicate below if a case may not be made public for reasons of confidentiality.

If relevant, describe any reason to keep this case confidential:

UiT Department of Physics and Technology, Case 1

Institution: UiT the Arctic University of Norway
Administrative unit: Department of Physics and Technology
Title of case study: Data assimilation and numerical modelling of the Barents Sea
Period when the underpinning research was undertaken: 2015-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2015 - 2021
Period when the impact occurred: 2021 -

1. Summary of the impact

WP5 of CIRFA (a Centre for Research-Based Innovation hosted by IFT) develops forecast model systems for high-latitude ocean and sea ice to improve forecasts for Arctic operations, and to provide an improved picture of the Arctic climate. This work integrates research on algorithm developments, conducted in other CIRFA WPs, in order to assimilate observational information from the satellite data into the forecast model systems. (Assimilation of observations into a model, is a process where model fields are changed towards observations, which is applied to initiate a forecast model before the forecasts are computed). In **Case 1**, we high-light the impact of this work related to the development of Met Norway's regional modelling system for the Barents Sea – "the Barents 2.5 model", which is a coupled ocean and sea-ice forecast system, and which covers the Barents Sea and the areas around Svalbard. An ensemble prediction system has been developed for this model, which provides uncertainty estimates of great value in an operational context. An operational implementation of this forecast model system was launched in August 2021.

2. Underpinning research

WP5 of CIRFA is founded on a strong cooperation between Norwegian Meteorological institute (MET Norway) and the Complex system modelling (CoSMo) and Earth Observation (EO) groups at Department of Physics and Technology (DPT), UiT. A PhD project by Sindre Fritzner within the CoSMo and EO groups at DPT (Fritzner, 2020) was dedicated to develop a sea-ice forecasting system that was later coupled to an ocean forecasting system. Fritzner applied an assemble-filter assimilation algorithm to a sea-ice model (Fritzner et al, 2018), and further developed the assimilation algorithm to take into account various observational products, such as satellite-based retrievals of sea-ice concentration, sea-ice thickness, and snow depth (Fritzner et al. 2019). Finally, Fritzner tested the sea-ice forecasting system against a numerically inexpensive machine-learning approach (Fritzner 2020).

Fritzner's PhD and postdoc work included development of capabilities of the Barents-2.5 model to assimilate sea ice observations, such that model forecasts represent the actual sea ice conditions present in the Arctic. Within CIRFA WP5, this methodology was transferred into operational routines at MET Norway and is today an integral part of MET's forecast system for sea ice. The data assimilation methodology was later extended to include other types of observations, such as the sea surface system; work which Fritzner assisted with during his post-doc.

Silje Iversen, which is PhD candidate at DPT in her 3rd year, developed a methodology to assimilate passive microwave observations of sea surface temperature. This methodology is on its way to be implemented in the operational forecast suite at MET Norway.

Staff:
Dr. Sindre Fritzner, CoSMo and EO, DFT: Phd student and postdoctoral fellow during the project
Prof. Rune Grand Graversen, CoSMo, DFT: Main supervisor of Fritzner.
Dr. Kai Christinsen, senior researcher, MET Norway: co-supervisor of Fritzner.
Dr. Keguang Wang, senior researcher, MET Norway: co-supervisor of Fritzner.
Dr. Johannes Röhrs, senior researcher, MET Norway, WP5 co-leader

Silje Iversen, PhD student, Met Norway and CosMo, DFT.
3. References to the research Fritzner S., Graversen R., Wang K., & Christensen K: Comparison between a multi-variate nudging method and the ensemble Kalman filter for sea-ice data assimilation. (2018) Journal of Glaciology, 64(245), 387-396. https://doi.org/10.1017/jog.2018.33 Fritzner S, Graversen R, Christensen KH, Rostosky P, Wang K: Impact of assimilating sea ice concentration, sea ice thickness and snow depth in a coupled ocean–sea ice modelling system. (2019) The Cryosphere, 8;13(2), 491-509, https://doi.org/10.5194/tc-13-491-2019 Fritzner S, Graversen R, Christensen KH: Assessment of High-Resolution Dynamical and Machine Learning Models for Prediction of Sea Ice Concentration in a Regional Application. (2020) Journal of Geophysical Research: Oceans,;125(11):e2020JC016277, https://doi.org/10.1029/2020JC016277 Fritzner SM: On sea-ice forecasting. (2020) Doctoral thesis. University of Tromsø, ISBN: 978-82-8236-395-2 https://hdl.handle.net/10037/18141 Iversen, S. C., Sperrevik, A. K., and Goux, O.: Improving the SST in a regional ocean model through refined SST assimilation, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2022-957, 2022.
4. Details of the impact Operational model forecasts from Barents-2.5 have shown to provide skill in sea surface temperature predictions, which is a direct result of WP5 work, (mainly Fritzner and versen). Skilful SST predictions further improve weather forecasts through model coupling, particular for rapidly changing conditions in the Arctic. SST predictions are further applied in icing algorithms at MET Norway, which are in daily shipping applications. Forecast of surface currents from the model system are used in contingency models for oil spill preparedness and search-and-rescue assistance. Ongoing work by WP5 post-doc Martina Idzanovic, MET Norway, and PhD Victor de Aguiar, EO, DPT, supports this work by documenting the skill of this trajectory modelling system.
5. Sources to corroborate the impact Forecast data is disseminated openly through https://thredds.met.no/thredds/fou-hi/barents_eps.html Forecasts are also used by the weather forecast division, through downstream products such as icing algorithms and trajectory forecasts.

UiT Department of Physics and Technology, Case no. 2

Institution: UiT, The Arctic University of Norway
Administrative unit: Department of Physics and Technology
Title of case study: On-chip nanoscopy a disruptive technology for life science and clinics: From basic research to innovative product
Period when the underpinning research was undertaken: 2013-2022
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-Present
Period when the impact occurred: 2017-2022

1. Summary of the impact (indicative maximum 100 words)

Very often in technology development, the impact translation is created long after the invention is made and by stakeholders from different disciplines. On-chip nanoscopy is one such example where the idea was conceptualized in 2012, yielding ERC Starting Grant to Ahluwalia in 2013. The first proof-of-principle established in 2015, patents followed in 2016 onwards and spin-off was created in 2019. A decade long journey, albeit seems long, has just started creating the impact in life sciences, hospitals and within infection biology. Also, indirect impact is creating of high-tech jobs in Tromsø, a greater innovation eco-system at the department and creating public-private partnership in bringing deep-tech. research into scalable production.

2. Underpinning research (indicative maximum 500 words)

Current paradigm: Diffraction limit of the microscope imposes that the smallest resolution is typically 250x250x500 nm^3 along x-y-z axis respectively. The need to have better resolution led to the invention of **optical nanoscopy**, that can provide resolution down to 10-50 nm. Due to its high impact, the **2014 Nobel Prize in Chemistry** was awarded to the developers of nanoscopy. The area imaged by such nanoscopes is limited to about 50x50 μm^2 **the trade-off being throughput.** Moreover**,** present nanoscopes are expensive (1 M €), complex and lacks the multi-modality, limiting its penetration and utility.

The pain point: Present nanoscope uses a '**simple glass slide'** to hold the sample and a '**complex and bulky microscope set-up'** to perform laser beam engineering in the free-space and use microscope objective lens to deliver laser light at the sample stage.

Proposed route via On-chip nanoscopy: We proposed to take out laser light steering and delivery from the microscope and transfer it to a photonic-chip equipped with optical waveguides. The entire generation and delivery of the illumination will rely on the photonic chip, eliminating the need of complex free-space light beam engineering. We hence **change the current paradigm** to **'a mass-producible photonic-chip'** to hold and illuminate the sample and a "**simple and compact optical microscope'** to image it. On-chip nanoscopy reported the largest ever field of view keeping super-resolution, the results were published twice in Nature Photonics in 2017 and 2020. The large imaging area enabled the penetration of on-chip nanoscopy in histopathology, vascular biology, neuron sciences, fishery sciences and for imaging of nano-sized virus, extra-cellular vesicles, nano-drugs carrier liposomes.

Projects: Support from 4 EU Projects: ERC STG, 2x-ERC PoC, and European Innovation Council (EIC) Transition and from 3 RCN projects: Nano2021, BioTEK2021, FORNY

Names of the key researchers and what positions they held at the administrative unit at the time of the research (where researchers joined or left the administrative unit during this time, these dates must also be stated).:
Professor Balpreet Singh Ahluwalia (PI)
Dr Øystein Ivar Helle (PhD student, graduated)
Dr David Andre Coucheron (PhD student, graduated)
Dr Ida Sundvor Opstad (PhD student, graduated)

Dr Marcel Lahrberg (PhD student, graduated)
Dr Firehun Tsige Dullo (Post-doc researcher, completed)
Dr Jean-Claude Tinguely (Post-doc researcher, completed)
Dr Deanna Wolfson (Post-doc researcher, completed)
Dr Vishesh Kumar Dubey (Post-doc researcher, completed)
Dr Azeem Ahmad (Post-doc researcher, on-going)
Luis Luis Villegas (PhD student on-going)
Nikhil Jayakuma (PhD student on-going)

Any relevant key contextual information about this area of research:
This research was at the cross-roads of several disciplines and biology. While, the method development happened at the Physics department, the impact translation happened mostly in biology, pharmacy, and fishery sciences. Several PhD/post-doc performed research with close cooperation with different departments/faculties.

3. References to the research (indicative maximum of six references)
This section should provide references to key outputs from the research described in the previous section, and evidence about the quality of the research. All forms of output cited as underpinning research will be considered equitably, with no distinction being made between the types of output referenced. Include the following details for each cited output:

1.
- Author(s): Robin Diekmann, Øystein I Helle, Cristina I Øie, Peter McCourt, Thomas R Huser, Mark Schüttpelz, Balpreet S Ahluwalia
- Title: Chip-based wide field-of-view nanoscopy
- Year of publication: 2017
- Type of output and other relevant details required to identify the output (for example, DOI, journal title and issue): Nature Photon 11, 322–328 (2017) https://doi.org/10.1038/nphoton.2017.55
- Details to enable the panel to gain access to the output, if required (for example, a DOI or URL). https://www.nature.com/articles/nphoton.2017.55

2.
- Author(s): Øystein Ivar Helle, Firehun Tsige Dullo, Marcel Lahrberg, Jean-Claude Tinguely, Olav Gaute Hellesø, Balpreet Singh Ahluwalia
- Title: Structured illumination microscopy using a photonic chip
- Year of publication: 2020
- Type of output and other relevant details required to identify the output (for example, DOI, journal title and issue): Nat. Photonics 14, 431–438 (2020). https://doi.org/10.1038/s41566-020-0620-2
- Details to enable the panel to gain access to the output, if required (for example, a DOI or URL). https://www.nature.com/articles/s41566-020-0620-2

3.
- Author(s): Øystein I Helle, David A Coucheron, Jean-Claude Tinguely, Cristina I Øie, Balpreet S Ahluwalia
- Title: Nanoscopy on-a-chip: super-resolution imaging on the millimeter scale
- Year of publication: 2019
- Type of output and other relevant details required to identify the output (for example, DOI, journal title and issue): Opt. Express 27, 6700-6710 (2019) https://doi.org/10.1364/OE.27.006700
- Details to enable the panel to gain access to the output, if required (for example, a DOI or URL). https://opg.optica.org/oe/fulltext.cfm?uri=oe-27-5-6700&id=405944

4.
- Author(s): Luis E Villegas-Hernández, Vishesh Dubey, Mona Nystad, Jean-Claude Tinguely, David A Coucheron, Firehun T Dullo, Anish Priyadarshi, Sebastian Acuña, Azeem Ahmad, José M Mateos, Gery Barmettler, Urs Ziegler, Åsa Birna Birgisdottir, Aud-Malin Karlsson Hovd, Kristin Andreassen Fenton, Ganesh Acharya, Krishna Agarwal, Balpreet Singh Ahluwalia

 Title: [Chip-based multimodal super-resolution microscopy for histological investigations of cryopreserved tissue sections]
 Year of publication: 2022
 Type of output and other relevant details required to identify the output (for example, DOI, journal title and issue): *Light Science and Application* **11**, 43 (2022).
https://doi.org/10.1038/s41377-022-00731-w

 Details to enable the panel to gain access to the output, if required (for example, a DOI or URL). https://www.nature.com/articles/s41377-022-00731-w

5.
 Author(s): Ida S Opstad, Florian Ströhl, Marcus Fantham, Colin Hockings, Oliver Vanderpoorten, Francesca W van Tartwijk, Julie Qiaojin Lin, Jean-Claude Tinguely, Firehun T Dullo, Gabriele S Kaminski-Schierle, Balpreet S Ahluwalia, Clemens F Kaminski
 Title: A waveguide imaging platform for live-cell TIRF imaging of neurons over large fields of view
 Year of publication: 2020
 Type of output and other relevant details required to identify the output (for example, DOI, journal title and issue): Journal of Biophotonics
https://doi.org/10.1002/jbio.201960222
 Details to enable the panel to gain access to the output, if required (for example, a DOI or URL). https://onlinelibrary.wiley.com/doi/full/10.1002/jbio.201960222

6.

 Author(s): Ankit Butola, David A Coucheron, Karolina Szafranska, Azeem Ahmad, Hong Mao, Jean-Claude Tinguely, Peter McCourt, Paramasivam Senthilkumaran, Dalip Singh Mehta, Krishna Agarwal, Balpreet Singh Ahluwalia
 Title: Multimodal on-chip nanoscopy and quantitative phase imaging reveals the nanoscale morphology of liver sinusoidal endothelial cells
 Year of publication: 2021
 Type of output and other relevant details required to identify the output (for example, DOI, journal title and issue): Proceedings of the National Academy of Sciences
https://doi.org/10.1073/pnas.2115323118
 Details to enable the panel to gain access to the output, if required (for example, a DOI or URL). https://www.pnas.org/doi/abs/10.1073/pnas.2115323118

4. Details of the impact (indicative maximum 750 words)
This section should provide a narrative, with supporting evidence, to explain:

On-chip nanoscopy was invented at UiT (Ahluwalia's lab)[1] and t**wo patent families[1]** covering the inventions of different on-chip nanoscopy methods were submitted in 2017 and 2018. Owing to high exploitation and commercial value of the invention, the innovation route was promptly opted. It resulted in **pre-commercialization projects**, Research Council of Norway (RCN) funded **Forny**, **BioTek** and **two ERC** PoC projects[3]. An important learning from these projects was that photonic chips are outside the core competence of existing microscopy companies. Chip-based nanoscopy is a new imaging platform. Consequently, the route to market requires active support on photonic-chip and prototype, via a spin-off. Thus, an important the spin-off, **Chip NanoImaging (CNI) AS[4]** was established in Oct-2019, with the aim to commercialize chip-based nanoscopy technology.

Chip Nanoimaging (CNI) AS created 5 high-tech job opportunities in Northern Norway and will be hiring 2-5 people during next 1-3 years of time-frame. The Chip NanoImaging was nominated by **Technoport** as one of ***Norway's Top 10 DeepTech Start-ups of 202****1* and was the **winner** of the event based on audience vote. The Chip NanoImaging also won best Investor-Pitch during

Norinnovas ScaleUp IX program in 2022. Chip NanoImaging AS is hosting a large European Union, EIC-Transition[5] project, a program that supports radical technologies that has potential to bring breakthrough products in the market.

Chip NanoImaging has been mentioned as an example of a company that transforms high end research into business using ERC and EIC programs:
"*How frontier science becomes a commercial prospect: Chip NanoImaging use ERC and EIC grants as stepping stones to transform ideas into market ready, low cost nanoscopy technology. This could be a gamechanger for researching viruses and cancers*."

This is quoted from the blog post "Groundbreaking EU research programme creates ecosystems for new business" by UKRO's Sean Rowlands [6].

Penetration of technology in different market segments:

- **Life science:** Both primary & cell lines have been validated, e.g. HeLa, kerotonocytes, neurons-cells, U2OS cells, etc.
- **Dissemination to 3 hospitals:** 1. UNN hospital, Tromsø Norway, 2. Radiumhospitalet Oslo, Norway and Karolinska University Hospital, Stockholm, Sweden for Tissue sections/Histopathology samples: human colon cancer, Kidney & liver from mouse, and heart tissue sections from pig, human placenta samples from **Karolinska Institutet (KI)**, Sweden.
- **Infection Biology**: Benchmarked the utility of on-chip nanoscopy for super-resolution imaging of single isolated particles, such as SARs-Cov2-19, HiV and bacterias (EColi)

The impact of chip-based nanoscopy on the scientific community and society has been already widely recognized: the research outcome has been published in more than 20+ journal articles and attracted 25+ invited talks, seminars/ workshops; on-chip nanoscopy was highlighted as **one of the four ERC projects** identified by the EU **"spot-light ERC projects**" identified for "**fight against Covid-19**", during EU Research & Innovation Days 2020, after our efforts to image individual SARS-Cov2-19 virus[9].

5. Sources to corroborate the impact (indicative maximum of ten references)

1. https://www.youtube.com/watch?v=_ImDp7FPty4&t=5s
2. USA Patents: US10983326B2 and US11454791B2
3. https://site.uit.no/nanoscopy/funding/
4. www.chipnano.com
5. https://nanovision-eic.eu/
6. https://www.ukri.org/blog/groundbreaking-eu-research-programme-creates-ecosystems-for-new-business/
7. https://scholar.google.no/citations?user=aeIyzeMAAAAJ&hl=en
8. https://erc.europa.eu/sites/default/files/document/file/COVID19-Frontier_research_in_the-spotlight.pdf
9. https://www.biorxiv.org/content/10.1101/2020.09.04.283085v1.abstract

UNIS 1

Institution: University Centre in Svalbard - UNIS
Administrative unit: UNIS
Title of case study: From CCS to Geothermal energy in the Arctic
Period when the underpinning research was undertaken: 2007- to date
Period when staff involved in the underpinning research were employed by the submitting institution: 2007 – to date
Period when the impact occurred: 2011 – to date

1. Summary of the impact

The aim of the research at Longyearbyen CO_2 Lab was to investigate the possibilities of carbon catchment and storage. The community's district heating system, powered by Norway's only coal fuelled power plant was the targeted energy source. The original objective was to demonstrate the full CCS value chain. Now that coal is phased out, this research work has formed the basis for designing the planned geothermal heating of the town, serving the Green strategy for the local community.

2. Underpinning research

All settlements in Svalbard, including the capital of Longyearbyen (population 2400), currently have isolated energy systems with coal or diesel as the main energy source. The Longyearbyen CO_2 project was initiated by UNIS in February 2007, following an article in the local community paper Svalbardposten by UNIS-director Gunnar Sand and professor Alvar Braathen, about turning the town's main polluter, the coal-fuelled power plant, into a show case for carbon capture and storage (CCS). The captured CO_2, they proposed, could be stored in subsurface aquifers. Over a six-year period the Longyearbyen CO_2 Lab drilled eight wells. As all drill holes were fully cored, the project collected more than four kilometres of drill core, covering a succession from the frozen but otherwise unconsolidated overburden (cored in drill hole 8) to the Lower Cretaceous succession (seven drill holes), through Jurassic shales of the caprock (five wells), and into the storage unit sandstones of Early Jurassic to Late Triassic age (four wells), with the deepest well reaching a maximum depth of 970 m. With access to these unique datasets, more than 30 researchers from universities, research institutes and private companies have contributed to the efforts. The results have caused substantial attention within both academic and industrial communities as well as in the public domain.
http://co2-ccs.unis.no/LongyearbyenCO2-Project%20development.html

Following the governmental decision of phasing out coal mining and subsequently the coal fired powerplant, this wealth of data have formed the basis for evaluating the potential for geothermal based heating. The until now fragmented data sets relevant to characterize and assess the geothermal potential of Svalbard were compiled. The four research boreholes were fully cored and analysed for thermal conductivity. Geothermal gradients on Spitsbergen vary from 24°C/km in the west to 55°C/km in the south-east, with an average of 33°C/km. These analyses were complemented by thermal conductivity calculated from wireline logs in selected boreholes and four measurements on outcrop samples. 1D heat flow modelling on four boreholes calibrated with the measured thermal conductivities offers insights into heat transfer through the heterogeneous largely sedimentary succession. Svalbard's geology is well suited for geothermal exploration and potential production, though challenges related to permafrost, the presence of natural gas, heterogeneous reservoir quality and strongly lateral varying heat flow need to be adequately addressed prior to geothermal energy production.

2007 – 2013 Alvar Braathen, Professor, Department leader Arctic Geology, UNIS
2010 – present Snorre Olaussen, Emeritus Professor Arctic Petroleum Geology, UNIS
2010 – present Kim Senger, Associate Professor, Structural geology and basin analysis, UNIS

And many more as stated on the website:
http://co2-ccs.unis.no/Partners-id.html

3. Selected references to the research

1. Braathen, A., Bælum, K., Christiansen, H. H., Dahl, T., Eiken, O., Elvebakk, H., ... & Rød, K. (2012). The Longyearbyen CO 2 Lab of Svalbard, Norway—initial assessment of the geological conditions for CO 2 sequestration. Norwegian Journal of Geology/Norsk Geologisk Forening, 92(4).
2. Senger, K., Tveranger, J., Braathen, A., Olaussen, S., Ogata, K., & Larsen, L. (2015). CO2 storage resource estimates in unconventional reservoirs: insights from a pilot-sized storage site in Svalbard, Arctic Norway. Environmental Earth Sciences, 73(8), 3987-4009.
3. Van Stappen, J. F., Meftah, R., Boone, M. A., Bultreys, T., De Kock, T., Blykers, B. K., ... & Cnudde, V. (2018). In situ triaxial testing to determine fracture permeability and aperture distribution for CO2 sequestration in Svalbard, Norway. Environmental science & technology, 52(8), 4546-4554.
4. Olaussen, S., Senger, K., Braathen, A., Grundvåg, S. A., & Mørk, A. (2019). You learn as long as you drill; research synthesis from the Longyearbyen CO2 Laboratory, Svalbard, Norway. Norwegian Journal of Geology, 99(2), 157-187.
5. Senger, K., Brugmans, P., Grundvåg, S. A., Jochmann, M. M., Nøttvedt, A., Olaussen, S., ... & Smyrak-Sikora, A. (2019). Petroleum, coal and research drilling onshore Svalbard: a historical perspective. Norwegian Journal of Geology, 99(3), 1-30.
6. Senger, K. et al. (2023, manuscript submitted to Geothermics) The subsurface thermal state of Svalbard and implications for geothermal potential

4. Details of the impact

The data acquired through the CO_2 Lab project have formed the basis for a feasibility study on geothermal energy by Store Norske Spitsbergen Kulkompani (SNSK) funded by ENOVA. At present the energy demand in Longyearbyen is 70 GWh thermal energy and 40 GWh electrical energy. The CO_2 emission from the coal-based power plant is 75 kiloton/year. The previous research has shown a sufficient temperature gradient to be able to use 1000-2000 m deep wells to supply the thermal energy demand. The potential for heating the new Svalbard Folkehøyskole building with geothermal wells was investigated as the first user case. This work supports the local Longyearbyen community in the transition to sustainable energy systems. These studies are presently an important contribution to the energy plan for Longyearbyen that is prepared by the local authorities (Longyearbyen Community Council).
In 2022, UNIS, SNSK and Longyearbyen Community Council signed an agreement to further develop the energy transition for Longyearbyen. In addition to its competence in geothermal energy, UNIS has appointed a professor and PhD candidates to further explore the potential for wind and solar power to be able to develop a reliable energy system based on an optimal energy mix. The knowledge-based innovation potential will be released by adapting and certifying existing energy technology to function in the high-Arctic, with a strict demand to ensure preservation of the vulnerable natural environment.
The aim is to supply the people living in the Longyearbyen settlement with 100% renewable within 10 years. Deep geothermal energy may prove to be the key to achieve this goal.The full impact of the research carried out as part of the CO_2 Lab will first be visible when the energy transition has been completed over the period 2023-2033.

5. Sources to corroborate the impact

SNSK, 2022. Utvikling av termisk energiforsyning på Svalbard basert på dype energibrønner. Enova konseptutredning, prosjektnummer 21-957.
https://www.snsk.no/energi/utviklingsprosjekter

https://www.lokalstyre.no/om-energiomstillingen.582567.no.html

https://geoforskning.no/vil-utbygge-geotermisk-energi-etappevis/

https://www.svalbardposten.no/energiomstilling-longyearbyen-lokalstyre-store-norske/sammen-kan-vi-na-bygge-en-helt-ny-kompetanse/495481

https://www.snsk.no/nyheter/8052/ll-unis-og-store-norske-skal-samarbeide-om-fornybar-energi

https://www.lokalstyre.no/longyearbyen-lokalstyre-unis-og-store-norske-skal-samarbeide-om-fornybar-energi-i-longyearbyen.6568798-321755.html

UNIS 2

Institution: University Centre in Svalbard - UNIS
Administrative unit: UNIS
Title of case study: Arctic Safety Centre
Period when the underpinning research was undertaken: 2016 – to date
Period when staff involved in the underpinning research were employed by the submitting institution: 2004 – to date
Period when the impact occurred: 2015 – to date

1. Summary of the impact

UNIS research on natural hazards and specifically snow avalanches has formed the basis for establishing the Arctic Safety Centre that offers:
- a semester package of 30 ECTS in Arctic safety courses for master and PhD students
- practical safety courses for local businesses and public authorities
- avalanche forecasting services for the local community and Governor of Svalbard
- technology development of early warning based on IoT snow sensors

2. Underpinning research

Understanding and adapting to climate change is one of the greatest ongoing societal challenges on Svalbard. Svalbard has an extensive snow avalanche problem ("snow avalanche" is referred to as "avalanches" from this point on). Avalanches pose a threat to roads, ski lift, snowmobile tracks, airport, infrastructure, and buildings, including houses, apartment buildings, schools, hotels, and restaurants. Avalanche risk is inherent to field-based activities such as backcountry skiing, snowmobiling, and dog sledging. Researchers, students, and travel operators have to consider avalanche risk when planning and conducting field-based activities. Most avalanches are dry slab avalanches, but also loose snow avalanches, wet snow avalanches, slush avalanches and cornice falls are common. Large areas with loose dry snow in combination with strong winds often create significant snowdrift. Thus, wind slabs are a common avalanche problem in Svalbard. Another common avalanche problem is the presence of persistent weak layers often develop in the snowpack due to cold and dry winters with a thin snow cover with a large vertical temperature gradient. This avalanche problem is overrepresented in fatal accidents in Svalbard. However, also warm spells and rain occur during winter and wets the snowpack. Thus, wet slabs, wet loose and slush avalanches are avalanche problems to be aware of, despite the high latitude. Eckerstorfer and Christiansen (2011) described the avalanche situation in Svalbard and the Longyearbyen area in more detail. This knowledge was further developed by Hancock in close collaboration with the department of operations and field safety. This lead funding by the ministry of foreign affairs to establish a centre for Arctic safety at UNIS (2017-2019).
The Arctic safety centre was established in 2020 and was further supported by the ARCT-RISK project (2021-2024), which is focussed on the key role the Arctic plays in understanding and mitigating the challenge of climate adaptation, as the climate already is changing more rapidly in these regions than anywhere else in the world. This means successful risk governance strategies developed in response to destabilized climate conditions in Arctic locations serves as important experiences for future climate change adaptation in mainland Norway and other relevant parts of the world. Longyearbyen, Svalbard is used as a "living lab" to study and develop approaches to risk governance that will reduce systemic risks (i.e. risks related to a combination of climate change, natural hazards and rippling effects on citizens, infrastructure and societal functions).
To achieve the project's objectives a transdisciplinary approach involving perspectives from technology, safety science, natural science and social science is applied. The project team consists of experts from the Norwegian University of Science and Technology, the University Centre in Svalbard, NTNU Social Research, SINTEF and the University of Stavanger

2004 – present Hanne H. Christiansen, Professor Arctic Geology/Geophysics, UNIS
2005 – 2015 Jan Otto Larsen, associate Professor Arctic Technology, UNIS
2009 – 2018 Markus Eckerstorfer, Researcher Arctic Geology, UNIS
2014 – 2019 Christopher Borstad, Professor Arctic Geophysics, UNIS
Arctic Safety Centre:
1998 – present Fred Skancke Hansen, Director HSE and infrastructure, UNIS
2009 – present Martin Indreiten, Leader Arctic Safety Centre, UNIS
2016 – present Holt Hancock, Researcher, Arctic Geology and Arctic Safety Centre, UNIS
2016 – present Siiri Wickström, post-doctoral Researcher, Arctic Geophysics and ASC, UNIS
2018 – present Eirik Albrechtsen, adjunct Professor, Arctic Safety Centre, UNIS and NTNU
2018 – present Bjørn Ivar Kruke, adjunct Professor, Arctic Safety Centre, UNIS and UiS
2018 – present Abbas Barabadi, adjunct Professor, Arctic Safety Centre, UNIS and UiT

3. Selected references to the research

1. Eckerstorfer, M., & Christiansen, H. H. (2011). Topographical and meteorological control on snow avalanching in the Longyearbyen area, central Svalbard 2006–2009. Geomorphology, 134(3-4), 186-196.
2. Indreiten, M., & Svarstad, C. (2016). The Longyearbyen fatal avalanche accident 19th December 2015, Svalbard: Lessons learned from avalanche rescue inside a settlement. In Proceedings of the international snow science workshop (pp. 356-362).
3. Hancock, H., Prokop, A., Eckerstorfer, M., & Hendrikx, J. (2018). Combining high spatial resolution snow mapping and meteorological analyses to improve forecasting of destructive avalanches in Longyearbyen, Svalbard. Cold Regions Science and Technology, 154, 120-132.
4. Hancock, H., Eckerstorfer, M., Prokop, A., & Hendrikx, J. (2020). Quantifying seasonal cornice dynamics using a terrestrial laser scanner in Svalbard, Norway. Natural Hazards and Earth System Sciences, 20(2), 603-623.
5. Wickström, S., Jonassen, M. O., Cassano, J. J., & Vihma, T. (2020). Present temperature, precipitation, and rain-on-snow climate in Svalbard. Journal of Geophysical Research: Atmospheres, 125(14).
6. Hancock, H., Hendrikx, J., Eckerstorfer, M., & Wickström, S. (2021). Synoptic control on snow avalanche activity in central Spitsbergen. The Cryosphere, 15(8), 3813-3837.

4. Details of the impact

Svalbard has an extensive avalanche problem and seven people died in avalanches from 2000 to 2018. To mitigate the problem, the Norwegian Avalanche Warning Service included public avalanche warnings for Svalbard on Varsom.no in February 2016. To assist evacuations by local authorities, local warnings for Longyearbyen were started as a temporary measure days after the fatal accident in December 2015, when an avalanche hit ten buildings. NVE and UNIS launched a public avalanche warning service for Svalbard in February 2016, after a 17-days test period in April/May 2015. The Arctic Safety Centre at UNIS carried out the field observations and NVE the forecasting. Since then, public warnings are published daily for the region Nordenskiöld Land (Svalbard) from the beginning of December to the end of May, based on 2-3 observations weekly. The primary objective of the Arctic Safety Centre is to develop knowledge and tools to make sense of and deal with effects of climate change on society's ability to protect the life and health of its citizens and to maintain critical infrastructure and function.
In collaboration with the AT department at UNIS, the centre offers three MSc courses in Arctic Safety forming a semester package of 30 ECTS for master and PhD students. A course in Arctic Safety and Preparedness was arranged in collaboration with NTNU-Videre. The course received great interest in the local community, and the 25 study places were a hundred percent oversubscribed. The course had participants from local business, administration, emergency preparedness actors and internal participation from UNIS and will be offered regularly.
The centre coordinates the local snow observation group, which provides weekly snow observations for the local avalanche warning system in Longyearbyen. The service is delivered

to the Longyearbyen Community Council and is a key source of information for the avalanche warning system which is used to protect people and infrastructure in Longyearbyen.
The centre has worked closely with Telenor Svalbard on the development of snow sensors in the last couple of years. The sensor technology uses IoT technology (Internet of Things) to send snow depth measurements in real time. These provide supplementary information about the snow cover that is used in the local avalanche warning system.

In 2020, a three-year project was started with Nordkapp municipality in mainland Norway. The project is based on the experiences from Longyearbyen and the same type of technology and sensors will be used in a local avalanche warning system for exposed infrastructure in Nordkapp.

The Arctic Safety Centre takes a lead in developing safety measures against climate driven natural hazards. ASC ensures documentation of risks using story telling skills within the Longyearbyen society, and systematically develops procedures and training courses to avoid accidents. This is highly valued by the local authorities and companies.

Climate driven natural hazards are a global challenge amplified in the Arctic. The ongoing ARCT-RISK project receives great international attention, which indicates that Longyearbyen has the potential to become a "climate adaption laboratory”. This is in line with UNIS´ Green strategy (https://www.unis.no/about/strategy-and-plans/green-strategy/). ASC is the main tool for UNIS to ensure safety for people and the natural environment in Svalbard. Practical and theoretical competence on Arctic safety has a great societal impact through our students that bring this knowledge out into the world (about 800 individual students from more that 40 countries attend courses at UNIS yearly).

5. Sources to corroborate the impact

Engeset, R. V., Landrø, M., Indreiten, M., Müller, K., Mikkelsen, O. A., & Hoseth, K. I. (2020). Avalanche warning in Svalbard. NVE Rapport;35/2020, Norwegian Water Resources and Energy Directorate Oslo, Norway
https://publikasjoner.nve.no/rapport/2020/rapport2020_35.pdf

https://www.unis.no/project/arct-risk/
https://www.ntnu.edu/iot/arct-risk

https://www.lokalstyre.no/folkemoete-om-skredvarsling-og-skredsikring.6573558-321755.html

[DeptChemistry] [1]

Institution: University of Bergen	
Administrative unit: Department of Chemistry	
Title of case study: Investigations of intermediates and byproducts formed in industrial production of iohexol	
Period when the underpinning research was undertaken: 2010 - 2022	
Period when staff involved in the underpinning research were employed by the submitting institution: 1993 - present	
Period when the impact occurred: 2012 - 2021	

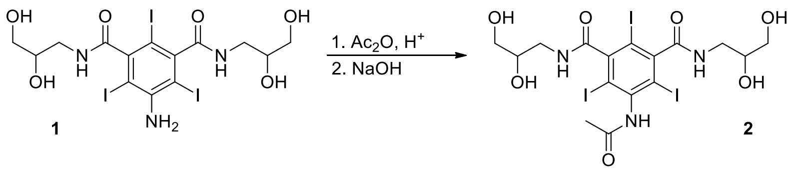
1. Summary of the impact

By isolating and structure elucidating the main byproducts formed in the industrial production of iohexol, several steps in the process could be optimized so that the byproduct yields were significantly reduced. This paved the way for the development of improved and more cost-effective work-up procedures, which ultimately gave purer iohexol in higher yield. As part of the project, it was also studied if it would be possible to replace a batch synthesis with a flow process. This research has given insight that has been valuable in the development of a continuous process for iohexol.

2. Underpinning research

Process development has always been in focus in the chemical industry. Many aspects are considered in such an endeavor, but two issues are particularly important, chemical yield and by-product formation. Overall, the best way to improve a chemical process is by reducing the latter. Lower levels of impurities may not only pave the way for more efficient purification; it may even be possible to skip a purification step and significantly reduce production costs.

With this as a backdrop, GE HealthCare planned to study in detail the multistep process leading to iohexol, the active ingredient in the X-ray contrast agent Omnipaque, with the aim of reducing the level of impurities formed in each step and thereby improve the process. To achieve this, the strategy would be to isolate as many by-products as possible, determine their structures, and study their chemical. The first step to investigate would be the acetylation of aniline derivative 5-amino-*N*,*N'*-bis(2,3-dihydroxypropyl)-2,4,6-triiodoisophthalamide (**1**) to prepare acetamide 5-acetamido-*N*,*N'*-bis(2,3-dihydroxypropyl)-2,4,6-triiodoisophthalamide (**2**); the second would be the preparation of **1** by iodination of its corresponding iodine-free aniline.



1 **2**

The implementation of the plan was facilitated by the Industrial PhD program launched by Research Council of Norway in 2008. GE HealthCare Lindesnes approached Professor Leiv K. Sydnes at Department of Chemistry, University of Bergen and asked if he was willing to be PhD supervisor for GE researcher Torfinn Håland under the Industrial PhD program. He accepted, and a PhD project was started in 2010. The study was planned to take four years instead of three so that Håland could keep a 25% position at company to keep contact with his colleagues and update them on the progress made.

Industrial PhD projects are by nature somewhat different from a classical university PhD project. An important difference is the secrecy to secure that useful discoveries can give the company a competitive advantage. That was secured through agreements in place before the project involving Håland started; in fact they are still in place.

The starting point for Håland's project was the discovery that the crude product from the preparation of **2** from **1** contained fair amounts of several unknown impurities. During his PhD study, the main impurities were isolated and structure elucidated, and subsequent mechanistic studies revealed how they were formed. Håland defended his PhD thesis in 2014.

Another PhD project started with GE researcher Ingrid S. Skinnarland in 2016. She studied the preparation of **1** by iodination of the corresponding iodine-free aniline following the approach developed by Håland. She also studied the possibility of performing the reaction in a flow system to speed up the reaction and get a cleaner product. She kept a 25% position as researcher at GE throughout the study. She defended her thesis in 2022 (delays due to maternity leaves and COVID).

Professor/Professor Emeritus (from 2018) Leiv K. Sydnes was in charge for both projects at Department of Chemistry. He also interacted with other researchers at GE throughout.

Håland and Skinnarland carried out research at University of Bergen, GE HealthCare Lindesnes, and GE HealthCare Storo.

3. References to the research

1. Torfinn Håland and **Leiv K. Sydnes,** Formation of *N,O*-Acetals in the Production of X-ray Contrast Agents, *Organic Process Research & Development* **2014**, *18*, 1181-1190.

2. Torfinn Håland, Formation of impurities in an industrial process – structure elucidation and mechanistic studies, *PhD Thesis*, University of Bergen, **2014**, 223 pages

3. HAALAND, TORFINN; PREPARATION OF INTERMEDIATES OF X-RAY CONTRAST AGENTS, *Canadian Patent 2 881 707*, PCT Publication Date: 2014/05/15, Issue Date: 2021/01/12; WIPO I PCT; WO 2014/074315 Al, 15 May 2014 (15.05.2014); 20 pages.

4. Torfinn HAALAND; **Arne ASKILDSEN**; **Rita Heskestad KALLEBERG**; **Sumihar SILALAHI**; **Alf Martin FARBROT**; **Inger Dagny SAANUM**, *ALTERNATIVE PROCESS FOR THE PURIFICATION OF AN INTERMEDIATE IN THE SYNTHESIS OF NON-IONIC X-RAY CONTRAST AGENTS,* US 2016/0289174 A1; Oct. 6, **2016**; 9 pages.

5. Inger Dagny Saanum; Torfinn Haaland; Rita Heskestad Kalleberg, *ALTERNATIVE* ACETYLATION PROCESS IN THE SYNTHESIS OF NON-IONIC X-RAY CONTRAST AGENTS, US 2016/0304438; Pub. Date: Oct. 20, **2016**, 5 pages.

6. Ingrid Schiager Skinnarland, Investigations of intermediates and byproducts formed in an industrial process – structure elucidation and mechanistic studies, *PhD Thesis*, University of Bergen, **2022**, 306 pages.

4. Details of the impact

The impact of the scientific collaboration between GE HealthCare Lindesnes and Department of Chemistry grew gradually from 2010 and can be regarded at least as fourfold.

1. Results from the PhD thesis of Håland became the basis for further studies of the process at GE, and this resulted in four patents.
2. On the basis of these patents and other studies performed by Håland in collaboration with colleagues at GE, a new process for the production of iohexol was developed. After due approval by the regulatory authorities, the new process was successfully implemented on an industrial scale a few years ago. As a result, the unit cost of iohexol was reduced significantly. This has contributed to strengthen the position to the Lindesnes site relative to competitors around the world, and to secure that GE Healthcare continues to invest in the Lindesnes facility for increasing the production capacity.
3. Due to increased production volumes at GE HealthCare Lindesnes, the company became interested in exploring the possibility of switching (in part) to a continuous process for the preparation of iohexol. Some aspects of this process-chemical challenge were studied in the PhD project of Skinnarland, and a significant body of her results gave valuable guidance "in the endeavors for developing a continuous process". In this context, GE HealthCare Lindesnes has stated as follows:
4. The collaboration also generated several analogy studies, which were carried out by several Master student in the Sydnes research group.

In this context, the following quotes from the attached statements from GE HealthCare Lindesnes (see below) are highly relevant:

"The collaboration with the Department of Chemistry, represented by Professor Leiv K Sydnes, at University of Bergen during the last decades has contributed to strengthening the competetiveness of the Lindesnes Site. In the last 10-15 years, the collaboration has been closer and more extensive, and two PhDs have been produced in that period. In addition to improving the manufacturing process, the work has also increased the level of competence within the organization. This is essential for staying in business when competing in a global market."

"The competitiveness the collaboration described above has contributed to is part of the basis for GE HealthCare's recent announcement of an $80 million investment to increase manufacturing capacity by 30 percent at its Active Pharmaceutical Ingredient s (API) site in Lindesnes, Norway. The investment - which is creating around 100 new jobs – is part of GE HealthCare's broader commitment to address significant future global demand for iodinated contrast media."

"In conclusion, the general knowledge and the high competence at the Department of Chemistry at the university of Bergen have been very valuable in the collaboration in the collaboration with GE HealthCare. Even though the area of contrast agents is not a specific field of expertise at the Department, the in-depth chemistry expertise has contributed to better understanding of chemical processes at the Lindesnes Site. The Department has also contributed to higher competence within the Lindesnes organization."

It should also be mentioned that the department's sophisticated NMR and MS equipment, which is run and looked after by highly competent staff, played an instrumental role in the successful structure elucidation of all the products synthesized and isolated.

Beneficiaries
As the quotes above and the attached letter below show, GE HealthCare benefitted significantly from the collaboration. However, in this context the importance of the Industrial PhD program and Research Council of Norway (RCN) should not be underestimated. Without this funding scheme for researchers in industry, it is not obvious that the research project that were funded by RCN, would have been carried out as quickly and efficiently as they were.

As for the Department of Chemistry, it was regarded as a benefit to experience that knowledge and competence generated through decades turn out to be highly relevant in the chemical industry. This indeed contributes to fulfil the university's obligation to serve society.

5. Sources to corroborate the impact
Letter dated January 12, 2023, signed by lead scientist Dr Torfinn Håland, and innovation and development leader Erlend S. Fævelen, both of GE Healthcare AS, Lindesnes Site.

GE Healthcare AS

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12. January 2023

Collaboration GE HealthCare and University of Bergen

GE HealthCare AS is Norway's largest pharmaceutical company with approximately 1,000 employees, evenly distributed between the production facilities at Lindesnes and in Oslo. GE HealthCare AS has an annual revenue of ~$1 billion and contributes to 2% of the mainland exports. GE HealthCare delivers contrast media to X-ray, MR, and molecular imaging, and is the world's largest producer of X-ray contrast agents, and also has extensive activity within Research and Development.

The Lindesnes Site was established in 1974, and the contrast agents iohexol and iodixanol have been produced since 1982 and 1990, respectively. The incredible success and adventurous journey until now had not been possible without focus on continuous improvements and substantial R&D activity. The Lindesnes site, being a manufacturing site, has a local R&D department, ensuring close collaboration with operations and industrially focused development. This R&D department was established in the early 1980s and today (2023) holds 19 scientists.

Collaboration with universities and research institutes became important few years later, and one example of this is the Department of Chemistry at the University of Bergen, represented by Professor Leiv K. Sydnes. During many years, the collaboration with Professor Sydnes on several projects has led to better understanding of the chemistry, which is of high importance given the complexity and importance of the chemistry involved in the manufacturing processes.

The industrial PhD program was started in Norway by the Research Council of Norway in 2008, and this led to a closer and more extensive collaboration between GE HealthCare Lindesnes and Professor Sydnes from the Department of Chemistry at the University of Bergen. An industrial PhD project was started in 2010 with title “Formation of impurities in an industrial process – structure elucidation and mechanistic studies.” Leading up to the industrial PhD, several unknown impurities at that time were discovered in the process solution prior to the purification steps in the production of one of the intermediates in the iohexol process

Therefore, structure elucidation of these followed by mechanistic studies of how they are formed could potentially lead to a substantially improved understanding of the production process, facilitating process improvements. Both the enhanced understanding and implemented process improvements were achieved as a direct result of the industrial PhD project. The work led to several process patents and a scientific paper. Following the completion of the PhD, the knowledge obtained led to inventing a new and improved synthesis, reducing the formation of the investigated impurities significantly.

As X-ray contrast agents are considered as medicinal products, the manufacturing processes have to be performed in accordance with guidelines and regulations registered and approved by regulatory authorities. There are therefore many limitations for how the processes can be performed, for instance reaction temperatures, crystallization temperatures, concentrations, types and amounts of reagents, catalysts, and solvents. If it is desirable to make changes in a process that require a new regulatory approval, it will normally take several years before such approval is provided.

The invention above had to be approved by regulatory authorities, and therefore it took several years before it could be implemented on industrial scale. This was successful and strengthened the competitiveness to the Lindesnes Site.

Pharmaceuticals and fine chemicals are traditionally manufactured in batch mode. With increasing production volumes, continuous manufacturing is becoming more relevant. This transfer can be challenging but has many potential benefits worth evaluating. Some years ago, it was started a project aiming for transferring a complex industrial batch synthesis to a flow process. This project was supported by a new industrial PhD project that was started in collaboration with Professor Sydnes from the Department of Chemistry at the University of Bergen. The new knowledge generated from this work was very valuable for guidance in the challenges that arose in the endeavors for developing a continuous process. The PhD work also gave a deeper insight into the mechanisms involved in transferring the batch process to continuous mode.

The collaboration with the Department of Chemistry, represented by Professor Leiv K. Sydnes, at University of Bergen during the last decades has contributed to strengthening the competitiveness of the Lindesnes Site. In the last 10-15 years, the collaboration has been closer and more extensive, and two PhDs have been produced in that period. In addition to improving the manufacturing process, the work has also increased the level of competence within the organization. This is essential for staying in business when competing in a global market.

The competitiveness the collaboration described above has contributed to is part of the basis for GE HealthCare's recent announcement of an $80 million investment to increase manufacturing capacity by 30 percent at its Active Pharmaceutical Ingredients (API) site in Lindesnes, Norway. The investment – which is creating around 100 new jobs – is part of GE HealthCare's broader commitment to address significant future global demand for iodinated contrast media, used in X-ray and Computed Tomography (CT) procedures around the world to enhance visualization of organs, blood vessels and tissues across disease pathways.

President & CEO of GE HealthCare Pharmaceutical Diagnostics, Kevin O'Neill, said, "We expect global demand for iodinated contrast media to double in the next 10 years, driven by global prevalence of chronic disorders and significant growth in CT procedures. This investment in capacity expansion at the Lindesnes facility is another example of how we, as an industry leader, are addressing this growing demand to meet the needs of our customers and their patients across the globe."

In conclusion, the general knowledge and the high competence at the Department of Chemistry at the University of Bergen have been very valuable in the collaboration with GE HealthCare. Even though the area of contrast agents is not a specific field of expertise at the Department, the in-depth chemistry expertise has contributed to better understanding of the chemical processes at the Lindesnes Site. The Department has also contributed to higher competence within the Lindesnes organization.

Best regards

Torfinn Håland

Erlend Schön Fævelen

Torfinn Håland, PhD
Lead Scientist
GE Healthcare AS, Lindesnes Site

Erlend S. Fævelen
Innovation and Development Leader
GE Healthcare AS, Lindesnes Site

[DeptChemistry] [2]

Institution: University of Bergen
Administrative unit: Department of Chemistry
Title of case study: ArbaOne biorefinery development
Period when the underpinning research was undertaken: 2015-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2015-2021
Period when the impact occurred: 2016-2021

1. Summary of the impact (indicative maximum 100 words)

The work comprised identification and quantification of byproducts formed during steam explosion of lignocellulosic feedstocks. The compounds were initially evaluated in the context of reducing emissions into the environment from the process and HMS-evaluation. Based on the knowledge of amounts and types of molecules present, the major objective became to develop strategies for revovery and purification of bio-based chemicals from the aqueous side-streams in the ArbaOne biorefinery, where Arbacore black pelles are the major product..

2. Underpinning research (indicative maximum 500 words)

There is a longstanding cooperation between the research group and the company Arbaflame AS within research on the development of a wood-based biorefinery using a novel approach to maximise resource valorisation. Based on previous RCN-based biofuel cooperation, UiB and Arbaflame have worked since 2015 on developing fundamental understanding and technical solutions for extracting economically valuable biobased chemicals from the aqueous side-streams that are produced during steam explosion pretreatment (STEX) of wood chips. The process is used for production of black pellets that can substitute for coal in in power plants. The first RCN project was “Arba prosessutvikling” (2017-2018, RCN no 256381) which formalised previously directly funded research. The subsequent projects include ArbaHeat – Horizon 2020 (2019-2022); ArbaBioRef (2020-2023); ArbaFeed (2020-2024), Nærings-PhD (2021-2023) with a total funding for UiB of 6 .5 MNOK, where the projects have been initiated by Arbaflame with UiB as a research partner. The process development has resulted in a full-scale industrial plant, ArbaOne, at Grasmo in eastern Norway https://www.arbaflame.no/technology-1. The UiB participation is focussed on the identification and quantification of small organic molecules dissolved in the condensate and/or adsorbed on STEX-treated mass and on the brown pellets products, and the evaluation of their potential value. This includes evaluation of recovery option for furfural, together with technical industry consultants. The cooperation has financed postdoctoral researchers, and one ongoing industrial PhD. At present (2022), four papers in peer-reviewed journals have been published from the joint work, and several more are in progress.

The development of the NMR capabilities at UiB through the National NMR Ptatform (NNP) has been an important factor for establishing a novel methodology for the required analysis of small organic moleculs in aqueous solutions, e.g. formic and acetic acid, methanol, furfural and hydroxy-methyl-furfural (HMF).

The research is grounded in the organic analysis competence developed at the Department of Chemistry that has developed as a result of continuous activity in the geochemistry and natural compounds chemistry research groups in the late decades of the 1900s. This competence base was furter expanded into research on thermochemical conversion of fresh biomass. In-depth knowledge of natural biomass conversion in a organic geochemistry context provided a solid basis for developing methods for analysis and quantification of organic molecules in aqueous solution produced in steam explosion of wood chips and other lignocellulosic plant materials.

Researchers involved in the projects: Professor Tanja Barth (2011-2021)
Postdoctoral researcher Camilla Løhre (2016-2019)
Postdoctoral researcher Solmaz Ghoreishi (2019-2021)
NæringsPhD Dag Helge Hermundsgård (2020-2021)
Summer projects for Master’s students

3. References to the research (indicative maximum of six references)

Peer reviewed paper:
Løhre,C; Underhaug, J.; Brusletto, R.; Barth, T. (2021) A workup protocol combined with direct application of quantitative NMR-spectroscopy of aqueous samples from large-scale steam explosion of biomass. ACS Omega 2021, 6, 10, 6714-672
https://doi.org/10.1021/acsomega.0c05642

Peer reviewed presentations:
Solmaz Ghoreishi, Dag H. Hermundsgård, Camilla Løhre, Joakim Lindegaard Molnes, Tanja Barth (2021) Quantitative NMR analysis of the aqueous product streams from large pilot-scale steam explosion revealing high value-added platform chemicals. Presented at the 29th EUBCE (Marseille, digital conference) https://www.eubce.com/why-attend/29th-european-biomass-conference-exhibition/
Camilla Løhre, Tanja Barth, Rune Brusletto (2020) Side-stream effluent from large scale steam explosion at blackpellet plant revealing high furfural-content and added product value. Presented at the 29th EUBCE (Marseille, digital conference)
https://www.eubce.com/milestones/
Rune Brusletto, Gianluca Marcotullio, Mike Kleinert, Camilla Løhre, Tanja Barth (2019) Recovering furfural from the aqueous waste stream in ArbacoreTM brown pellets production. Presented at 27th EUBCE (Lisboa) https://www.eubce.com/milestones/

Reports:
Solmaz Ghoreishi, Camilla Løhre, Tanja Barth (2020) NMR analysis of effluents/condensates and filtrates from steam explosion and multivariate data analysis of the generation of furfural and some other valuable organic components: Yields and concentrations. Available upon request
Solmaz Ghoreishi, Camilla Løhre, Heidi Marina Hammer Mayhew, Tanja Barth (2020) Chemical analysis of condensate and pressed water from steam explosion of chlorine containing wood. Available upon request.
Camilla Løhre, Tanja Barth (2017) Distillation and total organic carbon measurement of condensates from steam explosion of wood chips. Available upon request.

4. Details of the impact (indicative maximum 750 words)
The major impact of the research was a shift of focus from considering the aqueous organic products as a problem in terms of HMS and pollution to the recognition that they comprise an added value as biobased renewable chemicals. This shift of persception came already in 2015-2016, and led to consideration of the aqueous side-stream as a resource for a biorefinery. In the full-scale ArbaOne plant which opened in 2021, the production of biobased chemicals play an important part in the overall economy. The identification and quantification of the chemical byproducts has been a necessary part of the overall development of Arbaflame from being a pellets producer to comprising a full-sale biorefinery.

5. Sources to corroborate the impact (indicative maximum of ten references)
Letter (enclosed) from CTO at Arbaflame AS, Rune Brusletto.

Arbaflame website: https://www.arbaflame.no/
Carbon transition: About Arbaflame: https://www.carbn.no/portfolio/arbaflame-as
Process Worldwide: Norway: Circular Economy Arbaflame Project to Produce 70'000 tons of Biomass Pellets Annually https://www.process-worldwide.com/arbaflame-project-to-produce-70000-tons-of-biomass-pellets-annually-a-1059795/
Bioenergy International: Arbaflame poised to start up ArbaOne
https://bioenergyinternational.com/arbaflame-poised-to-start-up-arbaone/

Oslo, 16. January 2022

To whom it may concern

Confirmation of the industry/research cooperation between Arbaflame and the Department of Chemistry, UiB

Arbaflam is pleased to confirm the importance and usefulness of the long-standing cooperation with UiB in the field of biorefinery development based on the steam explosion technology used in production of Arbacore pellets.

The cooperation has been important for identifying the biobased chemicals present in the condensed water from the steam explosion, and for developing the understanding of how these components could be exploited as additional biorefinery product – starting with furfural, which has a large commercial potential. The cooperation includes the initial analysis of condensates to determine their composition and investigations of how the feedstock for the process and the steam explosion conditions influence the amounts of chemicals available for recovery. The cooperation also includes chemical analytical support during establishment of the ArbaOne biorefinery, including setting up on-site analytical capacity for furfural determination in the process water using UV. Follow-up analysis in troubleshooting of process challenges have been part of the ongoing cooperation, e.g. the analysis of black solid particles formed in the process units and developing an understanding of the mechanisms behind the formation of such particles.

The cooperation has mainly been organised with a series of RCN projects initiated and owned by Arbaflame: Arba prosessutvikling, ArbaBioRaf, ArbaFeed, an industrial PhD (in part RCN funded) and the large European demonstration project Arbaheat. Arbaflame plans to continue the cooperation in the consortia that have been developed. Arbaflame does not have the capacity to establish advanced chemical laboratories within the company, so the flexible cooperation with well-equipped research groups at UiB and the research institutes (SINTEF, RISE-PFI) is very important for the biorefinery development over time.

Arbflame supports the academic publication of central results from the cooperation to encourage knowledge dissemination in this evolving industry sector.

Best regards

Rune Brusletto

Rune Brusletto

(cto)

[GEO] [1]

Institution: University of Bergen (UiB)	
Administrative unit: Department of Earth Science (GEO)	
Title of case study: Marine mineral resources and the associated environment	
Period when the underpinning research was undertaken: 2011-2021	
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-2021 (see page 2)	
Period when the impact occurred: 2017-2021	

1. Summary of the impact

The rising demand for metals in high-tech technology and the electrification of society has led to major interest in marine mineral resources world-wide. Norway has extensive deep-sea areas within its jurisdiction. The Centre for Geobiology (2007-2017) and the succeeding Centre for Deep Sea Research (2017-2026) has discovered, mapped, and investigated most of the hydrothermal sulphide deposits and hydrogenic manganese crusts that presently are known within the Norwegian Exclusive Economic Zone. As the only Norwegian research environment with multi- and interdisciplinary deep-sea competence the Centre's researchers have provided unique and comprehensive scientific knowledge and advises to the governmental effort to clarify the resource potential and environmental impact of potential mining of these resources.

2. Underpinning research

The interdisciplinary Centre for Geobiology (2007-2017) and the succeeding Centre for Deep Sea Research (2017-2026) have in the reporting period carried out an extensive deep-sea research program, with a particular focus on the Arctic Mid-Ocean Ridge (AMOR) in the Norwegian-Greenland Sea. The research has been based on access to a modern research vessel (G.O. Sars), and a national deep submergence facility (NORMAR) established by the Centre. The deep-sea research effort has also been founded on a range of analytical laboratories established and supported by this research activity.

In the last decade, our deep-sea research has spanned form marine geophysics and geology, via petrology and geochemistry to geomicrobiology and marine biology. Ship-based seafloor mapping and high-resolution seafloor mapping and imaging using novel technologies have resulted in understanding of the highly dynamic geology of the volcanic spreading ridge areas, including discovery of hot vent fields and seafloor massive sulphide (SMS) deposits. Oceanographic surveying of the water column above parts of the ridge system has provided quantitative data on hydrothermal fluxes, and the detection of hydrothermal plumes that has guided the search for vent fields at the seafloor. The vent fields that we have discovered, have been sampled to document geological and biological characteristics. Several of the vent fields have been used as natural laboratories, where a range of experiments and instruments have been deployed. Together this has resulted in understanding of water-rock-life interactions, and the diversity and metal content of hydrothermal mineral deposits, and the ecosystems associated with active vent fields and SMS deposits.

Extensive sampling of sediment cores along the ridge system followed by radiocarbon dating, has allowed accurate estimates of sedimentation rates, and helped us to establish a temporal frame of reference along the ridge axis. High-resolution seafloor mapping and sub-bottom profiling using autonomous underwater vehicles, have then provided detailed volcanological datasets, and quantitative knowledge about the age of the volcanic seafloor that is variably buried by sediments. This has given statistical data about the rate of volcanic activity and the renewal of the seafloor by volcanic eruptions. This knowledge has then become important for estimating the burial rate of SMS deposits, that is critical for resource estimates.

Manganese crusts represent a potential source for several critical elements. We discovered the first Mn-crust in the Norwegian-Greenland Sea more than two decades ago. In the reporting period we have mapped and sampled Mn-crust from many seamounts in both the Norwegian and the Greenland Sea. First, this was driven by our basic research interests and the opportunity to use the record of the thick Mn-crusts to understand changes in the ocean water composition through time. But, as the interest in deep sea mineral resources developed, the coverage and thickness of Mn-crust on seamounts of different ages, and how they can be detected and mapped using autonomous underwater vehicles, also became of interest and was included in the Centres´ research program.
Key centre researchers at the Department of Earth Science involved in this research the last decade (2012-2021): Rolf Birger Pedersen (Professor) Ingunn H. Thorseth (Professor) Sabina Strmic Palinkas (Adjunct Associate Professor 2019-) Steffen Leth Jørgensen (postdoctoral researcher 2017-2019, Associate Professor 2021-) Desiree Roerdink (postdoctoral researcher 2013-2017, Associate Professor 2017-) Eoghan Reeves (Associate professor 2015-) Filipa Marques (postdoctoral researcher, 2013-2018) Thibaut Barreyre (postdoctoral researcher 2017-) Benjamin Eickmann (postdoc 2009-2012) Tamara Baumberger (postdoc 2012-2015) Ingeborg Økland (PhD 2013, postdoc 2013-2016) Anne Stensland (PhD candidate 2013-2018) Karen Johannessen (PhD candidate 2013-2020) Alden Denny (PhD candidate 2013-) Anders Bjerga (PhD candidate 2017-) Håvard Stubseid (PhD candidate 2017-) Stian Rolfsen Gilje (PhD candidate 2018-) Solveig Onstad (PhD candidate 2018-)
3. References to the research Stubseid H, Bjerga A, Haflidason H, Pedersen RB (2021). Unveiling the volcanic evolution of the Mohns Ridge, EGU General Assembly 2021, 19–30 Apr 2021, EGU21-1050, https://doi.org/10.5194/egusphere-egu21-1050 (manuscript in revision for publication in Nature Communications). Marques AFA, Roerdink DL, Baumberger T, de Ronde CEJ, Ditchburn RG, Denny A, Thorseth IH, Okland I, Lilley MD, Whitehouse MJ, Pedersen RB (2020). The Seven Sisters Hydrothermal System: First Record of Shallow Hybrid Mineralization Hosted in Mafic Volcaniclasts on the Arctic Mid-Ocean Ridge. *Minerals*, 10: 439, doi:10.3390/min10050439. Stensland A, Baumberger T, Mork AK, Lilley M, Thorseth IH, Pedersen RB (2019). 3He along the ultraslow spreading AMOR in the Norwegian-Greenland Seas. *Deep-Sea Research Part I – Oceanographic research papers* 147: 1-11, doi.org/10.1016/j.dsr.2019.04.004. Johannessen K, Vender Roost J, Dahle H, Dundas SH, Pedersen RB, Thorseth IH (2017) Environmental controls on biomineralization and Fe-mound formation in a low-temperature hydrothermal system at the Jan Mayen vent Fields. Geochim. Cosmochim. Acta 202: 101-123, doi.org/10.1016/j.gca.2016.12.016. Baumberger T, Früh-Green GL, Thorseth IH, Lilley MD, Hamelin C, Bernasconi SM, Økland I, Pedersen RB (2016). Fluid composition of the sediment-influenced Loki's Castle vent field at the ultra-slow spreading Arctic Mid-Ocean Ridge. *Geochim. Cosmochim. Acta,* 187: 156-178, https://doi.org/10.1016/j.gca.2016.05.017

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Jørgensen SL, Hannisdal B, Lanzèn A, Baumberger T, Flesland K, Fonseca R, Øvreås L, Steen IH, Thorseth IH, Pedersen RB, Schleper C (2012). Correlating microbial community profiles with geochemical data in highly stratified sediments from the Arctic Mid-Ocean Ridge. *Proc. Natl. Acad. Sci*. U.S.A. (PNAS), doi710.1073/pnas.1207574109.

4. Details of the impact

The rising demand for metals in high-tech technology and the electrification of society has led to an interest in marine mineral resources world-wide. Norway has extensive deep-sea areas within its jurisdiction and the Ministry of Petroleum and Energy (MPE) has given the Norwegian Petroleum Directorate (NPD) the task to map the most commercially interesting mineral deposits on the Norwegian continental shelf. In 2019 a new law that regulate seabed mineral exploration under Norwegian jurisdiction (the Seabed Mineral Act) entered into force, and in 2020 the Norwegian government decided to initiate an opening process for mineral activities on the Norwegian continental shelf.

The discovery of hydrothermal vent fields and associated mineral deposits along the AMOR by the Centre were communicated by public media and at national and international meetings and conferences. This and the growing international focus on deep-sea mineral resources generated a public and commercial interest in the deep sea. We decided to follow a route to provide our science-based knowledge and expertise on deep sea resources and environmental issues to the government, companies, and the public.

As the only Norwegian research environment with multi- and interdisciplinary deep-sea competence, research experience and operational capacity, the Centre had a unique scientific knowledge base and expertise to support the governmental effort in clarifying the resource potential and environmental impact of potential mining of these resources. As a result, the NPD has collaborated closely with the GEO researchers at the Centre since 2017. First by supporting our strictly science driven research cruises. The funding gave increased capacity to carry out and gather important information on volcanic and hydrothermal activity, marine mineral deposits, and associated ecosystems. By this collaboration NPD built expertise by having their own researchers onboard to observe and learn. From 2019 and onwards we guided the planning and execution of the NPD surveys that have been based on the use of commercial survey companies. This has included two AUV-surveying cruises in 2019 and 2021, and a drilling cruise in 2020. The success of these cruises was largely based on our earlier findings that were used to direct the surveys to the most promising areas. Over the last two years the Centre has organized and executed cruises on ground truthing remote sensing findings from survey cruises. The cruise has been fully funded by NPD and has been based on the use of national research vessels and the services of our deep-sea submergence facility (NORMAR). The Centre has had the privileges to use the ship time for student training and collected data and material for our basic research program.

The Centre has also carried out most of the analytical work on samples collected under the NPD cruise, either in our own laboratories, or in commercial labs after sample preparations at UiB. The NPD has supported the Centre with funding for two PhD positions and almost 10 Master student projects.

The Centre has given numerous presentations and provided reports and material for ministries and directorates that are responsible for the marine environmental and resource management. We have also provided material to the Ministry of Climate and Environment and the Ministry of Petroleum and Energy for their notification to the Norwegian Parliament. Recently we visited the Parliament to inform politician about the resource potential and environmental issues of marine minerals.

The Centre summarized our findings and knowledge about the natural habitats and ecosystems in a report that formed the factual foundation for a recent Governmental impact assessment of deep-sea mineral exploration and extraction (Pedersen et al. 2021). Furthermore, the large knowledge and database that we have develop in the last two decades, also formed an important part of the factual basis for a recent NPD-report on the marine mineral resource potential (https://www.npd.no/globalassets/1-npd/fakta/havbunnsmineraler/publikasjoner/2023/ressursvurdering-havbunnsmineraler-20230127.pdf)- This is the other key report that the Norwegian Parliament will base their upcoming decision about the opening of the Norwegian deep-sea area for mineral exploration.

5. Sources to corroborate the impact

Rolf B. Pedersen, Bernt Rydland Olsen, **Thibaut Barreyre**, **Anders Bjerga, Alden Denny**, Mari Heggernes Eilertsen, Ilker Fer, **Haflidi Haflidason**, Jon Thomassen Hestetun, **Steffen Jørgensen**, Pedro A. Ribeiro, Ida Helene Steen, **Håvard Stubseid**, Anne Helene S. Tandberg, **Ingunn Thorseth** (2021). Fagutredning Mineralressurser i Norskehavet: Landskapstrekk, naturtyper og bentiske økosystemer, Oljedirektoratet, rapport, 120 p. (www.npd.no/globalassets/1-npd/fakta/havbunnsmineraler/fagutredning-mineralressurser-norskehavet-naturforhold-uib.pdf).
(GEO researchers in bold)

Bernt Rydland Olsen, **Ingeborg Elisabeth Økland**, **Ingunn Hindenes Thorseth**, **Rolf Birger Pedersen**, Hans Tore Rapp (2016). Environmental challenges related to offshore mining and gas hydrate extraction, Miljødirektoratet, rapport M-532, 28 p. (www.miljodirektoratet.no/publikasjoner/2016/april-2016/environmental-challenges-related-to-offshore-mining-and-gas-hydrate-extraction/).
(GEO researchers in bold)

[GEO] [2]

Institution: University of Bergen (UiB)
Administrative unit: Department of Earth Science (GEO)
Title of case study: Quantification and dissemination of climate risk to guide sustainable adaption
Period when the underpinning research was undertaken: ≤2011 and ongoing
Period when staff involved in the underpinning research were employed by the submitting institution: Bakke (2011-), Jansen (1985-), Kleiven (2005-), Meckler (2015-), Nesje (1997-), Ninnemann (2002-)
Period when the impact occurred: From 2011 and ongoing

1. Summary of the impact

Understanding, quantifying, and communicating climate risk is essential to achieve a knowledge-based policy for adapting to climate change and developing robust and sustainable infrastructure and energy supply. Norway today has more awareness of climate change, has a better educated public, and is better adapted to climate risks due to the sustained climate research program at GEO and the development of decision support tools, knowledge co-creation with stake-holders, and direct policy advice.

2. Underpinning research

The Department of Earth Science (GEO), UiB, has been a leading environment for extracting lessons about how the climate system operates under different climate states to better understand future climate change. The research excellence was formalized in 2003 when **Jansen** led the winning proposal to the Norwegian Research Council for a centre of excellence and the Bjerknes Centre for Climate Research (BCCR) was formed (2003-2012). Based on its outstanding external reviews and societal importance, the centre has been renewed multiple times and continues through direct government funding.

GEO remains a key contributor to BCCR through its ground-breaking work on quantifying past climate change, including throughout the last decade. The quality of the work on past climate change was evidenced by **Jansen** being appointed as a lead author of the paleoclimate chapter (e.g. ref. 1), the technical summary, and the summary for policy makers of the 2013 IPCC report. Sustained efforts by scientists at GEO to develop approaches for extracting climate information from geologic archives has led to the establishment of multiple national infrastructures for advanced analyses of sediment archives (EARTHLAB, 2013-2016, **Bakke**), isotopes (FARLAB, 2015-2021, **Ninnemann and Meckler**) and fluid inclusions (FluidMICS, 2021, **Meckler**) for quantifying past climates. These infrastructures, together with infrastructure for field work, provide a synergistic analytical pipeline for extracting novel insights into the range, rate, extremes, and thresholds of climate variability under varying climate states; essential for constraining models and understanding the consequences of climate changes for society. The primary research focus has been aimed at fundamentally understanding the processes and feedbacks underlying climate change. However, these methods, results, and infrastructure facilities are simultaneously being used to provide targeted knowledge on climate risk (for e.g. planning infrastructure, energy production, and setting local and national policies). Examples of this include research on:

<u>Extremes and floods:</u> Applying the analytical capabilities of EARTHLAB, **Bakke** has worked with three regional municipalities of differing sizes, geography, and vulnerability to flooding to co-create new knowledge and document how the frequency and cumulative risk of extreme flooding vary with large scale climate change [e.g. 2, 3].

Glaciers and energy production (hydropower): Based on several research projects, the subglacial terrain beneath the Folgefonna and the Jostedalsbreen ice caps have been mapped. The mapping revealed complex terrain under the glaciers with extensive valley systems with up to 600 meters of ice. The map of new waterways in a warmer climate when the glaciers are smaller shows that the present-day draining out of these glaciers will change dramatically [4].

Tipping points: **Ninnemann** and **Kleiven** have pioneered decadal scale reconstructions of ocean circulation and carbon cycling (using FARLAB infrastructure). The work, which is reported in a series of three papers in *Science* starting in 2008, revealed the existence of instability thresholds for the major climate tipping element, the Atlantic overturning circulation, during warmer climate states [e.g. 5]. Such circulation changes are consequential for society through their influence on sea level, climate, and the distribution and sequestration of carbon in the ocean [e.g. 6].

Jostein Bakke, Professor (GEO since 2011)
Eystein Jansen, Professor (GEO since 1985)
Helga Kleiven, Associate Professor (GEO since 2005; Aug. 2021 director of the Bjerknes Centre for Climate Research)
Nele Meckler, Professor (GEO since 2014)
Atle Nesje, Professor (GEO since 1997)
Ulysses Ninnemann, Professor (GEO since 2002)

3. References to the research

[1] Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., González Rouco, J.F., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas, M., Shao X., Timmermann, A., 2013, Information from Paleoclimate Archives. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[2] Johansson, F.M.E., Bakke, J., Støren, E.N., Paasche, Ø., Engeland, K., Arnaud, F., 2020, Lake Sediments Reveal Large Variations in Flood Frequency Over the Last 6,500 Years in South-Western Norway. *Frontiers in Earth Science*, https://doi.org/10.3389/feart.2020.00239

[3] Røthe, T.H., Bakke, J., Støren, E.N., 2019, Glacier outburst floods reconstructed from lake sediments and their implications for Holocene variations of the plateau glacier Folgefonna in western Norway. *Boreas*, https://doi.org/10.1111/bor.12388.

[4] Johansson, F.E., Bakke, J., Støren, E.N., 2022, Gillespie, M.K., Laumann, T., 2022, Mapping of the Subglacial Topography of Folgefonna Ice Cap in Western Norway—Consequences for Ice Retreat Patterns and Hydrological Changes. *Frontiers in Earth Science*, https://doi.org/10.3389/feart.2022.886361

[5] Galaasen, E.V., Ninnemann, U.S., Kessler, A., et al., 2020, Interglacial instability of North Atlantic Deep Water ventilation. *Science*, https://www.science.org/doi/10.1126/science.aay6381

[6] Olsen A. and Ninnemann, U., 2010, Large $\delta^{13}C$ Gradients in the Preindustrial North Atlantic Revealed, *Science*, DOI: 10.1126/science.1193769

4. Details of the impact

Impacts of glacier melt and flood research:
The flood and subglacial mapping and drainage route studies have been carried out as close collaborations with municipalities and hydropower industries with the aim to supply actionable climate knowledge to shape future policy, and guide adaption and investment [7]. The projects were designed to co-produce knowledge with the stakeholders to guarantee that the data directly

address the needs of the decision-makers. The flood data has been used to re-calculate the occurrence interval for floods in Odda, Voss and Nesttun after the approach outlined in a recent paper by members of the research group [2022 and ongoing, ref 4].

The mapping of subglacial terrain and their significance for future drainage pathways has been used to update the investment and renewal plans for hydro companies at Folgefonna starting in 2022 [8]. Regarding specific scenarios, in the EvoGlac project (PI: **Nesje**, 2016-2019) the future development, including runoff and possible consequences for hydropower production, under different climate scenarios was assessed for Hardangerjøkulen, an ice cap located in central southern Norway.

Impacts arising from Tipping elements:
Shaping policy: Reports funded by the Norwegian Environmental Agency [9] and private agencies [The Norwegian Climate Foundation; ref. 10] which provide commercial and municipal planning advice regarding future climate risks in order to guide adaption policy have incorporated the findings on ocean circulation, sea level [e.g. 11 and ref. 1, which **Jansen** was a co-author of], and carbon sequestration pathways.
Shaping education aims: **Kleiven** incorporated these research outputs on the impacts of climate change on people's lives into "Generation Green", funded by the Norwegian governments "climate lift" program. The program was developed to provide climate information to the public and guide the adoption of climate-friendly measures. Training climate ambassadors to reach educators, more than 140,000 students and teachers across Norway participated in the program between 2009 and 2012. The overall aims of the program, and content of the manuscript, was used as background for the new national teaching plan developed by the directorate for education and training [2020, ref. 13].

5. Sources to corroborate the impact

[7] https://hordaflom.norceresearch.no/

[8] https://www.nrk.no/vestland/meiner-kraftbransjen-ikkje-tek-bresmelting-pa-alvor-1.16002066

[9] Climate in Norway 2100–a knowledge base for climate adaptation; NCCS Report, 2017, https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiW_uyytK37AhVjDRAIHazvA60QFnoECA4QAQ&url=https%3A%2F%2Fwww.miljodirektoratet.no%2Fglobalassets%2Fpublikasjoner%2FM741%2FM741.pdf&usg=AOvVaw3aoXwk6w4dcIDGLmCLxhfg. A. Nesje was a contributing author. The report from the ministry of environment and produced by the Norwegian Centre for Climate Services has been used to guide decision makers and developers in climate adaption in Norway.

[10] Vippepunkter i Klimasystem ("tipping points in the climate system"), January 14, 2021, https://klimastiftelsen.no/publikasjoner/vippepunkter-i-klimasystemet/#innhold , Report by the Norwegian Climate Foundation on tipping points in the climate system which QGP members Ninnemann and Nisancioglu contributed to.

[11] Simpson, M.J.R., Nilsen, J.E.Ø., Ravndal, O.R., Breili, K., Sande, H., Kierulf, H.P., Steffen, H., Jansen, E., Carson, M., Vestøl, O., 2015. Sea Level Change for Norway: Past and Present Observations and Projections to 2100. Norwegian Centre for Climate Services. Report 1/2015. ISSN 2387-3027, Oslo, Norway.

[12] Lawrence, D., Rapport nr. 81-2016 Klimaendring og framtidige flommer i Norge, ISBN: 978-82-410-1534-2

[13] https://sokeresultat.udir.no/finn-lareplan.html

[GEO] [3]

Institution: University of Bergen (UiB)
Administrative unit: Department of Earth Science (GEO)
Title of case study: Arctic geophysics
Period when the underpinning research was undertaken: 2011 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: Mjelde (1997 -), Johansen (1995 -)
Period when the impact occurred: 2011 – 2021

1.Summary of the impact

Impact areas: Political, society, scientific, educational and transition to green energy

- Political: Geoscientific input used in international negotiations under the Law of Sea and Norway's claims of sovereignty offshore, and responsibility for the first seismic survey in the former disputed area in the Eastern Barents Sea towards Russia.
- Society: Provides underlying data for developing strategies to evaluate the hydrocarbon (HC) potential in the Barents Sea, and seabed minerals west of Svalbard.
- Scientific: Provides data underpinning the need for the national research initiative ARCEx (The Research Centre for Arctic Petroleum Exploration, 2014 – 2022) and later the GoNorth (Geoscience in the Northern Arctic) program (2017-2024).
- Educational: New multidisciplinary education of master and PhD students (Svalex).
- Transition to green energy: Spin-off results of methodology for screening sites for offshore windmill anchoring and underground CO_2 sequestration.

2. Underpinning research

This activity seriously began in the late 70s and early 80s when the Research Vessel "Håkon Mosby" was equipped for seismic surveying to facilitate cruises north of Svalbard in the courtesy of researchers in solid earth physics (geophysics) at GEO. In the late eighties a collaboration with Japan (Universities of Hokkaido and Tokyo) on the use of ocean bottom seismic nodes ('OBS Project') began, this was long before this technology started to develop for use in the oil and gas industry. This collaboration enabled seismic studies of the even deeper structures of the Earth's crust and provided important mapping of the transition from continental to oceanic crust. These maps provide imperative information for Law of the Sea and Norway's claims of sovereignty and thereby international right to govern over these resources, also when it comes to harvesting the sea, e.g., fisheries. Thanks to GEO's data around Jan Mayen, along the Mohns and Knipovich Ridges, and north of Svalbard, Norway obtained large new areas beyond 200 nautical miles in 2011. The enormous present and future societal impact have yet to be quantified.

Increased knowledge of the Earth's crust and the geological evolution of the Arctic has given important data for Norway to evaluate its potential for future income related to natural resources: oil, gas, and seabed minerals. Along with offshore seismic surveying, GEO has developed efficient methods to do land seismic surveying at the Arctic tundra. This work led to the development of the so-called "snow-streamer". With increased focus on the resource potential in the Barents Sea, seismic land data from Svalbard has become of increased value since Svalbard represents an uplifted, exposed part of the potential hydrocarbon system in the Barents Sea.

GEOs data on Svalbard and in the northern Barents Sea have documented small likelihood for finding commercial hydrocarbon prospects there, thus saving the society for large exploration costs. On the other hand, the OBS project's data in the southern Barents have provided valuable information to oil companies, thus reducing the exploration risk (e.g., Clark et al., 2013). Furthermore, GEOs data, in the yet to be explored, eastern Barents Sea (former disputed area with Russia; Shulgin et al., 2018), and along the westernmost Barents Sea margin (where the OBS project has documented rotated fault blocks also north of the Bear Island, Clark et al. (2013, and refs therein), will represent important resources for information if and when these areas are opened for exploration. These rich datasets both onshore Svalbard and offshore were crucial to the founding of ARCEx and GoNORTH.

Along with the increased focus on the environmental impact of seismic surveying in areas populated with breading sea mammals and fish, the need to review the potential harm of the geoscientific surveying is under strict public scrutiny and requires the development of methods which can be viewed as "environmentally friendly". During the ARCEx project several experimental campaigns were undertaken to review consequences and potential harms of seismic noise to sea mammals during seismic investigation (Stemland et al. 2019). Specifically, experiments were performed on floating ice to better understand these issues. These studies received academic awards (Johansen et al., 2019, Johansen and Ruud, 2020) and made spin-off results which now is tested for possible use in screening the seabed for potential deployment of offshore windmills (Johansen and Ruud, 2020).

The studies are also highly relevant for understanding the consequences of increasing melting of sea ice and thawing of the Arctic tundra. This study is now evolved into forming a new academic course at UNIS (www.unis.no) starting in 2024 on geophysical exploration and monitoring in Arctic. Geoscientific exploration and monitoring of the Arctic including the Polar Basin must, due to the rapid ongoing climatic changes, be viewed as one of the key areas in geoscientific research in the years to come for preserving Norway's self-interests and manifest Norway as an important contributor to international policy regulating this part of the hemisphere.

GEO's seismic data on various scales are extensively used by groups involved in seabed mining projects along the Knipovich Ridge, like the Norwegian Petroleum Directorate (NPD). Such resources are needed in the green transition. GEO's data have improved NPDs possibilities to obtain research funding from the Ministry of Petroleum and Energy.

GEO's developments of improving seismic methods are relevant for a range of activities within climate research, and thus the understanding of global climatic change. As an example, the OBS project has suggested a global link between Cenozoic pulsations in mantle plumes and glaciations. Another example is the innovative method developed by Grad et al. (2011), where OBS seafloor multiples, generally considered as noise, were successfully inverted for the velocity in the water layer, thus providing a new oceanographic tool.

Rolf Mjelde, professor
Tor Arne Johansen, professor

3. References to the research

Clark, S.A., Faleide, J.I., Hauser, J., Ritzmann, O., Mjelde, R., Ebbing, J., Thybo, H. and Flueh, E., 2013. Stochastic velocity inversion of seismic reflection/refraction traveltime data for rift structure of the southwest Barents Sea. Tectonophysics, 593, 135-150, doi: 10.1016/j.tecto.2013.02.033.

Grad, M., Mjelde, R., Czuba, W., Guterch, A., Schweitzer, J. and the IPY Project Group., 2011. Modelling of seafloor multiples observed in OBS data from the North Atlantic - new seismic tool for oceanography? Polish Polar Research, 32, 405-422.

Johansen, T.A., Ruud, B.O., Tømmerbakke, R. and Jensen, K., 2019. Seismic on floating ice: data acquisition versus flexural wave noise. Geophysical Prospecting, 67, 532-549. Doi: 10.1111/1365-2478.12756
(Received best paper award for 2019 in this journal.)

Johansen, T.A. and Ruud, B.O., 2020. Characterization of seabed properties from Scholte waves acquired on floating ice on shallow water, Near Surface Geophysics, 18, 49 -59. Doi: 10.1002/nsg.12082
(received best paper award for 2020 in this journal and most cited paper for 2020/2021)

Shulgin, A., Mjelde, R., Faleide, J.I., Høy, T., Flueh, E.R. and Thybo, H., 2018. The crustal structure in the transition zone between the western and eastern Barents Sea. Geophysical Journal International, 214, 315-330.

Stemland, H.M., Johansen, T.A., Ruud, B.O. and Aniceto, A.S., 2019. Measured sound levels in ice-covered shallow water caused by seismic shooting on top of and below floating ice, reviewed for possible impacts on true seals, First Break, 37, 35-42. Doi: 10.3997/1365-2397.2018010

Stemland, H.M., Johansen, T.A., Ruud, B.O. and Mavko, G., 2020. Elastic properties as indicators of heat flux into cold near-surface Arctic sediments, Geophysics, 85, MR309-MR323. Doi: 10.1190/geo2019-0662.1

4. Details of the impact

Research in Arctic geophysics has been ongoing at GEO for several decades. This research has been led by Professor Rolf Mjelde and Professor Tor Arne Johansen. Specific impacts of the research are:

1. Research papers and reports which provide maps and cross-sectional images showing the nature of the continental margin in the western Barents Sea, and that further describe the origin of the sedimentary basins and their tectonic history. This knowledge was the basis for the Norwegian government in negotiating territorial claims (2011), and it is important input for evaluating the resource potential for oil, gas and seafloor minerals (2011-present, e.g. Equinor). Thus, the impact of this work is on decisions on how to explore the region in the self-interest of Norway, and the global need for energy and minerals for the green transition. The OBS team also did a Law of the Sea related OBS survey for Denmark (GEUS) along the East Greenland Fracture Zone.

2. Seismic data from onshore Svalbard provides data of the resource potential here, but it is also important for classification of potential oil and gas reservoirs in the Barents Sea (2011 to present; e.g. Equinor).

3. Development of geoscientific surveying methods in areas which are difficult to explore due to complex sea ice, and, which also provide physical data for sound levels and potential harm of seismic noise on sea mammals living close to the ice edge. This was an important focus for ARCEx and led to extra funding from Vår Energy to test various experimental procedures for acquiring best possible seismic data on floating ice. The results have now an impact on the design of the acquisition set up for seismic surveying on floating ice.

4. Spin-off results which are important in developing seismic monitoring of CO_2 sequestration (see http//co2-ccs.unis.no).

5. The research involved master and PhD students in geoscience in Norway which developed into an annual event “Svalex” where national and international geoscience students received 10 days, in late August, of training in surveying in Arctic (Svalbard). The main outcome has been to expose most of Norway’s best geoscience students to full scale seismic acquisition for more than 10 years (2001-2014), providing the non-geophysical students with a broad overview of geophysical data opportunities and pitfalls. GEO received UiBs teaching award ‘Ugleprisen’ for the project.

6. The research has led to an OBS profile coverage on the mid-Norwegian Margin and in the Barents Sea being the largest in the world. This has enabled GEO and other research groups using the data to develop a detailed understanding of the tectono-magmatic evolution of the margins, including the interaction between plate tectonic and mantle plume processes. The OBS projects led by GEO have modified the way continental margins are studied worldwide (before 2011-present); from a procedure with very sparce OBS coverage modelled with regards to P-waves only, to a procedure where OBS profiles form the baseline, and the modelling includes P-waves, S-waves and potential field data.

7. The research carried out in the OBS group inspired GEOMAR, Germany, to acquire their own large pool of OBS instruments, and the developed OBS models form a significant portion of the NAG-TEC Tectonostratigraphic Atlas (GEUS).

8. Furthermore, the research has expanded into collaborative geological projects, such as geodynamical modelling (Geodynamics and Basin Studies Group, GEO, UiB), structural modelling (Potsdam, IFE) and temperature modelling (IRIS). The geological component of GEO's research has benefited from long cooperation with the Department of Geosciences, University of Oslo (GEO-UiO), who has developed their own capacity to model OBS data.

9. The Geological Survey of Norway (NGU) have used GEO's crustal scale OBS models extensively as basis for understanding the shallower basin structure, links with structures observed on land, and in developing models for continental margin evolution. This joint research with NGU has increased the number of research staff within this field at the NGU, and attracted additional funding for e.g., acquisition of potential field data from the Ministry of Trade, Industry and Fisheries. Researcher Laurent Gernignon (NGU) writes (2023): 'The OBS models are very important for us to calibrate our various 2D/3D potential field models along the rifted margin and Barents Sea. They have been used in most of the onshore-offshore projects carried out at NGU over the last 15 years.'

10. GEO is aiming for dissemination of research results towards the general public. One recent project that has gained a lot of attention was Yngve Kristoffersen's (professor emeritus, GEO,UiB) innovative and spectacular drift across, and along, the Lomonosov Ridge on the hovercraft "Sabvabaa" during the winter 2014-2015.

11. Furthermore, the development of seismic methods for exploration on sea ice and means to obtain data of potential negative effects on surrounding sea mammals, and how to reduce such negative effects, are used by jurisdiction authorities when decisions are made to allow or decline seismic acquisition of coastal areas in Svalbard.

12. Our research also shown how near-surface seismic data can be used to screen the strength of the seabed for anchoring off-shore windmills. A new project 4SWIND is funded by RCN and Equinor where this technology will be further tested. Another type of research within this regard is the modelling of OBS multiples (Grad et al., 2011), providing information about the Vp/Vs ratio on the seafloor, and thus seafloor properties.

13. Another outcome of the OBS project concerns the extensive cooperation with Equinor's research center. In this cooperation GEO focused on basic research, Equinor on applied research and when this research was 'mature', the product was commercialized by WesternGeco as the first tool for 4C OBS exploration and monitoring. The enormous present and future societal impact have yet to be estimated.

5. Sources to corroborate the impact

Law of the Sea: Harald Brekke (NPD)
Seafloor minerals: Sissel Eriksen (NPD)
NGU modelling: Laurent Gernignon
GEOMAR OBSs: Ernst Flueh

NAG-TEC: John Hopper, GEUS GEO-UiO: Jan Inge Faleide Potsdam modelling: Leni Wenderoth IFE modelling: Magnus Wangen IRIS modelling: Willy Fjeldskaar GoNorth: Gunnar Sand (SINTEF) ARCEx: Alfred Hanssen

[GEO] [4]

Institution: University of Bergen (UiB)	
Administrative unit: Department of Earth Science (GEO)	
Title of case study: Earthquake monitoring for a safe society	
Period when the underpinning research was undertaken: 2011-2021	
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-2021(see page 2)	
Period when the impact occurred: 2011-2021	

1. Summary of the impact

Through its continuous monitoring and the related research activities, the Norwegian National Seismic Network (NNSN) delivers real-time data on ground motion throughout Norway, fast information on specific events such as earthquakes or explosions, as well as long-term baseline data and information for e.g. seismic hazard assessment.

2. Underpinning research

The Norwegian National Seismic Network (NNSN) comprises several activities with the overarching objective to monitor earthquakes in the Norwegian region, to advance the understanding of earthquakes and to contribute to reduction of risk from earthquakes. The region monitored stretches from the Mid-Atlantic ridge in the west to the interior of Fennoscandia in the east, and from the North Sea in the south to the Arctic Sea in the north. Instrumental monitoring in Bergen goes back to 1905, and today a modern seismic network of more than 40 stations is in operation (Demuth et al., 2016). Seismic catalogues are produced routinely and form the basis for seismic hazard calculations (Ottemöller et al., 2018). Seismicity maps are also the starting point for research work that is done to better resolve spatio-temporal details of the seismicity and to advance the understanding of the causes of seismicity.

Earthquake studies in Norway predate the first instruments, but have developed enormously with the availability of instrumental data and increasing computing power. The coastal area of Nordland has been of particular interest as one of the largest earthquakes in historic times occurred here (Lurøy, 1819; M=5.9) and shallow earthquake swarms are regularly observed. With the deployment of dense networks and use of advanced signal processing it is now possible to resolve details of how these swarms are developing in time and space (Shiddiqi et al., 2021). Another area that was studied in detail is Storfjorden, southeast of Spitsbergen, where a significant earthquake sequence started in 2008 and still continues (Ottemöller et al., 2021). Additional work was done to resolve regional differences in attenuation (Demuth et al., 2019) and earthquake physical parameters (Demuth et al., 2019). The results from such studies have implications for the understanding of earthquakes in intraplate areas, which allows to reduce uncertainties in seismic hazard calculations in Norway.

In parallel with improved monitoring, historical archives of earthquake felt reports available at UiB allow for reanalysis of historical earthquakes using modern methods. This allows for more reliable magnitude estimates of the largest historical earthquakes which is crucial for reliable estimates of future seismic hazard as well as for understanding the potential of earthquakes to trigger secondary effects such as landslides (Mäntyniemi et al., 2020).

Seismic monitoring of the offshore regions has been of importance since the 1980s for the oil and gas producing industry. Background monitoring is required to assess the hazard, but also to monitor if production is resulting in additional seismicity. Recently, the capability to detect and locate seismicity has improved because of access to data from permanent reservoir monitoring. Research on how best to use these data in combination with land-based stations is currently going on. With the planned start of carbon storage in 2024, both the seismicity catalogue and monitoring infrastructure are used to assess risk and establish a seismicity baseline prior to injection.

Funding for the NNSN project was provided by Offshore Norge (previously Norwegian Oil and Gas Association) and the University of Bergen in five year periods (2013-2017, 2018-2022).

The key people that were involved in this research are:

Lars Ottemöller, Professor, at UiB since 2009
Mathilde Sørensen, Professor, at UiB since 2011
Stephane Rondenay, Professor, at UiB since 2011
Henk Keers, Associate Professor, at UiB since 2010
Felix Halpaap, Postdoc, in position since 2019
Andrea Demuth, PhD student, 2013-2019
Hasbi Ash Shiddiqi, PhD student, 2019-2022

3. References to the research

Demuth, A., Ottemöller, L. and Keers, H., 2016. Ambient noise levels and detection threshold in Norway. *Journal of Seismology*, *20*, pp.889-904.

Demuth, A., Ottemöller, L. and Keers, H., 2019. QL g wave tomography beneath Norway. *Journal of Seismology*, *23*, pp.151-164.

Demuth, A., Tjåland, N. and Ottemöller, L., 2019. Earthquake source parameters in Norway determined with empirical Green's functions. *Journal of Seismology*, *23*, pp.715-724.

Mäntyniemi, P.B., Sørensen, M.B., Tatevossian, T.N., Tatevossian, R.E. and Lund, B., 2020. A Reappraisal of the Lurøy, Norway, Earthquake of 31 August 1819, *Seismological Research Letter*, 91(5), 2462-2472, https://doi.10.1785/0220190363

Ottemöller, L., Strømme, M.L. and Storheim, B.M., 2018. Seismic monitoring and data processing at the Norwegian National Seismic Network. *Summary of the Bulletin of the International Seismological Centre*, *52*(I), pp.27-40. https://doi.10.31905/1M97CSYL

Ottemöller, L., Kim, W.Y., Waldhauser, F., Tjåland, N. and Dallmann, W., 2021. The Storfjorden, Svalbard, Earthquake Sequence 2008–2020: Transtensional Tectonics in an Arctic Intraplate Region. *Seismological Research Letters*, *92*(5), pp. 2838-2849. https://doi.org/10.1785/0220210022

4. Details of the impact

The NNSN combines monitoring and research to provide stakeholders with objective information on earthquakes and related events. There are direct long-lasting benefits from the earthquake monitoring to the society, we provide examples in the following:

1. Earthquake data from the NNSN form the basis of any seismic hazard assessment for Norway. Several such studies (national, site- or region-specific, many not public) have emerged in recent years (e.g. Carlton et al., 2019). Furthermore, data are currently used to develop a new and open national seismic hazard model for Norway.

2. The NNSN provides open access to both waveform and catalogue data in an internationally standardised way. The catalogue data are shared with the European Mediterranean Seismological Center and the International Seismological Center, while waveform data are distributed through the Norwegian node of the European EIDA system that is coordinated within ORFEUS.

3. Data processing software (SEISAN; Havskov et al., 2021) has been developed for use by the NNSN since the early 1990s. The software is used globally at various seismological observatories and has had a significant impact, especially in developing countries.

4. The NNSN provides continuous monitoring to fulfil safety criteria for offshore installations in Norway. The support by the operating companies to the NNSN is coordinated by Offshore Norge This monitoring will be highly relevant also in the future when CO_2 injection is planned to start in 2024.

5. In Norway, moderate size earthquakes occur, leading to widespread concern in the population. Data from the NNSN allow to provide timely and precise information on an event to media, authorities, industry, and other stakeholders.

6. An earthquake scenario was included as part of a national risk assessment by the Norwegian Directorate for Civil Protection (DSB) (Nasjonalt risikobilde; Ch. 11) in 2014. The scenario considers the potential effects of an M6 earthquake near Bergen and is largely based on data from the NNSN and input from researchers associated with NNSN.

5. Sources to corroborate the impact

Carlton et al., 2019: https://ngi.brage.unit.no/ngi-xmlui/handle/11250/2620174

Nasjonalt risikobilde, 2014: https://www.dsb.no/rapporter-og-evalueringer/nasjonalt-risikobilde-2014/

Havskov et al., 2021: https://doi.org/10.1785/0220190313

UiB-GFI Impact case 1

Institution: University of Bergen, UiB
Administrative unit: Geophysical Institute, GFI
Title of case study: Scientific basis underpinning the Paris Agreement
Period when the underpinning research was undertaken: 2007-present
Period when staff involved in the underpinning research were employed by the submitting institution: 2007-present
Period when the impact occurred:2016-present

1. Summary of the impact

The below describes the impact of work done by different research groups at the Geophysical Institute to form the scientific basis for underpinning a legally binding international treaty on climate change (the Paris Agreement) and national climate assessments.

2. Underpinning research

After the establishment of the Climate Dynamics group in year 2000 around the effort of building a global coupled climate model (the Bergen Climate Model). The institute strengthened its commitment to the model development by hiring Prof. Heinze as part of the biogeochemistry group in 2004 to add a marine biogeochemical component to the model. The group delivered together with other colleagues affiliated to the Bjerknes Climate Research Centre its's first contribution to the IPCC WG1 assessment in 2007.

The same year the Norwegian Earth System Climate Modeling Consortium (https://www.noresm.org) was established (now consisting of the University of Bergen, University of Oslo, the Norwegian Meteorological Institute, Bjerknes Centre for Climate Research, NORCE, NERSC, NILU and CICERO) in order to assure a critical mass of researchers continuing the effort started in Bergen. The Norwegian Earth System Model (NorESM) has since then been a cornerstone in Norwegian large scale climate modelling. Delivering climate simulations for use in all IPCC WG1 assessments after 2007.

In 2011, building on the NorESM efforts and using state of the art data assimilation methods, the Norwegian Climate Prediction Model (NorCPM) was initiated at the Geophysical Institute through the hiring of Noel Keenlyside. The model system was developed to deal with prediction from seasonal-to-decadal time scale in order to close the gap between numerical weather forecast and traditional climate projections. The Bjerknes Climate Prediction Unit (https://bcpu.w.uib.no/) for seasonal to decadal forecasting was established in 2018 and is now part of the international Centre for Annual-to-Decadal Climate Prediction (https://hadleyserver.metoffice.gov.uk/wmolc/) lead by the World Meteorological Organization.

Since 2011 the Geophysical Institute has been participating in all large scale national projects progressing the NorESM system: EARTHCLIM (2011-2014, lead by Prof. H. Drange (Climate Dynamics Group)), EVA (2014-2018 , lead by Prof. C. Heinze (Biogeochemistry group)), INES (2018-2026) and KeyClim (2019-2023, WP leader Prof. A. Sorteberg (Climate Dynamics Group).

As a consequence of the long going efforts in coupled climate modelling several of the institutes' researchers has been selected to contribute to the IPCC WG1's assessment and special reports as lead authors, co-coauthors or review editors:

- Prof A. Sorteberg (Climate Dynamics group). Review Editor IPCC Climate Change 2021 - The Physical Science Basis, Chapter 11: Weather and Climate Extreme Events in a Changing Climate
- Prof. L.H. Smedsrud (Physical Oceanography group). Contributing Author IPCC SROCC, 2019. Special Report on Ocean and Cryosphere Climate Change. Summary for Policy Makers. Chapter 3: Polar Regions.
- Prof Christoph Heinze (Biogeochemistry group). Review Editor IPCC Climate Change 2013 - The Physical Science Basis, Chapter 6, Carbon and Other Biogeochemical Cycles.
- Prof. N. Keenlyside (Climate Dynamics group). Contributing Author IPCC Climate Change 2013 - The Physical Science Basis, Chapter 2, Changing State of the Climate System.
- Prof A. Sorteberg (Climate Dynamics group). Lead author IPCC SREX, 2012. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Chapter 3 Changes in Climate Extremes and their Impacts on the Natural Physical Environment
- Prof C. Heinze (Biogeochemistry group). Lead author Climate Change 2007 - The Physical Science Basis, Chapter 4, Couplings Between Changes in the Climate System and Biogeochemistry

Names of the key researchers

- Noel Keenlyside (professor, 2011-present). Leading the Norwegian Climate Prediction Model effort. https://www.uib.no/en/persons/Noel.Sebastian.Keenlyside
- Asgeir Sorteberg (professor, 2011-present). Involved in the atmospheric modelling since the start of the Bergen Climate model. https://www.uib.no/en/persons/Asgeir.Sorteberg
- Christoph Heinze (professor, 2004-present). Involved in the marine biogeochemistry modelling since 2004. https://www.uib.no/en/persons/Christoph.Heinze
- Helge Drange (professor, 2008-present). Initiating the oceanic part of the Bergen Climate model and later the NorESM effort. https://www.uib.no/en/persons/Helge.Drange
- Nils Gunnar Kvamstø (professor 2006-2021). Initiating the atmospheric part of the Bergen Climate model. https://www.uib.no/en/persons/Nils.Gunnar.Kvamst%C3%B8
- Camille Li (professor, 2017-present). Involved in NorESM with emphasis on atmospheric dynamics. https://www.uib.no/en/persons/Camille.Chia-Mau.Li
- Lea Svendsen (associate professor, 2018-present). Involved in the Norwegian Climate Prediction Model with emphasis on decadal and multidecadal timescales. https://www.uib.no/en/persons/Lea.Svendsen
- Ingo Bethke (scientist, 2019-present). Leading scientist in the Norwegian Earth System and Norwegian Climate Prediction Model development. https://www.uib.no/en/persons/Ingo.Bethke

3. References to the research

Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Doscher, R., Gehlen, M., Gruber, N., Holland, E., Hov, O., Joos, F., Matthews, J. B. R., Rodven, R., and Wilson, S.: The quiet crossing of ocean tipping points, P Natl Acad Sci USA, 118, ARTN e2008478118, 10.1073/pnas.2008478118, 2021, https://www.pnas.org/doi/10.1073/pnas.2008478118

Heinze, C., Eyring, V., Friedlingstein, P., Jones, C., Balkanski, Y., Collins, W., Fichefet, T., Gao, S., Hall, A., Ivanova, D., Knorr, W., Knutti, R., Loew, A., Ponater, M., Schultz, M. G., Schulz, M., Siebesma, P., Teixeira, J., Tselioudis, G., and Vancoppenolle, M.: ESD Reviews: Climate feedbacks in the Earth system and prospects for their evaluation, Earth Syst Dynam, 10, 379-452, 10.5194/esd-10-379-2019, 2019, https://esd.copernicus.org/articles/10/379/2019/

Seland, O., Bentsen, M., Olivie, D., Toniazzo, T., Gjermundsen, A., Graff, L. S., Debernard, J. B., Gupta, A. K., He, Y. C., Kirkevag, A., Schwinger, J., Tjiputra, J., Aas, K. S., Bethke, I., Fan, Y. C., Griesfeller, J., Grini, A., Guo, C. C., Ilicak, M., Karset, I. H. H., Landgren, O., Liakka, J., Moseid, K. O., Nummelin, A., Spensberger, C., Tang, H., Zhang, Z. S., Heinze, C., Iversen, T., and Schulz, M.: Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations, Geosci Model Dev, 13, 6165-6200, 10.5194/gmd-13-6165-2020, 2020, https://gmd.copernicus.org/articles/13/6165/2020/gmd-13-6165-2020.html

Bethke, I., Y. Wang, F. Counillon et. al. (2021): NorCPM1 and its contribution to CMIP6 DCPP. Geoscientific Model Development, 14 (11), 7073-7116

Wang, Y., F. Counillon, N. Keenlyside, L. Svendsen, S. Gleixner, M. Kimmritz, P. Dai, Y. Gao: Seasonal predictions initialised by assimilating sea surface temperature observations with the EnKF Climate Dynamics, 53 (9), 5777-5797 https://doi.org/10.1007/s00382-019-04897-9, 2019

L. S. Graff, T. Iversen, I. Bethke, J. B. Debernard, Ø. Seland, M. Bentsen, A. Kirkevåg, C. Li, and D. J. L. Olivié: The "NorESM1-Happi" used for evaluating the role of ocean and sea-ice feedbacks under global warming of 1.5°C and 2°C. Earth Syst. Dynam., 10, 569-598, https://doi.org/10.5194/esd-10-569-2019, 2019

4. Details of the impact

The IPCCs series of assessment and special reports has been the scientific backbone of the political process under the United Nations Framework Convention on Climate Change. Leading to treaties like the Kyoto Protocol (2008 to 2012 and 2013-2020) and the Paris agreement (2016 - present).

Science has played a substantial role in facilitating the political process through the IPCC. All IPCCs assessments of scenarios of possible future climate change has since 1995 been strongly linked to the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project (CMIP) which collect and make multi-model climate output openly available in a standardized format. This service secures worldwide access to a wealth of global climate simulations that can be used for various research. As an example, the CMIP publication database service (https://cmip-publications.llnl.gov/) has 811 papers that uses NorESM or NorCPM CMIP5 or CMIP6 data. Given that listing your publication in the database is voluntary this is a fraction is of the real number. According to the database the NorESM simulations done for CMIP5 is the 6th most cited climate data in the database and we expect the new CMIP6 data to be equally successful.

Though the Norwegian coupled climate modelling effort was initiated at the Geophysical Institute 20 years ago, the current NorESM and NorCPM effort is today very much a national effort through the above-mentioned Norwegian Earth System Climate Modeling Consortium and the impact of the research is a good example of how different relatively small research groups can organize around a common scientific tool to help deliver internationally important contributions.

The isolated impact of the institutes contribution to the now worldwide understanding of the treats of climate change is undoubtedly small and impossible to quantify. However, the fact that four of the professors at the institute has been contributing directly to the writing of IPCC reports and the continuous delivery of open access climate simulation data over the last 15 years testifies to the active role of the institute.

On a European level the NorESM simulations act as boundary conditions for running regional climate simulations for Europe through projects like EuroCordex (https://www.euro-cordex.net/) and the European Climate Prediction System (https://www.eucp-project.eu/).

Nationally, the seasonal to decadal modelling efforts through the NorCPM is now an important tool for the recently started center for research-based innovation Climate Futures (https://www.climatefutures.no) funded by the Norwegian research Council (2020-2028). The centre has around 40 industry and governmental partners that help co-develop methods and practices for climate risk management on seasonal to decadal timescales.

5. Sources to corroborate the impact (indicative maximum of ten references)

Eyring et al., (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev., 9, 1937–1958, 2016 https://doi.org/10.5194/gmd-9-1937-2016

Williams et al., (2016). A Global Repository for Planet-Sized Experiments and Observations. Bulletin of the American Meteorological Society Vol. 99: Issue 10 https://doi.org/10.1175/BAMS-D-15-00132.1

UiB-GFI Impact case 2

Institution: University of Bergen, UiB
Administrative unit: Geophysical Institute, GFI
Title of case study: The Barents Sea “ice edge” and the management plan
Period when the underpinning research was undertaken: 2010-present
Period when staff involved in the underpinning research were employed by the submitting institution: 2010-present
Period when the impact occurred:2020-present

1. Summary of the impact

The Norwegian Government’s Management plans for marine areas set the regulations “to facilitate value creation while also maintaining natural diversity”. The Barents Sea is home to Norway’s main fisheries, a region of most pronounced climate change including sea ice retreat. The combination of climate change, environmental concerns, and the exploration of resources, makes the management for the Barents Sea a particularly debated issue. GFI contributed significantly to the knowledge basis, the public and political debate, and to the specific alternatives voted over in the national assembly – Stortinget – for the last revision in 2020.

2. Underpinning research

The northern seas, and the northern seas in climate, have persistently been the focus of the Geophysical Institute and then the Bjerknes Centre when established. The Barents Sea has been a particular priority for Bjerknes-partner Institute of Marine Research through its his-tory because of the sea’s prominence for Norwegian fisheries and the management thereof. With climate change, sea ice retreat and the cooperation within the Bjerknes Centre, it soon also become a focal point of collaborative research within the centre, starting from about 2005. The effort up to then, is summarized in the review of Smedsrud et al. (2013).

A particular reference point is Årthun et al. (2012), where the authors – amidst several Bjerknes papers circling the issue at the time – in a most basic way related the variable Atlantic inflow to the interannual fluctuation and long-term retreat of the sea-ice cover; more ocean heat, less sea ice. (An also coining the term “Atlantification” in an oceanographic context.)

The relation was further elaborated, and its degree of predictability 1–2 years into the future detailed in Onarheim et al. (2015). Thus, zooming in both on the issue of the (near) future extent of the Barents Sea ice cover and on presenting one benchmark for the emerging field of climate prediction. The latter – an observation-based benchmark for the predictability of northern climate rooted in the ocean (including Arctic sea-ice, but also European temperatures and precipitation) – was pursued on continental scale in Årthun et al. (2017).

Having established a predictive potential for the near-term future, GFI researchers moved on more systematically to assess the future state of the ice cover considering the long-term future evolution as projected by climate models (Onarheim and Årthun 2017), including considering the Arctic in general (Årthun et al. 2019).

Main findings of the climate-model projection-based studies are the documentation of what – on current trend – will be the future absence of Arctic sea-ice in summer (within about 20 years for the Barents Sea); the driving role increased heat import with the inflow of Atlantic Water in this, both through the main gateway of the Barents Sea but also via the Fram Strait; and that there still can be single years and even single decades where the sea ice cover increase on the underlying trend toward an ice-free Arctic.

3. References to the research

Årthun, M., T. Eldevik, and L.H. Smedsrud, 2019: The role of Atlantic heat transport in future Arctic winter sea ice loss. J. Climate, 32, 3327–3341.

Onarheim, I.H., and M. Årthun, 2017a: Toward an ice-free Barents Sea. Geophys. Res. Lett., 44, 8387–8395.

Årthun, M., T. Eldevik, E. Viste, H. Drange, T. Furevik, H.L. Johnson, and N.S. Keenlyside, 2017: Skillful prediction of northern climate provided by the ocean. Nature Communications, 8, DOI: 10.1038/ncomms15875

Onarheim, I.H., T. Eldevik, M. Årthun, R.B. Ingvaldsen, and L.H. Smedsrud, 2015: Skillful pre-diction of Barents Sea ice cover. Geophys. Res. Lett., 42, 5364–5371.

Smedsrud, L.H., I. Esau, R.B. Ingvaldsen, T. Eldevik, P.M. Haugan, C. Li, V.S. Lien, A. Olsen, A.M. Omar, O.H. Otterå, B. Risebrobakken, A.B. Sandø, V.A. Semenov, and S.A. Sorokina, 2013: The role of the Barents Sea in the Arctic climate system. Rev. Geophys., 51, 415–449.

Årthun, M., T. Eldevik, L.H. Smedsrud, Ø. Skagseth, and R. Ingvaldsen, 2012: Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat. J. Climate, 25, 4736–4743.

4. Details of the impact

Having quantified the basic relation of more ocean heat–less sea ice, already inferred by Helland-Hansen and Nansen in 1909, an op-ed (Eldevik and Årthun 2012; “Nansen got it right”) pointing both to the relation’s practical importance and to the historical significance was published in tandem with the peer-review paper (Årthun et al. 2012). What eventually became a strategy was thus established – to publish an op-ed or similar in a national news outlet in tandem with the publication of our research related to the pertinent issue of Barents Sea and Arctic Ocean sea-ice retreat.

As the public and political debate concerning the upcoming update of the Barents Sea management plan was gaining momentum in 2015, including the contested issue of what should define the regulatory definition of the sea ice extent (“iskanten”) that constrains commercial activities, Onarheim et al. (2015) was published. Accompanying this was the op-ed Onarheim and Eldevik (2015; “The line has to be put somewhere”), outlining the predictability of the ice-cover and the implications for the revised line of sea-extent the government was arguing for.

The latter included pointing to the fact that the region defined to be “ice-free” in the suggested update of management plan was well within the reach of the sea ice’s interannual variability. Not claiming a causal relation with the op-ed, the government nevertheless lost the parliamentary vote for an updated management plan including a less restrictive regulatory definition of the ice edge. There was accordingly no update of the management plan in 2015. (With then prime minister Erna Solberg famously noting that “we didn’t move the ice edge, it moved itself”.)

With the 2015 vote lost, the government and all other parties involved, including public interest, soon turned their attention to the more complete revision coming up and to be voted over in 2020. And at the same time, the GFI and Bjerknes Centre research on the present and future state and predictability of the Arctic sea-ice covered progressed, including the accompanying public dissemination in national media (Onarheim and Årthun 2017b).

The knowledge basis for the governmental management plans largely resides with “Faglig forum”, a science committee rooted in the relevant governmental research institutes and management directorates. In their report for the upcoming revision of the Barents Sea management plan they failed to reach a consensus on what should be the revised regulatory “ice edge”. Two alternatives were pointed to, one precautious and restrictive for future oil and gas exploration, one that moved the baseline substantially north – and north of most prospective licenses to operate. The government was in favour of the latter.

GFI stepped into this based on our ongoing research (e.g., Årthun et al. 2019). Our advice, or rather point of view (Eldevik, Årthun, and Olsen 2019), was two-fold: 1) in general, the perspectives both of “Faglig forum” and the suggested revision failed to take the future into account (the data basis was fundamentally empirical and retrospective), and 2) that the future evolution – and thus the relevance of the regulatory definition used – depends on to what extent society succeeds with reaching the goals of the Paris Agreement (the more in compliance, the less sea ice loss).

This was picked up by WWF (2019), and there was a resonance with the parliamentary groups of the three government parties that invited WWF and two scientific experts (Eldevik, GFI, and von Quillfeldt, Norwegian Polar Institute) to a meeting in the national assembly to be briefed (ABC 2020).

The debate ran through the spring on which regulatory definition to settle for. GFI’s concluding contribution was the op-ed Eldevik (2020; “Fifteen is not the middle way between thirty and never”) in the run-up to the parliamentary debate. In this Eldevik “translated” the peer-review research to the specific measure in contention, the so-called ice-frequency. The op-ed argued that the government’s suggested alternative for moving the regulatory limit substantially northward was at odds with at the same time aiming to uphold the Paris Agreement (quantified in terms of the risk for sea ice in regions then open to operations).

The argument was taken up in parliament and became a substantial part of the white paper to be voted over, including directly referring to and quoting from the op-ed (Stortinget 2020). With the government this time securing a majority for its point of view in parliament, a regulatory definition consistent with our advised ended up being the minority position.

The peer-review papers referred to above also contributes to our other impact case 1 on the IPCC-process, and the issues of related climate predictability also have prominent presence in the policy report (EASAC 2021). Our dedication to the research and in-tandem public out-reach on the ongoing rapid change of the Barents Sea was also key to placing GFI most centrally in what is presently probably Norway’s biggest research project, The Nansen Legacy (Eldevik et al. 2014).

5. Sources to corroborate the impact (indicative maximum of ten references)

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IFT 1

Institution: University of Bergen
Administrative unit: Institutt for Fysikk og Teknologi
Title of case study: The scientific and societal impact of the Birkeland Centre for Space Science
Period when the underpinning research was undertaken: 2013 - 2022
Period when staff involved in the underpinning research were employed by the submitting institution: 2013 - 2022
Period when the impact occurred: 2013 - 2022

1. Summary of the impact

The Birkeland Centre for Space Science (BCSS) is a center of excellence established in 2013 by the Research Council of Norway. BCSS researchers, powered by the center's critical mass, timescale and management structure, allowed both a large academic impact at international level, and a societal impact at national level, by bringing space science closer to the general public, fostering and supporting local space industry, and educating highly skilled workforce as well as the next generation of space scientists.

2. Underpinning research

BCSS (PI Prof. N. Østgaard) is a center of excellence dedicated to fundamental research in space physics, based at the University of Bergen and with nodes at NTNU and UNIS. BCSS has been a unique powerhouse for scientific discoveries, development of space instrumentation, and the education of highly skilled workforce and the next generation of space scientists since 2013, consolidating and expanding the space physics activities at the University of Bergen, already established in the 1960's. BCSS activity is framed in three main research teams (dynamics of the asymmetric geospace, energetic particle precipitation, hard radiation from thunderstorms), and contributed more than 400 scientific papers over the last ten years. Here we focus on three lines of research which contributed to the largest academic impact.

1) A paradigm shift in the understanding of the asymmetry of geospace

Characterizing and understanding how and why the auroras in the northern and southern hemispheres are not similar has been the focus of researchers from University of Bergen since 2004. It started with a couple of papers describing that auroras were indeed displaced in the two hemispheres (Østgaard et al., 2004, 2005). Another milestone in this research was a paper by Laundal and Østgaard (Nature 2009) that found that the auroras could be not only displaced but completely different in the north and south. This result made it to the front page of Nature July 2009. A break-through in understanding how the asymmetries is created was presented in three papers by Tenfjord et al.(2015, 2016 and 2018). Here it was shown that it is the asymmetric loading of magnetic pressure and not tail reconnection that is the source of asymmetries. Several features that this new understanding predicts, like asymmetric plasma flows in the ionosphere was shown by Reistad et al., (2016, 2018). The asymmetric current patterns in the two hemispheres were presented by Laundal et al., 2018. The two last papers (Ohma et al., 2018 and Østgaard et al. 2018) have applied this understanding and also explained how the asymmetries are removed by tail reconnection, contrary to what many have thought. Since 2004 this research has led to 4 PhDs, 11 Master´s and 22 publications. This research has been a truly group effort at BCSS and represents a paradigm-shift in understanding the asymmetric geospace.

2) The ASIM instrument onboard the International Space Station as a new benchmark in the field of energetic radiation from thunderstorms and lightning

The Atmosphere-Space Interactions Monitor (ASIM) onboard the International Space Station is a mission of the European Space Agency, the first one specifically designed for the observation of short bright bursts of gamma-rays from thunderstorms and lightning, termed terrestrial gamma-ray flashes (TGF). The scientific payload consists of an X / gamma-ray instrument (MXGS) and an optical instrument (MMIA). The MXGS detector was designed and built at the Institute for Physics and Technology in collaboration with national and international space industries and represents the most complex space instrument realized by Norwegian Academia to date. The design and development of the instrument started in 2004 and continued within the premises of the BCSS to the launch in 2018 followed by the scientific operations which are still ongoing. The novelty of the payload stands in the simultaneous observation in gamma-ray and optical bands, never attempted before. This makes ASIM the current benchmark in this field of research, providing breakthroughs in our understanding of the intimate relationship between TGFs and lightning. In 2019 we reported the simultaneous observation of a TGF and ultraviolet emission associated to perturbations in the ionosphere known as ELVE. This was theoretically predicted few years before but never observed previously. The results were published in the prestigious journal Science (Neubert et al., 2019) and were also awarded the cover page of the issue.

3) Interdisciplinary branching towards high-energy astrophysics: the ASIM instrument shed light on the intimate structure of highly magnetized neutron stars

On 15th April 2020 a very short and bright gamma-ray burst triggered many space missions equipped with gamma-ray detectors, including ASIM. Soon, the burst turned out to be the giant-flare of a highly magnetized neutron star (magnetar) in a nearby galaxy 11-million light-years away from our galaxy. The photon flux was so large that most of the instruments were heavily affected by instrumental effects, which suppressed photon detection during the brightest phase of the event. MXGS onboard ASIM did not suffer from significant instrumental effects, thanks to its architecture designed to record TGFs, which can be much brighter on shorter time scales. This allowed us a detailed timing analysis of the few milliseconds of the main burst phase, evidencing the presence of Quasi-Periodic Oscillations (QPO) at about 2 and 4 kHz, the first observation of this kind in these objects. These observations are consistent with plasma / wave interaction in the neutron star’s strong magnetic field, shedding light to the generation mechanism of these rare giant flares. To obtain these results, we set up a fruitful collaboration with international high-energy astrophysics experts, expanding the academic impact of the ASIM mission to neighbouring fields. The results were published in the prestigious journal Nature (Castro-Tirado et al., 2021).

Key researchers:

Name	Position	Dates	Involved in
Nikolai Østgaard	Professor		Asymmetry and ASIM
Karl Magnus Laundal	Researcher	2013 -	Asymmetry
Paul Tenfjord	PhD / Postdoc / Researcher	2013 - 2022	Asymmetry
Jone Reistad	PhD / Postdoc / Researcher	2013 -	Asymmetry
Anders Ohma	PhD / Postdoc	2013 -	Asymmetry
Christian Snekvik	Postdoc	2014 - 2018	Asymmetry
Kjetil Ullaland	Professor	2013 -	ASIM
Martino Marisaldi	Professor	2016 -	ASIM
Andrey Mezentsev	Postdoc / Researcher	2013 -	ASIM
Georgi Genov	Senior Engineer	2013 - 2022	ASIM
Shiming Yang	Senior Engineer	2013 -	ASIM

3. References to the research

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(42 citations, Web of Science)

Castro-Tirado, **Østgaard**, Gogus, Sánchez-Gil, Pascual-Granado, Reglero, **Mezentsev**, Gabler, **Marisaldi**, Neubert, Budtz-Jørgensen, **Lindanger, Sarria**, et al., Very-high-frequency oscillations in the main peak of a magnetar giant flare, Nature, 2021, https://doi.org/10.1038/s41586-021-04101-1
(4 citations, Web of Science)

4. Details of the impact

The BCSS proposal stemmed from a strategic investment of the Institute for Physics and Technology, that supported the initiative with significant resources allocation. The BCSS kickstart benefited also from the large momentum provided by an ERC Advanced Grant (P.I. N. Østgaard) and by the involvement in the ASIM mission, supported by the Norwegian Space Agency. All these concurrent activities were instrumental for the successful establishment of BCSS in 2013. BCSS then paid back to the academic community and to society at large this initial investment, by delivering outstanding science, disseminating the results extensively, and supporting the national space industry. BCSS has taken full advantage of stable, long-term funding, showing that the 'Center of Excellence' funding scheme pays off. Proof of evidence stand, for example, in the ASIM project, started in 2004 and supported until 2025, and in the work on hemispheric asymmetries, started in 2001 and conducive to breakthrough results in 2018-2019. These long-term efforts would have hardly been achievable with short-term grants only.

BCSS has placed Norway in an international leading role in space physics. Our work on hemispheric asymmetries inspired and supported large international initiatives: a dedicated focus group in the US NSF's Geospace Environment Modeling program, the Community for the Unified Study of Interhemispheric Asymmetries at the University of Texas Arlington, and two international teams at the International Space Science Institute in Switzerland. A coming NASA flagship mission, Geospace Dynamics Constellation, has the exploration of interhemispheric asymmetries as one of its science goals, highlighting our work in the final report.

The impact of the ASIM mission has been judged so positively by ESA that the mission has been extended and will be supported at least up to 2025, including two relocations of the payload, one in 2022 and one planned in 2023. BCSS peculiar connection with the microelectronics group, and our leading roles in the design and delivery of space instrumentation, helped Norwegian industry to enter international space projects.

A long track-record of ground-breaking science, merged with successful deliveries of flight hardware, opens unprecedented opportunities for early career researchers to flourish in an environment of world leading merited expertise. In the frame of BCSS, 59 Master and 21 PhD Thesis were delivered. This, in addition to our dedicated teaching programs for high school, bachelor, Master, PhD students, and the organization of four international research schools (with participants from more than 22 institutions and 14 countries), contributes society with a multitude of highly skilled, critical thinking, motivated workforce.

BCSS contributed to the cultural enrichment of the society by a wide range of education, outreach, and dissemination activities, supported by a dedicated Education and Public Outreach group and by a suitable allocation of resources. These activities include:

- Popular science papers (newsletters, commentaries, articles, blogs, anthology, annual reports)
- Targeted outreach via dedicated website, Facebook, YouTube and Twitter (4500+ followers)
- Public outreach events (annual science fair “Forskningsdagene” and “Forsker Grand Prix”, Bergen Science Center “VilVite”, Christie Conference, Bergen Philharmonic Orchestra concert uniting science and art)
- Participation in national/international radio/TV programs
- Press releases resulting in 1000+ news media articles worldwide, often released in partnership with the European Space Agency or the American Geophysical Union
- News stories in New York Times, Scientific American, National Geographic

5. Sources to corroborate the impact

Academic impact:

- Final report of the NASA Geospace Dynamics Constellation, indicating the study of the hemispheric asymmetry as one of its main science goals (science objective 2.6 on page 2-29): https://science.nasa.gov/science-red/s3fs-public/atoms/files/GDC%20STDT%20Report%20FINAL.pdf
- AGU press release on TGFs: https://birkeland.uib.no/agu-press-release-scientists-detect-dark-lightning-linked-to-visible-lightning/
- AGU press releases on ASIM results: https://news.agu.org/press-release/scientists-unveil-new-discoveries-about-gamma-ray-flashes-coming-from-thunderstorms/
- AGU press release on BCSS results on hemispheric asymmetries: https://news.agu.org/press-release/new-study-presents-surprising-explanation-for-differences-in-southern-and-northern-lights/

Education:

- List of Master Thesis: https://birkeland.uib.no/publication/masters-theses/
- List of PhD Thesis: https://birkeland.uib.no/publication/phd-dissertations/
- International research schools on TGFs (https://www.uib.no/ift/127530/birkeland-centre-space-science-bcss-hosts-successful-research-school) and on energetic particle precipitation (https://birkeland.uib.no/solar-impact-on-the-winter-polar-atmosphere-from-space-to-surface/)

Public outreach:

- BCSS news archive: https://birkeland.uib.no/category/highlights2/
- Interview by the Journal Nature to BCSS leader about ASIM results: https://birkeland.uib.no/nature-interview-about-asim-project-with-bcss-leader/
- Media coverage of the ASIM results on the giant magnetar flare: more than 635 media outlet. https://birkeland.uib.no/media-news-about-the-new-asim-observations/
- “picture of the week” at the NASA HEASARC website: https://heasarc.gsfc.nasa.gov/docs/objects/heapow/archive/transients/grb200415_asim.html
- Space Hurricane in National Geographic: https://birkeland.uib.no/space-hurricane-in-national-geographic/

IFT 2

Institution: University of Bergen
Administrative unit: Department of Physics and Technology
Title of case study: Achieving Energy Security with Reduced Carbon Footprint
Period when the underpinning research was undertaken: 2003-2022
Period when staff involved in the underpinning research were employed by the submitting institution: 1981-2022
Period when the impact occurred: 2011-2022

1. Summary of the impact

Transitioning to a carbon-neutral society is a global challenge in urgent need of affordable, low-risk technologies with high public acceptance. Our impact is underpinned by the development, demonstration and verification of such technologies that reduce the carbon footprint of fossil fuels, improve the security and economics of underground CO2 storage and provide sustainable energy production strategies. We emphasize bridging the gap between fundamental research, technology development, and demonstration by deploying a unique multi-scale approach. Our work is within Carbon Capture, Utilization, and Storage (CCUS) and we are at the international forefront of research on 1) CO2 storage in hydrate accumulations with associated natural gas production, 2) Combined CO2 enhanced oil recovery (EOR) and CO2 storage, 3) Advanced in-situ visualization of fluid flow in porous media, and 4) Hydrogen storage and production. Our research impacts the scientific community, industrial stakeholders, and governmental officials involved in addressing challenges related to global energy security and combating climate change. Our efforts have resulted in industry adoption of our technologies through field pilot testing which demonstrated carbon neutral natural gas production and increased CO2 storage volumes in more economically viable CO2 EOR processes. In addition, we have impacted international scientific and educational networks by leading a NORAD project for CCUS education in developing countries in South America, provided an online CCUS courses for more than 200 reservoir engineers in the oil industry and graduated more than 20 PhD and 80 MSc students from 2010-2021. Our work has also impacted society by providing new public outreach tools (FluidFlower CO2 Storage Exhibition at Bergen Natural History Museum) to increase the awareness of methods to mitigate climate change.

2. Underpinning research

Our curiosity-driven multiscale research approach evaluates strategies to use subsurface reservoirs to reduce global CO2 emissions and provide energy security. We start by understanding fundamental multiphase fluid flow physics in porous media using controlled small-scale systems in the laboratory. The governing physics that describe fluid flow are scale dependent because the importance of the acting physical forces vary at different scales. Small-scale flow characteristics at pore-scale, at core-scale and at rock block-scale are used as input into numerical simulators for predicting flow on the reservoir-scale. By experimentally investigating the same fluid flow physics at increasing length scales we are well equipped to upscale from the pore-scale to the field-scale.

We have used microfluidics to experimentally study pore-scale events and CO2 flow at high pressure. In opaque-core scale systems, we have developed quantitative four-dimensional (4D) visualization of CO2 flow, linking the sediment structure to local flow properties by applying MRI and CT imaging at oil companies' research laboratories, combined with medical PET/CT imaging technologies at the University Research Hospital in Bergen. More than 115 students had research terms at ConocoPhillips Research Center, OK, USA. We also derive reservoir-scale simulation modeling parameters from high pressure, high temperature corefloods to predict field scale controls on fluid flow functions. Our experimental and modeling protocol is applied in combination to quantify fluid flow across scales. The focus is to develop technologies to reduce the carbon footprint of fossil fuel energy production, improve the security, sustainability, and economics of underground CO2 storage, and provide new energy production strategies. Two cases of success are outlined below, where the underpinning research went from idea to worldwide patenting, and finally to field piloting within a 9-year period.

Case 1: Carbon neutral gas production from gas hydrates
The idea of storing CO2 in hydrates with associated spontaneous methane production was developed from thermodynamic calculations via experimental laboratory verification to a field pilot, resulting in a worldwide patented technology that may provide carbon neutral fossil energy with zero CO2 emission to the world for 200 years; all within a 9-year period.

Sequestration of CO2 in hydrate reservoirs spontaneously results in natural gas production, with no heat injection and no hydrate melting was proven experimentally in 2004 and the first results published in 2006 (Graue et al, 2006, Kvamme et al 2007). This win-win situation offers thermodynamically long-term CO2 storage and simultaneous access to vast amounts of methane bound in gas hydrates. Every methane molecule released requires a CO2 molecule to be released, so the exchange process is truly carbon neutral. This research, initiated and led by Prof. Graue was a game changer in the hydrate community and sparked a new research front on CH4-CO2 exchange in hydrate bearing sediments. The first successful experimental results proving the concept was conducted by Geir Ersland (MS student at the time) and Jim Stevens in ConocoPhillips laboratory in Bartlesville, Oklahoma: the CH4-CO2 conversion was demonstrated using Magnetic Resonance Imaging (MRI).

After several years of continued research and development, US Dept. Of Energy (USDOE), ConocoPhillips and JOGMEC (Japanese National Oil and Gas Company) performed a field test using our technology. Oil companies and investors in the petroleum industry are very conservative and new investments and implementation of new innovations require large scale field pilots to demonstrate that the technology works outside a laboratory. The final results of the research were achieved after the successful completion of the large-scale experiments performed in the Kuparuk oil field in Alaska in 2011-2012 and published in 2014. The impact of the research was therefore not achieved before the period 2014-2022 where several countries, oil companies and governmental lead academic-industry collaborations were initiated. Due to low gas prices in the USA, the shale gas revolution made it economically challenging to implement the innovative technology in North America. Gas prices and the need for energy, especially in Southeast Asia, |made the technology very attractive in Asia. In 2022, MoUs with two Indian governmental institutions were signed and plans for on- and off-shore field tests made in collaboration with Norwegian, US and Indian stakeholders, including several oil companies, were launched.

Key researchers involved in this case are Principal Investigator (PI) Arne Graue, Professor from 1997 – present; Bjørn Kvamme, Professor from 2000 until he retired in 2020; Geir Ersland, PhD student 2005 – 2008, post doc from 2008-2012 and then Associate Professor from 2012 – present; Jarle Husebø, PhD Student 2005 – 2008; Knut Arne Birkedal, PhD Student 2005 – 2008; with an additional 10 PhD and 40 MSc students graduated from the hydrate research activities.

Case 2: CO2 foam for low carbon oil production
The concept of using mobility control foam in CO2 EOR and CO2 storage applications has been developed and verified in our laboratories over the past 10 years. CO2 foam injection involves injecting a foaming agent (surfactant) with CO2 either simultaneously or in alternating slugs. Foam improves the CO2 mobility ratio relative to oil and water thereby increasing reservoir sweep efficiency and resulting in larger net CO2 retention potentials. An international collaboration was established, including 13 universities/research institutions and 10 oil and service companies in five countries, with the common goal to develop CO2 foam systems from the laboratory and field pilot scale.

Our work has involved extensive screening and verification of increased displacement and CO2 storage with foam, compared to conventional CO2 injection. A CO2 foam system was optimized in the laboratory by Sunniva Fredriksen and Zachary Paul Alcorn in 2018 (PhD Students at the time) under NFR CLIMIT project 249742. Within this project, we also deployed and developed our upscaling methodology to predict field response using numerical modeling (Sharma et al 2020). This laboratory and modeling research culminated in a CO_2 foam pilot in a mature field in the Permian Basin, USA (Alcorn et al. 2019; 2020). We led the design and implementation of the pilot research program which included laboratory screening, modeling and close collaboration with international academic partners and industrial stakeholders. This work demonstrated increased CO_2 storage with foam and reduced operational costs compared to conventional CO_2 injection.

Key researchers involved in this case are Principal Investigator (PI) Arne Graue, Professor from 1997-present; Martin Fernø, PhD student from 2005 – 2008, Post-doc from 2009 – 2012, Associate Professor from 2012 – 2017, and Professor from 2017 – present; Geir Ersland, PhD student 2002 – 2005, and then Associate Professor from 2012 – present; Bergit Brattekås, PhD student 2009 – 2014, and then Researcher from 2014 – present; Zachary Paul Alcorn, PhD student 2015 – 2018, and then Researcher from 2018 – present; Sunniva Fredriksen, PhD student from 2015 – 2018; with an additional 10 PhD and 40 MSc students graduated.

3. References to the research (indicative maximum of six references)

1. Graue, A., Kvamme, B., Baldwin, B.A., Stevens, J., Howard, J., Aspenes, E., Ersland, G., Husebø, J., Zornes, D.R. 2006. Environmentally Friendly CO_2 Storage in Hydrate Reservoirs Benefits from Associated Natural Gas Production. SPE OTC 2006-05-01-2006-05-04. https://doi.org/10.4043/18087-MS
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6. Ersland, G., Hauge, L.P., Gauteplass, J., Graue, A. and Fernø, M.A., Pore-to-Core Imaging of Hydrate Formation using MRI and Silicon Micromodels, 7th International Conference on Porous Media & Annual Meeting, Padova, Italy; 18-21 May 2015.

4. Details of the impact

Our research impacts the scientific community, industrial stakeholders, and governmental officials involved in addressing challenges related to global energy security and climate change mitigation. Performing experiments at multiple scales and with advanced imaging technologies has provided unparalleled quantitative and qualitative insight into dominant storage and displacement mechanisms. Thus, we have addressed scientific challenges of upscaling and visualizing in-situ fluid migration and interactions within opaque porous media. Our work has impacted society by providing new public outreach tools and increased awareness of how to mitigate climate change. Moreover, we have provided much needed insight for accelerating CCUS deployment with impartial, cross-boundary, knowledge-based advice. Our unique pore-to field-scale approach addresses critical knowledge needs to accelerate the time to market of a cost-effective, low environmental impact and resource efficient CCUS technology. We assemble international research teams to address technological and environmental focus areas of importance from a global perspective. Team members from Europe, USA and India represent key regional hubs for CCUS knowledge building and collaboration. In addition, the regional energy and societal challenges presented in each region establish a unique take on offering new, innovative CO2 storage technologies. Although there is growth in Norway with a full-scale CCS project, many other countries have yet to develop CCS due to the high capital costs associated with carbon capture and transport. Therefore, we focus on a robust global strategy through international collaboration and knowledge building to address broad process challenges worldwide. Providing the industry with disruptive CO2 technologies providing industrial revenues in CO2 storage enables CCUS worldwide and may represent an important export technology for Norway.

Our impact cases developed and field-tested CO2 storage technologies that aimed to ensure safe, long-term CO2 storage at minimum costs. Our previous and current research emphasizes patented technologies utilizing CO2 to enhance oil and gas recovery with simultaneous CO2 storage.

Case 1: Carbon neutral gas production from gas hydrates
Our work has shown that exposing natural gas hydrates to CO2 will spontaneously produce methane without adding additional energy (Graue et al, 2006, ref. 1). This win-win situation offers thermodynamically long-term CO2 storage and simultaneously access to vast amounts of methane bound in gas hydrates. Every methane molecule released requires a CO2 molecule to be released, so the exchange process is truly carbon neutral. The significant impact of developing a carbon neutral gas production technology with opportunities of net zero CO2 emission when utilizing fossil energy from methane through hydrogen as energy carrier, represents a disruptive new CCUS technology for the oil industry. Increased methane production offers substitution of coal to gas in power plants globally and thus reduce CO2 emissions by 50%; facilitated with CO2 capture by more than 90%. Net zero CO2 emission is achieved by converting methane to hydrogen, with CO2 as waste product, to be used for reinjection for more methane production from hydrates.

This technology was tested in a field pilot in Alaska in 2012 where a neutral carbon cycle exchange was demonstrated at a large scale, providing energy for the future twice the amount of all fossil fuels combined worldwide. Hydrate technology has been co-patented in 143 countries by the University of Bergen and ConocoPhillips and was successfully tested in a Field Pilot in Alaska in 2012 (see papers for reference). The operator for the field test was ConocoPhillips, but USDOE also contributed US$ 11.6mill. as did the Japanese oil company JOGMEC; all contributors provided a total of US$ 28mill. to complete the field test. The field test produced 800 000scf of methane by injecting 200 000scf of CO2 and then depressurizing the hydrate formation during a huff and puff operation lasting 28 days.

Case 2: CO2 foam for low carbon oil production
From 2019-2020, we led and implemented the CO2 foam pilot for EOR and CO2 storage in a mature oil field in the Permian Basin, USA. Our strategy for performing the field test in Texas was because Texas has available CO2 and infrastructure for CO2 transport to the well head through pipelines, has 45 years of CO2 EOR experience and offers onshore oil fields at very low operating costs. This work demonstrated increased CO2 storage, improved oil recovery, and reduced operational costs with foam, compared to conventional CO2 injection. The pilot resulted in an increase in oil production by nearly 30%, compared to conventional CO2 EOR (amounting to US$ 2mill). In addition, CO2 foam injection was 20% less expensive than conventional CO2 EOR at 70% foam quality because 30% of the injection stream is low-cost surfactant solution, which replaced more expensive purchased CO2. Finally, CO2 foam mobilized oil even when initiated after a mature CO2 flood.

This successful project provided the synergy between the need for increased energy production and the reduction in anthropogenic CO2 emissions. However, additional development is needed to verify foam systems for successful field-wide implementation. Specifically, the previous field pilot demonstrated that remaining oil was mobilized even after years of conventional CO2 flooding. Therefore, we are working to conduct new pilots directly after a completed waterflood to target a larger remaining oil saturation. In addition, laboratory results have shown significantly improved efficiency and economics due to more oil being produced faster and additional CO2 being stored when CO2 foam is injected earlier.

Way Forward
Our recent strategy has been to continue conducting large-scale research experiments by performing optimally designed field pilots to demonstrate the promising research results for industry and stakeholders. The ambition is to encourage the implementation of these new innovations to mitigate climate change, while meeting the growing energy demand worldwide. Preparation of similar field pilots in Europe and India are currently being emphasized. We will transfer knowledge to maximize the oil recovery and CO2 storage potentials on Norwegian Continental Shelf (NCS) to ensure safe, long-term CO2 storage at minimum costs.

During a current one–year research term for Prof. Graue at Rice University in Houston, TX, one new field pilot has been started in Texas and 5 more are in negotiations, including one in the Middle East and one in India. The impact from our CO2 Foam EOR Research is demonstrated by increased interest from the petroleum industry to emphasize CCUS projects to produce more sustainable energy for the future in oil and gas production with simultaneous CO2 storage and reduced carbon footprint. Specifically in the USA, our ambition is to contribute to restarting the US CCUS Flagship Project of the World's largest CO2 capture as retrofit to a coal fired power plant in Texas. We believe that by providing disruptive technologies at improved economic and environmental conditions, along with increased oil prices and with help of the Inflation Reduction Act recently approved by the US Congress, our technology may contribute to restarting a project that was closed in 2021 due to low oil prices and conventional and inefficient CO2 EOR. We are currently in negotiations with the oil company operating the oil field receiving anthropogenic CO2 through the 81-mile-long pipeline from the coal fired power plant, to offer our CO2 Foam EOR Technology for improving oil recovery by CO2 injection.

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IFT 3A

Institution: University of Bergen (UiB)
Administrative unit: Department of Physics and Technology (UiB-IFT)
Title of case study: Finite amplitude systematic errors in acoustic fish abundance measurements
Period when the underpinning research was undertaken: 2000 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2008 - 2021
Period when the impact occurred: 2011 - 2021

1. Summary of the impact

The fisheries industry is the second largest contributor to Norway's economy, after oil and gas. Acoustic stock assessment surveys using echosounders from a fleet of research vessels provide important knowledge basis for management of marine resources by national authorities, allocation of quotas to the fishery fleet, and international agreements and regulations in this respect. Control of systematic errors in the acoustic methods for observation and measurement is crucial.

Norway, by the Institute of Marine Research (IMR) and Kongsberg Maritime AS (KM, formerly Simrad), is in the forefront of fishery research methods and technology. A challenge was identified by KM around 2000, where the performance of new and more accurate echosounder technology was impeded by non-linear distortion and finite amplitude attenuation phenomena in the propagation of acoustic signals in water. It was realized that the observed phenomena could imply significant systematic errors in acoustic fish abundance measurements, both in historical data and for the newest cutting-edge echosounder systems.

The impact case discussed here is the establishment of a traceable theoretical acoustics framework to manage systematic errors in fish abundance estimation and species identification, caused by finite amplitude (non-linear) sound propagation effects in on-ship calibration and survey operation of scientific echosounders.

2. Underpinning research

2.1 Background and challenges (2000-2007)

Echosounder-based acoustic methods are today *the* tool for monitoring the abundance of marine resources, particularly for the most important pelagic species. Regular ship surveys are conducted in fjords and at the continental shelf using scientific echosounders in the 20-500 kHz frequency range. Acoustic scattering theory and sonar processing is used for fish abundance estimation and species identification. Reference data for species identification are obtained by trawl samples. Efforts are currently being made to reduce or eliminate such trawl sampling, for animal protection, and for better utilization of ships and fuel. One also works to enable acoustic data collection by remote-operated and autonomous vehicles, which cannot perform trawl sampling. IMR is responsible for providing abundance data to Norwegian authorities.

Since the 1960-70ies, IMR and KM have collaborated closely and developed world leading methods and instruments for fish abundance estimation using echosounders in ship surveys. These soon became dominant technologies, used by most fisheries nations and research groups worldwide.

In the 1990ies KM (by Helge Bodholt, group leader for transducer development) collaborated with UiB-IFT (by assoc. prof. Magne Vestrheim) to investigate the new piezoelectric composite transducer technologies being introduced in medical ultrasound and underwater acoustics at the time. KM implemented and further developed the technology for use in their echosounder transducers. Advantages of piezoelectric composites relative to the priorly used piezoelectric ceramic technologies include better acoustic coupling to sea water, higher electro-acoustic conversion efficiency, and larger frequency bandwidth.

Around 2000, during testing of a new and more efficient echosounder system with piezoelectric composite transducers, KM (by Frank Tichy, Helge Bodholt, and coworkers) experienced challenges that had not been observed earlier in this application. The transmitted acoustic signals experienced waveform distortion and accompanying excess attenuation at the operating frequency [1]. Possible explanations could be non-linearities in the sound propagation in the water, or possibly cavitation. It was realized that the observed phenomena could imply significant errors in the acoustic methods used for fish abundance estimation and species identification, especially for operational frequencies 100 kHz and higher, and that finding answers to these questions was essential.

In 2000, KM (by Bodholt and Tichy) approached UiB (by Vestrheim) and Christian Michelsen Research (CMR) (by Per Lunde) in Bergen, to make quantitative simulations using the Bergen Code programme for simulation of finite-amplitude sound propagation, developed by Profs. Jaqueline Naze Tjøtta, Sigve Tjøtta and coworkers at UiB in the 1980-90ies. IMR (by Rolf Korneliussen) also announced their strong interest in this work. The efforts resulted in two confidential reports, which later (in 2011) have been revised, down-classified, and made open access [2,3]. The reports strongly indicated that the observations reported by KM were caused by finite amplitude (non-linear) sound propagation effects in the sea.

This situation raised two major questions:

(1) How would these finite amplitude effects – for available and commonly used excitation power levels – affect the accuracy of the fish abundance estimation and species identification measurements, viewed within the conventional theoretical framework used at the time? This conventional theoretical framework neglects finite amplitude effects. The question regards both (i) the routine on-ship single-target calibration of echosounders made before each field survey, and (ii) the acoustic volume backscattering measurements performed in the field surveys.

(2) What maximum excitation power levels would be acceptable in calibration and field surveying for different echosounder frequencies, to keep the resulting errors on abundance estimation and species identification within acceptable limits?

KM and IMR found it necessary to publish preliminary maximum limit recommendations for echosounder power levels [4,6], knowing and communicating that they built on an insufficient scientific foundation. Despite this, due to the importance of the topic and lack of other recommendations, these documents [4,6] have been used as guidelines in the international fishery community up to recently.

The consortium consisting of CMR (by Lunde, project leader), UiB (Vestrheim), IMR (Korneliussen) and KM (Tichy) went on to receive a three-year project grant from NFR (2003-06; NFR MARE program, project no. 152790), educating one PhD candidate (Audun Pedersen). Pedersen's thesis was successfully defended in 2007 [5]. Besides accurate measurement and modelling results confirming and extending the earlier findings [1-3], the thesis proposed "ad hoc" mathematical expressions to account for finite amplitude (non-linear) effects as an extension to the conventional theoretical framework used in fisheries acoustics. The proposed expressions were supported by the laboratory and field survey measurements.

2.2 Impact (2011-2021)

Efforts in 2010-11 to publish the proposed new expressions with supporting field data in a leading international scientific acoustics journal were not successful. A formal theoretical derivation of the proposed mathematical expressions, including the pre-existing conventional mathematical framework they built upon, was called for.

A research program was therefore initiated in 2011 to formally derive a traceable theoretical acoustic framework ("functional relationship") for description and management of errors in scientific fisheries acoustic measurement data, caused by finite amplitude (non-linear) sound propagation effects in calibration and survey operation. The work was initiated and driven by

Per Lunde (from 2008 with UiB), in a collaboration with Audun Pedersen (from 2012 with ClampOn AS; from 2020 with UiB), Rolf Korneliussen (IMR), and Frank Tichy (KM).

From 2012 until 2021 a series of publications [7-13] filled "gaps" in the formal theoretical fundament for single-target and volume scattering in fisheries acoustics, both for small-amplitude (linear) and finite-amplitude (non-linear) sound propagation conditions.

A first formal derivation of the power budget equations including finite amplitude effects in fisheries research echosounder measurements was presented in conference proceedings [7,10] (SSPA-2012, ASA-2015). Only an extract of the mathematical derivation was included [7], omitting essential details. It can be shown that Pedersen's ad-hoc proposed equations [5] are equivalent to those presented in [7,10,12].

A first detailed and relatively complete derivation of the conventional linearized power budget equations for single-target and volume backscattering in fisheries acoustics was presented in [8] (FH-2013). The derivation was limited to small-amplitude (linear) sound propagation conditions in calibration and survey operation of the echosounder. Emphasis was put on clarification of which assumptions, approximations, and limitations that underlie this conventional theoretical framework used in fisheries acoustics.

Alternative formulations of the linearized theory derived in [8] were presented in [9] (FH-2014). A main objective was to formulate a generic (instrument independent) and unifying theory of the power-budget and echo-integrator equations for single-target and volume backscattering, that can explain the different (and often confusing) power-budget and calibration factor formulations in the literature, and how these different (and apparently diverging) formulations are interrelated. This successful work was considered necessary as a fundament for peer-reviewed publishing of the theory for the finite amplitude (non-linear) case [12]. The main results of [9] were published in [11].

In [12] (JMSE-2020), the equations preliminary presented in [7,10] for finite amplitude (non-linear) echosounder operation were formally presented in a peer-reviewed journal publication. A detailed and relatively complete mathematical derivation of the finite-amplitude power budget equations for single-target and volume backscattering in fisheries acoustics was given.

In [13] (AA-2022), the finite-amplitude power budget equations derived in [12] were compared with field survey data collected by Pedersen [5], with agreement mainly within the experimental uncertainty for volume backscattering measurements on fish. It was demonstrated that the framework established in [5,7-13] is functional for describing the measurement of volume backscattering under conditions of significant finite-amplitude sound propagation. Secondly, a method to account for finite-amplitude effects in echosounder calibration was proposed within the same mathematical framework.

This series of publications [5,7-13] finally offer a consistent and traceable theoretical framework ("functional relationship") for single-target and volume backscattering measurement in fisheries acoustics. The equations apply to both small-amplitude and finite-amplitude operation of echosounders and can be used to reduce or correct for finite amplitude effects in calibration and survey operation.

Key researchers of the impact are Principal Investigator (PI) **Per Lunde**, professor 2008–present (Senior scientist 1992-2008 with Christian Michelsen Research AS, Bergen); and **Audun O. Pedersen**, PhD, assoc. prof. 2020–present (R&D Manager 2012-2020 with ClampOn AS, Bergen). External key collaborators are **Rolf J. Korneliussen**, PhD, Head of research, Ecosystem Acoustics, Institute of Marine Research (IMR); and **Frank Tichy**, PhD, R&D Manager, Kongsberg Maritime (KM).

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4. Details of the impact

A traceable theoretical acoustic framework ("functional relationship") has been established for description and management of errors in fish abundance estimation, including acoustic discrimination between species, caused by finite amplitude (non-linear) sound propagation effects [5,7-13]. It applies to low and high-power operation of echosounders. Assumptions and approximations underlying the theory are given in [12]. Comparison with experimental field survey data have given agreement mainly within the experimental uncertainty [13].

It has been demonstrated [13] that the framework established in [5,7-13] is functional for describing the measurement of volume backscattering under conditions of significant finite-amplitude sound propagation. The framework includes consideration of routine on-ship echosounder calibration by means of a reference target. It constitutes a model for quantifying and correcting for finite amplitude sound propagation effects in on-ship calibration and survey operation of fisheries research echosounders [13].

The management of finite-amplitude effects is important for conventional narrowband fisheries acoustic methods, and even more for wideband acoustic methods introduced in recent years.

Of particular interest is the leakage of acoustic energy from low to higher frequency bands through waveform distortion, referred to by some as "nonlinear crosstalk" [16].

Work based on 12,13] is ongoing in the UiB-IMR-KM consortium to replace the tentative recommendations for maximum echosounder excitation power levels [4,6], to reduce or avoid finite amplitude sound propagation effects in calibration and survey operation. A further intention is to propose model-based approaches to manage significant finite-amplitude effects in the sonar processing itself.

An experimentally tested theoretical acoustic framework of this type is important for the international marine research community, for regulation of marine resources by national authorities, quota allocation to the fishery fleet, and international agreements and regulations in this respect. A framework of this type and capability has not previously been available.

Stakeholders include national authorities and fisheries industry in fisheries nations[1]. Stakeholders also include organizations such as the International Council for Exploration of the Seas (ICES), Copenhagen, Denmark, working e.g. through the ICES Working Group on Fisheries Acoustics, Science and Technology (WGFAST) (https://www.ices.dk/community/groups/Pages/WGFAST.aspx).

5. Sources to corroborate the impact

Publications from 2017-2022 citing the impact case publications [5,7-13] include:

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[1] WGFAST membership nations include Norway, United Kingdom, Ireland, Poland, Germany, Netherlands, Belgium, France, Spain, Portugal, Italy, Greece, Iceland, Denmark, Sweden, Finland, Lithuania, Estonia, Latvia (Europe); USA, Canada, Mexico, Chile, Peru (America); Australia, New Zealand (Oceania); India, China, Japan, Repl. Korea (Asia); Senegal, Morocco (Africa).

IFT 3B

Institution: University of Bergen (UiB)
Administrative unit: Department of Physics and Technology (UiB-IFT)
Title of case study: Guided ultrasonic waves (GUW): from fundamental research to industry solutions
Period when the underpinning research was undertaken: 2002-2022
Period when staff involved in the underpinning research were employed by the submitting institution: 1992 - 2022
Period when the impact occurred: 2011-2022

1. Summary of the impact

The impact case discussed here exemplifies how fundamental research, education, and cutting-edge academic results in guided ultrasonic wave physics has been transferred into innovations, company establishment, and new methods and products in industry.

Many industries have critical need for safe and cost-effective methods to monitor and measure production processes and structural integrity in onshore, offshore, and subsea infrastructure. Characterization methods for construction materials is a related and equally important need.

The research group's scientific and educational strategy has enabled both a large academic impact at international level, and a societal impact at national level, by (i) bridging the gap between fundamental research, technology development, and company establishment; (ii) fostering and supporting local international industry; and (iii) educating highly skilled workforce and the next generation of scholared scientists.

2. Underpinning research

GUW fundamental research

Our impact is underpinned by scientific and industrial research at Christian Michelsen Research (CMR, now part of NORCE) and UiB from the mid 1980ies, within (i) ultrasonic fiscal (sales) flow measurement of oil and gas; (ii) full-wave modelling of elastic waves in layered solid-fluid media, including guided ultrasonic waves (GUW); and (iii) finite element modelling and construction of piezoelectric transducers. This includes theoretical, experimental, and constructional work, leading e.g., to prototype commercial fiscal flow meters for oil and gas (1985-2005). Per Lunde (1985-2008 with CMR) and Magne Vestrheim (1985-1992 with CMR; 1992-2013 with UiB) were among the key researchers driving these innovations.

On this fundament, research was initiated in 2002 to develop a next generation of fiscal ultrasonic flow meters, based on GUW. The work was made as part of a three-year CMR-UiB strategic institute programme (SIP, 2003-2006, 18 MNOK) supported by NFR, Statoil and Gassco, initiated and managed by Lunde. The idea was to combine non-invasive clamp-on transducers and leaky Lamb waves to generate a wide-beam sound field in the flow, thus improving the robustness to entrained gas, particles, water, and wear in the flow, relative to traditional multipath flowmeters. A straight pipe without the penetrations found in conventional flowmeters would eliminate contamination and flow disturbance related to transducer cavities. Non-invasive instrumentation is also highly advantageous with respect to the cost and safety of operation and maintenance. Accuracy of fiscal flow metering is always a significant challenge, even for single-phase flow (oil or gas). For two-phase flow (gas in oil, water in oil, liquid in gas), the challenges increase dramatically, and satisfactory solutions have not been available.

Promising results from this initial work was continued in a UiB-CMR Petromaks project (2007-09), supported by NFR and Norsk Hydro. It soon became clear that a fundamental research program including PhD education would be beneficial to the development of GUW-based ultrasonic flow metering. The further research was focused along two "tracks":

(A) Development of GUW-based precision flow measurement methodology and instrument,
(B) Fundamental research to explore and better understand the physical phenomena and acoustic fields occurring in this and other GUW applications.

Track A is described further under Application 1 below. Track B summarized in the following has contributed to significant academic impact, and eventually Applications 2 and 3 below.

At CMR (2007-2011) [2], and from 2009 at UiB [2-8], laboratory experiments and quantitative and powerful mathematical-numerical modelling of GUW measurement systems were built up, providing detailed knowledge of the generation and propagation of leaky Lamb waves in plates and pipes and the generation of wide-beam sound fields in the fluid. Already in 2012 the analytical-numerical and finite element modelling realized in the group was cutting-edge in the international scientific literature [3,4], demonstrating more complete and accurate descriptions of the ultrasonic measurement system than shown by others.

Over the recent ten years, the fundamental research along track B has been largely concentrated on characterizing, modelling, and understanding diffraction and complex beam dispersion effects that are involved in interaction of acoustic beams with zero group velocity (ZGV) points and "backward waves" propagating in fluid-embedded viscoelastic plates. In backward waves (also referred to as dispersion diagram regions of negative group velocity) the elastic wavefronts move in opposite direction of the energy flux. In the lab, previously unknown and anomalous phenomena associated with backward waves and beam diffraction have been discovered and demonstrated in measurements and modelling, like beam enhancement [2,5-8], frequency downshift of certain plate thickness resonances [2,4-8], nearfield beam narrowing [4-8], nearfield beam splitting [8], and nearfield notches [8]. Understanding the physics involved in such wave phenomena is essential in applications like tailored wave propagation and energy redistribution [15], designing mode dispersions for metamaterial concepts [15], fluid and elastic material characterization [10,17,22], measurement of plate and pipe wall thickness, corrosion inspection, and inspection and imaging of discontinuities and defects [22,14,16,18,20,8].

Application 1: GUW helical wide-beam clamp-on flow measurement

The achievements of the GUW-based flow metering experiments under the mentioned SIP (2003-06) and Petromaks (2007-09) projects constituted a promising basis for further industrial development. A series of 7 national and international patents on the technology have been granted (cf. e.g. [1]), constituting a basis for CMR's establishment of the company Xsens AS in 2013 https://xsensflow.com/. In 2022 the number of employees had grown to 13. PI of the early GUW flow metering development, Per Lunde (with CMR 1985-2008; from 2008 with UiB), served as member of Xsens's Scientific Advisory Board 2013-2017. The company is today delivering GUW-based clamp-on flow meters with helical wide-beam technology.

Remi Kippersund (MSc from UiB 2001, scientist with CMR 2001-2016 and working closely with Lunde e.g. on development of industrial multipath liquid flow meter (2001-2006) and GUW deposit detection technologies (2008-2011), from 2016 VP R&D with Xsens) joined the project from 2007, and soon became a key researcher on testing and further technology development. Kippersund has been the main inventor of the helical clamp-on transducer design that is enabled by the GUW approach. The GUW-induced wide-beam improve robustness to entrained gas, particles, water, wear, and pipe deposits, relative to traditional in-line flow meters. The unique helical wide-beam sound field in the fluid covers a larger part of the pipe cross-sectional area, which leads to increased accuracy relative to earlier clamp-on flowmeters that are limited to diagonal acoustic paths. No other company has a similar technology.

Industry applications include liquid flow rate metering (e.g., fiscal allocation metering), liquid gas and wet gas metering, and water-in-oil fraction measurement, using GUW-based external sensors. In 2019 Xsens AS won the prestigious "OTC Spotlight on New Technology Award" price at the Offshore Technology Conference (OTC) in Houston, USA.

Application 2: GUW structural integrity measurement

Recruitment of highly skilled graduates educated and trained in the UiB-IFT group has over the recent years led to introduction of GUW-based inspection methods in the international groups NDT Global and TSC Subsea, under their common parent company, Previan. The NDT Global AS and TSC Subsea AS subdivisions in Bergen emerged (in 2020) from the company Halfwave AS, which in turn was founded as a spin-off from Det Norske Veritas (DNV), Høvik, in 2011. With their proprietary ART (Acoustic Resonance Technology) pipe inspection tools, an ultrasound-based scanning technique allowing high-precision measurements without liquid couplant, Halfwave was active worldwide in the fields of subsea and in-line inspection.

NDT Global AS has hired a total of 5 graduates from the UiB-IFT group: 3 PhD graduates, and 2 MSc researchers (currently under PhD graduation). With this new expertise in the company, and as a supplement to ART, NDT Global has recently introduced GUW-based methods for gas pipe integrity measurement and crack detection [9]. It is based on directional gas coupled GUW generation in the pipe wall, allowing contactless ultrasonic scanning.

Over the recent few years, TSC Subsea has hired 2 MSc graduates from the UiB-IFT group. TSC Subsea focuses on subsea pipe and structural integrity measurement using water-coupled ART tools. In a collaboration with the UiB-IFT group and NORCE, TSC Subsea is currently exploring use of GUW for offshore wind turbine integrity monitoring. The project is part of the SFI Smart Ocean centre for research-based innovation, involving MSc and PhD education. The recruitment of the UIB-IFT graduates has been decisive for the introduction of GUW technology in NDT Global and TSC Subsea.

Application 3: GUW-DAS downhole monitoring for production management

In this application, GUW and DAS (distributed fiber-acoustic sensing) are combined to enable downhole production monitoring in offshore oil-producing wells by local measurement of flow noise. The frequency contents and character of downhole acoustic noise contain information of water/gas breakthrough in the oil producing zone, - information that is essential for production management of the well. Monitoring is enabled using a non-intrusive fiberoptic cable mounted externally on the production pipe, up to several km long. Noise from the oil flow propagates as acoustic and elastic guided waves (GUW) through the piping and fluid annulus to the fiberoptic cable, in which the elastic strain distribution along the cable is measured locally and globally from the topside platform, based on fiberoptic interrogation and optical backscattering (DAS).

Through modelling and experiments, UiB's expertise on GUW is utilized to reveal the underlying physics mechanisms involved in the acoustic propagation from flow noise in the pipe to strain in the fiberoptic cable. Such information may be used to evaluate and optimize the system. Numerical modelling of GUW-DAS measurement systems of this type does not appear to have been available before.

The work is ongoing as part of a Petromaks2 project supported by NFR (DIFI-PRO, 2020-2025), in a collaboration between NORCE (project leader), SINTEF, UiB, Equinor, Lundin (now AkerBP), and Saudi Aramco. Comparisons are made with laboratory experiments at SINTEF's Tiller loop in Trondheim, emulating Equinor's DAS installation at the Johan Sverdrup field. PhD education is an integral part of the work.

Key researchers of the impact

Key researchers of the impact are Principal Investigator (PI) **Per Lunde**, professor 2008 - present (Senior scientist 1992-2008 with Christian Michelsen Research AS, Bergen); **Magne Vestrheim**, assoc. prof. 1992 - 2013; **Magne Aanes,** PhD candidate 2009-2013, assoc. prof. 2014-2017, postdoctoral fellow 2017- 2018 (scientist CMR 2014-2017); **Mathias M. Sæther,** PhD candidate 2014-2018, postdoctoral fellow 2019 - present; **Marianne Solberg**, PhD candidate 2017 – present, and newly hired PhD candidates in the field (2022 – present).

External key contacts and researchers include Magne Husebø, CEO, Xsens AS; Remi Andre Kippersund, Vice President R&D, Xsens AS (MSc from UiB 2001); Magne Aanes, PhD, from

2018 Head of Sensor & Measurement Technology – Gas, NDT Global (MSc 2009 and PhD 2013, both UiB); Renate Grindheim, from 2019 Senior Acoustic Scientist, TSC Subsea (MSc from UiB 2019); Jan M. Kocbach, PhD, Chief Scientist NORCE (MSc 1997 and PhD 2000, both UiB); and Peter J. Thomas, Chief Scientist NORCE.

3. References to the research

[1] Kippersund, R.A., Frøysa, K.-E., **Lunde, P.**, "Flow measuring apparatus", US patent No. US 8,141,434 B2, filed 2010.05.07, granted 2012.03.27. 21 p. http://www.patentbuddy.com/Patent/8141434

[2] Lohne, K. D., **Lunde, P., Vestrheim, M.**, "Measurements and 3D simulation of ultrasonic directive beam transmission through a water-immersed steel plate", Proc. 34th Scand. Symp. Physical Acoustics, Geilo, Norway, Jan. 30 – Feb. 2, 2011, 29 p. http://www.norskfysikk.no/nfs/faggrupper/akustikk2011/index.html

[3] **Aanes, M.**, Lohne, K. D., **Lunde, P., Vestrheim, M.**, "Ultrasonic beam transmission through a water-immersed plate at oblique incidence using a piezoelectric source transducer. Finite element - angular spectrum modeling and measurements", Proc. 2012 IEEE International Ultrasonics Symposium, Dresden, Germany, 7-10 Oct. 2012. 6 p. DOI: 10.1109/ULTSYM.2012.0494.

[4] **M. Aanes,** "Interaction of piezoelectric transducer excited ultrasonic pulsed beams with a fluid-embedded viscoelastic plate. Finite element modeling, angular spectrum modeling and measurements", PhD thesis, University of Bergen, Norway (2014). https://bora.uib.no/bora-xmlui/handle/1956/7891?show=full

[5] **Aanes, M.**, Lohne, K.D., **Lunde, P., Vestrheim, M.**, "Beam diffraction effects in sound transmission of a fluid-embedded viscoelastic plate at normal incidence", J. Acoust. Soc. Am. 140(1), EL67-EL72 (2016). URL: dx.doi.org/10.1121/1.4954893

[6] **M. Aanes**, K.D. Lohne, **P. Lunde, M. Vestrheim**, "Beam diffraction effects in the backward wave regions of viscoelastic leaky Lamb modes for plate transmission at normal incidence", IEEE Trans. Ultrason. Ferroel. Freq. Contr. 64(10), 1558-1572 (2017). DOI: 10.1109/TUFFC.2017.2719627. URL: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7959104&source=authoralert

[7] **Aanes, M.**, Lohne, K.D, Kippersund, R.A., Frøysa, K.-E., **Lunde, P.**, "Time-of-flight dependency on transducer separation distance in a reflective-path guided-wave ultrasonic flow meter at zero flow conditions," J. Acoust. Soc. Am. **142**(2), 825-837 (2017). DOI: http://dx.doi.org/10.1121/1.4996851.

[8] **Sæther, M. M., Midtbø, S., Lunde, P.**, "Interaction of three-dimensional acoustic beam with fluid-loaded solid plate: Axial near- to farfield transmission at normal beam incidence", Ultrasonics **125** (2022), 106795, 13 p. https://doi.org/10.1016/j.ultras.2022.106795

[9] **Aanes, M.**, Haas, M., Andersen, K.A., Talberg, A.S., "Inline-inspection crack detection for gas pipelines using a novel technology", Proc. 14th Intern. Pipeline Conference, Calgary, Canada, Sep. 26-30, 2022.

4. Details of the impact

Guided acoustic waves (GUW) play an increasingly important role in science and technology. GUW can exist in plates, phonon crystals, pipes, shells, hollow cylinders, and multilayered structures of such [19]. GUW enables measurements over short to large distances in solid-fluid structures using a small number of sensors. GUW applications include non-destructive testing and evaluation (NDTE) [16,17,18,20], structural health monitoring (SHM) [14], flow metering [1,11-13], integrity measurement [14], crack detection [9], deposit detection, elastic and fluid material characterization [10,22], adhesion measurement, thickness measurement, corrosion measurement, downhole monitoring, etc. Contact-free GUW excitation and detection using immersion transducers is preferred e.g. when it is important to avoid influencing the structure's mechanical behaviour [14,17,9]. Contact transducers may be used when this is not critical [1].

As part of the impact, the UiB-IFT group has built up laboratory measurement systems to explore GUW, combined with development of advanced 3D modelling tools for accurate and quantitative description of GUW measurement systems, including piezoelectric transducer and acoustic propagation in the fluid and the fluid-immersed structure (e.g., plate) [3,4]. The propagation of piston-generated or real piezoelectric transducer beams at normal or oblique beam incidence to the plate are studied, based on unique own-developed finite element modelling, angular spectrum modelling, and a hybrid combination of these [5-8]. Beam diffraction, playing a very important role in many GUW measurement methods, is studied using these tools. These powerful tools enable study of contact-free excitation and detection of Lamb and leaky Lamb waves e.g. in the frequency bands of backward waves and zero group velocity (ZGV) points. The models represent cutting edge of scientific literature in this area.

Interest in ZGV points is caused e.g. by the possibility of using them to create high-quality acoustic resonators, super-sensitive to changes in the properties of the environment, suitable for development of a new class of acoustic sensors [10]. To date, ZGV resonances have been proposed for a wide range of applications including, for example, determination of Poisson's ratio, measurement of thickness and thickness profiles of plates, and probing of interfacial stiffnesses between two plates [22]. ZGV resonances can be generated and detected up to the GHz frequency regime in micron scale plates, and characterization methods can potentially be developed to determine elastic material properties in this frequency range, which are - although widely used and of great relevance in micro electronics industries - often unknown [22].

With respect to backward waves, similar concepts as what has been realized as a sub wavelength "Veselago" lens for negative refraction in optics, are thinkable in an acoustic waveguide as simple as a metal plate [22]. It has been speculated that broad-angle negative reflection may find application in NDT of structures supporting GUW, and in the development of new acoustic devices including resonators, lenses, and filters [22].

While laser technologies are used to excite and detect GUW in contact-free measurement methods (e.g., [22]), contact-free ultrasonics may be preferred in applications for which robustness is important. Our impact enables studying contact-free immersion methods [2-9], including the changes of backward waves, ZGV resonances, and other GUW modes, with changing fluid loading; fluid type and viscosity; material type, properties and damping; measurement setup; transducer properties, etc. Our impact can be used for exploring the complex physics involved, and for development of characterization measurement methods.

As illustrated (ref. Sect. 2-3, Applications 1-3, etc.), our work on GUW has had large academic impact at international level as well as societal impact for local international industry. The work has bridged gaps between fundamental research and industrial development and contributed to company establishment and creation of high-tech jobs.

The capabilities of the UiB-IFT group to support the mentioned industry applications is a direct consequence of the group's fundamental research programme on GUW phenomena [1-8], closely paired with education, advanced acoustics courses, and experimental and theoretical training, to "create" skilled graduates for industry and science.

5. Sources to corroborate the impact

Selected publications over the period 2017 - 2023 citing/addressing the impact [1-9] include:

[10] A. Smirnov, B. Zaitsev, I. Nedospasov, G. Nazarov, I. Kuznetsova, "Backward acoustic waves in piezoelectric plates: possible application as base for liquid sensors", Sensors, **23**, 648 (2023). https://doi.org/10.3390/s23020648

[11] D. A. Kiefer, A. Benkert, S. J. Rupitsch, "Transit time of Lamb wave-based ultrasonic flow meters and the effect of temperature", IEEE Trans. Ultras., Ferroel., Frequency Control, **69**(10), 2975-2983 (2022)

[12] J. Massaad, P. L. M. J. van Neer, D. M. van Willigen, E. C. Noothout, N. de Jong, M. A. P. Pertijs, M. D. Verweij, "Design and proof-of-concept of a matrix transducer array for clamp-on ultrasonic flow measurements", IEEE Trans. Ultras., Ferroel., Frequency Control, **69**(8), 2555-2568 (2022).

[13] S. Dixon, Z. Li, M. Baker, X. Bushi, L. Smith, "Clamp-on measurements of fluid flow in small-diameter metal pipes using ultrasonic guided waves", IEEE Trans. Ultras., Ferroel., Frequency Control, **70**, 7504403 (2021). https://ieeexplore.ieee.org/document/9570329

[14] E.V. Glushkov, N.V. Glushkova, O.A. Ermolenko, "Simulation of air-coupled transducer operation in structural health monitoring systems", Russian Journal of Nondestructive Testing, **58(**8), 666–678 (2022).

[15] T.J. Graham, J.D. Smith, A.P. Hibbins, J.R. Sambles, T.A. Starkey, "Experimental characterization of acoustic beaming from an elastic plate by coupled symmetric leaky Lamb modes", Phys. Rev. B **104**, 045105 (2021). https://journals.aps.org/prb/abstract/10.1103/PhysRevB.104.045105

[16] P. Kauffmann, M.-A. Ploix, J.-F. Chaix, C. Gueudre, G. Corneloup, F. Baque, "Interferences in the re-emission field of multimodal leaky Lamb waves propagating in an immersed plate: Analytical modelling, simulation and experimentation", Journal of Sound and Vibration **465** (2020) 115015.

[17] E.V. Glushkov, N.V. Glushkova, O.A. Miakisheva, "The distrib. of air-coupled transducer energy among the traveling waves excited in a submerged elastic waveguide", Acoust. Physics, **65**(6), 623–633 (2019).

[18] E.V. Glushkov, N.V. Glushkova, O.A. Miakisheva, "Backward waves and energy fluxes excited in acoustic medium with an immersed plate", Ultrasonics **94**, 158–168 (2019).

[19] B. Zaitsev, I. Kuznetsova, I. Nedospasov, A. Smirnov, A. Semyonov, "New approach to detect. of guided waves with negative group velocity: Modeling and experiment", J. Sound Vibration **442,** 155e166 (2019).

[20] P. Kauffmann, PhD Thesis, Aix-Marseille Univ., France (2018). https://hal.science/tel-01957078/document

[21] I.A. Nedospasov, V.G. Mozhaev I.E. Kuznetsova, "Unusual energy properties of leaky backward Lamb waves in a submerged plate", Ultrasonics **77** 95–99 (2017).

[22] Grünsteidl, C., "Effects and applications associated with zero group velocity Lamb waves", Johannes Kepler Univ. Linz, Austria (2017). https://epub.jku.at/obvulihs/download/pdf/1756743?originalFilename=true

[KI] [case number 1]

Institution: University of Oslo
Administrative unit: Department of Chemistry
Title of case study: Environmental impact of amine-based CO_2 capture
Period when the underpinning research was undertaken: 2009-2022
Period when staff involved in the underpinning research were employed by the submitting institution: 2009-2022
Period when the impact occurred: 2009-2022

1. Summary of the impact (indicative maximum 100 words)

Capturing CO_2 released from industrial point sources with amine solutions is nowadays recognized as a technologically mature and important method for reducing anthropogenic greenhouse gas emissions. When the use of this technology was first proposed in Norway two decades ago, concerns were raised about potential environmental and health impacts of amine emissions and the formation of harmful by-products (*e.g.*, nitrosamines). The Atmospheric Chemistry (AtmChem) group has studied these processes in detail for the last 15 years, thereby supporting the industry and authorities in their efforts to characterize and minimize the environmental risks associated with the large-scale deployment of this technology.

2. Underpinning research (indicative maximum 500 words)

When the problem of amine emissions and by-product formation was first raised 15 years ago, no measurement tools were available for characterizing these processes. Proton-transfer-reaction mass spectrometry (PTR-MS) had been developed at the University of Innsbruck (UIBK) in Austria in the mid-1990ies, and Dr. Armin Wisthaler had pioneered its use in atmospheric chemistry studies in the early 2000s. In the late 2000s, the optimization and characterization of the PTR-MS technology for the detection of amines and amine by-products became a focus of Dr. Wisthaler's work at UIBK. It remained in the focus when Dr. Wisthaler was appointed the Professor of Atmospheric Chemistry at UiO in 2014 and method development work extends to the present time (*e.g.*, Håland et al., 2022)

The atmospheric degradation of amines with a focus on the formation of nitrosamines, nitramines and other harmful substances was studied in the three "*Atmospheric Degradation of Amines*" (ADA 2009, ADA 2010, ADA 2011) projects and the "*Atmospheric Chemistry of Amines*" (ACA, 2015-2019) project funded by Norway's national programme for research, development and demonstration of CO_2 capture and storage technology CLIMIT. Prof. Claus J. Nielsen performed theoretical atmospheric chemistry studies and led a team of international researchers in experimental studies at the European Photoreactor (EUPHORE) in Spain. The work provided detailed insights into the atmospheric degradation mechanism of a variety of amines used for CO_2 capture (*e.g.*, Nielsen et al., 2012a,b). Importantly, the results also allowed to quantify the amount of nitrosamines and nitramines formed downwind of a CO_2 capture facility (*e.g.*, Tan et al., 2021).

The AtmChem group also measured the emissions of amines and amine degradation products at the Technology Centre Mongstad (TCM) and at a pilot CO_2 capture unit installed at the waste incinerator in Klemetsrud, Oslo. Continuous emission measurements have been carried out at TCM since 2013 in the frame of the three "*Amine Research and Monitoring*" (ARM) projects (2013-2017, 2018-2020, 2021-2023). The collaboration with TCM was initiated by Prof. Claus J. Nielsen and later continued by Prof. Armin Wisthaler. A variety of vendors (Aker Clean Carbon, Shell Cansolv, Carbon Clean Solutions, ION Clean Energy, FLUOR, Mitsubishi Heavy Industries, RTI International) tested and optimized their amine technologies at TCM, profiting from UiO's high-quality emission data. UiO's data were also used by TCM for ensuring safe operation, fulfilling emission-reporting duties and for optimizing emission reduction strategies (*e.g.*, Morken et al., 2014). The AtmChem group also carried out emission measurements during two test campaigns at the Klemetsrud pilot plant in 2019 and 2021, respectively. Amine emissions were found to be low, dispelling public and authority concerns over amine emissions in a densely populated area (Fagerlund et al., 2021).

3. References to the research (indicative maximum of six references)

A. Håland, T. Mikoviny, E. E. Syse, A. Wisthaler, On the development of a new prototype PTR-ToF-MS instrument and its application to the detection of atmospheric amines, Atmos. Meas. Tech. 15, 6297–6307, doi: 10.5194/amt-15-6297-2022 (2022)

J. Fagerlund, R. Zevenhoven, J. Thomassen, M. Tednes, F. Abdollahi, L. Thomas, C. J. Nielsen, T. Mikoviny, A. Wisthaler, L. Zhu, C. Biliyok, A. Zhurkin, Performance of an amine-based CO_2 capture pilot plant at the Klemetsrud waste incinerator in Oslo, Norway, Int. J. Greenh. Gas Con. 106, 103242, doi: 10.1016/j.ijggc.2020.103242 (2021)

W. Tan, L. Zhu, T. Mikoviny, C. J. Nielsen, A. Wisthaler, B. D'Anna, S. Antonsen, Y. Stenstrøm, N. J. Farren, J. Hamilton, G. Boustead, A. Brennan, T. Ingham, D. Heard, Experimental and theoretical study on the OH-Initiated degradation of piperazine under simulated atmospheric conditions, J. Phys. Chem. A 125(1), 411-422, doi: 10.1021/acs.jpca.0c10223 (2021)

A. K. Morken, B. Nenseter, S. Pedersen, M. Chhaganlal, J. K. Feste, R. B. Tyborgnes, Ø. Ullestad, H. Ulvatn, L. Zhu, T. Mikoviny, A. Wisthaler, T. Cents, O. M. Bade, J. Knudsen, G. de Koeijer, O. Falk-Pedersen, E. S. Hamborg, Emission results of amine plant operations from MEA testing at the CO2 Technology Centre Mongstad, Energy Procedia 63, 6023-6038, doi: 10.1016/j.egypro.2014.11.636 (2014)

C. J. Nielsen, H. Herrmann, C. Weller, Atmospheric chemistry and environmental impact of the use of amines in carbon capture and storage (CCS), Chem. Soc. Rev. 41(19), 6684-6704, doi: 10.1039/c2cs35059a (2012a)

C. J. Nielsen, B. D'Anna, R. Bossi, A. J. C.Bunkan, L. Dithmer, M. Glasius, M. Hallquist, A. M. K. Hansen, A. Lutz, K. Salo, M. M. Maguta, Q. Nguyen, T. Mikoviny, M. Müller, H. Skov, E. Sarrasin, Y. Stenstrøm,Y. Tang , J. Westerlund, A. Wisthaler, Atmospheric Degradation of Amines (ADA). Summary report from atmospheric chemistry studies of amines, nitrosamines, nitramines and amides, ISBN 978-82-992954-7-5, University of Oslo, Oslo, Norway (2012b)

4. Details of the impact (indicative maximum 750 words)

Norway has considered CO_2 capture and storage (CCS) as a key option for achieving its commitments to the Kyoto protocol since the mid-2000s. In 2006, the Norwegian Ministry of Petroleum and Energy and the former Statoil agreed to establish the European CO_2 Test Centre Mongstad (TCM). The world's largest facility for developing CO_2 capture technologies was inaugurated six years later. In 2009, a master plan for capturing CO_2 at full scale from the Mongstad gas power plant was submitted. The formation of carcinogenic nitrosamines emerged as a potential showstopper for amine-based CO_2 capture technology, but the ADA projects (see 2.) produced extensive basic knowledge on amine degradation products (Nielsen et al., 2010, 2011, 2012a,b; Tan et al. 2021a,b), thereby supporting the Norwegian Institute of Public Health in characterizing the risks associated with emissions from amine-based CO_2 capture. Major environmental and health concerns were alleviated, but the full-scale project described as Norway's "moon landing" was called off for economic reasons in late 2013, which lead to several years of stagnation in the field of CCS in Norway. Meanwhile Dr. Wisthaler was appointed Professor of Atmospheric Chemistry at UiO in 2014. He continued research into emissions of amines at TCM and established PTR-MS as the method of choice for online emission monitoring from amine-based CO_2 capture plants (Fagerlund et al., 2021; Languille et al., 2021a,b). A variety of vendors tested and optimized their amine technologies at TCM, profiting from UiO's high-quality emission data. UiO's data were also used by TCM for ensuring safe operation, fulfilling emission-reporting duties and for optimizing emission reduction strategies. PTR-MS measurements at a CCS pilot plant at Oslo's waste incinerator in 2019 and 2021 dispelled public and authority concerns over amine emissions in a densely populated area (Fagerlund et al., 2021). In 2020, Norway decided to implement the world's first full-scale CO_2 capture, transport and storage project ("Longship"), which includes two full-scale amine-based CO_2 capture plants at Oslo's waste incinerator and a cement plant in Porsgrunn, respectively. CCS is now

recognized as an important option for mitigating climate change, and several amine plants are currently being built or planned throughout the world. After years of basic research and collecting experience in pilot operations, UiO is at the forefront in supporting both the industry and the authorities with environmental monitoring solutions and impact assessments.
It is important to note that the AtmChem group is also supporting other industries (*e.g.*, indoor air purification, plasma-based purification of industrial gases, car exhaust aftertreatment) in their efforts to develop environmentally safe solutions.

5. Sources to corroborate the impact (indicative maximum of ten references)

B. Languille, A. Drageset, T. Mikoviny, E. Zardin, C. Benquet, Ø. Ullestad, M. Aronson, E. R. Kleppe, A. Wisthaler, Atmospheric Emissions of Amino-Methyl-Propanol, Piperazine and Their Degradation Products During the 2019-20 ALIGN-CCUS Campaign at the Technology Centre Mongstad (March 25, 2021). Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, Available at SSRN: https://ssrn.com/abstract=3812139 or http://dx.doi.org/10.2139/ssrn.3812139 (2021a)

B. Languille, A. Drageset, T. Mikoviny, E. Zardin, C. Benquet, Ø. Ullestad, M. Aronson, E. R. Kleppe, A. Wisthaler, Best practices for the measurement of 2-amino-2-methyl-1-propanol, piperazine and their degradation products in amine plant emissions (March 18, 2021). Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, Available at SSRN: https://ssrn.com/abstract=3812339 or http://dx.doi.org/10.2139/ssrn.3812339 (2021b)

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C. J. Nielsen, H. Herrmann, C. Weller, Atmospheric chemistry and environmental impact of the use of amines in carbon capture and storage (CCS), Chem. Soc. Rev. 41(19), 6684-6704, doi: 10.1039/c2cs35059a (2012b)

C. J. Nielsen, B. D'Anna, R. Bossi, A. J. C.Bunkan, L. Dithmer, M. Glasius, M. Hallquist, A. M. K. Hansen, A. Lutz, K. Salo, M. M. Maguta, Q. Nguyen, T. Mikoviny, M. Müller, H. Skov, E. Sarrasin, Y. Stenstrøm,Y. Tang , J. Westerlund, A. Wisthaler, Atmospheric Degradation of Amines (ADA). Summary report from atmospheric chemistry studies of amines, nitrosamines, nitramines and amides, ISBN 978-82-992954-7-5, University of Oslo, Oslo, Norway (2012a)

C. J. Nielsen, B. D'Anna, M. Karl, M. Aursnes, A. Boreave, R. Bossi, A. J. C. Bunkan, M. Glasius, M. Hallquist, A. M. K. Hansen, K. Kristensen, T. Mikoviny, M. M. Maguta, M. Müller, Q. Nguyen, J. Westerlund, K. Salo, H. Skov, Y. Stenstrøm, A. Wisthaler, Atmospheric Degradation of Amines (ADA). Summary report: Photo-oxidation of methylamine, dimethylamine and trimethylamine, NILU REPORT OR 2/2011, ISBN: 978-82-425-2357-0 (printed), 978-82-425-2358-7 (electronic) (2011)

C. J. Nielsen, B. D'Anna, C. Dye, C. George, M. Graus, A. Hansel, M. Karl, S. King, M. Musabila, M. Müller, N. Schmidbauer, Y. Stenstrøm, A. Wisthaler, Atmospheric Degradation of Amines (ADA). Summary report: Gas phase photo-oxidation of 2-aminoethanol (MEA), NILU REPORT OR 8/2010, ISBN: 978-82-425-2173-6 (printed), 978-82-425-2172-9 (electronic) (2010)

[KI] [case number 2]

Institution: University of Oslo
Administrative unit: Department of Chemistry, Catalysis Section
Title of case study: UiO-66 metal organic frameworks
Period when the underpinning research was undertaken:
Period when staff involved in the underpinning research were employed by the submitting institution: Lillerud (19XX-present); Tilset (1989-present); Olsbye (2001-present)
Period when the impact occurred: 2005-2022

1. Summary of the impact (indicative maximum 100 words)

Researchers in the Catalysis Section discovered and developed a novel series of nanoporous materials – the UiO-66 family of metal organic framework compounds. These zirconium based MOFs had unprecedented thermal and chemical stability. This was a breakthrough discovery that shifted the field away from being a scientific curiosity and paved the way for use of these materials in applications such as separation and catalysis. These materials have profoundly influenced and changed this field of chemical science, led to patents and a thriving start up business, and constitute the foundation for an ERC-SYNERGY grant.

2. Underpinning research (indicative maximum 500 words)

The underpinning research has been performed in the Catalysis Section over a period starting ca. 2005, and is still ongoing. Professor Karl Petter Lillerud, an expert in porous inorganic materials (zeolites), embarked on a fundamental, exploratory investigation into the preparation of an appearing class of porous materials, the metal organic frameworks. A key factor that facilitated the research was a tight collaboration with fellow Professors in the Catalysis Section; Professor Unni Olsbye and Professor Mats Tilset. This trio jointly hold the competence in inorganic synthesis and structure, organometallic and organic synthesis, and heterogeneous catalysis that was required for the impact to occur. A final, key component is a close collaboration with characterization experts at the University of Turin.

The research has been carried out by a number of master students, PhD candidates, and postdocs with combined Departmental, Research Council of Norway, and European funding: over this period: Jasmina Hafizovic (master/PhD: 2004-2008), Kai Chung Szeto (master/PhD: 2005-2008); Søren Jakobsen (master/PhD: 2006-2011), Merete H. Nilsen (researcher: 2005-2010); Mathivathani Kandiah (researcher: 2008-2011); Sigurd Øien-Ødegaard (master/PhD/researcher: 2010-2021); Greig Charles Shearer (PhD: 2011-2015); Sachin Chavan (researcher: 2014-2019); Knut Hylland Tormodssønn (master/PhD: 2014-2020); Guiseppe Rotunno (PhD: 2016-2022); Volodymyr Levchenko (PhD: 2017-2020); Gurpreet Kaur (PhD: 2017-2020); Andrea Lazzarini (researcher: 2017-2019); Sebastian Gutterød (PhD: 2017-2020);Mustafa Kumørcu (PhD: 2018-2021); Erlend Aunan (PhD: 2019-2022).

The first primary research breakthrough was the discovery of the UiO-66 series of Zirconium based metal organic framework compounds [Paper 1]. These materials were demonstrated to have unprecedented chemical and thermal stability, as well as tunable porosity. Importantly, the structure of the material was solved from X-ray data by Prof. Lillerud during a sabbatical at the University of Versailles. This period of uninterrupted research was paramount to analyse the complex data and to unleash the impact of the discovery.

The second major research step was to learn the ability to apply the toolbox of the organic chemist (Prof. Tilset) to modify MOFs by doing organic synthesis steps on the organic linker molecules and develop custom made linkers to create tailored materials, as exemplified Paper 2.

Third, the field was initially held back by poorly reproducible syntheses, and the understanding of how the synthesis conditions could affect the properties of the materials of interest was rudimentary. Through systematic research over a period of several years, it became possible to understand how the synthesis conditions could be tuned to lead to defects that both control the properties of the materials and can be used as an access point for functionalization [Paper 3].

Finally, applications emerge. In 2012 [Paper 4], UiO MOFs were investigated for hydrogen storage. In 2020 and 2021, however, two seminal contributions were published (Prof. Olsbye), in which UiO materials were used as heterogeneous catalysts in high temperature gas phase catalysis. Nickel functionalized UiO MOFs were used as catalysts for ethene dimerization [Paper 5], and Platinum functionalized materials for CO2 hydrogenation [Paper 6].

The principal investigators responsible for the research are:

Professor **Karl Petter Lillerud** (material science, structural chemistry)
Professor **Unni Olsbye** (heterogeneous catalysis, porous materials)
Professor **Mats Tilset** (organometallic chemistry, organic synthesis).

An extensive, decade long collaboration with experts in material characterization (spectroscopy and synchrotron science), Professors Silvia Bordiga and Carlo Lamberti (University of Turin, Italy) was decisive to understand and unleash the potential of the novel materials.

3. References to the research (indicative maximum of six references)

Paper 1 (4 386 citations): **"A New Zirconium Inorganic Building Brick Forming Metal Organic Frameworks with Exceptional Stability" J. Hafizovic Cavka, S. Jakobsen, U. Olsbye**, N. Guillou, C. Lamberti, S. Bordiga, **K.P. Lillerud,** Journal of the American Chemical Society 130 (2008) 13850-13851. DOI: 10.1021/ja8057953

Paper 2 (1 279 citations): "**Synthesis and Stability of Tagged UiO-66 Zr-MOFs**" **M. Kandiah, M. Hellner Nilsen**, S. Usseglio, **S. Jakobsen, U. Olsbye, M. Tilset**, C. Larabi, E. Alessandra Quadrelli, F. Bonino, **K.P. Lillerud**, Chemistry of Materials 22 (2010) 6632-6640.

Paper 3 (482 citations): "**Tuned to Perfection: Ironing Out the Defects in Metal−Organic Framework UiO-66**" **G. C. Shearer, S. Shavan,** J. Ethiraj, J. G. Vitillo, **S. Svelle, U. Olsbye,** C. Lamberti, S. Bordiga, **K. P. Lillerud**, Chemistry of Materials 26 (2014) 4068-4071. DOI: 10.1021/cm501859p

Paper 4 (347 citations): "**H2 storage in isostructural UiO-67 and UiO-66 MOF**" **S. Chavan**, J.G. Vitillo, D. Gianolio, O. Zavorotynska, B. Civalleri, **S. Jakobsen, M.H. Nilsen**, L. Valenzano, C. Lamberti, **K.P. Lillerud**, S. Bordiga, Physical Chemistry Chemical Physics, 14 (2012) 1614-1626 DOI: 10.1039/c1cp23434j

Paper 5 (9 citations): **"Co-catalyst free ethene dimerization over Zr-based metal-organic framework (UiO-67) functionalized with Ni and bipyridine" M. Kømurcu, A, Lazzarini, G, Kaur, E. Borfecchia, S. Øien-Ødegaard,** D. Gianolio, S. Bordiga, **K.P. Lillerud, U. Olsbye**, Catalysis Today 369 (2021) 193-202. DOI: 10.1016/j.cattod.2020.03.038

Paper 6 (76 citations): "**Hydrogenation of CO2 to Methanol by Pt Nanoparticles Encapsulated in UiO-67: Deciphering the Role of the Metal-Organic Framework**" **E. S. Gutterod, A. Lazzarini, T. Fjermestad, G. Kaur, M, Manzoli,** S. Bordiga, **S. Svelle, K. P.**

Lillerud, E, Skúlason, **S, Øien-Ødegaard, A, Nova, U. Olsbye,** Journal of the American Chemical Society, 142 (2020), 999-1009. DOI: 10.1021/jacs.9b10873

4. Details of the impact (indicative maximum 750 words)

The UiO-66 series of Zirconium based metal organic framework compounds possess exceptional chemical and thermal stability. When this stability was coupled to the richness in the chemistry inherent to this class of hybrid organic-inorganic materials, a tremendous potential for research and applications within very diverse fields could be explored. We shall highlight the impact of the UiO-66 materials within three areas:

1) Innovation and commercialization
2) Impact on the international research field
3) Impact on the Catalysis Section at the University of Oslo

The UiO-66 class of MOF materials have been protected by several patents [Patents 1-3], relying on the involvement of the UiO technology transfer office, Inven2. Having protected the IP made it possible to establish a startup business – ProfMOF [Weblink 1] – which specializes in bringing *excellent* MOFs to the market. Prof. Karl Petter Lillerud is Chief Executive Officer of ProfMOF. The vision of *excellence* in MOF product stems directly from the mastery of synthesis protocols to allow superior stability [Paper 1 and 3]. The UiO-66 patents have generated ca. 15 MNOK of income to UiO, Inven2, and the inventors. The establishment of ProfMOF was facilitated by a FORNY project (ca. 12 MNOK total budget), funded by the Research Council of Norway. ProfMOF is now a thriving startup with three employees, active towards diverse applications [e.g. Weblink 2]. Moreover, ProfMOF has engaged in bilateral collaborations with more than one company holding a top 10 position on the Fortune 500 list of the largest American companies (confidential, no corroborating source provided).

The breakthrough discovery of stable metal organic framework compounds have had tremendous impact on this area of research. In particular, the ability to tune properties and functionality [Papers 2, 4-6] has paved the way for applications of UiO-66 MOFs in very diverse fields, such as adsorption and separation, gas phase heterogeneous catalysis, photo- and electrocatalysis, sensors, healthcare/drug delivery, etc. It is hard to quantify this impact, but we estimate that hundreds of PhD theses worldwide are centred on the UiO-66 class of MOF materials. A search on google for UiO-66 returns ca. 5 500 000 hits [Weblink 3]. The same search on google scholar returns 50 000+ scientific hits [Weblink 4].

Finally, the UiO-66 materials have created strong visibility for the Catalysis Section at the University of Oslo, and provided an opportunity to try to bridge the gap between enzymatic catalysis and gas phase heterogeneous catalysis. Stable and tunable metal organic framework compounds are the ideal scaffold for hosting catalytically active metal centers that mimic the reactivity and specificity of enzyme catalysts found in nature. Thus, the discovery and development of the UiO-66 series of metal organic frameworks has opened up a new direction for research and led to the establishment of new scientific collaborations, e.g. with leading scientists at the Norwegian University of Life Sciences (Professor Vincent Eijsink, enzymologist) and the Max-Planck Institute for Chemical Energy Conversion (Professor Serena De Beer, spectroscopist). This collaboration, comprising also Professor Silvia Bordiga is structured within a very prestigious ERC-SYNERGY project. The CuBE project was awarded in 2019, and Professor Unni Olsbye is the coordinating principal investigator [Weblink 5].

5. Sources to corroborate the impact (indicative maximum of ten references)

Patent 1 . "Metal organic framework compounds" J. Hafizovic, U. Olsbye, K.P. Lillerud, S. Jacobsen, N. Guillou, WO2009133366 (2009); EP2291384B1 (2011); US9114348B2 (2015).

Patent 2 - "Process for preparing a zirconium-based metal organic framework" H. Reinch, K.P. Lillerud, S. Chavan, U. Olsbye, WO2016046383A1 (2016).

Patent 3 - "Process for the preparation of zirconium based MOFs" K.P. Lillerud, U. Olsbye, S. Chavan, WO2018046930A1 (2018)

Weblink 1 – ProfMOF start up webpage: https://profmof.com/

Weblink 2 - Extraction of Lithium ions: https://www.innomag.no/skal-utvinne-litium-ved-bruk-av-avanserte-nanomaterialer/

Weblink 3 – Google search for UiO-66; 5 000 000+ hits: https://www.google.com/search?q=UiO+66

Weblink 4 – Publications on UiO MOFs, 50 000+ hits for articles on google scholar: https://scholar.google.com/scholar?hl=no&as_sdt=0%2C5&q=%22UiO-66%22&btnG=

Weblink 5 – ERC SYNERGY project CuBE: https://www.cube-synergy.eu/

[KI] [case number 3]

Institution: University of Oslo
Administrative unit: Department of Chemistry
Title of case study: Dalton quantum chemistry program system
Period when the underpinning research was undertaken: 1981–2021
Period when staff involved in the underpinning research were employed by the submitting institution: **Prof. Trygve Helgaker (1981–1986,1989–),** **Prof. Thomas Bondo Pedersen (2009–),** **Sen. Engineer Simen Reine (2010–),**
Period when the impact occurred: 1997–2021

1. Summary of the impact

Dalton is a powerful general-purpose open-source program system for the study of molecular electronic structure at various levels of theory. It is known for its broad ~~f~~and advanced functionality for the calculation of molecular properties. The code reflects the research interests of a Scandinavian school of quantum chemist, who over the last 40 years have made several seminal contributions to the field. The implementation of these contributions in Dalton has brought these advances to the community of computational chemists, in academia and in industry, at no cost. Moreover, several ideas were first implemented in Dalton and later adapted by other, commercial and academic, quantum chemistry packages in routine use today, significantly increasing the impact by indirect routes. This is an extremely important, but hard to measure, impact of high-quality academic research.

2. Underpinning research

The Dalton quantum chemistry program system is a general-purpose open-source program for *ab initio* molecular electronic-structure calculations, with many users world-wide. Its impact follows from its powerful capabilities for calculation of molecular electromagnetic properties.

Dalton is the result of a collaboration among Scandinavian quantum chemists who have been in the forefront of the development of quantum chemistry for more than four decades. The capabilities of Dalton reflect their contributions to theoretical chemistry — most importantly in the area of molecular properties. The Dalton code, which now contains more than 2.2 million code lines, is best viewed as the by-product of research in theoretical chemistry rather than as a code designed by software engineers for computational chemists. Still, Dalton is not only a toolbox for research in electronic-structure theory — its broader impact stems from the fact that it has been downloaded and used by thousands in academy and industry since its first public release in 1997.

The underpinning research for Dalton can be traced back to an early Scandinavian interest in the calculation not only of total energies of molecules but also their properties, calculated as the response of the electrons to internal and external perturbations. Three early developments served as the initial impetus for what became Dalton: second-order multiconfigurational self-consistent field theory by Hans-Jørgen Jensen (Aarhus) and Hans Ågren (Uppsala) in 1984 implemented in SIRIUS, a formalism for time-independent properties by Trygve Helgaker (Oslo) in 1985 implemented in ABACUS, and response theory by Poul Jørgensen and Jeppe Olsen (Aarhus) in 1985 implemented in REPONS [1]. These developments were all formulated in a unified manner, using the formalism of second quantization [2], which has proven to be an enormously flexible framework for all subsequent developments.

In 1995, the Oslo group proposed to merge these codes into a single code, Dalton. The merge was carried out in Oslo. Dalton was first released in 1997 and distributed free of charge from Oslo.

Subsequent releases reflected new theoretical developments such as coupled-cluster theory, density-functional theory, and linear-scaling techniques [1]. At all levels of theory, a wide variety of molecular properties are available, describing interactions with electromagnetic fields, spectroscopic parameters (including NMR and EPR, rovibrational, electronic and x-ray spectroscopies) [3,4], thereby making Dalton unique.

Dalton was made open source in 2017 [5]. The status of the code is described in Ref. 1, which contains a reference to 154 papers that provide the theoretical background for Dalton and illustrative applications of the code. Among the 84 authors of this paper, 22 contributed from Oslo. Later developments have focused on setting up a more flexible Python platform for Dalton [6].

The following are key contributors to Dalton, now with permanent positions at KI:

Trygve Helgaker, research assistant (1981–1985), professor (1989–)
Thomas Bondo Pedersen, researcher (2009–2012), professor (2012–)
Simen Reine, PhD student (2004–2009), researcher (2010–14), senior engineer (2014–)

3. References to the research

1. K. Aidas, C. Angeli, K. L. Bak, V. Bakken, R. Bast, L. Boman, O. Christiansen, R. Cimiraglia, S. Coriani, P. Dahle, E. K. Dalskov, U. Ekström, T. Enevoldsen, J. J. Eriksen, P. Ettenhuber, B. Fernández, L. Ferrighi, H. Fliegl, L. Frediani, K. Hald, A. Halkier, C. Hättig, H. Heiberg, **T. Helgaker***, A. C. Hennum, H. Hettema, E. Hjertenæs, S. Høst, I.-M. Høyvik, M. F. Iozzi, B. Jansík, H. J. Aa. Jensen, D. Jonsson, P. Jørgensen, J. Kauczor, S. Kirpekar, T. Kjærgaard, W. Klopper, S. Knecht, R. Kobayashi, H. Koch, J. Kongsted, A. Krapp, K. Kristensen, A. Ligabue, O. B. Lutnæs, J. I. Melo, K. V. Mikkelsen, R. H. Myhre, C. Neiss, C. B. Nielsen, P. Norman, J. Olsen, J. M. H. Olsen, A. Osted, M. J. Packer, F. Pawlowski, T. B. Pedersen, P. F. Provasi, S. Reine, Z. Rinkevicius, T. A. Ruden, K. Ruud, V. V. Rybkin, P. Sałek, C. C. M. Samson, A. Sánchez de Merás, T. Saue, S. P. A. Sauer, B. Schimmelpfennig, K. Sneskov, A. H. Steindal, K. O. Sylvester-Hvid, P. R. Taylor, A. M. Teale, E. I. Tellgren, D. P. Tew, A. J. Thorvaldsen, L. Thøgersen, O. Vahtras, M. A. Watson, D. J. D. Wilson, M. Ziolkowski, and Hans Ågren,
The Dalton quantum chemistry program system, *WIREs Comput. Mol. Sci.* **4**, 269–284 (2014), DOI:10.1002/wcms.1172

   Invited paper describing the Dalton program package in 2014, with 84 co-authors. Trygve Helgaker is the invited, corresponding author. In addition, Thomas Bondo Pedersen and Simen Reine are co-authors of this paper. The paper contains 154 references to scientific publications describing the methods and algorithms implemented in Dalton. *1073 WoS citations.*

2. T. Helgaker, J. Olsen, and P. Jørgensen, *Molecular Electronic-Structure Theory*, Wiley, Chichester, 2000 (hardback); 2013 (paperback).

   Widely used, extensive monograph of electronic-structure theory, using second quantization, written by three of the original Dalton authors. The formalism presented here reflects the implementation in Dalton. *3936 Google Scholar citations.*

3. T. Hegaker, **M. Jaszunski**, and K. Ruud, *Ab Initio Methods for the Calculation of NMR Shielding and Indirect Nuclear Spin–Spin Constants*, *Chem. Rev*. **99**, 293–352 (1999); DOI: 10.1021/cr960017t

Invited review on the calculation of magnetic properties. *1258 WoS citations*.

4. **T. Helgaker**, S. Coriani, P. Jørgensen, K. Kristensen, J. Olsen, and K. Ruud, *Recent Advances in Wave Function.Based Methods of Molecular-Property Calculations, Chem. Rev.* **112**, 543–631 (2012); DOI: 10.1021/cr2002239

Invited review paper, describing the methods underling the implementation of properties in Dalton. All authors are contributions to Dalton; Helgaker is the invited author. *444 WoS citations*.

5. Homepage for Dalton: https://daltonprogram.org

6. J. M. H. Olsen, S. Reine, O. Vahtras, E. Kjellgren, P. Reinholdt, K. O. H. Dundas, X. Li, J. Cukras, M. Ringholm, E. D. Hedegård, R. Di Remigio, N. H. List, R. Faber, B. N. C. Tenorio, R. Bast, T. B. Pedersen, Z. Rinkevicius, S. P. A. Sauer, K. V. Mikkelsen, J. Kongsted, S. Coriani, K. Ruud, T. Helgaker, H. J. Aa. Jensen, and **P. Norman**, *Dalton Project: A Python platform for molecular- and electronic-structure simulations of complex systems,* *J. Chem. Phys.* **152**, 214115 (2020), DOI: 10.1063/1.5144298

Invited paper describing the development of the Dalton platform, with Simen Reine as one of three main authors and Thomas Bondo Pedersen, and Trygve Helgaker as co-authors. *29 WoS citations.*

3. Details of impact

The Dalton program has been distributed at no cost since its release in 1997 and as open source since 2017. This means that the code can be used also by those without the means to buy commercial software. The functionality and capabilities of Dalton have also been advertised through scientific publications including several reviews, talks at scientific meetings and workshops, the organization of summer schools and teaching at those schools. Two papers devoted to Dalton have been published.

The 900-page monograph *Molecular Electronic-Structure Theory* by Helgaker, Olsen and Jørgensen presents the electronic-structure models implemented in Dalton up to 2000. The authors of the monograph have also organized a two-week *Sostrup Summer School of Quantum Chemistry and Molecular Properties* every second year from 1991 to 2019, to a total of 622 students. At each school, the techniques and methods implemented in the Dalton program were taught.

The members of the theory group at the Department of Chemistry, UiO, have contributed to Dalton in a number of ways. The proposal to create a merged Dalton code was proposed by Helgaker and carried out at UiO. The Oslo group was also responsible for the distribution of Dalton until it became open source.

Regarding the theoretical developments underlying Dalton, the UiO group has contributed second-quantization formalism for perturbations, methods for calculating time-independent properties, molecular magnetic properties, the Lagrangian method for nonvariational wave functions, derivative integral evaluation, geometry optimization, and direct ab initio dynamics.

The UiO group has contributed the following parts of the Dalton code: all molecular integral evaluation, main responsibility of code to time-independent molecular properties (geometrical, magnetic), all geometry-optimization and molecular-dynamics code, all DFT code, and important contributions to the coupled-cluster code and linear-scaling code. Several features in Dalton were first features, which were later included in other codes (if at all). Some such feature is the first ab initio calculation of an NMR spectrum and direct ab initio molecules dynamics.

The contributions to Dalton from the UIO group can be judged from 2014 Dalton paper [1]: among the 84 authors of the paper, 22 contributed while working at UiO and 17 of these contributed only from UiO. Among the 154 references given in the Dalton paper, 55 have one or more co-authors from UiO. Helgaker is a co-author of the 49 references, the second most contributing author after Jørgensen (51 references). Helgaker is also the corresponding author of the paper, which has been cited more than thousand times since 2014.

The Dalton code has from the beginning been distributed for free to computational chemists and experimentalists in academia and industry. The most important use of Dalton is for the calculation of molecular properties — in particular, frequency-dependent properties up to cubic response, one-, two- and three-photon processes, NMR and EPR parameters, circular dichroisms (ECD, VCD, VROA). Before Dalton became open source in 2017, more than 5000 licences had been extended, about one license every working day since its release the first in 1997.

4. Sources to corroborate the impact

1. Poul Jørgensen, Aarhus University, Denmark
2. Jeppe Olsen, Aarhus University, Denmark
3. Hans Jørgen Aa. Jensen, University of Southern Denmark
4. Hans Ågren, Uppsala University, Sweden
5. Kenneth Ruud, UiT, The Arctic University of Norway
6. Peter Taylor, Tianjin University, China
7. Jürgen Gauss, University of Mainz, Germany
8. Wim Klopper, Karlsruhe Institute of Technology, Germany
9. Dave Tozer, Durham University, UK
10. Denis Jacquemin, University of Nantes, France

[GEO] [1]

Institution: University of Oslo
Administrative unit: GEO
Title of case study: Defining *in situ* reference conditions within EU's Water Framework Directive.
Period when the underpinning research was undertaken: 2008 - present
Period when staff involved in the underpinning research were employed by the submitting institution:

Name(s):	Role(s):	Period employed by submitting institution:
Elisabeth Alve	Professor	2008 - present
Silvia Hess	Post-doc/Senior Lecturer	2008 - present
Vincent M.P. Bouchet	Post-doc	2008 - 2012
Jane K. Dolven	Researcher	2009 - 2010
Christopher J. Duffield	PhD-student	2010 - 2014
Anouk T. Klootwijk	PhD-student	2017 - 2021

Period when the impact occurred: 2018 and onwards

1. Summary of the impact

The overreaching aim has been to develop new methods within "environmental stratigraphy" to define Ecological Status and *in situ* reference (i.e., pre-pollution) conditions in coastal waters, as required by EU's Water Framework Directive. In 2018, the revised version of the Norwegian guidance document for classification of environmental status implemented the recommendation to use the retrospective «foraminifera method» to define *in situ* reference condition in areas where deviation from reference conditions is suspected to occur. Since then, the method has successfully been used in fjords along the Norwegian coast from Finnmark in the north, via Vestland and Rogaland to the Oslo fjord.

2. Underpinning research

Monitoring the status of marine soft-bottom environments was traditionally based on macrofaunal surveys, for which standardized methods were established. Benthic foraminifera (protists) are also good indicators of marine soft-bottom environments e.g., because of their fast turnover rates and high degree of specialization. Due to their preservation in the fossil record, they are particularly useful for defining past environmental conditions. However, it was first in 2011 that a group of 37 scientists from 13 countries got together in what was called the FOraminiferal BIo-MOnitoring (FOBIMO) expert workshop, held in Switzerland, and agreed on a suite of standard methods for foraminifera-based biomonitoring. Our micropaleontology group at the Department of Geosciences (UiO) was central in this work.

Following publication of the internationally standardized FOBIMO-protocol (Schönfeld et al., 2012), our group lead the work on the development of a foraminifera-based sensitivity index, called Foram-AMBI (Alve et al., 2016), similar to the well-established marine benthic macrofauna-based index, AMBI, which is commonly applied to assess present-day ecological quality status in marine soft-bottom environments. The work was based on 19 published data sets on fully marine NE Atlantic and Arctic fjord, continental shelf, and slope assemblages for which total organic carbon (TOC) data were available. We also illustrated how benthic macrofaunal indices can be adapted to foraminifera through intercalibration of data from common sites. As an example of how benthic foraminifera can fit into governmental monitoring programs, we focused on Norwegian conditions by proposing a new foraminifera-based multimetric index, NQI_f (Alve et al., 2019). The index was an adaptation of the Norwegian Quality Index (NQI), which is an internationally inter-calibrated macrofauna index used to assess ecological quality status in marine soft-bottom environments. The study was based on published and new data for soft-bottom benthic foraminifera, macro invertebrates, and associated bottom water dissolved oxygen and sediment total organic carbon (TOC). The inter-calibration was based on linear regression and the ecological quality status (EcoQS) class boundary values for the foraminifera indices were derived from boundary values for the macrofauna indices defined by the Norwegian governmental guidelines. The correlations between foraminifera and macrofauna for the multimetric NQI and the diversity indices H`log2 and ES100 were all acceptable for inter-calibration (according to the WFD guidelines). These correlations gave us the "tools" we needed to test if the method works on fossil assemblages in dated sediment cores. Studies in several fjords along the Norwegian coast have shown this to be the case (e.g., Dolven et al., 2013; Hess et al., 2020).

3. References to the research

Alve, E., Korsun, S., Schönfeld, J., Dijkstra, N., Golikova, E., Hess, S., Husum, K., Panieri, G., 2016. Foram-AMBI: A sensitivity index based on benthic foraminiferal faunas from North-East Atlantic and Arctic fjords, continental shelves and slopes. *Mar. Micropaleontol*. 122, 1-12. https://doi.org/10.1016/j.marmicro.2015.11.001

Alve, E., Lepland, A., Magnusson, J., Backer-Owe, K., 2009. Monitoring strategies for re-establishment of ecological reference conditions: possibilities and limitations. *Mar. Poll. Bull*. 59: 297-310. https://doi.org/10.1016/j.marpolbul.2009.08.011

Bouchet, V.M.P., Alve, E., Rygg, B., Telford, R., 2012. Benthic foraminifera provide a promising tool for Ecological Quality assessment of marine waters. *Ecol. Indicat*. 23: 66-75. https://doi.org/10.1016/j.ecolind.2012.03.011

Dolven, J.K., Alve, E., Rygg, B., Magnusson, J., 2013. Defining past ecological status and *in situ* reference conditions using benthic foraminifera: A case study from the Oslofjord, Norway. *Ecol. Indicat*. 29, 219-233. https://doi.org/10.1016/j.ecolind.2012.12.031

Hess, S., Alve, E., Andersen, T.J., Joranger, T., 2020. Defining ecological reference conditions in naturally stressed environments – How difficult is it? *Mar. Environ. Res.* 156, 104885. (https://doi.org/10.1016/j.marenvres.2020.104885).

Klootwijk, A.T., Alve, E., Hess, S., Renaud, P.E., Sørlie, C., Dolven, J.K., 2021. Monitoring environmental impacts of fish farms: Comparing reference conditions of sediment geochemistry and benthic foraminifera with the present. *Ecol. Indicat*. 120 (2021) 106818. (https://doi.org/10.1016/j.ecolind.2020.106818).

Schönfeld, J., Alve, E., Geslin, E. Korsun, S., Jorissen. F., Spezzaferri, S., and members of the FOBIMO group, 2012. The FOBIMO (FOraminiferal BIo-MOnitoring) initiative - Towards a standardised protocol for soft-bottom benthic foraminiferal monitoring studies. *Mar. Micropaleontol*. 94-95, 1-13. https://doi.org/10.1016/j.marmicro.2012.06.001

4. Details of the impact

The retrospective "foraminifera method" was implemented in the Norwegian guidance document in 2018, and it is particularly applicable in waters suspected to classify as reflecting "moderate" or worse ecological status (Pedersen et al., 2016; Veileder 02:2018). Since this implementation, the method has been tested and successfully applied in a number of studies along the Norwegian coast from Finnmark and Troms in the north, via Vestland and Rogaland to the Skagerrak coast and the Oslo fjord in the south-east.

The retrospective foraminiferal analyses of dated sediment cores can be used in combination with geochemical analyses to determine if an investigated area is stressed for natural reasons, e.g. oxygen depleted. If the stress is natural, it is not necessary to invest money and work to improve the ecological status.

Our research has been performed in close co-operation with the Norwegian Environmental Agency, the Council for water and sewage technical cooperation in the Inner Oslo fjord and the Norwegian Institute for Water Research (NIVA). An outcome of these collaborations was that members of our (UiO's) micropaleontology group were invited to attend the Norwegian Environmental Agency's expert group to develop new class boundaries and methods for soft-bottom fauna in biomonitoring (Pedersen et al., 2016).

Other collaborating institutions include Rambøll, Norconsult, COWI, University of South-Eastern Norway, Forsvarsbygg, Akvaplan-niva AS, and various universities in Europe and USA.

Funding has, in addition to governmental institutions, been through the Research Council of Norway- funded project 'Paleoecological reconstructions of marine soft-bottom Ecological Status and *in situ* reference conditions: calibrating benthic foraminifera with macrofauna and hydrographic data' (PES, no. 184870).

Our case study has included supervision of 20 Master students, 2 PhDs, and 3 post-docs.

Our group attended five international FOBIMO-workshops during the development and standardization of methods. We were also invited to participate in two international training schools focusing on biomonitoring approaches based on benthic foraminifera.

5. Sources to corroborate the impact

Our micropaleontology group was invited as members of the expert group of the Norwegian Environmental Agency which developed new class boundaries and methods for soft-bottom fauna in biomonitoring (Pedersen et al., 2016):

Pedersen, A., Alve, E., Alvestad, T., et al., 2016. Bløtbunnsfauna som indikator for miljøtilstand i kystvann. Ekspertvurderinger og forslag til nye klassegrenser og metodikk. Miljødirektoratet M-633, 58 pp. https://www.miljodirektoratet.no/globalassets/publikasjoner/m633/m633.pdf

The "foraminifera method" was implemented in the Norwegian guidance document in 2018 (Veileder 02:2018):

Veileder, 02:2018. Klassifisering av miljøtilstand i vann: Økologisk og kjemisk klassifiseringssystem for kystvann, grunnvann, innsjøer og elver, 220 pp. https://www.vannportalen.no/veiledere/klassifiseringsveileder/

Selected collaboration projects with Norwegian governmental bodies resulted in the following reports:

Alve, E., Hess, S., Sørlie, C., Klootwijk, A.T., Dolven, J.K., 2018. Akvakultur og naturtilstand i en Nordnorsk fjord: har miljøstatus forandret seg? Miljødirektorat-report: MD17SF8F99.

Dolven, J.K., Hess, S., Hylland, K., Alve, E., 2018. Foraminiferer som miljøindikator for vannkvalitet og levevilkår på sjøbunnen i Indre Oslofjord. Fagrådets rapport nr. 114, 23 pp. http://www.indre-oslofjord.no/uploads/Sluttrapport_foraminiferer_2018_Fagrdetsrapportnr_114.pdf

Hess, S., Alve, E., 2014. Undersøkelser av den historiske oksygenutviklingen og naturtilstanden i Horten Indre Havn. Institutt for Geofag, Universitetet i Oslo. 63 pp. ISBN 978-82-91885-44-5. https://www.horten.kommune.no/_f/p1/i07082651-eb85-4041-87ce-57acbaa1f92b/2014-undersokelser-av-den-historiske-oksygenutviklingen-og-naturtilstanden-i-horten-indre-havn-utgitt-av-uio1.pdf

Hess, S., Alve, E., Dolven, J.K., 2019. Bruk av foraminiferer som miljøindikator for vannkvalitet og levevilkår på sjøbunnen i Indre Oslofjord: Har dypvannsfornyelsen og bedrede oksygenforhold i Bunnefjorden våren/sommeren 2018 hatt effekt på foraminiferfaunaen på sjøbunnen? Fagrådets rapport nr. 116, 17 pp.

Hess, S., Alve, E., Helland, A., 2021. E16 og Vossebanen, Arna – Stanghelle. Miljøforholdene i Sørfjorden og Veafjorden, Vestland, dagens og tidligere tiders tilstand. 37 pp.https://www.vegvesen.no/globalassets/vegprosjekter/utbygging/e16banearnastanghelle/vedlegg/fagrapporter/miljo/miljoforholdene-i-sorfjorden-og-veafjorden-dagens-og-tidligere-tiders-tilstand_uas-01-q-00029.pdf

[GEO] [2]

Institution: University of Oslo
Administrative unit: Department of Geosciences
Title of case study: Carbon dioxide storage and mineralization in the Norwegian Sea
Period when the underpinning research was undertaken: 2011-2021
Period when staff involved in the underpinning research were employed by the submitting institution: Continuously
Period when the impact occurred: Continuously

1. Summary of the impact

All scenarios of the 6th International Panel on Climate Change that simulate a temperature increase below 2 °C by 2100 involve the storage of carbon dioxide, in addition to massive reductions of greenhouse gas emissions. The geological storage of carbon dioxide in the subsurface is considered as a critical technology Norway is currently developing and wish to scale up by 2050 to become a world-leading economic activity. Carbon dioxide geological storage research at the Geoscience Department at the University of Oslo relies on long term building of basic knowledge of the Norwegian Continental Shelf and the Norwegian Sea, reinforced by the current federal Longship project on a full Carbon and Capture (CCS) chain. Improved Technology Readiness Level (TRL) has validated subsurface storage volumes and reduced uncertainty (risk) in preparation of costly industrial offshore operations in which subsurface sandstone aquifers are used as storage bodies. The longer-term fate of injected carbon dioxide towards immobile, fixed carbon dioxide confirms capability of the technology. New, lower TRL research has proven viability of storage in volcanic provinces where carbon dioxide can be fixed permanently into carbonate minerals within years. In the past ten years, researchers at the Geoscience Department have performed many studies on carbon storage in rocks, in both salty aquifers and volcanic, mafic, and ultra-mafic rocks.

2. Underpinning research

Reduced greenhouse gas emissions to the atmosphere as a mitigation to climate change require deep insight into carbon dioxide storage processes to become a dependable technology. Our research underpins six targets: (i) qualifying carbon dioxide geological storage prospects of the Norwegian Continental Shelf (NCS), (ii) mineral trapping of carbon dioxide in volcanic and ultramafic-mafic rocks, (iii) CO2-brine-mineral stability and reactions and formation of carbonate minerals at the pore- to the core-scales, (iv) reservoir-seal rock-physical properties, (v) fault-risking for carbon dioxide storage purposes, and (vi) carbon dioxide storage in basalt. Work covers three avenues: a) reservoir-seal systems of aquifers and depleted hydrocarbon fields as viable storage targets, b) fluid and mineral response to carbon dioxide exposure versus carbon dioxide trapping mechanisms, and c) carbon dioxide trapping in volcanic and mafic/ultramafic rocks prone to reactions and hence efficient and rapid mineral trapping.

Research has been performed in two Green-Energy Research centres (FME) on carbon dioxide handling (FME's SUCCESS [2010-18] and NCCS [2016-23]), in the Centre of Excellence Physics of Geological Processes, which has now evolved into the Njord Centre, and in numerous other projects funded by the Research Council of Norway, the industry, the University of Oslo, and the European Union (including one ERC Advanced Grant DIME, and two Marie Curie ITN Abyss and FlowTrans). Many contributions were also produced in the Longyearbyen CO2 Lab project in Svalbard, which inspired CCS developments in Norway and Europe. The funds allocated to the activity exceeds MNOK 250 in the past ten years.

The main impacts from the body of work over years cover: (i) production of knowledge validated by more than one hundred scientific articles on the geological storage of carbon dioxide, (ii) improved TRL (viability, integrity) for numerous sites of the Norwegian Continental Shelf that facilitate and de-risk the paired federal-industrial endeavour on the shelf, (iii) confirmed and hence build confidence around the technology - it will enable targeted goals on permanently stored carbon dioxide in the subsurface, and (iv) confirmed and developed models and tools that forecast the fate of injected carbon dioxide, and (v) recent production of patents on carbon dioxide related technologies.

Outputs and hence value creation include more than one hundred articles in international peer-review journals, and hundreds of conference contributions and industry dialog meetings. We have educated nearly 30 PhD-Postdoc's and ca. 35 Masters, many of whom are emerging leaders in the CO2-storage industry. This knowledge building and transfer is key for CCS to become a global climate mitigation technology.

Name of key researchers: profs Alvar Braathen, Helge Hellevang, Nazmul Mondol, Ivar Midtkandal, Ingrid Anell (start 2014), Per Aagaard (retired 2019), Jens Jahren and researcher Anja Sundal (until 2020) (SUCCESS/NCCS and spinoffs); profs Bjørn Jamtveit, Håkon Austrheim (retired 2020), François Renard (start 2015), Luca Menegon (start 2017), and Olivier Galland (Njord Centre).

References to centres:
https://www.sintef.no/projectweb/nccs/
https://www.mn.uio.no/njord/english/

3. References to the research

1) Hövelmann, J., Austrheim, H., & Jamtveit, B. (2012). Microstructure and porosity evolution during experimental carbonation of a natural peridotite. Chemical Geology, 334, 254-265. https://doi.org/10.1016/j.chemgeo.2012.10.025
2) Ogata, K., Senger, K., Braathen, A., and Tveranger, J., 2014. Fracture corridors as seal-bypass systems in siliciclastic reservoir-caprock successions: field-based insights from the Jurassic Entrada Formation (SE Utah, USA). Journal of Structural Geology 66, 162-187. http://dx.doi.org/10.1016/j.jsg.2014.05.005
3) Montes-Hernandez, G., & Renard, F., 2016. Time-resolved in situ Raman spectroscopy of the nucleation and growth of siderite, magnesite, and calcite and their precursors. Crystal Growth & Design, 16(12), 7218-7230. https://pubs.acs.org/doi/10.1021/acs.cgd.6b01406
4) Miri, R., & Hellevang, H., 2016. Salt precipitation during CO2 storage - a review. International Journal of Greenhouse Gas Control, 51, 136-147. https://doi.org/10.1016/j.ijggc.2016.05.015
5) Sundal, A., Nystuen, J. P., Rørvik, K. L., Dypvik, H., & Aagaard, P., 2016. The Lower Jurassic Johansen Formation, northern North Sea–depositional model and reservoir characterization for CO2 storage. Marine and Petroleum Geology, 77, 1376-1401. https://doi.org/10.1016/j.marpetgeo.2016.01.021
6) Mulrooney, M.J., Osmond, J.L., Skurtveit, E., Faleide, J.I., and Braathen, A., 2020. Structural analysis of the Smeaheia fault block, a potential CO2 storage site, northern Horda Platform, North Sea. Marine and Petroleum Geology 121, 1-33, doi.org/10.1016/j.marpetgeo.2020.104598

4. Details of the impact

With improved certainty that subsurface carbon dioxide storage is a reliable technology, the main impact of the research is a foreseen reduction in carbon dioxide emissions to the atmosphere, as a mitigation to climate change. The main users/beneficiaries of our research gains and knowledge building are private companies utilizing the Norwegian Continental Shelf, and Norwegian authorities (Norwegian Petroleum Directorate, Ministry of Oil and Energy, Ministry of Foreign Affairs). As knowledge building and TRL gains are long-lasting efforts before applicable as industrial technologies, impacts are gradual and continuous.

Significant educational outputs (~50% of our students are recruited by industry companies) and publication of state-of-the-art results (see above) placed the work in the global forefront, facilitating major, cost-efficient, and less risky CCS operations on the Norwegian Continenal Shelf. Close collaborations with the oil-gas-CO2 industry represent significant value creation, as highlighted in the evaluation of the Petromaks and Climit programs of the Research Council of Norway. Relevance is well reflected in the continued industrial and public funding. Impacts on public acceptance of CCS come from education (university, high schools) and public media presence via national TV, newspapers, and other popular science outputs (e.g, online journal Titan.uio.no). The Longyearbyen CO2 Lab with its inspiring promotion program was debated in the Norwegian Parliament years before CCS technology became prevalent on the global agenda, acting as a main educator in the public Norwegian CCS landscape.

Signs of impact can be summarized as: (i) Citations on articles and invited talks on conferences; (ii) Numerous industry dialog meetings and tailored industry seminars (knowledge building); (iii) Knowledge and dataset provider for carbon dioxide storage industry; (iv) Guidance to industry in decision/investment processes; e.g., Smeaheia as uncertain storage container (NCCS) and Johansen Fm qualities; (v) Numerous MSc and PhD's with jobs in industry and federal regulators, (vi) Success in winning grants - national, EU and USA funding; (vii) Contributions to evaluation and promotion of the technology of CCS, e.g., for the Norwegian Ministry of Foreign Affairs in South Africa; (viii) Extensive review of carbon dioxide storage literature and for funding bodies.

5. Sources to corroborate the impact

1) Eva Halland, former director on CCS at the Norwegian petroleum Directorate (eva.halland@carbongeo.no)
2) Phillip Ringrose, lead CCS technology in Equinor (phiri@equinor.com)
3) Sveinung Hagen, lead CCS business development in Equinor (svehag@statoil.com)
4) Tord Lien, NHO, Chair of the NCCS Board, Minister of Petroleum and Energy from 2013 to 2016.
5) Mona Mølnvik, director of NCCS and in Sintef (Mona.J.Molnvik@sintef.no).
6) Nils Røkke, Executive Vice President Sustainability, Sintef (nils.a.rokke@sintef.no)
7) Peter Kelemen, Professor at Columbia University, leader of the Oman Drilling Project, (peterk@ldeo.columbia.edu)
8) Sigurður Gíslason, Professor at the University of Iceland, former president of the European Association of Geochemistry (2018-2020) and co-founder of Carbfix (sigrg@hi.is)

[GEO] [3]

Institution: University of Oslo
Administrative unit: GEO
Title of case study: Geological knowledge informed the exploration risk assessment of Norwegian energy sector and global climate models
Period when the underpinning research was undertaken: 2011-2021
Period when staff involved in the underpinning research were employed by the submitting institution: Continuously
Period when the impact occurred: Continuously

1. Summary of the impact

Geological knowledge was generated and shared with the petroleum industry for reducing exploration risk on the Norwegian Continental Shelf (NCS). Our understanding of fundamental geological processes, and their role in development of sedimentary basins/margins, provide important constraints for how the petroleum industry evaluate and de-risk their petroleum systems and potential traps. The knowledge has also been beneficial to Norwegian authorities when the offshore extended economic zone was established, and for other strategic purposes related to the petroleum potential of the NCS.

The long-term efforts and results from studies of the Norwegian continental margin made a significant contribution to the IODP (International Ocean Discovery Program) with several proposals submitted by members of our group. One of them resulted in the successful drilling at the volcanic Møre and Vøring margins in 2022, with Sverre Planke from UiO as co-chief. Another IODP expedition scheduled for 2024 has UiO co-proponents (Gaina) and will focus on the role of continental margin evolution in changing the climate in the past.

2. Underpinning research

In the last geo-evaluation, the panel concluded that we had an international leadership in the study of North Atlantic passive margins. Consequently, the Department has kept and further developed the focus on this topic through several projects addressing various aspects of basin/margin formation and development.

Regional geological studies require that inter-disciplinary teams utilize an integrated approach to gain new knowledge that is cumulative in nature. It is therefore difficult to bring examples of specific results/findings and their direct or immediate impact for a particular user/company. at a specific time.

We have therefore selected a series of projects carried out during the evaluation period, which are thematically inter-related and have partly overlapped in time and space (providing synergies between the individual projects). PI's at UiO include profs Jan Inge Faleide (JIF), Alvar Braathen (AB) and Carmen Gaina (CG). At UiO these projects have included additional 10 academic staff and 15 PhDs/Postdocs/Researchers.

<u>BarMod</u>: Barents Sea Tectonic Basin Modelling - with focus on potential petroleum systems in the Central Barents Sea Region (2011-2015); PI: JIF.
<u>OMNIS</u>: Offshore Mid-Norway: Integrated Margin and Basin Studies (2012-2015); PI: JIF.
<u>TriasNorth</u>: Reconstructing the Triassic Barents Shelf; basin infill patterns controlled by gentle sags and faults (2014-2018); PI: AB.
<u>ARCEx</u>: Research Centre for Arctic Petroleum Exploration[1] (2014-2021); UiO Co-PI: JIF.
<u>CEED-MOD</u>: Integrated basin studies - linking plate tectonics, mantle dynamics and surface processes to basin evolution (2019-2022); PI: JIF.
<u>Suprabasins</u>: Sedimentary response to growth of major extensional fault systems (2019-2023); PI: AB.
<u>NAG-TEC</u>: Northeast Atlantic Geoscience Tectonostratigraphic Atlas[2] (2011-2016); UiO Co-PI: CG.

4D Arctic: Structure and evolution of Arctic crust and mantle based on multi-scale geophysical studies (2013-2017); PI: CG.
NOR-R-AM (1 & 2): Changes at the Top of the World through Volcanism and Plate Tectonics: A Norwegian-Russian-North American collaboration in Arctic research and education (2017-2023); PI: CG.

[1] UiO partner in a national centre lead by UiT, including 10 academic and 11 industry partners.
[2] A collaboration of the geological surveys in 7 European countries that produced state-of-the-art geological and geophysical database of the North Atlantic – sponsored by 19 energy companies.

The main goal of the projects targeting the Norwegian Continental Shelf (BarMod, OMNIS, TriasNorth, ARCEx, Suprabasins) was to advance our understanding of fundamental processes leading to the formation and development of sedimentary basins, by combining key academic competences with industry long-term experience. This provided new and important knowledge to reveal the hydrocarbon potential and to reduce exploration risks on the NCS. Key topics addressed, many of them are closely interlinked, include: Structural geology and tectonics; depositional systems and sediment infill history; vertical motion and temperature histories and their impact on petroleum systems; numerical and analogue modelling; linking basin architecture to underlying crust and upper mantle; linking subsurface cases at the NCS to outcrop studies of relevant field analogues to obtain more details on structural and stratigraphic relationships.

The regional North Atlantic projects (OMNIS, NAG-TEC, CEED-MOD) have focused on rifting, continental breakup and evolution of the conjugate margins offshore mid-Norway and NE Greenland. Key topics addressed include: Plate tectonic and paleogeographic reconstructions; mantle dynamics, geodynamic processes, linking deep and shallow/surface processes; intra-plate stress, far-field and local compressional stresses affecting the basin configuration (structuring, trap generation and potential hydrocarbon leakage). Note that the outcome of these projects has been used as a crucial input to climate models of the past that also informed climate modelling of present day.

The Arctic projects (4D Arctic and NOR-R-AM 1 & 2) aimed to enhance international collaboration in the Circum-Arctic region and advance knowledge on continental margin tectonics. This resulted in novel models of the present day crustal architecture and tectonic evolution of the High Arctic and its connections to the North Atlantic, and in an IODP proposal that is scheduled in 2024. The new models also used for modelling paleo-climate in the Arctic-North Atlantic regions are informing our knowledge about past and present glaciations.

3. References to the research

Altogether, the projects included in the case published more than 50 papers in international journals, some of them in high impact journals. Among these, we have selected 7 papers as representative examples of the work carried out and results achieved:

Gac, S., Huismans, R.S., Simon, N.S.C., Faleide, J.I. & Podladchikov, Yu.Yu. (2014) Effects of lithosphere buckling on subsidence and hydrocarbon maturation: A case study from the ultra-deep East Barents Sea basin. *Earth and Planetary Science Letters*, 407, 123-133. (BarMod) http://dx.doi.org/10.1016/j.epsl.2014.09.029

Abdelmalak, M.M., Faleide, J.I., Planke, S., Gernigon, L., Zastrozhnov, D., Shephard, G.E. & Myklebust, R. (2017) The T-Reflection and the deep crustal structure of the Vøring Margin, offshore mid-Norway. *Tectonics*, 36, 2497–2523. (OMNIS) https://doi.org/10.1002/2017TC004617

Zastrozhnov, D., Gernigon, L., Gogin, I., Planke, S., Abdelmalak, M.M., Polteau, S., Faleide, J.I., Manton, B. & Myklebust, R. (2020) Regional structure and polyphased Cretaceous-

Paleocene rift and basin development of the mid-Norwegian volcanic passive margin. *Marine and Petroleum Geology*, 115, 104269. (OMNIS) https://doi.org/10.1016/j.marpetgeo.2020.104269

Mulrooney, M.J., Leutscher, J. & Braathen, A. (2017) A 3D structural analysis of the Goliat field, Barents Sea, Norway. *Marine and Petroleum Geology*, 86, 192-212. (TriasNorth) http://dx.doi.org/10.1016/j.marpetgeo.2017.05.038

Hassaan, M., Faleide, J.I., Gabrielsen, R.H. & Tsikalas, F. (2019) Carboniferous graben structures, evaporite accumulations and tectonic inversion in the southeastern Norwegian Barents Sea. *Marine and Petroleum Geology*, 112, 104038. (ARCEx) https://doi.org/10.1016/j.marpetgeo.2019.104038

Lebedeva-Ivanova, N., Gaina, C., Minakov, A. & Kashubin, S. (2019) ArcCRUST: Arctic crustal thickness from 3D gravity inversion. *Geochemistry, Geophysics, Geosystems*, 20, 3225-3247. (4D Arctic) https://doi.org/10.1029/2018GC0080982019

Straume, E., Nummelin, A., Gaina, C. & K. Nisancioglu, K. (2022) Climate transition at the Eocene – Oligocene controlled by bathymetric changes to the Atlantic – Arctic oceanic gateways, *Proceeding of National Academy of Science*, 119, e2115346119 (NOR-R-AM) https://doi.org/10.1073/pnas.2115346119

4. Details of the impact

The main users/beneficiaries of our key research insights and findings are energy companies exploring and exploiting the Norwegian Continental Shelf. Altogether, the NCS projects included in this impact case had 13 industry partners (most of them involved in several of the projects): Statoil/Equinor, Lundin, AkerBP, Eni Norge/Vår Energi, Wintershall DEA, OMV, Shell, ConocoPhillips, GDF Suez/Engie, Edison, Tullow Oil, DONG/INEOS, Spirit Energy/Sval-Energi.

In addition, Norwegian authorities (Norwegian Petroleum Directorate, Ministry of Oil and Energy, Ministry of Foreign Affairs) have benefitted from our knowledge and results, for example as advisor in UN Law of the Seas matters in relation to establishing the outer limits of the Norwegian Continental Shelf. We have also made significant contributions to various initiatives promoting Norwegian-Russian collaboration in the wider Barents Sea region coordinated from the Norwegian side by the Norwegian Petroleum Directorate and the Research Council of Norway. Other outcome that resulted from detailed geological and geophysical mapping of oceanic basins is used, and may be used to asess offshore natural hazards or other potential natural resources.

Our knowledge and results were disseminated through various channels, including (1) Project/consortium meetings/workshops (all project partners); (2) Industry visits (to individual partners); (3) Petroleum conferences (e.g., NCS Exploration Recent Advances, May 2019); (4) International Scientific Conferences (e.g., EGU, AGU, AAPG); (5) Scientific publications in international journals. Most importantly, UiO academics and collaborators have trained more than 60 students who were employed by the industry, government agencies, and other national and international universities.

Our scientific results and knowledge transfer have been used at multiple levels by the industry, especially when preparing for licensing/APA round applications. Below are few selected examples of direct impact:

<u>Barents Sea</u>: (1) The geology of the SE Norwegian Barents Sea including the Norwegian area of the former disputed area between Norway and Russia was considered when establishing the border between the two countries. (2) Our models of the timing and causes of hydrocarbon trap formation informed drilling locations for hydrocarbons. (3) Detailed studies of Triassic sedimentary systems to establish better temporal links between source areas, sediment routing

and sedimentary sinks, and better understanding large-scale driving forces for sag/warp basins.

Mid-Norwegian margin: (1) The temperature histories and evolution of the continental margin based on our results were important parameters in industry exploration models. (2) Our results from studies of the outer margin made significant contributions to the planning and implementation of the successful IODP drilling expedition in 2022.

Suprabasins: The successful drilling and field developments (e.g. Sverdrup Field) on the Utsira High in the North Sea led to increased focus on other structural highs on the NCS. Our geological models have contributed to further exploration in these areas.

Arctic: (1) The NOR-R-AM project focusses on educating the next generation of Arctic explorers, and Circum-Arctic scientific collaboration. Through annual international summer courses in Svalbard (University Center in Svalbard, UNIS) and many international conferences and workshops, 16 researchers from 8 institutes formed a solid network and mentored several Early Career Scientists. Over 60 international students (PhD, Msc) were involved. (2) Our Arctic research activities made the foundation for our role in the GoNorth Program (Geosciences in the Northern Arctic) and the DYPOLE project (Dynamics of polar confined basins – The Eurasia Basin from breakup in greenhouse to present in icehouse conditions) awarded by NFR in 2021.

GPlates: A group of researchers from the Department were the co-founders and substantially contributed to the open source, most popular plate tectonic reconstruction digital application: GPlates (gplates.org, https://en.wikipedia.org/wiki/GPlates). This tool is used by universities, industry and educational sector worldwide.

5. Sources to corroborate the impact

(1) Jakob Skogseid, Equinor (jaksk@equinor.com)
(2) Ian Sharp, Equinor (isha@equinor.com)
(3) Ketil Solli, Equinor (keso@equinor.com)
(4) Rolando de Primio, Lundin (now merged with AkerBP) (rolando.diprimio@akerbp.com)
(5) Alastair Welbon, Lundin (now merged with AkerBP) (alastair.welbon@akerbp.com)
(6) Olav A. Blaich, AkerBP (olav.antonio.blaich@akerbp.com)
(7) Filippos Tsikalas, Vår Energi (filippos.tsikalas@varenergi.no)
(8) Harald Brekke, NPD (Harald.Brekke@npd.no)
(9) Tarjei Nødtvedt Malme, NFR (tnm@forskningsradet.no)

[GEO] [4]

Institution: University of Oslo
Administrative unit: Department of Geosciences (GEO)
Title of case study: Hydrological Extremes – Drought Impacts
Period when the underpinning research was undertaken: 2002 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: 1996 – 2021 (permanent staff)
Period when the impact occurred: 2013-2021

1. Summary of the impact (indicative maximum 100 words)

Hydrological extremes may have severe impacts on nature and society, and recent decades have seen an increase in the frequency and severity of extreme events. The unit (GEO) contributes to an improved understanding of the flood and drought hazard under global change (climate and human interventions) as demonstrated in numerous publications and research output, including a review paper on challenges in modeling and predicting flood and drought (2021). Knowledge that are vital for water managers to take well-informed decisions. As for reported impacts, focus is on drought and three specific impact cases are reviewed; i) a European drought impact database, ii) a community website (the European Drought Centre), including open-access software and tools, and iii) an open access, publically available textbook on hydrological drought.

2. Underpinning research (indicative maximum 500 words)

Research insight has been gained thanks to our participation in a series of EU-projects on the topic of hydrological extremes, drought in particular, both prior to the reporting period (ARIDE 1998-2000, AstHyDA 2002-2004) and during (WATCH 2007-2011, XEROCHORE 2008-2011, DROUGHT-R&SPI 2011-2015). Active participation in international research networks building on these collaborative efforts have ensured a long-term gain. Notable, the unit has contributed to a better understanding of drought as a natural hazard, including underlying processes, changes and trends, and environmental and socio-economic impacts at the pan-European scale. Underpinning research by the team, led by Prof. Tallaksen, is documented in a series of research outputs addressing the drought hazard. Key innovations include (full references are given under section 3):

- A study on runoff trends across Europe responding to the lack of available river flow data by filling the white space on the European map using estimates of trends from a multi-model ensemble of simulated runoff. Model estimates were most reliable in reproducing trends in annual runoff, winter runoff, and high flow, whereas trends in summer low flow were more uncertain and should be viewed with caution. Trends in annual runoff based on the ensemble mean revealed a pronounced continental dipole pattern of positive trends in western and northern Europe and negative trends in southern and parts of Eastern Europe, not previously demonstrated (co-author: Tallaksen, 2012).
- A study on the performance of a suite of off-line, global (hydrological and land surface) models in mapping spatial and temporal patterns of large-scale hydrological droughts in Europe. The ability of large-scale models to satisfactory represent drought is key to provide trust in climate projections. The high model dispersion in temporal and spatial persistence of drought identified implies that conclusions should be made with care when only a limited number of models are used to predict future impacts of drought (Lead author: Tallaksen, 2014);
- A study on drivers for European scale drought revealed that a weakening of the prevailing westerly circulation is associated with drought onset. Such conditions are linked to variations in the eastern Atlantic/western Russia (EA/WR) and North Atlantic

Oscillation (NAO) atmospheric circulation patterns and constitute vital knowledge for improved forecasting and prediction of drought (Co-authors: Stagge, Tallaksen, 2015);

- A thorough testing and refinement of the two most prominent meteorological drought indices: the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI), providing recommendation for their use across the diverse climatology of Europe. This include a novel approach to account for prolonged periods of zero precipitation as commonly experienced in semi-arid climates such as southern Europe (Lead: Stagge, co-author: Tallaksen, 2015). These have become commonly used indices in the drought community, and software developed for their derivation is made publically available (Impact case ii).
- The first study to reveal a regional divergence in drought likelihood across Europe as measured by the two well-known drought indices SPI and SPEI (1958-2014). Notably, increases in temperature and evaporation have enhanced droughts in southern Europe while counteracting increased precipitation in northern Europe. This is consistent with projections under climate change (Lead: Stagge, co-author: Tallaksen, 2017).
- A unique, web-based database - the European Drought Impact Report Inventory (EDII) - of text-based reports on drought impacts. The unit (Stagge, Tallaksen) contributed to the development of the EDII database (2013, Impact case i).
- An innovative approach, linking physical drought indices with indicators of drought impacts, building on the EDII database, as a first step in estimating drought risk across Europe. The study was led by the unit in cooperation with the University of Freiburg, Germany. This type of analysis is vital to enable better monitoring, prediction and adaptation to drought as a natural hazard. Since then the approach has gained momentum in the wider science community and is frequently referred to as impact-based prediction (2015, Impact case i).
- A detailed investigation of drivers, characteristics and extremeness of the record-breaking 2018 drought event in Europe (Lead: Bakke, co-author: Tallaksen, 2020).

Key researchers:

- Lena M Tallaksen, prof. in hydrology, full time employed during the whole evaluation period
- James H Stagge, postdoctoral researcher, full time employed (1.08.2012 – 31.7.2015)
- Sigrid J Bakke, PhD student, full time employed (1.08.2018 – 31.04.2023, including parental leave)

James Stagge was funded by the EU project DROUGHT-R&SPI. The key objective of the project was to improve drought preparedness through increased knowledge, drought management plans and an improved science-policy interfacing. It was by nature a true interdisciplinary project, including both natural and social scientists. The project built on competence gained over several years (PI Tallaksen).

Sigrid J Bakke is funded by the faculty in a 4-year PhD position, including 25% teaching commitment.

3. References to the research (indicative maximum of six references)

A selection of publications related to drought (refer section: 2. Underpinning research). Key researchers at the unit are indicated in bold. Level of citations is given as the percentile in Scopus. Papers preceded by * are cited in the IPCC AR6 or AR5 report: Physical science basis (2013, 2021), highlighting their relevance and quality of research.

*****Stahl, K., **Tallaksen**, L.M., Hannaford, J. & van Lanen, H.A.J. (2012) Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. Hydrol. Earth Syst. Sci., 16, 2035-2047. doi:10.5194/hess-16-2035-2012; 97th percentile.

***Tallaksen**, L.M., and Stahl, K. (2014) Spatial and temporal patterns of large-scale droughts in Europe: model dispersion and performance. Geophys. Res. Letters, 41(2), 429-434. doi: 10.1002/2013GL058573; 93th percentile.

*Kingston, D.G., **Stagge**, J.H., **Tallaksen**, L.M. and Hannah, D.M. (2015) European-Scale Drought: Understanding Connections between Atmospheric Circulation and Meteorological Drought Indices. J. Climate, 28, 505–516. doi: 10.1175/JCLI-D-14-00001.1; 88th percentile.

Stagge, J.H., **Tallaksen**, L.M., Gudmundsson, L., Van Loon, A.F. and Stahl, K. (2015) Candidate distribution for climatological drought indices (SPI and SPEI). Journal of Climatology, doi: 10.1002/joc.4267; 99th percentile.

***Stagge**, J.H. Kingston, D., **Tallaksen**, L.M. and Hannah, D. (2017) Observed drought indices show increasing divergence across Europe. Scientific Reports 7, Article number: 14045 (2017), doi:10.1038/s41598-017-14283-2 (among the top 100 most highly accessed Earth science article in 2017); 93th percentile.

Bakke, S. J., Ionita, M., and **Tallaksen**, L. M. (2020) The 2018 northern European hydrological drought and its drivers in a historical perspective, Hydrol. Earth Syst. Sci., 24, 5621–5653, https://doi.org/10.5194/hess-24-5621-2020, 2020; 96th percentile.

Brunner, M., Slater, **Tallaksen** and Clarke (2021) Challenges in modeling and predicting floods and droughts: A review. WIREs Water, e1520, doi: 10.1002/wat2.1520; 97th percentile.

4. Details of the impact (indicative maximum 750 words)

i) The European Drought Impact Report Inventory (EDII)

The unit has played a key role in establishing the European Drought Impact Report Inventory (EDII), a unique database of text-based reports on drought impacts, along with the European Drought Reference (EDR) database, a web-based database that consolidates information about historical large-scale drought events in Europe. Together they provided a single entity, publicly available site that disseminate vital information about historical drought events and their impacts (published 2013). The EDII consists of > 5000 drought impact reports from across Europe.

GEO researchers have played a key role in implementing and hosting these 2 databases that are publicly available through the European Drought Centre website (Impact case ii). Stagge was responsible for the development of the EDR database, including an interactive user interface and several visualization tools. The unit (Tallaksen, Stagge) contributed to the development of the EDII database (work led by the University of Freiburg, Germany) and was responsible for implementing and hosting both databases at the unit. The EDII has been presented at several international events addressing the best practise to deal with drought, and the database gained significant interest as the first of its kind for Europe. Tallaksen participated in several of these events in addition to meetings organised by the European Commission (EC) in the framework of the Copernicus Emergency Management Service (2017, 2019, 2020). Tallaksen further initiated a feasibility study (publ. 2018) and contributed to early negotiations with the EC Joint Research Centre (JRC) in Ispra, Italy (meetings in 2017, 2018), with the aim to transfer the database to an operational organisation who could take the responsibility for its further development. These negotiations were later followed up by the University of Freiburg and the EDII database has recently been transferred to the European Drought Observatory for Resilience and Adaptation (EDORA) at JRC (2021). This demonstrates its value, novelty and societal relevance for the wider community. The EDII database and developments thereof will help improve risk assessment in different sectors across Europe and thus increase drought preparedness in widely different hydroclimatological regimes.

ii) The European Drought Centre (EDC)

The unit (Tallaksen) is one of the main funders and coordinator of the European Drought Centre (EDC) – a virtual knowledge centre with the aim to coordinate drought activities in

Europe. The EDC hosts the original EDR and EDII databases as well as several user tools. As such, it promotes collaboration and capacity building between scientists and the user community and thereby increase preparedness and resilience of society to drought. EDC was originally established in May 2004, whereas a major revision was undertaken in 2014, including new technical solutions, design and facilities. The EDC provides relevant information for the drought community and offers access to resources such as online, open access learning material (Impact case iii), and software and tools for drought analysis.

iii) Open access version of a Textbook on Hydrological drought

A textbook on Hydrological Drought (Editors: Tallaksen and van Lanen) was made publically available in 2018 on the EDC website (originally published in 2004). The textbook provides a comprehensive review of processes and estimation methods for streamflow and groundwater drought. It includes a qualitative conceptual understanding of drought features and processes, a detailed presentation of estimation methods and tools, practical examples and key operational aspects of drought. The book has been downloaded more than 500 times from people in more than 70 countries since its launch online in 2018, many of which are developing countries with less means and access to knowledge. It has also been the basis for several one-week international study courses on drought organised by the editors, latest in Bhutan 2010 and Syros 2014 as part of other initiatives. The practical organisation of the summer schools was facilitated the local project partners, whereas researchers at the unit designed and ran the course jointly with Henny van Lanen (co-editor), including providing a series of lectures and exercises (Tallaksen, Stagge).

5. Sources to corroborate the impact (indicative maximum of ten references)

i) The European Drought Impact Report Inventory (EDII)

The orignal database (developed in the EU-DROUGHT-R&SPI project) is available at: https://www.geo.uio.no/edc/droughtdb/index.php

Information about the purpose, objectives and scope of the database is presented at the DRMKC – Disaster Risk Management Knowledge Centre of the European Commission: https://drmkc.jrc.ec.europa.eu/knowledge/support-system-horizon-europe/securing-the-european-drought-reference-edr-and-impact-report-inventory-edii-databases-for-the-benefit-of-drm-a-feasibility-assessment

The development of the database is documented in the paper:

Stahl, K., Kohn, I., Blauhut, V., Urquijo, J., De Stefano, L., Acácio, V., Dias, S., **Stagge**, J. H., **Tallaksen**, L. M., Kampragou, E., Van Loon, A. F., Barker, L. J., Melsen, L. A., Bifulco, C., Musolino, D., de Carli, A., Massarutto, A., Assimacopoulos, D., and Van Lanen, H. A. J. (2016) Impacts of European drought events: insights from an international database of text-based reports. Nat. Hazards Earth Syst. Sci., 16, 801-819, doi:10.5194/nhess-16-801-2016.

Examples of studies linking physical drought indices with indicators of drought impacts (based on the EDII), allowing impact-based predictions to be made based on advanced statistical techniques:

Stagge, J.H., Kohn, I., **Tallaksen**, L.M. and Stahl, K. (2015) Modeling drought impact occurrence based on meteorological drought indices in Europe. J. Hydrol., 530, 37-50, doi:10.1016/j.jhydrol.2015.09.039

Blauhut, V., Stahl, K., **Stagge**, J.H., **Tallaksen**, L.M., Stefano, L. De, Vogt, J. (2016) Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors. Hydrol. Earth Syst. Sci. 20, 2779–2800. https://doi.org/10.5194/hess-20-2779-2016

The original database hosted at GEO (2013) along with country specific updates (provided later by the University of Freiburg) has been transferred to EDORA – European Drought Observatory for Resilience and Adaptation in 2021 in collaboration with the University of Freiburg:
https://edo.jrc.ec.europa.eu/edora/php/index.php?id=201

ii) The European Drought Centre (EDC)
http://europeandroughtcentre.com/about-us/edc/
Software and tools:
http://europeandroughtcentre.com/software/

iii) Open-access textbook
The first edition of the textbook on hydrological drought (published in 2004, see reference below) was made available online (on the European Drought Centre website) in 2018.
http://europeandroughtcentre.com/resources/hydrological-drought-1st-edition/

Tallaksen, L.M. & van Lanen, H.A.J. (2004) (Eds) Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Sciences 48. Elsevier B.V., the Netherlands, 580p. Available online since 2018.

A second edition of the textbook is in preparation since 2018 and its expected publication date is June 2023
https://www.elsevier.com/books/hydrological-drought/tallaksen/978-0-12-819082-1

[GEO] [5]

Institution: University of Oslo
Administrative unit: Department of Geosciences (GEO)
Title of case study: IPCC- Intergovernmental Panel on Climate Change
Period when the underpinning research was undertaken: 2000-2022
Period when staff involved in the underpinning research were employed by the submitting institution: 2000-2022
Period when the impact occurred: 2017-2022

1. Summary of the impact

The IPCC is the UN's body for assessing the science related to climate change. It forms the all-important scientific basis for negotiations under the UN Framework Convention on Climate Change leading the Paris Agreement to limit global warming to 2°C. Without the strong scientific basis provided by the IPCC reports, these negotiations would be even more challenging.

Scientists from the Department of Geosciences (GEO) have been selected as authors for the 2018 and 2021 assessment reports based on their scientific merits. They have also contributed with basic research on several topics related to the climate system. The IPCC reports cite more than 50 papers with authors from the department.

2. Underpinning research

The research at GEO that has supported the IPCC reports is the result of a long-term commitment to high-quality basic and applied research in climate science over several decades. This is manifested in two ways as

1. Climate scientists from GEO are recognized internationally as experts in their field and they have been nominated by the Norwegian Environment Agency and selected by the IPCC as authors for the 2018 and 2021 reports of its 6th assessment cycle (and for reports prior to 2010)

2. Climate scientists from GEO have published a large number of high quality studies published in peer reviewed journals that formed the basis for the assessment by the IPCC (more than 50 citations in the 2018 special reports and the 2021 AR6 report).

In the longer perspective, also the education of PhD-candidates should be mentioned (now working in other institutions) who do high quality research that contributes to the assessments. At GEO we have developed a strong scientific expertise on important aspects of climate science, in particular on aerosols and clouds, atmospheric chemistry and short-lived climate forcers (SLCFs), climate sensitivity, cryosphere, hydrosphere and natural hazards. This has been achieved through a number of basic research projects funded mainly by the EU and RCN over many decades.

A particular focus at GEO has been on understanding the processes by which non-CO_2 climate forcers affect climate (e.g., methane, ozone and aerosols) and how feedback mechanisms affect the final climate response. This includes effects of emissions of black carbon aerosols and their effects on Arctic climate change and the indirect effects of aerosols on cloud effective forcing through changes in cloud microphysics (e.g., droplet size) and cloud lifetimes. Instrumental in this research has been the development and use of the Norwegian Earth System model (NorESM). The NorESM model has been used extensively to test process understanding (or lack of that) that is challenged by new observational datasets. The model has also been used extensively (in collaboration with Norwegian partners outside UiO) to perform the baseline simulations (CMIP6) that are crucial for the IPCC reports.

The net effect of the feedbacks determines the response in terms of global warming to the forcing from the emissions. Using new remote sensing data and Earth system models, we have studied the specific feedbacks related to mixed phase clouds. Satellite data has shown that the amount of ice in these clouds is less than previously thought, thus the negative feedback from melting of ice in these clouds is smaller. When accounting for this in models the simulations show a higher climate sensitivity.

The climate sensitivity has also been studied using observed temperature changes in the atmosphere and ocean to constrain simpler energy balance models and estimate the sensitivity using advanced statistical methods.

A further major focus of climate research at GEO is about the cryosphere and hydrosphere and include advanced analysis of I) remote sensing data to quantify climate changes and their impacts, such changes of mountain glaciers and permafrost, and related natural hazards, and ii) hydrological extremes, drought in particular.

Key Researchers and topics:

Trude Storelvmo (PhD student 2003-2006), Professor (2018-). Aerosols,Clouds,Climate sensitivity
Terje Berntsen (Researcher (part-time UiO/CICERO) 1994-2007, Professor 2007-). SLCFs, Climate sensitivity, land-atmosphere interactions
Andreas Kääb (Professor 2005-), Terrestrial cryosphere, natural hazards, remote sensing)
Regine Hock (Professor 2019-), Glacier modelling, high-mountain water resources

3. References to the research (indicative maximum of six references)

In the case of GEO contributions to the IPCC reports it is a challenge to select the key outputs from the research that has allowed scientists to be selected as authors and outputs that forms the basis for the assessment (points 1 and 2 in section 2 above).
Scientists from GEO have contributed as authors to two special reports from 2018 and the 6th assessment report from 2021:

- Climate Change and Land (2018, https://www.ipcc.ch/srccl/)
- The Ocean and Cryosphere in a Changing Climate (2018, https://www.ipcc.ch/srocc/)
- AR6 Climate Change 2021: The Physical Science Basis (2021, https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/)

For the 2018 and 2021 IPCC reports, there are more than 50 papers published in peer-reviewed journals with authors from GEO that are cited. In addition to that, there are a large number of papers on the author's publication lists that form the basis for the selection of authors for the reports.

Six key references from GEO authors that are cited in the 2018 and 2021 reports:

Skeie R.S., Berntsen T., Aldrin M., Holden M, and Myhre G. Climate sensitivity estimates – sensitivity to radiative forcing time series and observational data. 2018. Earth Syst. Dynamics., 9, 879-894. https://doi.org/10.5194/esd-9-879-2018

Lund, M.T., B. Aamaas, C. W. Stjern, Z. Klimont, T. K. Berntsen, and B. H. Samset. A continued role of short-lived climate forcers under the Shared Socioeconomic Pathways, Earth Syst. Dynam., 11, 977–993, 2020. https://doi.org/10.5194/esd-11-977-2020

Storelvmo, T., T. Leirvik, U. Lohmann, P.C.B. Phillips, and M. Wild, 2016: Disentangling greenhouse warming and aerosol cooling to reveal Earth's climate sensitivity. Nature Geoscience, **9(4)**, 286–289, doi:10.1038/ ngeo2670.

Bjordal, J., T. Storelvmo, K. Alterskjær and T. Carlsen (**2020**): Equilibrium climate sensitivity above 5°C plausible due to state-dependent cloud feedback. **Nature Geoscience,** 718- 721. doi: 10.1038/s41561-020-00649-1.

Hugonnet R., McNabb R., Berthier E., Menounos B., Nuth C., Girod L., Farinotti D., Huss M., Dussaillant I., Brun F., Kääb A. (2021). Accelerated global glacier mass loss in the early twenty-first century. Nature 592, 726–731

Kääb A , S Leinss, A Gilbert, Y Bühler, S Gascoin, SG Evans, P Bartelt, E Berthier, F Brun, W-A Chao, D Farinotti, F Gimbert, W Guo, C Huggel, JS Kargel, GJ Leonard, L Tian, D Treichler & T Yao (2018): Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. Nature Geoscience, 11, 114-120.

The Skeie et al. paper uses our competence on SLCFs to estimate global forcing time series that were used as input to a simple energy balance model. Working with statisticians from the Norwegian computing center (Aldrin and Holden), observational time series of air temperatures and ocean heat content were used to constrain estimates of climate sensitivity. This paper was referenced in Chapter 7 of the 2021 IPCC report. It can be noted that both Skeie and Myhre (now working at CICERO) received their PhDs from GEO.

The Lund et al. paper also uses our long-term research on chemically active climate forcers (the SLCFs) to analyze how different emissions pathways for these compounds in the global emission scenarios (SSPs) affect their contributions to future climate change. This paper was referenced in Chapter 6 of the 2021 IPCC report. It can be noted that Lund, Aamaas and Stjern (now working at CICERO) received their PhDs from GEO.

Bjordal et al. presents the discovery, based on climate models and satellite observations, that there is a considerable state-dependence associated with cloud phase feedbacks, in which cloud changes have a damping effect on climate change under moderate warming, which vanishes with stronger warming. All authors are current or former GEO employees.

Storelvmo et al. (2016) presented a new method to calculate Earth's Transient Climate Sensitivity based on observations and advanced statistical analysis. This line of research is currently continued at GEO through two projects funded by the Research Council of Norway.

Hugonnet et al. 2021 has 4 GEO co-authors and is based on methods developed at GEO. The study presents the most detailed and accurate global measurement of glacier changes available to date and forms the backbone of IPCC assessments of, for instance, global glacier changes, sea-level contribution from melting glaciers, glacial run-off changes, and other impacts from glacier change.

Kääb et al. 2018 has 3 GEO (co-)authors. It is referenced in SROCC as an extreme case for climate change impacts on the mountain cryosphere, and as example for cascading effects and hazards from changes in mountain climate and cryosphere.

4. Details of the impact (indicative maximum 750 words)

Global warming is a major threat to human society and natural ecosystems. Both mitigation and adaptation are and will be costly, with a need for globally coordinated measures. The Paris agreement states that global warming should be limited to 2°C. To achieve this, draconian global emission reductions are needed. Also, the impacts of climate change must be understood in order to develop robust adaptation strategies. The beneficiaries of the IPCC work belong clearly the international community, and in particular the policy makers participating in the negotiations under the UNFCCC. This has been the case since both UNFCCC and IPCC were established three decades ago. Without a solid common understanding of the scientific basis, including an understanding of the uncertainties, negotiations (such as the COP-27 meeting in Sharm el-Sheikh, November 2022) would be even more difficult than they already are.

To give useful advice to policy makers on exactly how large reductions need to be, the sensitivity of the climate system must be constrained. The sensitivity is commonly defined as the warming following a doubling of CO2 when the system has reached a new equilibrium (ECS), Unfortunately, this sensitivity has proven to be very difficult to estimate accurately, due to the complex forcing and feedback mechanisms in the climate system.

It is very difficult to exactly pin-point how the research at GEO and the contribution from our IPCC authors have contributed to the international climate negotiations and agreements. As an example, where our research on climate sensitivity and our work as authors on the reports has contributed is the estimated remaining carbon budgets under the Paris agreement. With the assessed uncertainty range for the climate sensitivity, the remaining carbon budget (allowed cumulative emissions from 2020) are 900, 500, and 300 $GtCO_2$ for a 17%, 50% and 83% likelihood of keeping the temperature below 1.5°C respectively. The historic emissions are estimated to 2390 $GtCO_2$ (until 2020)

GEO’s research on mountain cryosphere and climate change impacts on it contributed to shape IPCC’s assessment of past and projected future changes in mountain and polar glaciers and permafrost, and of the impacts of their changes on societies and ecology through changes in river run-off and mountain hazards.

A specific impact is the selection of GEO scientist as authors and chapter scientist for the 2018 to 2021 reports:

Special Report on the Ocean and the Cryosphere (2019):
Andreas Kääb: Lead Author. Chapter 2 High Mountain Areas
Regine Hock (at UiO from 1.9.2019): Coordinating Lead Author. Chapter 2 High Mountain Areas
Pierre-Marie Lefeuvre: Contributing Author and Chapter Scientist. Chapter 2: High Mountain Areas
Thorben Dunse: Contributing Author. Chapter 3: Polar Regions

Special Report on the Climate Change and Land (2018):
Moa Sporre and Terje Berntsen: Contributing Authors. Chapter: 2 Land-Climate interactions

AR6 Climate Change 2021: The Physical Science Basis.
Trude Storelvmo: Coordinating Lead Author. Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity. Drafting Author: Summary For Policymakers. Coordinating Author: Technical Summary
Terje Berntsen: Lead Author. Chapter 6: Short-lived climate forcers. Contributing Author: Technical Summary
Sara Blichner: Contributing Author Chapter 6 Short-lived climate forcers and Technical Summary.
Andreas Kääb and Regine Hock: Contributing Authors Chapter 9: Ocean, Cryosphere and Sea Level Change

5. Sources to corroborate the impact (indicative maximum of ten references)

1. The Norwegian Government: The reports from IPCC are recognized globally as the most reliable basis for knowledge about climate change. https://www.regjeringen.no/no/aktuelt/ipcc-rapport-klimaendringene-krever-tilpasning/id2902468/ (translated from Norwegian)

2. Norwegian Environment Agency (Miljødirektoratet): "The reports from UN's climate panel (IPCC) is the most important scientific basis about climate change for the international negotiations under the UN's framework Convention on Climate Change (UNFCCC)." https://www.miljodirektoratet.no/ansvarsomrader/klima/fns-klimapanel-ipcc/ (translated from Norwegian)
3. US Department of state: "The Intergovernmental Panel on Climate Change's (IPCC) newest report makes it clear – climate change is already a crisis. " (https://www.state.gov/intergovernmental-panel-on-climate-change-working-group-i-contribution-to-the-sixth-assessment-report/)
4. European Environmental Agency (EEA): "Intergovernmental Panel for Climate Change (IPCC). Widely regarded as the most authoritative international voice on the science and impacts of climate change." (https://www.eea.europa.eu/help/glossary/eea-glossary/ipcc).

DP case number 1

Institution: University of Oslo	
Administrative unit: Department of Physics	
Title of case study: Bringing the discovery of the Higgs boson to classrooms and lay audiences worldwide	
Period when the underpinning research was undertaken: 1996 – (see below).	
Period when staff involved in the underpinning research were employed by the submitting institution: The ATLAS experiment at CERN was approved in 1996, the experiment started taking data in 2008, and the Higgs boson was discovered in 2012. The HEP group was involved in all phases; the planning, construction and exploitation of the experiment, as well as the dissemination of the results, as described in this case."	
Period when the impact occurred: 04/07/2012 - 31/12/2022	

1. Summary of the impact (indicative maximum 100 words)

HEP researchers play leading roles in the ATLAS collaboration at the LHC, which in 2012, together with the CMS collaboration, announced the first observation of the Higgs boson. The discovery attracted global media attention in July 2012 and researchers at the HEP section helped the lay audience to understand and appreciate this huge break-through in elementary physics through attendance in direct news programs, new articles, posting in social media and blogs and live-streaming of the official announcement at the local institute. Moreover, researchers and students in HEP quickly extended the educational material, used every year in the International Masterclasses in Particle Physics (IMC), by including real data from the Higgs discovery. Since then tens of thousands of high school pupils and teachers all around the world have had the unique experience to re-discover the Higgs using the same data and methods as the real discovery.

2.Underpinning research (indicative maximum 500 words)

The Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator, started up in September 2008 with proton-proton collisions at the record-high center of mass energy of 8 TeV. One of the large multi-purpose particle detectors recording the proton-proton collisions at the LHC is the ATLAS detector, which in 2012, together with the CMS experiment, claimed the discovery of a new particle in the search for a Higgs boson [**3.1**]. Ten years after the discovery much more data, at even higher energies, has been recorded and analyzed and the new particle's properties have been confirmed to be compatible with the Higgs Boson [**3.2**]. The existence of the Higgs Boson was predicted independently by three teams of theorists already in the 1960's to address the fact that the weak bosons of the Standard Model were observed to have non-zero masses despite the fact that the only mathematically consistent theory required them to be massless. To solve this problem the Brout-Englert-Higgs (BEH) mechanism was introduced, proposing the existence of a new field throughout the universe which gives masses to some of the elementary particles. This field could be verified by the discovery of its associated particle - the Higgs boson - and was for several decades the last missing piece of the Standard Model of particle physics. Thus the discovery in 2012 represented a huge and long awaited breakthrough in modern physics.

The ATLAS Collaboration is one of the largest scientific collaborations in the world, composed of around 5.900 physicists, engineers, technicians, students and administrators. Researchers in HEP have played key roles in the design, construction and operation of the ATLAS-experiment [**3.3**]. The HEP group has also had significant involvement in the development of the World LHC Computing Grid and the distributed data management, an absolute necessity to be able to store and analyze the huge volumes of data recorded by the ATLAS detector [**3.4**, **3.5**]. HEP members did also participate in the analysis of the data leading up to the discovery of the Higgs Boson. Professor *Alex Read* and his PhD student *Lillian Smestad* had been working directly on the analysis searching for the Higgs Boson since the start-up of the LHC in

2008 and were heavily involved in the analysis at the time of the discovery. *Read* was part of the coordination team and thus one of the physicists closest to the discovery.

3.References to the research (indicative maximum of six references)

3.1 ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, 2012, Phys.Lett.B 716 (2012), 1-29, DOI: https://doi.org/10.1016/j.physletb.2012.08.020

3.2 ATLAS Collaboration*, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery*, 2022, Nature 607, 52–59, DOI: https://doi.org/10.1038/s41586-022-04893-w

3.3 ATLAS Collaboration*, ATLAS detector and physics performance: Technical Design Report*, 1999, https://cds.cern.ch/record/391177

3.4 ATLAS Collaboration*, ATLAS Computing: technical design report*, 2005, https://cds.cern.ch/record/837738

3.5 D. Cameron, V. Garonne, F. Ould-Saada et al., Rucio*: Scientific Data Management*, 2019, Computing and Software for Big Science 3, 11, DOI: https://doi.org/10.1007/s41781-019-0026-3

4. Details of the impact (indicative maximum 750 words)
Researchers at HEP contributed significantly to the data taking, processing and analysis leading up to the discovery of the Higgs boson in 2012. The active participation and expertise in the intricate process from the initial proton-proton collisions to the discovery of a new particle gave unique opportunities for the researcher at HEP to inspire and help the audience understand the process and implications of this huge breakthrough. The public outreach activities and follow-ups from the discovery includes; 1) news coverage and public events, 2) development of material for outreach and education and 3) public material and social media.

4.1 News coverage

HEP researchers went live on the main TV channel in Norway, *NRK*, as well as being cited and interviewed in national media including *Aftenposten*, *Dagbladet* and *VG* [**5.1**]. The discovery continued to attract public interest and researchers in HEP have shared their expertise and experience through several articles and podcasts over the past years. A podcast made in connection with the 10-year anniversary of the discovery has so far been downloaded more than 17.000 times.

Several events at the university were also arranged with participation and help from the HEP community. On the day of discovery three PhD students at HEP working in the ATLAS Collaboration followed the live streaming of the announcement of the discovery at CERN in the main auditorium at the Department of Physics. A party was arranged at the university to celebrate the 2013 Nobel Prize in Physics to Peter Higgs and François Englert, a direct consequence of the discovery at CERN a year earlier.

Researchers in HEP initiated the showing of the movie Particle Fever at Cinemateket, a cinema in the center of Oslo with space for around 100 people, in 2014. Read gave a scientific introduction prior to the first show of the movie.

4.2 Material for outreach and education

Researchers at HEP have developed the most widely spread exercise, known as the *Z-path* [**5.2**], which is a part of the annual International Masterclasses in particle physics (IMC). Since the start-up in 2005 IMC have significantly extended their impact area including as many as 213 institutes in 46 countries in the 2016 edition [**5.3**], and has continued to increase since then. One of the main contributors to the expansion has been the *Z-path*, which was the first IMC package to include ATLAS data and simulations, initiated by Prof. *Farid Ould-Saada* and his students; *Maiken Pedersen*, *Magnar Bugge*, *Vanja Morisbak* and *Eirik Gramstad*. This effort later culminated in the release of ATLAS open data from LHC Run 2 in 2020 [**5.4**].

One of the main goals of the *Z-path* educational material is to follow the heartbeats of the experiments at the absolute forefront in the field of high energy physics. Thus immediately following the Higgs discovery a fraction of the data used in the actual discovery, including real Higgs candidate events, were added to the mix of data available to the pupils. In the *Z-path* exercise the pupils study the data and try to discover something themselves. Obviously they are “re-discovering” the well known particles, but in addition simulations of hypothetical particles such as Gravitons (inspired by the infamous 750 GeV di-photon excess observed in 2016 [**5.5**]) and new heavy gauge bosons are included, allowing the students to experience a “surprising” discovery. Given the limited number of Higgs candidate events available the students do not have enough statistics to claim a discovery of the Higgs boson. However, in the discussions at the end of the masterclass the results are used to explain that if more events had been analyzed, using the same technique as the pupils now master, one would eventually see a significant deviation from the expectations - exactly like how the Higgs boson was first discovered at the LHC.

A research project studying the impact of outreach and out-of-school activities on Norwegian upper secondary students’ motivations for entering into science, technology, mathematics and engineering (STEM) education looked at the effect of the IMC program at UiO in 2010 [**5.6**]. Despite this study being carried out before the Higgs discovery the pupils who were interviewed as part of the research project all reported that the out-of-school activities were stimulating and that it provided a variety of experiences which they did not necessarily get through regular lectures at school. The authors claim that one of the success factors of the IMC is that it manages, through its diverse program, to reach a range of different pupils, with various wishes, interests and preferences. One of the students expressed:

“*When you’re at school, you only learn stuff others have already discovered before you, and it is like there is not much more to discover. In Masterclass you see how much there actually is to do research on, and how much we don’t know. I think perhaps the most interesting part was to discover that*”.

This just underpins the importance of following the heartbeats of the field and always include the latest development in the educational material, as is pursued in the *Z-path* exercise.

4.3Public material and social media

HEP researchers helped develop material to reach out to a broader audience with more detailed explanations of the discovery and the physics behind it. A YouTube video was made with the help from the institute/faculty where Read explains about the newly discovered particle. The video exists in both English [5.7] and Norwegian [5.8] and has had more than 20.000 views since 2013. Instagram stories on the departments’ Instagram profile as well as blogs featuring HEP researchers have also been used as means to reach out to a broader public.

5. Sources to corroborate the impact (indicative maximum of ten references)

5.1 Collated list of media coverage of the observation of the Higgs (*see below)
5.2 http://zpathweb.hepp.uiocloud.no/InternationalMasterclasses
5.3 Marcia Begalli and Uta Bilow, Sharing LHC Research and Discovery

with High School Students, https://link.springer.com/content/pdf/10.1007/978-3-319-96163-7.pdf?pdf=button (Chapter 4)
5.4 F. Ould-Saada et al., *Review of the 13 TeV ATLAS Open Data release*, 2020, https://cds.cern.ch/record/2707171
5.5 ATLAS Collaboration, *Search for resonances in diphoton events at √s = 13 TeV with the ATLAS detector*, 2016, *Journal of High Energy Physics*. **2016** (9): 001. doi:10.1007/JHEP09(2016)001.
5.6 Fredrik Jensen, *The Impact of Outreach and Out-of-School Activities on Norwegian Upper Secondary Students' STEM Motivations*, 2015, https://doi.org/10.1007/978-94-007-7793-4_12
5.7 https://youtu.be/3ak0iR3KT1E
5.8 https://youtu.be/lA6TfV1Kze0

***5.1** Collated list of media coverage of the observation of the Higgs boson

1. *Er higgsbosonet funnet ved LHC?* FFV nr. 3 2012 http://www.norskfysikk.no/nfs/ffv_old/2012/FFV_2012-3.pdf
2. *Hva vet vi om Higgs-partikkelen ti år etter oppdagelsen?*, FFV nr. 2 2022
3. *Podkasten Universitetsplassen, med tilhørende artikkel*, https://titan.uio.no/naturvitenskap/2022/higgs-10-ar-det-var-rockekonsertstemning
4. https://radio.nrk.no/podkast/ekko_-_et_aktuelt_samfunnsprogram/sesong/201211/l_e0c84e99-1a6e-4a35-884e-991a6eaa35e4
5. *Hva er så sensasjonelt?*, Kronikk i Dagsavisen, https://www.dagsavisen.no/kultur/2012/07/13/hva-er-sa-sensasjonelt/
6. Are Raklev, Alex Read, Lillian Smestad, Farid Ould-saada, *Oppdagelsen av en partikkel*, Kronikk i Aftenposten, https://www.aftenposten.no/meninger/kronikk/i/LQa1/oppdagelsen-av-en-ny-partikkel
7. *Gudepartikkelen er funnet*, Sommeråpent, NRK, no longer available
8. *Historisk gjennombrudd*, Dagsrevyen, NRK, http://tv.nrk.no/serie/dagsrevyen/nnfa19070412/04-07-2012#t=10m54s
9. *Higgspartikkelen*, Dagsnytt 18, http://nl.nrk.no/podkast/aps/3720/nrk_dagsnytt_atten_2012-0704-0715_6347702616.mp3
10. I dag kommer fysikere til å sprette sjampanjen - Dagbladet, http://www.dagbladet.no/2012/07/04/nyheter/utenriks/higgs-bosonet/cern/vitenskap/22408298/
11. *Det er bursdag, konfirmasjon og bryllup på én gang*, Dagbladet, http://www.dagbladet.no/2012/07/04/nyheter/utenriks/lhc/forskning/cern/22412481/
12. *Dette er Higgsbosonet og derfor er det viktig*, VGTV, http://www.vgtv.no/#!id=54598
13. *Vi har funnet "Gudepartikkelen"*, VG nett, http://www.vg.no/nyheter/utenriks/artikkel.php?artid=10058625
14. *Derfor er "Gudepartikkelen" historisk*, VG nett, http://www.vg.no/nyheter/utenriks/artikkel.php?artid=10058640
15. *Inn i en ny æra*, Aftenposten, https://www.aftenposten.no/norge/i/dObz1/cern-forsker-inn-i-en-ny-aera
16. *Se, det finnes!*, Dagsavisen, https://www.dagsavisen.no/nyheter/innenriks/2012/07/05/se-det-finnes/
17. *En milepæl i vår forståelse av naturen*, Stavanger Aftenblad, https://www.aftenbladet.no/lokalt/i/1yv6l/en-milepael-i-vaar-forstaaelse-av-naturen
18. *Vi har funnet en partikkel*, forskning.no, https://forskning.no/fysikk/vi-har-funnet-en-partikkel/694183
19. *Har de funnet Higgs?*, forskning.no, https://forskning.no/kjernefysikk/har-de-funnet-higgs/694399

DP case 2

Institution: University of Oslo	
Administrative unit: Department of Physics	
Title of case study: Space Weather Products for the Arctic Regions	
Period when the underpinning research was undertaken: 2011-2021	
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-2021	
Period when the impact occurred: 2020	

1. Summary of the impact

Space Weather impacts the modern society, which nowadays is highly dependent on the satellite-based communication, navigation, and related services. One of the space weather effects that are common in the Arctic is the formation of irregularities in ionospheric plasma density and the consequent disturbance of trans-ionospheric radio signals. We have developed data products and models that will contribute to the space weather forecasting. They will provide users with information on the severity of space weather conditions for the operations, with the aim to reduce risks of operations in the Arctic regions. The work has been carried out together with the European Space Agency and is now available and being implemented for operational purposes.

2. Underpinning research

The state of the polar ionosphere depends on the geomagnetic activity and is highly variable due to direct coupling of the ionosphere to the interplanetary space in the polar regions. Instabilities and turbulence in the ionosphere lead to plasma structuring. Resulting irregularities in ionospheric plasma density can impact the propagation of trans-ionospheric radio waves and lead to diffraction and refraction of the signal. Thus, the signal received on the ground is subject to scintillation and can be distorted in both phase and amplitude. This can severely impact the performance of systems relying on satellite signals, such as the Global Navigation Satellite Systems (GNSS), which include GPS, Galileo, or GLONASS systems. Under strong disturbances, the GNSS positioning may become unavailable. Understanding these processes in coupled ionosphere-magnetosphere-thermosphere system, and creating foundations for space weather nowcasting and forecasting services have been the world-wide efforts, also supported by the European Space Agency (ESA), NASA, other space agencies and research councils.

The research sections for Plasma and Space Physics and for Electronics at the Department of Physics have over years developed instrumentation for in-situ measurements of the plasma irregularities with sounding rockets and satellites. Their multi-needle Langmuir probes have been flown on many sounding rockets [1], including the rocket missions from the USA and Japan (NASA, JAXA). They are currently being flown on satellites (Norsat-1, Brick-II), are mounted on a lunar rover, and will also be installed on the International Space Station in spring 2023. Data collected by these instruments have contributed significantly to our understanding of the irregularity formation in the polar ionosphere and gave the foundation, together with the ground-based observations, for developing models and space weather forecasting services.

In 2014 the 4DSpace Strategic Research Initiative was established at the Faculty of Mathematics and Natural Sciences, UiO. 4DSpace is hosted at the Department of Physics, and it includes four research sections: plasma and space physics, electronics, nanoinformatics (Department of Informatics), and mechanics (Department of Mathematics). Through a multidisciplinary approach, 4DSpace has focused on integrated studies of the polar ionosphere, with the in-situ measurements, ground-based observations (with own observatories in Svalbard, Northern Norway, Antarctica) [2], theory and numerical simulations. 4DSpace has hosted several designated projects, including the ERC CoG project. Since 2015, 4DSpace has been involved in working with the European Space Agency on space weather related projects. Through the data analysis of data from the Swarm satellites, the group has developed data products, which allow for detecting and characterising the polar cap patches as well as structuring and characterising of the plasma variability [3,4]. These are now available for public use and continuously delivered to the ESA data servers as the IPIR data product [4]. The corresponding model has been developed for the propagation of the polar cap patches [5], the method is now a patent that has been further taken by the industrial partner for commercialisation. Furthermore, the work has continued towards modelling and forecasting of ionospheric conditions that are severe for the GNSS signal propagation [6]. Based on its experience, 4DSpace has been successful in leading international consortia, within projects funded by ESA, for the development of ionospheric models and space weather forecasting services. These include the Swarm-VIP project (Norway, UK, Italy, Poland) for developing the model for ionospheric plasma variability based on the Swarm satellite data, the FORSWAR project for developing the forecast of severe scintillation conditions over Greenland (Norway, Spain, Germany, Poland), and ISPA for implementing the space weather forecast for ionospheric scintillations in the Arctic as a part of the ESA Space Situation Awareness/Space Weather (Norway, Poland – ongoing project).

Names of the key researchers

Wojciech Miloch, associate professor/professor, 2011-now
Lasse B. N. Clausen, associate professor/professor, 2012-now
Ketil Røed, associate professor/professor, 2014-now
Jøran Moen, professor, 2011-2020
Yaqi Jin, PhD student/postdoctoral fellow/researcher, 2012-now
Daria Kotova, postdoctoral fellow/researcher, 2019-now
Andres Spicher, PhD student/postdoctoral fellow/researcher, 2014-2021
Anna Fæhn Follestad, PhD student, 2016-2020
Per Høeg, associate professor, 2019-2022

The name-list is just a selection and it is indicative. All members of the 4DSpace Strategic Research Initiative have contributed to different aspects of the activity. 4DSpace had between 30 and 50 participants (including master students). The number varied due to different number of students and PhD research fellows over the years.

3. References to the research (indicative maximum of six references)

Journal publications:

[1] A. Spicher, W.J. Miloch, L.B.N. Clausen, and J.I. Moen, Plasma turbulence and coherent structures in the polar cap observed by the ICI-2 sounding rocket, J. Geophys. Res. Space Physics, 120, 10959-10978 (2015), doi:10.1002/2015JA021634.
[2] Y. Jin, J. I. Moen, W. J. Miloch, GPS scintillation effects associated with polar cap patches and substorm auroral activity: Direct comparison, J. Space Weather Space Clim., 4, A23 (2014), https://doi.org/10.1051/swsc/2014019.
[3] A. Spicher, L. B. N. Clausen, W. J. Miloch, V. Lofstad, Y. Jin, and J. I. Moen, Interhemispheric study of polar cap patch occurrence based on Swarm in situ data, J. Geophys. Res. 122, 3837–3851 (2017), doi:10.1002/2016JA023750.
[4] Y. Jin, Ch. Xiong, L.B.N. Clausen, A. Spicher, D. Kotova, S. Brask, G. Kervalishvili, C. Stolle and W.J. Miloch, Ionospheric plasma irregularities based on in situ measurements from the Swarm satellites. J. Geophys. Res. 124, e2020JA028103. https://doi.org/10.1029/2020JA028103 (2020).
[5] A. Fæhn Follestad, L.B.N. Clausen, E.G. Thomas, Y. Jin, A. Coster, A. (2019). Polar cap patch prediction in the expanding contracting polar cap paradigm. Space Weather 17(11), p. 1570–1583. doi: 10.1029/2019SW002276.
[6] Y. Jin, L. B. N. Clausen, W. J. Miloch, P. Høeg, W. Jarmołowski, P. Wielgosz, J. Paziewski, B. Milanowska, M. Hoque, J. Berdermann, H. Lyu, M. Hernandez-Pajares, E. Monte-Moreno, A. Garcıa Rigo, Climatology and Modeling of Ionospheric Irregularities over

Greenland Based on Empirical Orthogonal Function Method, J. Space Weather Space Clim. 12, 23 (2022, submitted Nov. 2021), DOI: https://doi.org/10.1051/swsc/2022022

4. Details of the impact

The approach within 4DSpace Strategic Research Initiative for understanding the ionospheric irregularities and their impact on GNSS signals has been decisive in obtaining the impact in the field. To address the problem, 4DSpace had several activities in parallel – the development of the instrumentation, development of numerical codes, data analysis from satellites and development of models. Successful development of instrumentation has led to flying the instruments on several sounding rockets and satellites. The Langmuir probes invented by UiO received a patent in 2013 (**Patent, Langmuir probe, WO2014111476A1, 2013**) and have since been space qualified for ESA by a Norwegian company EIDEL. They are now flown on satellites. Experience in data analysis from the in-situ experiments allowed the group to become an important partner for data analysis from the ESA's Swarm satellites. 4DSpace has developed new data products, which have been regularly provided to the ESA servers, as the IPIR dataset since 2019. It is now an official ESA data product (available at https://swarm-diss.eo.esa.int in the folder Level2daily/Entire_mission_data/IPD/) and this dataset has been extensively used by the global community to study plasma irregularities and ionospheric variability globally. It forms a basis for the Swarm-VIP models (project consortium led by the UiO), but it is also used by other research and development projects (e.g., by research groups in the Netherlands or in Italy). The statistical studies with the IPIR dataset are providing basis for future space weather models, and currently, upon a request from ESA, a new version of the data product, IPIR-fast, is being implemented to allow for fast data processing and near real time results accessibility and space weather nowcasting/forecasting applications.

At the same time, the ground-based studies within 4DSpace have focused on the relationship between structuring in the ionosphere and scintillations observed on the ground. These studies carried out with UiO's instrumentation in the Arctic and in Antarctica led to better understanding of the space weather effects, and larger number of case studies and statistical analysis, laid foundations for modelling and forecasting. The first models have been related to the polar cap patches and their propagation across the polar cap and were based on results from both ground-based and satellite measurements. The model was patented in 2020 (**Patent, Space Weather Forecasting, WO2021083799, 2020**). In 2019/2020 the group received grants from ESA and EU to develop the detailed models for ionospheric variability and to predict conditions for ionospheric scintillations. In all cases the group was leading the international consortia. The first model on the variability of ionospheric plasma based on Swarm in situ data (Swarm-VIP), has employed the IPIR data product for the development of a semi-empirical model. The model is now being published. In 2020, 4DSpace started development of the prototype for the space weather forecasting (Forecasting Space Weather in the Arctic Region, FORSWAR-project, https://nebula.esa.int/content/forecasting-space-weather-arctic-region-forswar). The project activity resulted in novel approaches for the forecasting of ionospheric irregularities.

The result of the long-term research and development efforts is that the 4DSpace Strategic Research Initiative is now developing products for the ESA's Space Weather / Space Situation Awareness programme as well as for ESA's Earth Observation. The new models for the scintillation forecast in the Arctic (ISPA) include coordination with the industrial partners, and future users, which are testing the products.

The impact is within a broader aspect of the space weather modelling and forecasting. It is two-fold. The instruments developed and provided by the 4DSpace together with their industrial partner EIDEL have been now used for sounding rockets (USA, Japan), and satellites (Norway, The Netherlands) and a lunar rover (UAE, since 2020). They are now being flown to the International Space Station, and they have been proposed for ESA's future missions (e.g., France). The impact is primarily on the scientific community and space industry, where the instruments are a cutting-edge instrumentation for the space weather studies and monitoring.

Another Impact is providing data products and models for the scientific community worldwide. The IPIR data product is now being used by the community worldwide and is also available thorugh a interactive tool VirEs for Swarm (https://vires.services/). The models are forming a basis for space weather forecasting services. These are now being implemented for ESA's Space Weather / Space Situation Awareness as an operational service. The users for this service will be industries operating in the Arctic regions, as well as individuals using GNSS services. The impact will be increased safety of operations in the Arctic regions.

The impact was achieved by active dissemination of the results and participations in workshops and discussions, which allowed for applying the results and creating data products and services based on them.

5. Sources to corroborate the impact (indicative maximum of ten references)

[1] EIDEL website on mNLP probe https://eidel.no/en/product/multi-needle-langmuir-probe/

[2] Press news on the mNLP probes going to the Moon (in Norwegian): https://www.titan.uio.no/teknologi/2021/arabisk-manebil-skal-bruke-norsk-teknologi.html

[3] News on the ground-based observatory and space weather activities within 4DSpace: https://forskning.no/antarktis-forskeren-forteller-om-forskning/forskeren-forteller-jakter-pa-sorlyset/294519

[4] Documentation on ESA website - FORSWAR: https://nebula.esa.int/content/forecasting-space-weather-arctic-region-forswar

[5] Documentation on ESA website – IPIR: https://earth.esa.int/eogateway/activities/ipir

[6] Article about Grand Challenge Inititative Cusp (in Norwegian): https://www.titan.uio.no/innovasjon/2016/innleder-gigantsamarbeid-med-nasa.html

[7] ESA Media coverege from the Swarm and Cryosat Science meeting in Banff, Canada: https://www.esa.int/ESA_Multimedia/Videos/2017/07/Banff_Swarm_and_CryoSat_science

[8] Media on collaboration with Japan: https://forskning.no/partner-romfart-arktis/plasma-i-verdensrommet-kan-true-sikkerheten-til-skip-i-arktis/373834

[9] ESA article on the mNLP probes: "ESA plasma sampler headed to the Moon and ISS" https://www.esa.int/Enabling_Support/Space_Engineering_Technology/ESA_plasma_sampler_headed_to_the_Moon_and_ISS

[10] Reuters News Agency (07.2015), Northern Lights rocket launch could solve GPS interference: https://www.youtube.com/watch?v=kTV2YOIbGKw

DP case 3

Institution: UiO
Administrative unit: Department of Physics
Title of case study: Developing learning resources, investigating student learning and teacher professional development in modern physics
Period when the underpinning research was undertaken: 2014-2019
Period when staff involved in the underpinning research were employed by the submitting institution: 2015-109 for the majority of involved staff members
Period when the impact occurred: 2015 ->

1. Summary of the impact (indicative maximum 100 words)

The ReleQuant project (2015-2019) combined development of online learning resources in general relativity and quantum physics for upper secondary school with research on students' understanding and learning. It also included research on how pre- and in-service physics teachers developed their competence through participating in the project. Key outcomes included

a. free, research-based online learning resources
b. increased knowledge about student understanding and learning in secondary as well as higher education, which have fed into
c. increased professional competence for teaching modern physics among pre-and in-service teachers and university teaching staff
d. increased competence among physics education researchers and teachers in collaborating in design-based research
e. international research collaboration relations
f. inspiration for learning resources (tasks, textbooks,…) for secondary andhigher education physics.

ReleQuant was led by the Physics education section (UiO) in collaboration with NTNU, with physics teachers in upper secondary schools, and with the Norwegian Centre for Science Education.

2. Underpinning research (indicative maximum 500 words)

Through Design-based research methodology, ReleQuant developed the online learning resources Quantum physics and General relativity (https://www.viten.no/eng/) through several rounds of development and classroom trials in collaborating schools. The project's starting point was the physics curriculum for upper secondary school, which required students to develop a qualitative understanding of general relativity and to reflect on the philosophical implications of quantum physics. There was little previous research on student learning in these areas and few resources for teachers. The ReleQuant resources emphasise students' use of oral and written language to express and develop their understanding, and visualize abstract principles by means of animations, simulations, video clips and examples of modern physics technological applications.

Data analysed in ReleQuant included written and oral student responses to assignments given in the learning resources, and interview data with students and with pre- and in-service teachers. The project included two PhD students at UiO and a number of masters' students at UiO and NTNU. The research (www.mn.uio.no/fysikk/english/research/projects/relequant/) provided results concerning:

- student understanding and learning challenges within specific topics such as the Schrödinger's cat thought experiment, observation in quantum physics, the wave-particle duality of quantum objects; Heisenberg's uncertainty relations; curved space-time; the equivalence principle, etc.
- opportunities and challenges in the physics classroom when using learning approaches (some of them untraditional) such as small-group discussions of qualitative concepts and philosophical implications; thought experiments, metaphors and analogies; improvised representations, etc.
- competence development as experienced by pre- and in-service physics teachers when participating in a research and development project

The research has provided:
- physics students and teachers with free, research-based, online learning resources in quantum physics and relativity
- teachers and lecturers with a better knowledge of student understanding and student challenges when learning modern physics in upper secondary school as well as in undergraduate higher education
- researchers with a model of how learning resource development may be integrated with pre- and in-service teacher education in a DBR project
- teacher educators with resources (for instance textbook chapters) for use in pre- and in-service teacher education concerning teaching and learning modern physics and concerning varied classroom approaches

Key researchers involved:

Angell, Carl (professor, UiO, retired Dec 2016)
Bungum, Berit (professor, NTNU)
Bøe, Maria Vetleseter (assoc. professor, UiO)
Frågåt, Thomas (PhD student, UiO)
Henriksen, Ellen Karoline (professor, UiO)
Kersting, Magdalena (PhD student, UiO; PhD attained 2019)
Tellefsen, Cathrine W (senior lecturer, UiO)

Other participants: Rolf Steier, Arnt Inge Vistnes, Susanne Viefers, plus master's students at NTNU and UiO)

2. References to the research (indicative maximum of six references)

Frågåt, T, Bøe, MV, Angell, C (2022). Providing Professional Development for Physics Teachers through Participation in a Design-Based Research Project. *Nordic Studies in Science Education* 18(1), 112–127.

Bøe, M. V., & Viefers, S. (2021). Secondary and University Students' Descriptions of Quantum Uncertainty and the Wave Nature of Quantum Particles. *Science & Education*, 1-30.

Bungum, B., Bøe, M. V., & Henriksen, E. K. (2018). Quantum talk: How small-group discussions may enhance students' understanding in quantum physics. *Science Education*, 102(4), 856-877.

Bøe, MV, Henriksen, EK, Angell, C (2018). Actual versus implied physics students: How students from traditional physics classrooms related to an innovative approach to quantum physics. *Science Education* 102 (4), 649-667

Henriksen, EK, Angell, C, Vistnes, AI, Bungum, B (2018). What Is Light? Students' Reflections on the Wave-Particle Duality of Light and the Nature of Physics. *Science & Education* 27, 81–111.

Kersting, M, Henriksen, EK, Bøe, MV, Angell, C (2018): General relativity in upper secondary school: design and evaluation of an online learning environment using the model of educational reconstruction. *Physical Review Physics Education Research* 14 (1), 010130

Kersting, M., & Steier, R. (2018). Understanding curved spacetime. *Science & Education*, 27(7), 593-623. F

See https://www.mn.uio.no/fysikk/english/research/projects/relequant/ for a complete list of ReleQuant research publications.

4. Details of the impact (indicative maximum 750 words)

Improved learning opportunities in modern physics for students in secondary and higher education

With the research-based learning resources offered at www.viten.no, Quantum Physics and General Relativity, students and teachers have available valuable resources complementing physics textbooks. Each of the learning resources has had an average of around 500 registered users yearly during the last couple of years (corresponding to roughly 15 % of all final-year physics students in upper secondary school). Probably, many more have used parts of the resources without registering as users (registration is not necessary for viewing and interacting with the resources, but is needed if teachers are to have access to reading and commenting on students' work in the online platform). Quantum Physics was revised in 2022 as a result of a new national physics curriculum that has taken effect since 2021.

ReleQuant's focus on qualitative interpretation of quantum physics may have contributed to the choice to focus on "quantum objects" in the new national Physics curriculum (https://www.udir.no/lk20/fys01-02). Also, the project appears to have inspired authors of upper secondary physics textbooks; the chapters on general relativity and on quantum physics in ERGO, the most widely used textbook, shows striking similarities with the ReleQuant resources in discussion tasks, illustrations, examples etc. In higher education, ReleQuant has also collected data among students at the Department of Physics, UiO, and has contributed to developing a broader set of tasks and problems, training the students to discuss the nature of quantum phenomena rather than just performing calculations.

Improved professional competence for pre- and in-service teachers

Physics teachers having received pre- or in-service training during and after the ReleQuant project period have been presented with findings concerning student understanding, typical learning challenges and fruitful teaching approaches. This has happened through chapters in the Norwegian textbook used in most physics teacher training programmes (see point 5) and through numerous dissemination activities from ReleQuant. Thus, teachers are better prepared to guide students' learning process in modern physics. The project has also alerted teachers to a broader range of learning and assessment opportunities, including writing and discussion tasks, use of simulations, attention to historical-philosophical aspects of physics, etc.

Better competence among researchers in conducting Design-based research in collaboration with teachers

The ReleQuant project has given the involved researchers valuable experience with collaborating with teachers in development work. Several central ReleQuant researchers have after the project gone on to use DBR and related methodological approaches in projects at the UiO, NTNU and Oslo Metropolitan University.

Improved competence for developing learning resources on the viten.no platform

In ReleQuant, physics education researchers collaborated with developers of educational resources at the Norwegian Centre for Science Education (NCSE). At the time of starting work in ReleQuant, the centre was looking for a new web architecture for their portfolio of resources at www.viten.no, since the previous, flash-based resources needed replacement. The ReleQuant resources became an arena for trialling a new web solution, and experiences from classroom testing of the resources were used by the NCSE in developing subsequent resources. The collaboration has also sparked a closer collaboration relation between the ReleQuant researchers and the NCSE developers, so that a learning resource on radioactivity has been developed in a recent collaboration involving research undertaken by a master's student.

Strengthened international research network in «Einsteinian physics»
In 2016, ReleQuant entered into a collaboration with a research group at the University of Western Australia (UWA), and a delegation with researchers and pre- and in-service teachers from the project visited UWA in late 2016. This collaboration has supported a research proposal to the Australian Research Council which received funding in 2019 (LP180100859), allowing the project to be extended to include a number of international collaboration partners. This collaboration has engendered several conference papers, and an international seminar was held in Germany in 2019. Both the PhD students associated with ReleQuant have been visiting scholars in Australia during 2018-2019. An international, edited book on teaching and learning «Einsteinian Physics» was published in 2021 (see point 5), with a physicist from Australia (UWA) and one of the ReleQuant PhD students as editors. The improved international network is also illustrated by ReleQuant researchers being invited to assess PhD theses in modern physic education abroad.

5. Sources to corroborate the impact (indicative maximum of ten references)

Here we list sources demonstrating the potential impact the project may have on involved user groups (students, teachers, researchers) through resources and publications available to, and aimed at, these user groups.

General Relativity. Free, online learning resource hosted by the Norwegian Centre for Science Education, www.viten.no/ (Norwegian) and https://www.viten.no/eng/

Quantum physics. Free, online learning resource hosted by the Norwegian Centre for Science Education, www.viten.no/ (Norwegian) and https://www.viten.no/eng/

Kersting, M & Blair, D (2021). *Teaching Einsteinian Physics in Schools: An Essential Guide for Teachers in Training and Practice*. Routledge, ISBN: 9780367752590

Chapters 21 («Teaching quantum physics») and 23 («Teaching relativity») in the book Angell, C; Bungum, B; Henriksen, EK; Kolstø, SD; Persson, RJ & Renstrøm, R (2019). *Fysikkdidaktikk [Physics Education].* Cappelen Damm Akademisk. ISBN 978-82-02-62335-7.

Henriksen, EK; Angell, C & Tellefsen, CW (2015). Prosjekt ReleKvant: Skreddersydde læringsressurser i fysikk, utviklet av forskere, lærere og lektorstudenter. I Rindal, Ulrikke Elisabeth; Lund, Andreas & Jakhelln, Rachel Elise (Red.), *Veier til fremragende lærerutdanning [Pathways to excellent teacher education]*. Universitetsforlaget. ISBN 9788215025148

Bungum, B; Bøe, MV & Henriksen, EK (2017). Kvantesnakk: Korleis kan diskusjonar i smågrupper støtte elevar si læring? *Naturfag [Free, online journal about science teaching, aimed at teachers]*. ISSN 1504-4564. 2017(2), s. 50–53.

Web page of the undergraduate course in Quantum Physics at the University of Oslo, where description of course content and learning gaols have been updated to include «In seminars, you will reflect and discuss scientific questions in groups, and you will also get the opportunity to think broadly about what a particle, energy and time is" and "After completing the course,

you are able to discuss and explain the key concepts and principles of quantum physics"
https://www.uio.no/studier/emner/matnat/fys/FYS2140/index-eng.html

Description of research results from ReleQuant in the magazine Classroom physics:
https://spark.iop.org/sites/default/files/media/documents/ClassroomPhysicsDecember2021Web.pdf

The Einstein-first project at the University of Western Australia: www.einsteinianphysics.com
Heraeus seminar, General Relativity as a Challenge for Physics Education: https://www.we-heraeus-stiftung.de/veranstaltungen/seminare/2019/general-relativity-as-a-challenge-for-physics-education/

In addition to these, a large number of presentations have been given in various fora; see https://www.mn.uio.no/fysikk/english/research/projects/relequant/ for a complete list.

DP case 4

Institution: University of Oslo
Administrative unit: Department of Physics
Title of case study: Introduction of proton therapy in Norway
Period when the underpinning research was undertaken: 2011-2023
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-2023
Period when the impact occurred: 2016-2023

1. Summary of the impact

Researchers from the bio- and medical physics section at UiO have been advocates for proton cancer therapy for many years. Their research in radiation physics and radiobiology, their collaboration with preclinical and clinical researchers at Oslo University Hospital (OUS), and their cross-disciplinary research efforts within the PROCCA (protons contra cancer) consortium have all been essential to build the necessary competence and expertise for establishing proton therapy in Norway. The UiO researchers have played leading roles in various national committees that led to the decision to build two proton therapy centers in Oslo and Bergen. The research activities involving cell irradiations at the Oslo Cyclotron Laboratory at UiO and animal experiments at DCPT Aarhus (Denmark) were crucial for designing the preclinical beam line at the proton therapy center at OUS.

2. Underpinning research

Researchers from the section for bio- and medical physics (BMF) at UiO have studied effects of ionizing radiation in various systems, ranging from detectors, molecular systems, cells, animals and humans. This includes studies with protons and relies on expertise in radiation dose measurements and calculations as well as effect measurements in biological model systems. Their unique background, knowledge and experience in both physics and radiobiology has been pivotal for catalyzing the political decision to introduce proton therapy in Norway. This is evident from several national reports on the evaluation and introduction of proton therapy.

The research has mainly been carried out by Nina Edin and Eirik Malinen, but also by earlier (now retired) scientific members of the section. This research has been a continuous activity at the section for several decades. More recently, the group has led the cross-disciplinary Protons Contra Cancer (PROCCA, 2019-2023) project comprising researchers from physics, clinical medicine, oral biology, and psychology. The project investigates different response mechanisms, including healthy tissue damage, induced by proton irradiations and compares them with X-ray induced responses in head and neck cancer patients. Moreover, the project investigates how these responses affect the quality of life for cancer survivors, both in terms of physical and psychological health.

The BMF team furthermore collaborates with researchers from the section for nuclear and energy physics and from the section for high-energy physics at UiO on particle accelerator technology for proton therapy. It is investigated how novel accelerator technology developed at CERN can be used to further improve proton therapy in areas of dose contrast and precision treatment. Research topics include flash therapy with ultra-high dose rates administered over short times, and grid therapy with highly heterogeneous dose profiles using strongly focused proton beams.

Names of the key researchers

Section for bio- and medical physics:
Eirik Malinen, professor (2011-2023)
Nina Frederike Jeppesen Edin, associated professor (2011-2023)
Eli Olaug Hole, professor (2011-2022)

Einar Sagstuen, professor (2011-2021)
Anne Marit Rykkelid, PhD student (2018-2023)
Delmon Arous, PhD student (2019-2023)
Section for nuclear and energy physics:
Andreas Görgen, professor (2017-2023)
Sunniva Siem, professor (2017-2023)
Section for high-energy physics:
Erik Adli, professor (2019-2023)
Kyrre Ness Sjøbak, researcher (2019-2023)

3. References to the research (indicative maximum of six references)

E.Waldeland, O.Dahl, O.H.Odland, S.Kvaløy, J.Lund, E.Malinen, K.Marienhagen, R.Sylvarnes, L.P.Muren, G.Pedersen, B.Pedersen, P.O.Vadset, A.D.Wanderås, O.Mella. Particle therapy in Norway - report from the national project group. Radiotherapy and Oncology, Volume 111, Supplement 1, 2014, Pages S54-S55. DOI: 10.1016/S0167-8140(15)30905-1

E Waldeland, EO Hole, B Stenerlöw, E Grusell, E Sagstuen, E Malinen. Radical formation in lithium formate EPR dosimeters after irradiation with protons and nitrogen ions. Radiation research 174 (2), 2010, pages 251-257. DOI: 10.1667/RR2035.1

Malinen E, Søvik Å. Dose or 'LET' painting--What is optimal in particle therapy of hypoxic tumors?
Acta Oncol, 54 (9), 2015, pages 1614-22. DOI: 10.3109/0284186X.2015.1062540

Tordis J. Dahle, Anne Marit Rykkelid, Camilla H. Stokkevåg, Andrea Mairani, Andreas Görgen, Nina J. Edin,E ivind Rørvik, Lars Fredrik Fjæra, Eirik Malinen &Kristian S. Ytre-Hauge. Monte Carlo simulations of a low energy proton beamline for radiobiological experiments. Acta Oncologica, Volume 56, 2017, pages 779-786. DOI: 10.1080/0284186X.2017.1289239

Rykkelid A, Siem S, Ytre.Hauge K, Malinen E, Edin, NFJ. Very high relative biological effectiveness found at the distal end of the proton Bragg peak. Radiotherapy and oncology, 2018. 127: p. S1259-S1259. DOI: 10.1016/S0167-8140(18)32589-1

Grigalavicius M, Mastrangelopoulou M, Berg K, Arous D, Ménard M, Raabe-Henriksen T, Brondz E, Siem S, Görgen A, Edin NFJ, Malinen E, Theodossiou TA. Proton-dynamic therapy following photosensitiser activation by accelerated protons demonstrated through fluorescence and singlet oxygen production. Nat Commun, 10 (1), 2019, 3986. DOI: 10.1038/s41467-021-27175-x

Rykkelid AM, Thingstad EK, Mariampillai AE, Syljuåsen R, Malinen E, Edin, NFJ. Increased immunogenic calreticulin signaling at the distal end of the proton Bragg peak. Radiotherapy and oncology, 2020. 152: p. S245-S246. DOI: 10.1016/S0167-8140(21)00467-9

Samnoy AT, Ytre-Hauge KS, Malinen E, Tran L, Rosenfeld A, Povoli M, Kok A, Summanwar A, Rohrich D. Microdosimetry with a 3D silicon on insulator (SOI) detector in a low energy proton beamline. Radiat. Phys. Chem., 176, 2020, 109078. DOI: 10.1016/j.radphyschem.2020.109078

Dahle TJ, Rusten E, Stokkevåg CH, Silvoniemi A, Mairani A, Fjæra LF, Rørvik E, Henjum H, Wright P, Boer CG, Forsback S, Minn H, Malinen E, Ytre-Hauge KS. The FLUKA Monte Carlo code coupled with an OER model for biologically weighted dose calculations in proton therapy of hypoxic tumors. Phys Med, 76, 2020, 166-172. DOI: 10.1016/j.ejmp.2020.07.003

Gorgen A, Guttormsen M, Larsen AC, Siem S, Adli E, Edin NFJ, Gjersdal H, Henriksen G, Malinen E, Modamio V, Schoultz B, Sobas PA, Theodossiou TA, Wikne JC. The Oslo Cyclotron Laboratory. Eur. Phys. J. Plus, 136 (2), 2021, 181. DOI: 10.1140/epjp/s13360-021-01150-3

Reaz F, Sjobak KN, Malinen E, Edin NFJ, Adli E. Sharp dose profiles for high precision proton therapy using strongly focused proton beams. Sci Rep, 12 (1), 2022, 18919. DOI: 10.1038/s41598-022-22677-0

4. Details of the impact

Due to their competence and experience in radiation physics and radiobiology as outlined above, researchers from the bio- and medical physics section at UiO were invited to participate in national and regional committees and working groups to decide on the construction of one or several proton therapy centers in Norway. The national collaborations included experts and clinicians from all Norwegian health regions and concerned the general introduction of proton therapy in Norway. This effort resulted in the construction of two proton therapy centers in Oslo and Bergen, which are scheduled to start operation in 2024 and 2025, respectively. The efforts and committee decisions are documented various national reports.

The regional collaboration within the Oslo region has mainly been between UiO and the Oslo University Hospital. The UiO group has been the major contributor to the design of the pre-clinical research area and infrastructures at the upcoming proton therapy center in Oslo. The center will have a dedicated research room where the section for biophysics and medical physics and the section for high-energy physics plan to perform pre-clinical experiments and prototyping for improved proton therapy. This pre-clinical research area will be equipped with a gantry for animal irradiations and a small-animal PET scanner. These infrastructures will make the Oslo proton therapy center highly competitive on an international level.

Through their research activities at the Oslo Cyclotron Laboratory at UiO and collaborative research at proton therapy centers abroad, the UiO group has built competence and laid the foundation for a successful pre-clinical research program at the new proton therapy center at the Radium Hospital. Other scientists and clinicians working with experimental proton therapy will benefit from this competence and world-class research infrastructure. An active and competitive research program is essential for the success of the proton therapy center and will ensure the availability of cutting-edge treatment procedures. The most important beneficiaries, however, are cancer patients, who will receive effective treatments with fewer side effects. This will also have implications for society as a whole, as less toxic treatments mean faster recovery and return to working life, and higher quality of life.

5. Sources to corroborate the impact (indicative maximum of ten references)

Planning report (Planleggingsrapport, 2013):

https://helse-vest.no/seksjon/styresaker-arkiv/Documents/2013/19.06.2013/Sak%2007813%20B%20Vedlegg%201%20-%20Rapport,%20Planlegging%20av%20norsk%20senter%20for%20partikkelterapi-%2013.juni%202103.pdf

Conceptual report (Konseptrapport proton, 2016):
https://helse-sorost.no/Documents/Store%20utviklingsprosjekter/OUS/Radiumhospitalet/Konseptrapport%20-%20etablering%20av%20protonbehandling.pdf

Article from the popular science magazine "Apollon" (2020):
https://www.apollon.uio.no/artikler/2020/3_protonterapi.html
also published in the science and engineering magazine “Teknisk ukeblad” (2020):
https://www.tu.no/artikler/verdens-mest-moderne-straleterapi-mot-kreft-pa-vei-til-norge/498148

ITA case number 1

Institution: University of Oslo
Administrative unit: Institute of Theoretical Astrophysics
Title of case study: From Solar physics research to public outreach
Period when the underpinning research was undertaken:2013 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2003 - 2021
Period when the impact occurred: 2017 – 2021

1.Summary of the impact

Solar Physics research done on the basis of high-quality observations of the Sun from both ground-based and space-born instruments has reached a public audience both

in Norway:

1) RoCS followed up 171 Norwegian school pupils at the age of 15-16 years old (Junior High and High Scool) who participated in the European Solar Telescope (EST) International Contest in 2021. Two of the School teams were ranked #4 and 5 in the contest with 561 international teams.

2) RoCS delivered the article "Sunspots – traces of the Sun's complex magnetic field Solar" in 2019 to the popular "Almanac for Norway" which is published by the Institute of Theoretical Astrophysics, UiO. Circulation number: Ca. 30 000.

and abroad:

3) RoCS reaches an international audience through the delivery of Sun close up media with explanations at Wikimedia Commons. In February 2020, the European Solar Physics Division (ESPD) of the European Physical Society started a "Media of the Month" contest with the aim of building a collection of high-quality images, movies and other media of the Sun or related to the study of the Sun, hosted and freely available from Wikimedia Commons. RoCS researchers delivered prize winning entries five months of 2020.

2. Underpinning research

The solar atmosphere is very dynamic and some of the most fundamental physical processes occur on relatively small spatial scales. In order to gain better understanding of the workings of the solar atmosphere, advanced instrumentation is needed to resolve these fundamental spatial scales. Researchers at RoCS use a variety of high-resolution instruments, some at telescopes on the ground and some at telescopes that observe the Sun from space. For this impact case, RoCS used the Swedish 1-m Solar Telescope (SST) on the island La Palma in the Canaries (Spain), and two NASA satellites: the Interface Region Imaging Spectrograph (IRIS) and the Solar Dynamics Observatory (SDO).

The SST is one of the prime facilities for high resolution observations of the deep solar atmosphere. It is unparalleled for acquiring long time sequences of observations that cover the full dynamical evolution of different magnetic phenomena. It has produced some of the sharpest views on small scale magnetic field structures, including sunspots and pores. In order to achieve such high resolution and resolve fine details, the SST is dependent on a number of techniques: it has a specific optical design with excellent optics, it uses a system of adaptive optics that can quickly adjust the shape of a mirror to correct for turbulence-induced optical deformations, and it uses advanced image processing to remove residual defects. Furthermore, the SST relies on favourable weather conditions that are unique for the observatory site on La Palma. RoCS has been conducting several observing campaigns each year between 2010 - 2021. The advantage of having multiple observing campaigns is that

RoCS has one of the best chances of being lucky with the most optimal weather conditions. RoCS has acquired a number of unique time sequences that show the details of the dynamical evolution of small-scale magnetic structures such as magneto-convective elements, sunspots, and jets. These observations advance our understanding of the nature of magnetic fields in the solar atmosphere.

For all the RoCS observing campaigns at the SST, the observations are coordinated with telescopes in space: we plan the observations such that all telescopes observe the same area on the Sun. The IRIS and SDO observatories in space can observe the higher parts of the atmosphere that are invisible from the ground: the transition region and the corona. By coordinating our observations, we get a more complete view of the evolution and extent of different phenomena. For example, by combining SST, IRIS and SDO observations, we can cover structures from the surface up to altitudes of several 1000's of kilometres height, and cover temperature differences between 4000 K at the surface up to millions of K in the corona.

The unique close-up views of the complex dynamics of the solar atmosphere that SST, IRIS and SDO provide are fascinating and appealing to the general public. They form a fascinating example of the wonders of the universe that can inspire children to choose a career in science.

3. References to the research

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1)Authors: Esteban, Pozuelo S. de la Cruz Rodríguez; J. Drews A.; Rouppe van der Voort L.; Scharmer G. B.; Carlsson M.
Title: Observationally Based Models of Penumbral Microjets
Year of publication: 2019
DOI: 10.3847/1538-4357/aaf28a
Journal title and issue: The Astrophysical Journal, Volume 870, Issue 2
URL: https://ui.adsabs.harvard.edu/abs/2019ApJ...870...88E/abstract

2) Authors: Bose, Souvik; Henriques, Vasco M. J; Joshi, Jayant; Rouppe van der Voort, Luc.
Title: Characterization and formation of on-disk spicules in the Ca II K and Mg II k spectral lines
Year of publication: 2019
DOI: 10.1051/0004-6361/201936617
Journal title and issue: Astronomy & Astrophysics, Volume 631
URL: https://ui.adsabs.harvard.edu/abs/2019A%26A...631L...5B/abstract

3) Authors: Skogsrud, H.; Rouppe van der Voort, L.; De Pontieu, B.
Title: On the Multi-threaded Nature of Solar Spicules
Year of publication: 2014
DOI: 10.1088/2041-8205/795/1/L23
Journal title and issue: The Astrophysical Journal Letters, Volume 795, Issue 1
URL: https://ui.adsabs.harvard.edu/abs/2014ApJ...795L..23S/abstract

4) Authors: Vissers, Gregal J. M.; Rouppe van der Voort, Luc H. M.; Rutten Robert J.
Title: Automating Ellerman bomb detection in ultraviolet continua
Year of publication: 2019
DOI: 10.1088/2041-8205/795/1/L23
Journal title and issue: Astronomy & Astrophysics, Volume 626
URL: https://ui.adsabs.harvard.edu/abs/2019A%26A...626A...4V/abstract

5) Authors: Nóbrega-Siverio, D.; Martínez-Sykora, J.; Moreno-Insertis F.; Rouppe van der Voort, L.
Title: Surges and Si IV Bursts in the Solar Atmosphere: Understanding IRIS and SST Observations through RMHD Experiments
Year of publication: 2017
DOI: 10.3847/1538-4357/aa956c
Journal title and issue: The Astrophysical Journal, Volume 850, Issue 2
URL: https://ui.adsabs.harvard.edu/abs/2019A%26A...626A...4V/abstract

6) Authors: Vissers Gregal J. M.; Rouppe van der Voort Luc H. M.; Rutten Robert J.
Title: Ellerman Bombs at High Resolution. II. Triggering, Visibility, and Effect on Upper Atmosphere
Year of publication: 2013
DOI: 10.1088/0004-637X/774/1/32
Journal title and issue: The Astrophysical Journal, Volume 774, Issue 1
URL: https://ui.adsabs.harvard.edu/abs/2013ApJ...774...32V/abstract

4. Details of the impact

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1) RoCS followed up Norwegian Junior High and High schools who participated in the European Solar Telescope (EST) Contest in 2021. EST organized a competition for school students from all over Europe to make infographics on different topics related to the Sun. The infographics became part of the EST Solarpedia.

Altogether 171 Norwegian school pupils distributed over 46 teams at the age of 15-16 years old competed. Two Norwegian teams that were guided by RoCS finished in the top ten finalists of the competition, securing 4th and 5th positions from a total of 561 infographics which were submitted by students from 16 countries in Europe.

In preparation for the competition, students of Norwegian schools attended lectures on various topics of the Sun, held by Doctoral Research Fellow Aditi Bhatnagar, to prepare them for the competition. Four such lectures were given in total, both at the University of Oslo to schools in Asker and Sandvika and via Zoom to schools in Tromsø and Tønsberg.

Bhatnagar works on the research project “ISSRESS: Impact of small-scale reconnection events on the solar atmosphere” and used some of the media and knowledge from the produced papers mentioned above in her talks. All teams were invited to discuss their ideas and content with Bhatnagar. The teacher of the best team asked after the competition was over if RoCS could do more outreach work towards schools. They enjoyed the active learning process in getting to know our closest star – the Sun.

2) RoCS delivered the article “Sunspots – traces of the Sun's complex magnetic field Solar” in 2019 to the popular “Almanac for Norway” which is published by the Institute of Theoretical Astrophysics, UiO. Circulation number: Ca. 30 000. Three sunspot figures in the article are connected to three of the publications mentioned above. The almanac of Norway has been published since 1644. After the dissolution of the Denmark-Norway union in 1814, the almanac has been edited in Norway. In 1814, it was edited by the Danish astronomer Thomas Bugge. Christopher Hansteen became editor in 1815 and remained so until 1862. Directors and astronomers at the Observatory and ITA have been editing it ever since.

and abroad:

3) RoCS reaches an international audience through the delivery of Sun close up media with explanations at Wikimedia Commons. In February 2020, the European Solar Physics Division (ESPD) of the European Physical Society started a “Media of the Month” contest with the aim

of building a collection of high-quality images, movies and other media of the Sun or related to the study of the Sun, hosted and freely available from Wikimedia Commons. RoCS researchers delivered prize winning entries five months of 2020.

Wikimedia Commons is a media file repository making available public domain and freely licensed educational media content (images, sound and video clips) to everyone, in their own language. Wikimedia Commons is free. Everyone is allowed to copy, use and modify any files here freely as long as they follow the terms specified by the author,

The Wikimedia image/movie delivered by RoCS was most often not the subject itself of the scientific study, but the papers mentioned above contain the data that were used for the Wikimedia subject. For example, the granulation movie is made from CHROMIS Wideband data from May 2017. It is not known how many views or downloads the images have had.

Here are some examples of ESPD media of the month from RoCS:
Each link also lists (scroll down) a wikipedia page. Sometimes multiple languages use them.

1) https://commons.wikimedia.org/wiki/File:Sunspot_SST_05Sep2016.png
2) https://commons.wikimedia.org/wiki/File:Granulation_Quiet_Sun_SST_25May2017.webm
3) https://commons.wikimedia.org/wiki/File:Halpha_%2B700_limb_spicules_08Aug2007_SST.png
4) https://commons.wikimedia.org/wiki/File:Sunspot_AR11084_02Jul2010_SST.webm
5) https://commons.wikimedia.org/wiki/File:The_Solar_Chromosphere_at_the_highest_possible_resolution.png
6) https://commons.wikimedia.org/wiki/File:Coronal_jet_and_surge.png

5. Sources to corroborate the impact (indicative maximum of ten references)

ITA case number 2

Institution: University of Oslo	
Administrative unit: Institute of Theoretical Astrophysics	
Title of case study: From Cosmology and extragalactic research to public outreach	
Period when the underpinning research was undertaken: 2011– 2021	
Period when staff involved in the underpinning research were employed by the submitting institution: 2009 - 2021	
Period when the impact occurred: 2011 – 2021	

1.Summary of the impact

The research done based on the observations performed by the ESA Planck satellite, which mapped the anisotropies of the cosmic microwave background with high sensitivity and gave accurate numbers for the main parameters of the Universe, including its age, have had a major societal impact. The results were transmitted to the public, in places like high schools, websites, blogs, podcasts, radio and cafés. The impact and activities can be divided in to three sections:

1) Bridging astronomy and school
2) Role of women in science and gender balance in academia
3) Communicating astronomy to the public

2. Underpinning research (indicative maximum 500 words)

The research output from the Planck observations provided a major source of information relevant to several cosmological and astrophysical issues, such as testing theories of the early Universe and the origin of cosmic structures. Since the end of its mission, Planck has defined the most precise measurements of several key cosmological parameters, including the average density of ordinary matter, dark matter and dark energy in the Universe and the age of the Universe. Planck also provided the best picture of the early Universe when this was a thousand times smaller than it is today. This image was shown to the Norwegian and international public of all ages and backgrounds, and an enormous number of times.

Paper [1] presented the first joint Bayesian component separation analysis of Planck and WMAP, and provided the best full-sky estimates of synchrotron, free-free, CO and thermal dust emission published to date. Both the paper and the analysis effort were led by the Cosmo-Extra group of ITA and this effort was a key element in establishing both the subsequent and final Planck 2018 data release, as well as the ERC-funded next-generation Cosmoglobe and BeyondPlanck projects. The methods and results were improved and presented in final form in paper [2].

Paper [3] presented the initial results on the cosmological parameters from Planck, being improved in paper [4] and finally in paper [5], which is the final cosmological parameters paper of Planck. These are probably the most important results from the Planck satellite, building upon all previous work within the project, since ESA selected Planck in 1995. The group has participated in a large number of different parts of the project since 1998, including leading the construction of the EGSE of the LFI instrument, and especially by developing the algorithms for and writing the software for many parts of the analysis pipeline, with special emphasis on those concerning component separation, but also studies of large-scale anisotropies and non-Gaussianity of the CMB. All of this has been necessary for getting the final results.

3. References to the research (indicative maximum of six references)

[1] Planck Collaboration (incl. Eriksen, Gjerløw, Hansen, Lilje, Wehus [corresp. author]), 2016, "Planck 2015 results: X. Diffuse component separation: Foreground maps", Astronomy and Astrophysics, 10.1051/0004-6361/201525967, URL: https://www.aanda.org/articles/aa/full_html/2016/10/aa25967-15/aa25967-15.html

[2] Planck Collaboration (incl. Akrami, Eriksen [corresp. author], Hansen, Karakci, Lilje, Seljebotn, Thommesen, Wehus), 2020,
"Planck 2018 results: IV. Diffuse component separation",
Astronomy and Astrophysics, 10.1051/0004-6361/201833881,
URL: https://www.aanda.org/articles/aa/full_html/2020/09/aa33881-18/aa33881-18.html

[3] Planck Collaboration (incl. Eriksen, Gjerløw, Hansen, Lilje, Valiviita): 2014
"Planck 2013 results: XVI. Cosmological parameters",
Astronomy and Astrophysics, 10.1051/0004-6361/201321591
URL: https://www.aanda.org/articles/aa/full_html/2014/11/aa21591-13/aa21591-13.html

[4] Planck Collaboration (incl. Eriksen, Gjerløw, Hansen, Lilje, Wehus): 2016
"Planck 2015 results: XIII. Cosmological parameters",
Astronomy and Astrophysics, 10.1051/0004-6361/201525830
URL: https://www.aanda.org/articles/aa/full_html/2016/10/aa25830-15/aa25830-15.html

[5] Planck Collaboration (incl. Akrami, Eriksen, Hansen, Karakci, Lilje, Wehus): 2020
"Planck 2018 results: XIII. Cosmological parameters",
Astronomy and Astrophysics, 10.1051/0004-6361/201833910
URL: https://www.aanda.org/articles/aa/full_html/2020/09/aa33910-18/aa33910-18.html

4. Details of the impact (indicative maximum 750 words)

Many members of the Cosmo-Extra group of ITA participated in the activities described below, which built upon many research outputs of ITA, but with the Planck results as the most important, catching the largest public interest.

Bridging astronomy and school

1. ITA organises the Norwegian Olympiad on Astronomy and Astrophysics (https://www.mn.uio.no/astro/tjenester/publikum/ol-astronomi-og-astrofysikk/), coordinating and organising the exams and training camps for secondary school students. Every year, about 80 students from more than 12 schools register to participate in the national competition and the best attend the International Olympiad on Astronomy and Astrophysics (IOAA).

2. ITA educates secondary school teachers through seminars and workshops organised throughout the year. "Faglig Pedagogisk dag" (https://www.uio.no/om/samarbeid/skole/fagped-dag/) consists of a day seminar, where teachers have the opportunity to stay academically up-to-date. Planck results have been central.

3. ITA students and staff gives lectures in school at least 2-3 times a year in different languages (Norwegian, English, German, French, etc.); at different levels, from the early age in primary schools up to pupils in upper secondary schools. Moreover, each year, we host a small group of lower secondary school pupils during the so-called "Arbeidsuke". During three to four days, pupils get assigned a job task that makes them more acquainted with the type of skills, roles and responsibilities linked to an astrophysicist-type of job. The Planck results were especially utilised. More and more girls want to spend their work week at ITA (e.g., https://www.mn.uio.no/astro/om/aktuelt/aktuelle-saker/2022/Arbeidsuke.html)

4. ITA is co-leading IAU's Office for Young Astronomers (OYA), established in 2015 in collaboration with the Norwegian Academy of Sciences and Letters. It is the basis for the operation of the International Schools for Young Astronomers (ISYAs, https://www.iau.org/education/school_for_young_astronomers/). The ISYAs are three-week international postgraduate schools for regions where students have less opportunity to be directly exposed to the full extent of up-to-date astrophysics.

Role of women in science and gender balance in academia
With the goals of recognising the role of women in advancing science and encouraging girls to consider careers in astronomy, within the framework of IAU global project “Women and Girls in Astronomy” (https://www.iau.org/public/women-and-girls-in-astronomy/), ITA launched its “Women In Astrophysics” blog (https://titan.uio.no/blogg/women-astrophysics), a digital platform that tell the stories behind the women-astrophysicists of ITA. Authors of about 28 blog-posts are master’s students and early career researchers at ITA who shine the light on challenges and achievements during their career path, including writing about their research using Planck data.

Communicating astronomy to the public
Many ITA scientists joined the worldwide series of events known as “Astronomy on Tap - Drink in the Universe” (https://astronomyontap.org/) and launched its very first “Astronomy on Tap” - Oslo edition (Facebook link: https://www.facebook.com/AoTOslo/). Free events at a bar in Oslo city centre feature accessible, engaging science presentations on space and astronomy, very often with focus on the Planck results.

To nurture society’s interest in astronomy and astrophysics, the website of the Institute of Theoretical Astrophysics, alongside the social media accounts (“@astrofysikk” on Twitter, Facebook and Instagram) has been the main digital platform for science communication.
Those curious about the involvement of ITA in international space missions can visit the webpage “Universet”: https://www.mn.uio.no/forskning/tema/uioirommet/universet-hoved.html

Several popular scientific articles feature in the “Astronytt” section of ITA’s website (Norwegian: https://www.mn.uio.no/astro/forskning/aktuelt/aktuelle-saker/astronytt/, English: https://www.mn.uio.no/astro/english/research/news-and-events/news/), which help to showcase the impact of the research performed at ITA on society.

Numerous popular scientific articles about ITA research have been written for the online journal Titan.uio.no (https://titan.uio.no/kategorier/universet) and appeared on Forskning.no as well (https://forskning.no/tag/universet/planeter/mars/saturn/romfart/satellitter/romforskning/sorte%20hull/stjerner)

Podcast episodes: We have participated enthusiastically in the making of some episodes for podcasts “Universitetsplassen” (https://www.uio.no/om/aktuelt/universitetsplassen/podkast/) and “God Fysikk” (https://www.uio.no/om/aktuelt/podkast/index.html), created within the University of Oslo.

A detailed list of TV, radio and press coverage can be found in this webpage: https://www.mn.uio.no/astro/om/aktuelt/i-media/ and since as early as 2011, we have always been invited in the recording of the NRK radio program Abels Tårn (https://radio.nrk.no/podkast/abels_taarn) to discuss a variety of topics in astronomy and answer to multiple questions of the audience.

5. Sources to corroborate the impact (indicative maximum of ten references)

https://www.mn.uio.no/astro/tjenester/publikum/ol-astronomi-og-astrofysikk/
https://www.mn.uio.no/astro/om/aktuelt/aktuelle-saker/2022/Arbeidsuke.html
https://www.iau.org/education/school_for_young_astronomers/
https://titan.uio.no/blogg/women-astrophysics
https://www.mn.uio.no/forskning/tema/uioirommet/universet-hoved.html
https://www.mn.uio.no/astro/om/aktuelt/i-media/

1. Summary of the impact

The REDWIN project:

- Has contributed to a significant improvement of state-of-the-art geotechnical modelling of the soil and foundation for OWTs (Offshore Wind Turbines).
- Has removed barriers between structural and geotechnical engineers, facilitating the integration of the geotechnical discipline into the streamlined OWT design process.
- Has improved understanding of soil and foundation damping, and the contribution from foundation to the overall energy dissipation in the OWT system.

The most significant output is a library of new soil-foundation models for time-domain dynamic analysis. These overcome several of the limitations in existing design tools and allow designers to adopt more accurate models in the OWT analyses used in OWT design and in lifetime extension evaluations. Using more accurate models reduces uncertainties in the predicted loads and in the estimated OWT lifetime, leading to reduced risk and lower costs in the design.

2. Underpinning research

The key research insights and findings that underpinned the impact are:

1. Scientific formulation and validation of foundation models for shallow (e.g. bucket foundations) and deep foundations (e.g. monopiles) to be used in time-domain dynamic analysis of OWTs. This has contributed to a significant improvement of state-of-the-art geotechnical modelling of the soil and foundation for OWTs. Duration: 2015-2018.
    - This resulted in 12 research papers, 4 of them published in Level 2 journals (according to NPi, https://npi.hkdir.no/).
    - The developed models have been used in several following research projects, among other in WAS-XL (NFR Grant No. 268182) and in REDWIN2 (NFR grant 296511), and new initiatives have been taken for proposals to H2020 and Horizon Europe.
    - Key researchers:
        - Kristoffer Skjolden Skau, PhD student at NTNU and Researcher at NGI.
        - Ana M. Page, PhD student at NTNU and Researcher at NGI.
        - Hans Petter Jostad, Technical Director at NGI and Professor II at NTNU.
        - Gudmund Eiksund, Professor at NTNU.
        - Gustav Grimstad, Professor at NTNU.

2. Implementation of the developed models as Dynamic Link Libraries (DLL), and formulation of practical procedures for practitioners on how to use the new foundation models. This has facilitated the integration of the geotechnical discipline into the streamlined OWT design process. Duration: 2017-2022.
    - The developed foundation models have been implemented in several analyses tools for OWT design as part of the code-to-code comparison study OC6 hosted by the US National Renewable Energy Laboratory (NREL).
    - Additionally, several of the largest actors in the offshore wind energy industry (e.g. Equinor, Siemens Gamesa Renewable Energy) have implemented the new foundation models.
    - This resulted in 5 collaborative research papers (2 of them published in Level 2 journals), as well as a free DLL and a user manual.
    - Key researchers:
        - Kristoffer Skjolden Skau, PhD student at NTNU and Researcher at NGI.
        - Ana M. Page, PhD student at NTNU and Researcher at NGI.

- Hans Petter Jostad, Technical Director at NGI and Professor II at NTNU.
    - Gustav Grimstad, Professor at NTNU.
    - Tor Anders Nygaard, researcher at IFE.
    - Jacobus B. De Vaal, PostDoc researcher at IFE.

3. Improved understanding of soil and foundation damping. A procedure was established to estimate damping arising from the soil at various levels by first extracting damping at a soil element level and then utilize these results to compute an overall global foundation damping relevant for the integrated analysis. Such tools allow the structural engineer to get a better understanding of the contribution from foundation hysteresis damping to the overall energy dissipation in the OWT-foundation system. Duration: 2015-2018.
    - This resulted in 2 research papers, from which one of them won the ASTM Geotechnical Testing Journal’s Outstanding Article Award for 2020.
    - Key researchers:
        - Finn Løvholt, Technical Expert at NGI.
        - Christian Madshus, Technical Expert at NGI.
        - Knut H. Andersen, Technical Expert at NGI.

4. Processing and analysis of full-scale measurement data on existing OWT in the North Sea, and comparison of calculated OWT response with full-scale measurements. These studies demonstrated that the developed models are much more accurate than existing models in predicting the fundamental vibration properties of OWTs. Duration: 2015-2018.
    - This resulted in 3 research papers, 2 of them published Level 2 journals.
    - Key researchers:
        - Karin Norén-Cosgriff, Senior Specialist at NGI.
        - Amir M. Kaynia, Technical Expert at NGI.
        - Ana M. Page, PhD student at NTNU and Researcher at NGI.

5. Evaluation of the impact of foundation modelling on the structural response of typical OWT designs, and quantification the potential benefits of using the developed REDWIN foundation models for OWT analysis and design. Duration: 2015-2018.
    - This resulted in 5 research papers, 2 of them published Level 2 journals.
    - Key researchers:
        - Amir M. Kaynia, Technical Expert at NGI.
        - Ana M. Page, PhD student at NTNU and Researcher at NGI.
        - Kristoffer Skjolden Skau, PhD student at NTNU and Researcher at NGI.
        - Tor Anders Nygaard, Researcher at IFE.

6. Evaluation of the cost savings potential by using the developed REDWIN foundation models in design instead of the conventional modelling approach for an existing OWT in the North Sea. Duration: 2016-2018.
    - A 10% reduction in steel weight was estimated.
    - Key researchers:
        - Håkon Andersen, Engineer at Dr. Techn. Olav Olsen.

3. References to the research

References to key outputs from the research described in the previous section:

- Page, A. M., Grimstad, G., Eiksund, G. R., & Jostad, H. P. (2018). A macro-element pile foundation model for integrated analyses of monopile-based offshore wind turbines. *Ocean Engineering*, 167, 23-35. DOI: 10.1016/j.oceaneng.2018.08.019.

- Skau, K. S., Grimstad, G., Page, A. M., Eiksund, G. R., & Jostad, H. P. (2018). A macro-element for integrated time domain analyses representing bucket foundations for offshore wind turbines. *Marine Structures*, *59*, 158-178. DOI: 10.1016/j.marstruc.2018.01.011.
- Løvholt F., Madshus C., Andersen, K. H. (2019). Intrinsic soil damping from cyclic laboratory tests with average strain development. *Geotechnical Testing Journal*. DOI: 10.1520/GTJ20170411.
- Aasen, S., Page, A.M., Skau, K.S. & Nygaard, T.A. (2017). Effect of foundation modelling on the fatigue lifetime of a monopile-based offshore wind turbine. *Wind Energy Science*, 2(2): 361-376. DOI: 10.5194/wes-2-361-2017. N
- Page, A. M., Næss, V., De Vaal, J. B., Eiksund, G. R., & Nygaard, T. A. (2019). Impact of foundation modelling in offshore wind turbines: Comparison between simulations and field data. *Marine Structures*, 64, 379-400. DOI: 10.1016/j.marstruc.2018.11.010.
- Norén-Cosgriff, K & Kaynia, AM. (2021). Estimation of natural frequencies and damping using dynamic field data from an offshore wind turbine. *Marine Structures*, 76. DOI: 10.1016/j.marstruc.2020.102915

4. Details of the impact

The REDWIN project has helped remove barriers between structural and geotechnical engineers and represents an important step towards integrating the geotechnical discipline into a streamlined design process for OWT structures. This was achieved by developing state-of-the-art, effective, and practical foundation models that accurately represent of foundation and soil behaviour in integrated dynamic time domain analyses. A maintained focus on practicality and flexibility in the calibration of the model input have ensured that they are suitable for use by practicing engineers in all phases of OWT design. Their start-of-the-art formulation makes them also attractive for research applications, and several researchers external to the REDWIN project are actively using the models and verifying them against different applications.

From the start of the REDWIN project there was high emphasis for the project to publish its results in peer-reviewed international journals. This resulted in more than 30 publications in international peer-reviewed journals and at internationally recognized conferences. Focus was also given to disseminate outcomes of the project to practitioners in the offshore wind energy industry. This was – for example – achieved through the REDWIN final workshop in Oslo in November 2018 which gathered more than 100 participants from across the offshore wind industry and academia. This successful workshop had keynote speakers sharing their views on future opportunities and challenges the offshore wind energy industry will be facing and brought practitioners and researchers together to discuss the future needs for research and development in the industry.

In addition, the implementation of the REDWIN models in a standardised DLL format and their free distribution have facilitated the incorporation of the models in several design tools. In a first stage, presentations and meetings were held with potential users to present the potential of the models and how they could be incorporated in design tools. At a later stage, a collaboration between the REDWIN researchers and the National Renewable Laboratory (NREL) in the USA on the OC6 project helped reaching a broad audience. One of the goals of the OC6 project was to incorporate advanced soil-structure interaction models for representing the foundation behaviour. Participants for research and industry were asked to incorporate the REDWIN model in their OWT modelling tools and verify the implementation. As a result, several large industry actors, including offshore wind developers, consultants, certifiers, and researchers, have implemented the models in their own OWT analyses tools.

The results of the project have also given the partners ideas to launch new research proposals. For example, new initiatives have been taken for proposals and projects within NFR's and EC's programs. In particular, the research projects WAS-XL (NFR Grant No. 268182), between 2017 and 2021, and REDWIN2 (NFR grant 296511), between 2019 and 2022, have directly benefit from the REDWIN project results. Therefore, while enhancing the knowledge and expertise of the partners and serving the industry with new design tools, REDWIN has enabled the partners to achieve higher positions in the research community and step to other challenging domains.

In sum, the project has helped remove barriers between structural and geotechnical engineers and represents an important step towards integrating the geotechnical discipline into a streamlined design process for OWT structures. It is expected that the project results will enable lowering of the cost for future generations of OWT foundations, and that it will be an important tool for evaluating the potential for lifetime extension of existing offshore wind farms.

5. Sources to corroborate the impact

The impact can be corroborated by:

- The members of the Technical Advisory Team (TAG):
  1. Lars V. Andersen, Professor at Aarhus University. E-mail: lva@cae.au.dk.
  2. Ken Gavin, Professor at Delft University of Technology. E-mail: K.G.Gavin@tudelft.nl
  3. Tue Hald, Chief Specialist Tower Engineering, Vestas Wind Systems A/S. E-mail: tuha@vestas.com.
  4. Jens Schupp, Senior Lead Engineer at Ørsted. E-mail: jschu@dongenergy.de.
- The representatives from the industrial partners in the project:
  5. Ole Havmøller, Research Engineer at Equinor, E-mail: olehav@equinor.com
  6. Dariusz Eichler. Structural Engineer at Vattenfall Vindkraft A/S. E-mail: dariusz.eichler@vattenfall.com.
  7. Jacob Andersen. Principal Engineer at Vattenfall Vindkraft A/S, formerly Statkraft. E-mail: jacob1.andersen@vattenfall.com.
- Users of the developed foundation models:
  8. Roger Bergua, Researcher at the National Renewable Laboratory, NREL (USA). He led the implementation of the REDWIN model in the OC6 project. E-mail: Roger.Bergua@nrel.gov.
  9. Sara van Hoogstraten, Offshore Installation Manager at Ørsted. She verified the REDWIN models as part of her MSc thesis at Delft University of Technology in collaboration with Siemens Gamesa Renewable Energy. E-mail: SACVH@orsted.com.
  10. George Katsikogiannis, Researcher at SINTEF Ocean. He used the developed models as part of his PhD research at NTNU. E-mail: george.katsikogiannis@sintef.no.

Institution: Norwegian Geotechnical Institute
Administrative unit: Climate adaptation and hydrodynamics
Title of case study: EVOKED - Enhancing the value of climate data - translating risk and uncertainty utilizing a Living Labs approach
Period when the underpinning research was undertaken: 2017-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2017 - 2021
Period when the impact occurred: 2017 - 2021

1. Summary of the impact (indicative maximum 100 words)

The EVOKED project has:

- Facilitated and contributed to climate knowledge exchange, as a precondition for climate action, between scientists and climate adaptation practitioners at local municipalities and regional counties in Europe.
- Demonstrated co-production of climate services to advance their application and uptake by end users to support climate adaptation strategies.
- Co-lead the collaboration across the projects funded under European Research Area for Climate Services (ERA4CS) to leverage all project outputs and showcase co-production of climate services at the European policy level.

The most significant output is the report "Co-production of Climate Services. A diversity of approaches & good practice from the ERA4CS projects" (https://doi.org/10.3384/9789179291990).

2. Underpinning research (indicative maximum 500 words)

The key research insights and findings that underpinned the impact are:

1. The establishment of Living Labs at each of the EVOKED case study sites in Norway, Sweden, Germany, and the Netherlands. The Living Labs methodology guided the involvement of committed stakeholders in real-life 'laboratory' settings to test and develop alternative climate services for climate adaptation. Duration: 2017-2020.
    a. The Living Labs created space for knowledge exchange and learning about climate change impacts with a variety of end-users to include citizens, public administrators, practitioners, politicians, NGOs, landowners, and builders.
    b. The developed methodology was used in the H2020 funded PHUSICOS project (Grant agreement no. 776681) with NGI as coordinator.
    c. Key researchers in Norway:
        i. Amy M.P. Oen, Senior Researcher at NGI
        ii. Bjørn Kalsnes, Senior Researcher at NGI
        iii. Christina Ekeheien, Project advisor at NGI (2018-2020)
2. To ensure uptake, the process of creating climate services within the Living Labs followed a co-production process based on information design methodology which was developed as part of the EVOKED project. Briefly, the methodology starts by identifying the information needs of the relevant stakeholders and subsequently works though steps of identifying the issue to be addressed, the desired action to be taken, and finally the graphic format this information is to be presented. Duration: 2017-2021.
    a. This activity resulted in the creation of five case specific climate services which included story maps to illustrate climate change impacts, infographics, a process flow to facilitate dialogue about climate adaptation requirements, as well as revising an existing 'climate atlas' to select adaptation interventions.
    b. As of 2021, this activity has also resulted in four research articles published in peer-reviewed journals. Two additional articles are in the peer-review process.

c. The developed methodology was used in the H2020 funded REACHOUT project (Grant agreement no. 10103659) with EVOKED partner Deltares as coordinator and NGI as a partner.
d. Key researchers in Norway:
    i. Amy M.P. Oen, Senior Researcher at NGI
    ii. Bjørn Kalsnes, Senior Researcher at NGI
    iii. Regula Frauenfelder, Senior Researcher at NGI
    iv. Christina Ekeheien, Project advisor at NGI (2018-2020)

3. Assessment and synthesis of co-production methodologies and climate services outputs produced across projects funded under ERA4CS. Collaborating across all project experiences resulted in a guide to recommend good practices for transdisciplinary knowledge co-production of climate services for researchers, users, funding agencies, as well as private sector service providers. Duration: 2019-2021.
    a. This resulted in publishing an open access report together with representatives from 15 of the 26 ERA4CS funded projects.
    b. This formed the basis of receiving approval for one of the few Special Issue's in the journal *Climate Services* (impact factor 4.38).
    c. This formed the basis for a video to showcase selected cases presented during the 5th European Climate Change Adaptation conference in 2021. EVOKED partners from Larvik and North Brabaant are highlighted.
    d. Key researchers in Norway:
        i. Amy M.P. Oen, Senior Researcher at NGI

3. References to the research (indicative maximum of six references)

References to key outputs of the research described in the previous section with contributions from researchers in Norway (NGI researchers in bold text):

- Raaphorst, K., Koers, G., Ellen, G. J., **Oen, A.**, **Kalsnes, B.**, van Well, L., Koerth, J. & van der Brugge, R. (2020). Mind the Gap: Towards a Typology of Climate Service Usability Gaps. *Sustainability*, 12(4), 1512. https://doi:10.3390/su12041512.
- **Ekeheien, C.P.**; Almestad, C.; **Frauenfelder, R.**; Heggelund, I.; **Oen, A.** (2022). Ny bydel i naturen – Hva har utbygging å si for fremtidig overvannssituasjon ved Martineåsen i Larvik kommune? *Kart og Plan*, 115 (2): p. 154-169. https://doi.org/10.18261/kp.115.2.5.
- Máñez Costa, M.; **Oen, A.M.P.**; Neset, T.-S.; Celliers, L.; Suhari, M; Huang-Lachmann, J-T.; Pimentel, R.; Blair, B.; Jeuring, J.; Rodriguez-Camino, E.; Photiadou, C.; Jerez Columbié, Y.; Gao, C.;Tudose, N.-C.; Cheval, S., Votsis, A.; West, J.; Lee, K.; Shaffrey, L.C.; Auer, C.; Hoff, H.; Menke, I.; Walton, P.; Schuck-Zöller, S. (2021). Co-production of Climate Services. CSPR Report No 2021:2, Centre for Climate Science and Policy Research, Norrköping, Sweden. This report is part of the CSPR Report Series (ISSN 1654-9112) No. 2021:2 ISBN 978-91-7929-199-0 (PDF) DOI: https://doi.org/10.3384/9789179291990.
- **Ekeheien, C.**; **Kalsnes, B.**; **Oen, A.M.P.**; Vasbotten, M.; Heggelund, I. (2019): Klimatilpasning i en usikker fremtid. Article submitted to Geoforskning's dissemination competition. https://geoforskning.no/klimatilpasning-i-en-usikker-fremtid/

References to key outputs of the research described in the previous section with contributions from EVOKED research partners at Christian-Albrechts University Kiel in Germany:

- Reimann, L., Vollstedt, B., Koerth, J., Tsakiris, M., Beer, M., Vafeidis, A. T. (2021). Extending the Shared Socioeconomic Pathways (SSPs) to support local adaptation planning—A climate service for Flensburg, Germany. *Futures*, 127, 102691, https://doi.org/10.1016/j.futures.2020.102691.
- Vollstedt, B., Koerth, J., Tsakiris, N. Nieskens, M., Vafeidis, A. T. (2021). Co-production of climate services: a story map for future coastal flooding for the city of Flensburg. *Climate Services*, 22, 100225, https://doi.org/10.1016/j.cliser.2021.100225.

4. Details of the impact (indicative maximum 750 words)

The EVOKED project has contributed to move the field of research in climate services forward by facilitating, testing and evaluating the co-production of climate services at the local, regional and European level. The core of the research within the EVOKED project has been conducted between researchers and practitioners at five case study sites located in Larvik municipality in Norway, Värmland County in Sweden, the City of Flensburg in Germany, and two cases in the Netherlands: the Province of North Brabaant and the Water board Drents Overijsselse Delta in the Fluvius region. The end-user partners have been the driver of the co-production process by identifying needs, creating the climate service products and continuing their use after the completion of the project.

Larvik municipality in Norway identified a need to improve the dialogue between planners in the municipality and builders at an early planning phase for urban development projects. Workshops with landowners, builders and developers took place between November 2018 and September 2020 to develop a 'climate menu' checklist to frame the evaluation of climatic and environmental aspects related to new building developments with the Martineåsen area as a specific pilot case to test the 'climate menu'. Further testing of the 'Climate menu' is pending on the area regulation process for the Martineåsen area.

Värmland County in Sweden prioritised increasing climate change awareness among officials and politicians. In order to accomplish this, they co-developed a digital map-based climate story to illustrate climate impacts and adaptation solutions. The Living Labs took place in the autumn of 2019. The map is currently available on the website for Värmland County (https://www.lansstyrelsen.se/varmland/miljo-och-vatten/energi-och-klimat/klimatanpassning.html).

The City of Flensburg in Germany also identified a need to increase climate change awareness; however, they wished to target citizens and improve their knowledge about sea level rise and flooding impacts in the city. The Flensburg story map was created in an iterative process together with citizens in the period of November 2018 and September 2020 (http://meeresspiegelanstieg-in-flensburg.info).

The Netherlands is one of the European countries that has come furthest with climate adaptation and therefore, the end-user partners for the two Dutch case study sites decided to focus efforts on improving current climate services and to link this work to ongoing climate adaptation policy processes and the Livings Labs were coordinated with other high level meetings that took place between November 2018 and November 2020.In North Brabaant the work was linked to the revision of a regional version of the Dutch National Adaptation Strategy infographic designed together with the municipalities, waterboards, and the province (https://www.klimaatadaptatiebrabant.nl/hulpmiddelen/hulpmiddelen-detail/224/NAS-adaptatietool). In the Fluvius region, the practitioners wished to strengthen the existing work group to include the municipalities, the provinces as well as civic stakeholders are involved which deal with the interests of the agricultural industry and nature conservation. Efforts concentrated on updating their existing climate service, the 'climate atlas' (https://fluvius.klimaatatlas.net/).

Further to the co-production process, the EVOKED project initiated a comprehensive evaluation process as an essential aspect of the climate services co-production process. Research indicates that evaluating the process for developing climate services together with relevant users is essential for their future uptake. However, there are only two previously published studies that share detailed information on evaluation methods incorporated within the actual CS development process. Therefore, the EVOKED project included an evaluation process to assess the user experience of the stakeholders involved in the Living Labs and the satisfaction of the developed climate services. Questionnaires were developed and completed by Living Lab participants for a total of 12 completed questionnaires (about 140 respondents) from the combined case study sites. The results indicate that the use of evaluating the development of the climate services facilitates a more iterative process by better involving stakeholders within the co-production of the climate services. Furthermore, adequately addressing stakeholder needs and the use of the climate services are essential as these aspects give an indication to the uptake of climate service products which can support climate adaptation planning outcomes on the long-term.

In summary, EVOKED's end-user partners have had a central role in the project with activities tailored to their needs and their ongoing climate adaptation processes. They have specifically indicated that EVOKED will contribute to: improve the visualization of climate data for the local authorities, find ways to communicate the integrated risks associated with a changing climate, improve the access and applicability of climate knowledge, learn how the collaborating governments are able to shape the preparedness of communities at risk, as well as support in assessing vulnerability and in exploring potential adaptation options.

5. Sources to corroborate the impact (indicative maximum of ten references)

The impact can be corroborated by:

- Representatives from the public organisation partners participating in the project and users of the climate services developed:
    1. Marit Vasbotten, Environmental manager, Larvik Municipality, Norway, Email: marit.vasbotten@larvik.kommune.no
    2. Ingerid Heggelund, Planer, Larvik Municipality, Norway, Email: ingerid.heggelund@larvik.kommune.no
    3. Elin Ljunggren, Project coordinator, Värmland County Administration, Email: elin.ljunggren@lansstyrelsen.se
    4. Frank van Lamoen, Senior advisor, Province of North Brabant, the Netherlands, Email: FvLamoen@brabant.nl
    5. Jördes Wüstermann, CF City of Flensburg, Germany, Email: Wuestermann.Joerdes@Stadt.Flensburg

- Co-leads for the working group collaboration across the projects funded under European Research Area for Climate Services (ERA4CS):
    6. Maria Máñez Costa, Scientist, Climate Service Center Germany, coordinator of INNOVA (https://www.innovaclimate.org/), Email: maria.manez@hereon.de
    7. Tina Schmid Neset, Senior Associate Professor, Linköping University, coordinator of Citizensensing (https://citizensensing.itn.liu.se/), Email: tina.neset@liu.se

- Central Secretariat of JPI Climate (Belgian Science Policy Office, BELSPO), which was a co-funder of the ERA4CS program:
    8. Petra Manderscheid, Executive Director of the Central Secretariat, Email: petra.manderscheid@jpi-climate.belspo.be>
    9. Alexandre Fernandes, Senior Science Officer at the Central Secretariat, Email: alexandre.fernandes@jpi-climate.belspo.be

1. Summary of the impact

The GEOreCIRC project:

- Has contributed to a significant improvement of state-of-the-art related to the reuse of industrial by-products (industrial slag, biochar from waste wood) for the remediation of contaminated soil.
- Has contributed to a significant understanding in the occurrence and mobility of hexavalent chromium in concrete, highly relevant for assessment of risks related to the reuse of waste concrete.
- Has improved tools and method procedures for environmental and geotechnical characterization of surplus masses and waste for reuse, as well as better understanding of risks related to reuse of waste materials.
- Has contributed to collaboration between various stakeholders, identifying barriers which hinder the reuse of surplus masses and waste, and possible measures eliminating these barriers.

2. Underpinning research

The key research insights and findings that underpinned the impact are:

1. Identifying barriers that hinder the recycling of surplus materials and waste (e.g. regulatory, organizational, logistical and material quality) and possible measures to reduce these barriers. The work was carried out in close cooperation with stakeholders (authorities, site/problem owners, entrepreneurs, waste handling companies, consultants) involved in the project. Workshop with stakeholders on this topic was held in 2017. Duration: 2017-2018.
    - The results are presented in the GEOreCIRC report *Barrierer som hindrer nyttiggjøring, (Barriers that hinder reuse),* NGI-rapport 20160794-03-R, as well as in 2 scientific publications (1 peer-reviewed journal article)
    - Key researchers:
        - o Gudny Okkenhaug, Researcher at NGI and Assistant Professor II at NMBU.
        - o Erlend Sørmo, Researcher at NGI.
        - o Gijs D. Breedveld, Technical Director at NGI and Professor II at UiO.

2. Investigating the occurrence and geochemical speciation of hexavalent chromium in concrete, the leachability and mobility in the environment as a basis for the risk assessment reusing waste concrete. The work was carried out in close cooperation with Sintef and partly funded by Miljødirektoratet (Environmental Protection Agency). Duration: 2017-2019.
    - The results are presented in the GEOreCIRC report *Utlekking av treverdig og seksverdig krom fra betong (Leaching of trivalent and hexavalent chromium from concrete),* NGI-rapport 20180207-01-R. Furthermore, the work has resulted in 2 research papers (1 peer-reviewed journal article)
    - Key researchers:
        - o Cathrine Eckbo, Researcher at NGI.
        - o Sara Hale, Researcher at NGI.
        - o Gudny Okkenhaug, Researcher at NGI and Assistant Professor II at NMBU

3. Investigating the geotechnical and environmental properties of tunnel boring machine (TBM) masses with focus on reuse, including existing data, lab- and field testing. The work was carried out in collaboration with BaneNOR partly at the field site Gjersrud-Steinsrud, an urban development area. Duration: 2017-2019.
    - These results are presented in the GEOreCIRC report *Tunnelborkaks (TBM) – Karakterisering og nyttiggjøring (Tunnel boring machine (TBM) – characterization and reuse),* NGI-rapport 20160794-08-R, as well as in 3

research papers (1 peer-reviewed journal article). One master thesis was included in the work: *Investigation of Geotechnical Properties of TBM Spoil from the Follo Line Project.*

- Key researchers:
    - o Gunvor Baardvik, Researcher at NGI
    - o Jenny Langford, Researcher at NGI
    - o Marianne Dahl, Master student at NTNU, Institute of Civil and Environmental Engineering

4. Investigating the properties of lime cement stabilized clay with focus on the reuse of this material. A number of laboratory tests were carried out to determine the geotechnical parameters of the mixed materials of clay and lime-cement stabilized clay (strength, plasticity, compressibility and hydraulic conductivity) with the focus on the reuse as impermeable geological barriers. Duration: 2017-2019.
    - The results are presented in 2 research papers. One master thesis was included in the work: *Nyttegjøring og gjenbruk av kalk- sementstabilisert leire i deponier (Reuse and recycling of lime cement stabilized clay in landfills).*
    - Key researchers:
        - o Gunvor Baardvik, Researcher NGI
        - o Lincar Pedroni, Visiting Researcher NGI
        - o Emmi Charlotte Kristensen, master student NTNU
        - o Gudny Okkenhaug, Researcher at NGI and Assistant Professor II at NMBU

5. Developing characterization methods for contaminated soil. Investigating the effect soil amendments by reusing industrial waste products (industrial slag, biochar based on waste wood). Focus contaminants in soil were poly- and perfluorinated alkyl substances (PFAS) and metals related to shooting range soil (lead, cupper, antimony). These studies demonstrated that the tested amendments showed good retention capacity for several soil types. Det work was carried out in collaboration with Lindum AS. Duration: 2017-2019.
    - This resulted in 4 GEOreCIRC reports: 1) *Geokjemiske og geotekniske testmetoder forgjenvinning av overskuddsmasse og restprodukter.* NGI-rapport20160794-02-R; 2) WP3: *Eksisterende veiledere og retningslinjer for risikovurdering av spredning fra avfall og forurensedemasser.* NGI-rapport 20160794-09-R.; 3) *Spredning av miljøgifter ved gjenvinningstiltak,* NGI-rapport 20160794-10-R; 4) WP2E: *Research findings: Reuse of lightly contaminated building and construction materials.* NGI-rapport 20160794-06-R. Furthermore, the work resulted in 5 research papers (3 peer-reviewed journal articles). Two master theses were included in the work: 1) *Contaminated soil: Waste today, resource tomorrow? Coupling Hydraulic conductivity and leachability in soil characterization – a lab-based study. 2) Activated and enriched "designer" biochar as sorbent in remediation of PFAS and metal contaminated soils*.
    - Key researchers:
        - o Gudny Okkenhaug, Researcher at NGI and Assistant Professor II at NMBU.
        - o Sarah Hale, Researcher at NGI.
        - o Erlend Sørmo, Researcher at NGI.
        - o Gijs D. Breedveld, Technical Director at NGI and Professor II at UiO
        - o Ludovica Silvani, post doc at NGI
        - o Gerard Cornelissen, Researcher at NGI
        - o Hans Peter Arp, Researcher at NGI
        - o Yaxin Zhang, Visiting Researcher from Hunan University, China
        - o Karen Ane, master student, NMBU, Faculty of Environmental Sciences and Natural Management (MINA)

o Nora Bjerkli, master student at NMBU, Faculty of Environmental Sciences and Natural Management (MINA)

3. References to the research

All GEOreCIRC reports, including the project summary report are available at the home page *https://www.ngi.no/eng/Projects/GEOreCIRC*

References to key outputs (peer-reviewsx journal articles) from the research described in the previous section:

- Eckbo, Cathrine; Okkenhaug, Gudny; Hale, Sarah. The effects of soil organic matter on leaching of hexavalent chromium from concrete waste: Batch and column experiments. *Journal of Environmental Management* 2022; Volum 309.
- Hale, Sarah; Roque, Antonio José; Okkenhaug, Gudny; Sørmo, Erlend; Lenoir, Thomas; Carlsson, Christel; Kupryianchyk, Darya; Flyhammar, Peter; Žlender, Bojan. The reuse of excavated soils from construction and demolition projects: Limitations and possibilities. *Sustainability* 2021; Volum 13.(11)
- Langford, Jenny; Dahl, Marianne; Baardvik, Gunvor; Syversen, Fredrikke; Ofstad, Christian Strømme; Okkenhaug, Gudny; Rekve, Marie; Isachsen, Guro. TBM-spoil characterization and utilization at the Follo Line project. *IOP Conference Series: Earth and Environmental Science (EES)* 2021; Volum 710
- Silvani, Ludovica; Cornelissen, Gerard; Smebye, Andreas; Zhang, Yaxin; Okkenhaug, Gudny; Zimmermann, Andrew R.; Thune, Gorm; Sævarsson, Hilmar; Hale, Sarah. Can biochar and designer biochar be used to remediate per- and polyfluorinated alkyl substances (PFAS) and lead and antimony contaminated soils?. *Science of the Total Environment* 2019 ;Volum 694.
- Sørmo, Erlend; Silvani, Ludovica; Thune, Gorm; Gerber, Helmut; Schmidt, Hans Peter; Smebye, Andreas Botnen; Cornelissen, Gerhard. Waste timber pyrolysis in a medium-scale unit: Emission budgets and biochar quality. *Science of The Total Environment* 2020; Volume 718
- Zhang, Yaxin; Cornelissen, Gerard; Silvani, Ludovica; Zivanovic, Valentina; Smebye, Andreas; Sørmo, Erlend; Thune, Gorm; Okkenhaug, Gudny. Industrial byproducts for the soil stabilization of trace elements and per- and polyfluorinated alkyl substances (PFASs). *Science of the Total Environment* 2022; Volum 820.

Results from the GEOreCIRC project have been presented at several conferences and seminars. E.g. Nordrocs2018, Helsingør, Danmark; WASCON 2018, Tampere, Finland; Teknologidagene 2018, Trondheim; Nordic Biochar Conference, Stockholm, Sweeden; Miljøringen 2017, Oslo, Norway; Avfall Norge Deponiseminar 2017, Gardermoen, Norway; Seminar Mineralnæringen 2019, Stavanger, Norway.

4. Details of the impact

The GEOreCIRC project has helped developing methods that form the basis for increased recycling and utilization of a) Waste products and surplus materials that are slightly contaminated and are currently considered waste and b) Surplus materials that are considered clean and have potential for reuse. The focus of the project was on materials that arise in connection with construction projects and industrial activities, including surplus materials from infrastructure projects (road, railway) and building projects, e.g. geologically natural materials such as lightly contaminated soil, lime-cement-stabilized clay, and tunnel boring machine (TBM) materials. In addition, concrete/demolition materials, waste from the mineral industry, and slag from mineral-producing industries were included. From the beginning there was high emphasis for the GEOreCIRC project to collaborate with relevant stakeholders (e.g. authorities, site/problem owners, entrepreneurs, waste handling companies, consultants). During the whole project period (and beyond) there have been a strong stakeholder involvement with direct collaboration in several research cases.

One of the work packages in GEOreCIRC aimed to identify factors that hinder the recycling of surplus materials. The focus was on both practical and regulatory reasons, such as material properties that need improvement, current regulations, project logistics in the construction and demolition sector, or challenges faced by recipients of recycled materials. A survey was conducted among the stakeholders in the reference group through interviews and a workshop with barriers and obstacles as the main theme.

The GEOreCIRC project has helped to remove barriers for the reuse of TBM masses, which are both related to geotechnical (less favorable grain size distribution and shape compared to blasting material from the same rock) and environmental (contaminants) challenges. Both environmental and geotechnical properties have been compiled from various projects dating back to the 1980s. This review combined with laboratory and field tests on TBM material from the Follobane project, carried out in collaboration with Bane NOR and NTNU, has shown that the material is considered suitable for reuse as filling material. Similar, the project has shown the possible reuse of lime cement stabilized clay from construction work, either as geological impermeable barrier at landfill sites or as filling material, a work undertaken in collaboration with NOAH Langøya and NTNU.

The reuse of waste concrete from demolition and rehabilitation of buildings is challenging due to hexavalent chromium. Through literature review, lab and field testing, the GEOreCIRC project has investigated the contaminant levels, environmental mobility of this element, as well as possible measures to reduce environmental risks related to the reuse of waste concrete. The work was carried out in cooperation with Sintef and Miljødirektoratet (Environmental Protection Authorities), and the results forms part of the basis for new regulations related to reuse of waste concrete in the Norwegian waste regulation.

In the GEOreCIRC project, both methods for environmental and geotechnical characterization of contaminated soil, as well as methods for risk assessment have been tested and developed to assess opportunities or recycling. Furthermore, innovative methods for reuse of industrial by-products for soil amendment, e.g. immobilization of organic and inorganic contaminants have been developed. Collaborating partners as Lindum AS are currently using these methods for stabilizing waste soil prior landfilling.

The results of the project have given ideas and served as a basis for several new research proposals. In particular, VOW: Valorization of Organic Waste into Sustainable Products for Clean-up of Contaminated Water, Soil, and Air (BIA X project. 2019 - 2023 NFR Grant no. 299070) and the Center for research driven innovation (SFI) earthresQue, Rescue of earth materials and waste in the Circular Economy (NFR Grant No. 310042/F40), which started in 2020, are direct outcomes of the results and user partner collaboration in GEOreCIRC.

5. Sources to corroborate the impact

The impact can be corroborated by:

- The representatives from the user partners and reference group in the project:
    1. Thomas Henriksen, Forretningsutvikler, AF Decom, email: thomas.jolstad.henriksen@afgruppen.no
    2. Hilmar Thor Sævarsson, Direktør Sentral Produksjon, Norsk Gjenvinning; email: Hilmar.Thor.Saevarsson@lindum.no
    3. Fredrikke Syversen, Project Manager - Ny Vannforsyning Oslo, E6 Rentvannstunnelen, VAV, email: fredrikke.syversen@vav.oslo.kommune.no
    4. Gorm Thune, Consultant R&D, Lindum AS. Email: Gorm.Thune@lindum.no
    5. Vanja Alling, Senior researcher (previous Miljødirektoratet) email: vanja.alling@niva.no

Impact case guidelines

Each case study should include sufficiently clear and detailed information to enable the evaluation committee to make judgements based on the information it contains, without making inferences, gathering additional material, following up references or relying on members' prior knowledge. References to other sources of information will be used for verification purposes only, not as a means for the evaluation committee to gather further information to inform judgements.

Timeframes

- The impact must have occurred between 2011 and 2021
- Some of the underpinning research should have been published in 2010 or later
- The administrative units are encouraged to prioritise recent cases

Page limit

Each completed case study template will be limited to **five pages** in length. Within the annotated template below, indicative guidance is provided about the expected maximum length limit of each section, but institutions will have flexibility to exceed these so long as the case study as a whole remains no longer than **five pages** (font Arial size 10,5 or similar). Please write the text into the framed template under the sections 1–5 below. The guiding text that stands there now, can be deleted.

Maximum number of cases permitted per administrative unit

For up to 10 researchers: one case; for 10 to 30 researchers: two cases; for 30-50 researchers: three cases; for 50-100 researchers: four cases, and up to five cases for units exceeding 100 researchers.

Naming and numbering of cases

Please use the standardised short name for the administrative unit, and the case number for the unit (1,2,3, etc) in the headline of the case. Each case should be stored as a separate PDF-document with the file name: [Administrative unit short name] [case number]

Publication of cases

RCN plans to publish all impact cases in a separate evaluation report. By submitting the case the head of the administrative units consents to the publication of the case. Please indicate below if a case may not be made public for reasons of confidentiality.

If relevant, describe any reason to keep this case confidential:

[NGU] [1]

Institution: Geological Survey of Norway
Administrative unit: NGU
Title of case study: InSAR.no
Period when the underpinning research was undertaken: 2011 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 – 2021
Period when the impact occurred: 2018 – 2021

1. Summary of the impact

In Norway, the development and use of the technique known as Interferometric Synthetic Aperture Radar (InSAR) to measure surface displacement at mm/year scale based on satellite data, was initiated at NGU in collaboration with other institutions and agencies from around 2005. Taking advantage of the Sentinel satellites that were launched from 2014, a national center for InSAR processing was established at NGU in 2015. In November 2018, the InSAR.no service was launched, providing billions of deformation measurements across Norway. This was the first nationwide InSAR service worldwide to provide free, open, and regularly updated data to all users in society.

2. Underpinning research

In 2005 the Geological Survey of Norway (NGU) started working with the Norwegian Space Agency (NSA) and Norut (now part of NORCE) to develop the first operational InSAR processing capabilities in Norway. Using all the available data/scenes from the European Remote Sensing (ERS) satellites, a systematic InSAR processing was completed in 2009, covering the most landslide-areas in Norway. This led to the discovery of many unstable slopes throughout the country. In 2008 NGU began systematically acquiring Radarsat-2 images over landslide-prone areas and major cities in Norway (Oslo, Trondheim and Bergen), and this continued until 2018. These acquisitions have been crucial for NGU's landslide mapping program, and were the foundation for the activities described in this impact case.

In 2013, it became clear that Europe would soon have new radar satellites (Sentinel-1A, 1B, 1C etc.) that would provide unprecedented amounts of consistent data all over the world every 6 or 12 days. A working group was established by the NSA, including NGU, the Norwegian Water and Energy Directorate (NVE) and the national road and railroad authorities. The group published a report in 2014, "*Mapping and monitoring of avalanche danger and infrastructure using radar satellites and InSAR methodology: Basis for a strategic plan for public use of interferometry in Norway*" (published in Norwegian). This report became the basis for future use of interferometry in Norway. As recommended in the report, a national InSAR processing centre was established at NGU, which would provide free and open InSAR data to both public and government agencies.

In 2015, the development of the Norwegian Ground Motion Service began. NGU was leading the project and developing the necessary computing resources and working with Norut and the Dutch company PPO.Labs on research and development of InSAR Norway. The project was also supported by key stakeholders including the NVE and NSA. The research was not strictly constrained to the technical challenges of the InSAR method. Development of the methods were tightly linked to research, testing and use of the data in on-going projects run by e.g. the landslide group at NGU, in collaboration with NVE. This was not only useful to the on-going research and development of the InSAR procedure, but also ensured that the quality of the InSAR method was tested early during the development phase of the service.

After years of intensive research and development efforts, from design of innovative algorithms to implementation and testing of the service, InSAR.no was finally launched in November 2018. The service provides billions of deformations measurements all over Norway. The national map is up-dated every year. It is the first nationwide InSAR service to provide free and open data to all users and remains today the only national service with regularly updated data. The service gained wide acclaim and attention, and by 2019, the European Commission had tasked the European Environment Agency (EEA) with adding a ground motion product to the Copernicus Land Monitoring Service portfolio. NGU with Dr John Dehls as project leader led a consortium to define the technical details and specifications for the Service, the results of which formed the basis for a commercial procurement of services.
Names of the key researchers and what positions they held at the administrative unit at the time of the research: John Dehls (2011-21) Marie Keiding (2016-19) Marie Bredal (2017-21)

3. References to the research

Dehls, J.F., Lauknes, T.R., Hermanns, R.L., Bunkholt, H., Grydeland, T., Larsen, Y., Eriksen, H.Ø. and Eiken, T., 2014. Use of satellite and ground based InSAR in hazard classification of unstable rock slopes. In *Landslide Science for a Safer Geoenvironment* (pp. 389-392). Springer, Cham. http://dx.doi.org/10.1007/978-3-319-05050-8_60

Eriksen, H. Ø., Lauknes, T. R., Larsen, Y., Corner, G. D., Bergh, S. G., Dehls, J., & Kierulf, H. P. (2017). Visualizing and interpreting surface displacement patterns on unstable slopes using multi-geometry satellite SAR interferometry (2D InSAR). *Remote Sensing of Environment*, *191*, 297-312. https://doi.org/10.1016/j.rse.2016.12.024

Böhme, M., Bunkholt, H. S. S., Oppikofer, T., Dehls, J. F., Hermanns, R. L., Eriksen, H. Ø., Lauknes, T. R. & Eiken, T. (2018). Using 2D InSAR, dGNSS and structural field data to understand the deformation mechanism of the unstable rock slope Gamanjunni 3, northern Norway. In *Landslides and engineered slopes. Experience, theory and practice* (pp. 443-449). CRC Press. https://doi.org/10.1201/9781315375007

Larsen, Y., Marinkovic, P., Dehls, J.F., Perski, Z., Hooper, A.J. and Wright, T.J., 2017, July. The Sentinel-1 constellation for InSAR applications: Experiences from the InSARAP project. In *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (pp. 5545-5548). IEEE. https://doi.org/10.1109/IGARSS.2017.8128260

Dehls, J.F., Larsen, Y., Marinkovic, P., Lauknes, T.R., Stødle, D. and Moldestad, D.A., 2019, July. INSAR.No: A National InSAR Deformation Mapping/Monitoring Service in Norway--From Concept to Operations. In *IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium* (pp. 5461-5464). IEEE. https://doi.org/10.1109/IGARSS.2019.8898614

Costantini, M., Minati, F., Trillo, F., Ferretti, A., Novali, F., Passera, E., Dehls, J., Larsen, Y., Marinkovic, P., Eineder, M. and Brcic, R., 2021, July. European Ground Motion Service (EGMS). In *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS* (pp. 3293-3296). IEEE. https://doi.org/10.1109/IGARSS47720.2021.9553562

4. Details of the impact

The research and development of InSAR technology, including the build-up of significant IT infrastructure and processing capabilities, have shown to be very useful to monitor and measure a variety of phenomena, with significant societal benefit. Importantly, the integrated application of the methods with on-going applied research and development of mapping methods have been particularly rewarding. Some key aspects of the impacts will be described.

An important use of the service is to identify and monitor unstable rock slopes in Norway, add to the understanding the geological conditions of unstable slopes and evaluate associated hazard and risk. Norway has a long coastline with deep fjords penetrating inland, commonly with steep rocks slopes resulting from periods of glaciation. Small rock slope failures are frequent. However, historical records show that these areas are prone to large rock avalanches that have caused severe damage and loss of lives. Mostly because of displacement waves (tsunamis) in fjords and lakes, more than 280 lives were lost in Norway in the last 200 years. Using helicopters in the search for potential landslides is time-consuming and expensive. The InSAR.no service has proved to be a necessary and cost-effective tool in the search for, and mapping of, ground deformation in the steep terrains in Norway.

Having identified potentially unstable objects, mapping of their precise nature and a hazard and risk classification is undertaken to determine whether permanent 24/7 monitoring or other measures are necessary. Within local areas of deformation in a region of interest, InSAR data can be used to position specialized instrumentation (such as GPS networks and extensometers) designed to precisely measure and monitor surface deformation over limited areas. Currently, 9 high-risk sites are permanently monitored in Norway. 14 sites are subject to periodic monitoring. At these sites installed corner reflectors ensure InSAR measurements during winter. There are great benefits to society from identifying areas susceptible to slope-related hazards, so that infrastructure and houses and roads are not built in these areas. Access to the results from up-dated InSAR-data is a key element in this work.

Knowledge of subsurface conditions are of great importance during planning of large infrastructure projects. In Norway quick clays may be present in areas below the Marine Limit; i.e. the highest former seal level after deglaciation. Several examples show that combining information from InSAR data with e.g., geotechnical investigations is essential in locating transport routes and designing construction methods for roads and railroads.
In urban areas, the InSAR.no service is used to detect and monitor building settlements and subsidence that may be due to quick clay or lowering of the groundwater table during construction work and underground tunnelling. The method is also applied to monitor the stability of bridges, railroad lines and other infrastructure, and are therefore valuable also after the construction period.

InSAR data can be used to record changes in ice sheets and glaciers, providing crucial data in climate research. The service is also used to detect and monitor changes in the permafrost layer (thaw and heave) and soil creep in the Arctic region. These data underpin climate research and are crucial in planning for sustainable use of resources.

Internationally, InSAR data are used to observe crustal movements related to plate tectonic processes. The data are used to identify and assess potential natural disasters such as earthquakes and volcanic eruptions.

In Norway, NGU staff has presented the research and application of the InSAR method in numerous international scientific meetings and workshops. Likewise, the service has been promoted in national and local meetings, workshops and seminars, attended by large numbers of stakeholders. This includes several public agencies, e.g. NVE, NSA, road and railroad authorities, local communities, advisory companies and consultants. Since its launch in 2018, InSAR.no has had 100-150 daily professional users (80% in Norway).

In a wider perspective, NGU continues to play a vital role in the development and implementation of the European Ground Motion Service (EMGS), providing technical expertise and hosting key components of the service. The entire EGMS online service (https://egms.land.copernicus.eu/), distributing data for more than 10 billion locations in Europe, runs from NGU web servers in Trondheim, using the visualisation platform previously developed for the InSAR.no service.

5. Sources to corroborate the impact

Kartlegging og overvåking av skredfare og infrastruktur ved bruk av radarsatellitter og InSAR-metodikk. Grunnlag for en startegisk plan for offentlig bruk av interferometri i Norge. (*Mapping and monitoring of avalanche danger and infrastructure using radar satellites and InSAR methodology: Basis for a strategic plan for public use of interferometry in Norway*" (published in Norwegian, with English summary). NRS-rapport (2014)2. https://www.romsenter.no/no/Aktuelt/Publikasjoner/Kartlegging-og-overvaaking-av-skredfare-og-infrastruktur-ved-bruk-av-radarsatellitter-og-InSAR-metodikk

The Landslide Blog (Dave Petley):
InSARNORWAY: a national deformation map for Norway
https://blogs.agu.org/landslideblog/2018/12/13/insarnorway-1/

European Association of Remote Sensing Companies (2020):
Ground-Movement-Monitoring-in-Norway-final.pdf (earsc.org); downloaded from https://earsc.org/sebs/ground-motion-monitoring-in-norway/

NORSAR case 1

Institution: Stiftelsen NORSAR
Administrative unit: NORSAR
Title of case study: Large-scale carbon storage: best practice for injection monitoring
Period when the underpinning research was undertaken: 2009-present
Period when staff involved in the underpinning research were employed by the submitting institution: since 2009
Period when the impact occurred: 2014 – present

1. Summary of the impact

NORSAR's early research on CO2 injection and storage monitoring has pioneered the way of interpreting and understanding the relations between large-scale CO2 injection and the occurrence and patterns of seismicity. By leading and participating in focussed research projects with international participation, we identified new monitoring, data processing, and interpretation methods that aimed at directly answering needs from industry partners. Many publications in high-ranked journals underpinned the scientific value, while collaboration projects with industry demonstrated the applicability and impact of the findings. These findings now reveal further impact through contributing to best practice guidelines and regulations for cost efficient monitoring procedures.

2. Underpinning research

In 2009, NORSAR researchers were granted the project "Safety Monitoring of CO_2 Storages Using Microseismicity and 4D Seismic Modelling". This was the starting point of our research on how injection and storage of CO_2 could be monitored and safe storage being verified. Sensor deployment methods, real-time processing, analysis and interpretation methods were developed at the UNIS CO_2LAB on Svalbard. At the industrial-scale CO_2 storage project In Salah, Algeria, we then demonstrated for the first time the observation and causal relation between CO2 injection and the direct response of induced seismicity (*Goertz-Allmann et al., 2014*). The project was led by NGI with NORSAR as partner, funded by Gassnova and industry partners Sonatrach, BP and Statoil (2011-2012).

A follow-up project in collaboration with the Illinois State Geological Survey allowed us to study thousands of microseismic events during large-scale geological storage at Decatur, Illinois, USA (Illinois Basin - Decatur Project). Through detailed analysis of these tiny microseismic events, we could show that they occurred on small fractures that were too small to be identified on 3D seismic surveys. Furthermore, our analysis showed that seismicity primarily occurred in the basement, as a response to long-term injection (*Goertz-Allmann et al., 2017).* Further novel analysis combining surface, with shallow and deep downhole sensors allowed to further identify stress field directions and cluster events based on their type of shear faulting (*Langet et al., 2020*). Simultaneously, NORSAR researchers investigated induced seismicity at the Groningen gas field in the Netherlands, where highly complex velocity models needed to be integrated to understand the depth of the induced events. Knowledge sharing between these two projects resulted in improved event locations, also constraining the event depths at Decatur to high certainty.

After several years of analysis of the Decatur induced seismicity, NORSAR and collaborators put together a conceptual model for the occurrence of induced seismicity (e.g., *Dichiarante et al., 2021*). These knowledge gains helped to increase injection rates at following Decatur injections, while dramatically decreasing the amount of induced seismicity. This made the follow-up projects more cost-efficient and safer.

Cost-efficiency is even more important for offshore CO2 storage and its monitoring. As such, NORSAR is partner in a national research infrastructure grant to investigate cost-efficient monitoring methods using distributed fiberoptic sensing technology (soon part of ECCSEL).

This methodology will allow the usage of long offshore and in-well fiberoptic cables to conduct monitoring of induced seismicity and general deformation. Various sensor layouts to been modelled at NORSAR to optimally deploy such cables and to use the data in efficient array-beamforming applications (*Näsholm et al., 2022*). This knowledge is of equally high relevancy for existing offshore oil and gas infrastructure.

To bring together all the experience from field observations and to unite the findings with the developed conceptual model, we developed in a collaborative effort a unique laboratory test involving a cubic meter of reservoir sandstone. This sandstone was prepared to contain an artificial fault, several boreholes for fluid injection and pressure measurements. Subsequently, the whole sandstone block critically stressed in a tri-axial press, and different types of seismicity were released, depending on injection pressures and differential stresses applied (*Oye et al., 2022*). Through this laboratory experiment we bridged the gap to the field observations.

Volker Oye	Senior Research Geophysicist/Head of Department	
Daniela Kühn	Senior Research Geophysicist	
Bettina Goertz-Allmann	Senior Research Geophysicist	(2012 - present)
Andreas Wüstefeld	Senior Research Geophysicist	(2013 - present)
Ben Dando	Senior Research Geophysicist	(2015 - present)
Kamran Iranpour	Senior Software Engineer	
Nadege Langet	Research Geophysicist	(2015 - present)
Anna Maria Dichiarante	Structural Geologist	(2019 - present)
Alan Baird	Research Geophysicist	(2020 - present)
Peter Näsholm	Senior Research Geophysicist	(2013 - 2020, then 20%-present)
Matt Wilks	PostDoc, Geophysicist	(2016 - 2019)
Andreas Köhler	Senior Research Geophysicist	(2019 - present)

3. References to the research

Goertz-Allmann, B.P., D. Kühn, V. Oye, B. Bohloli, E. Aker. Combining microseismic and geomechanical observations to interpret storage integrity at the In Salah CCS site. 2014. *Geophysical Journal International.* https://doi.org/10.1093/gji/ggu010

Goertz-Allmann, B.P., S. J. Gibbons, V. Oye, R. Bauer, R. Will. Characterization of induced seismicity patterns derived from internal structure in event clusters, 2017. *Journal of Geophysical Research*, https://doi:10.1002/2016JB013731

Langet, N., B. Goertz-Allmann, V. Oye, R. A. Bauer, S. Williams-Stroud, A.M. Dichiarante, S. E. Greenberg. Joint Focal Mechanism Inversion Using Downhole and Surface Monitoring at the Decatur, Illinois, CO2 Injection Site. 2020. *Bulletin of the Seismological Society of America,* doi: https://doi.org/10.1785/0120200075

Dichiarante, A.M., N. Langet, R.A. Bauer, B.P. Goertz-Allmann, S.C. Williams-Stroud, D. Kühn, V. Oye, S.E. Greenberg, B.D.E. Dando. Identifying geological structures through microseismic cluster and burst analyses complementing active seismic interpretation. 2021. *Tectonophysics*, https://doi.org/10.1016/j.tecto.2021.229107

Näsholm, S.P., K. Iranpour, A. Wuestefeld, B. D. E. Dando, A. F. Baird, V. Oye. Array Signal Processing on Distributed Acoustic Sensing Data: Directivity Effects in Slowness Space. 2022. *Journal of Geophysical Research*, https://doi.org/10.1029/2021JB023587

Oye, V., Stanchits, S., Babarinde, O., Bauer, R., Dichiarante, A.M., Langet, N., Goertz-Allmann, B.P., Frailey, S. Cubic-meter scale laboratory fault re-activation experiments to improve the understanding of induced seismicity risks. 2022. *Nature Sci Rep* **12**, 8015, https://doi.org/10.1038/s41598-022-11715-6

4. Details of the impact (indicative maximum 750 words)

Safe injection and geological storage of CO_2 is an essential measure to reduce greenhouse gas emissions. NORSAR's research on CO_2 injection and storage monitoring has pioneered the way of interpreting and understanding the relations between large-scale CO_2 injection and the occurrence and patterns of seismicity.

To inform and educate the general public about the concepts of CO_2 capture, transport and storage, a TV crew from the national Norwegian TV NRK came to Longyearbyen on Svalbard in 2014. The aim was to make a documentary of the UNIS CO2Lab to be included in an episode of the popular scientific TV-show “Schrødingers Katt”, broadcasted on NRK. This episode was introducing the concept of CO_2 storage as climate change mitigation technology, including the need for CO_2 storage monitoring. In addition to the TV series that show-cased the concept of CO_2 storage in the Arctic, many governmental representatives from all over the world are visiting Svalbard, making the UNIS CO2Lab an impactful show-case.

Through partnerships and dissemination, giving talks and presentations on various national and international conferences and workshops, NORSAR became involved in important industrial-scale CO_2 storage projects like Krechba, In Salah, in Algeria; Decatur Illinois, USA; Quest, Alberta in Canada, and the Northern Lights project offshore Norway. Another steppingstone was NORSAR's involvement in the Centre for Geological Storage of CO_2, an Energy Frontiers Research Center, funded by the U.S. Department of Energy, where NORSAR was leading the geomechanics theme. This collaboration was intensified through US-Norway bilateral meetings and finally through add-on demonstration projects co-funded by DOE and Gassnova and in a later phase also through industry partners. This type of collaborative projects had proven to show strong characteristics of applied research and day-to-day collaboration with partners, and hence project results could directly be integrated by industry partners for their development of CO_2 storage projects. Strong and highly cited peer-reviewed publications were disseminated. In addition, international conferences and workshops served as discussion grounds, including discussion on monitoring technology with governmental agencies from various countries.

To further prepare Norway and Europe for offshore CO_2 storage monitoring, we further developed our knowledge and experience from hydrocarbon field monitoring using permanent reservoir monitoring systems towards CO_2 storage monitoring. Such experience includes seismicity monitoring from many hydrocarbon fields in the North Sea, from 2012 and still ongoing. One specific topic of interest became imminent with the occurrence of felt seismicity at the Groningen gas field in the Netherlands, a highly fractured, complex, and Europe's largest onshore gas field. The public perceived induced seismicity that could be felt as frightening and a causal relation between the seismicity and the induced seismicity ultimately led to a stop in production. In this project (2014-17) working with the challenges of precisely locating induced seismicity, and during follow-up projects with the Dutch State Supervision of Mines, NORSAR gained valuable experience with respect to public concerns and perceptions.

The knowledge base and technology for safe injection and storage of CO_2 have been significantly improved through recent years of research, however, the topic is still very relevant. NORSAR collaborates with other research institutes and industry in several projects, both nationally and internationally. NORSAR has gained the confidence to coordinate the EU ACT project ENSURE where not only the monitoring technology is in focus, but also people's perceptions and trust in the technology.

The results of the research have been disseminated through a number of channels, and we have been active in the national dialogue on the issues, such as roundtables and direct dialogue with the ministries.

5. Sources to corroborate the impact

https://tv.nrk.no/serie/schrodingers-katt/2014/DMPV73000514/avspiller NRK-TV: Schrødingers Katt. Topic 2: start at minute 23

https://www.polyteknisk.no/lytt-til-polypod-hva-betyr-uavhengig-monitorering-for-co2-lagring round-table discussion about independent monitoring of CO2 storage at Polyteknisk Forening

https://ensure.norsar.no/ EU-ACT project homepage

https://hordanet.no/ HNET Gassnova project homepage

https://science.osti.gov/-/media/bes/efrc/pdf/technical-summaries/GSCO2_technical_2017-11.pdf Summary of U.S. DOE funded 5-year Energy Frontiers Research Center (EFRC) Center for Geologic Storage of CO2

https://phys.org/news/2022-06-lab-earthquake-co2-underground-avert.html news blog Phys.org on Nature scientific reports paper

https://www.ntnu.edu/cgf
Research partner and lead of geohazards within the Center for Geophysical Forecasting

SUV 1

Institution: Norwegian Meteorological Institute
Administrative unit: Development Centre for Weather Forecasting (SUV)
Title of case study: Yr
Period when the underpinning research was undertaken: 2011 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 - 2021
Period when the impact occurred: 2011 - 2021

1. Summary of the impact (indicative maximum 100 words)

The quality of the forecasts at more than 10 million locations globally, the design of the presentation and the free data policy have placed Yr among the most popular global weather information sites growing to more than 11 million unique weekly users in the summer of 2021.

Yr can be characterised as a social innovation, which refers to the design and implementation of new solutions that imply conceptual, process, product, or organisational change, which ultimately aim to improve the welfare and wellbeing of individuals and communities. The organisation of the public weather forecasting and research at MET Norway now follows the same principle, with forecasters, researchers and technology experts working in teams. Both this organisational structure and Yr in itself has turned out also to be attractive for recruitment and in project acquisition.

2. Underpinning research (indicative maximum 500 words)

Clearer presentation of uncertainty information, a clear intent of all nuances in information, a thorough use of multimodal information, and consideration of users' needs can help improve communication of forecast uncertainty. A qualitative study based on semistructured interviews with 21 Norwegians showed the following: (a) only a portion of uncertainty information was used, (b) symbols were sometimes ascribed different meanings than intended, and (c) interpretations were affected by local experiences with wind direction and forecast quality. The informants' prior knowledge was found to prevail in the event of a conflict with forecast information, and an expected range of uncertainty was often inferred into single-valued forecasts. Additionally, (d) interpretations were affected by the integration of information used to predict the time and location of precipitation. Informants typically interpreted the degree of certainty differently (more or less uncertain) than was intended.

MET Norway introduced observations from Netatmo's network of weather stations in the postprocessing of near-surface temperature forecasts for Scandinavia, Finland, and the Baltic countries. The observations are used to continually correct errors in the weather model output caused by unresolved features such as cold pools, inversions, urban heat islands, and an intricate coastline. Corrected forecasts are issued every hour. Integrating citizen observations into operational systems comes with a number of challenges. First, operational systems must be robust and therefore rely on strict quality control procedures to filter out unreliable measurements. Second, postprocessing methods must be selected and tuned to make use of the high-resolution data that at times can contain conflicting information.

Since October 2013 a convective-scale weather prediction model has been used operationally to provide short-term forecasts covering large parts of the Nordic region. The model is now operated by a bilateral cooperative effort [Meteorological Cooperation on Operational Numerical Weather Prediction (MetCoOp)] between the Norwegian Meteorological Institute and the Swedish Meteorological and Hydrological Institute. The core of the model is based on the convection-permitting Applications of Research to Operations at Mesoscale (AROME) model developed by Météo-France.Specific modifications and updates have been made to suit advanced high-resolution weather forecasts over the Nordic regions.

AROME-Arctic convective-scale atmospheric prediction system of the European Arctic is compared with the ECMWF's medium-range forecasting, ensemble forecasting, and reanalysis systems. In general, AROME-Arctic adds value to the representation of the surface characteristics. The atmospheric boundary layer thickness, during stable conditions, is overestimated in the global models, presumably because of a too diffusive turbulence scheme. Instead, AROME-Arctic shows a realistic mean thickness compared to the radiosonde observations. When comparing with the largest wind speeds from ocean surface winds and at coastal synoptic weather stations during landfall of a polar low, AROME-Arctic shows the most realistic values. In addition to the model intercomparison, the limitation of the representation of sea ice and ocean surface characteristics on kilometer scales are discussed in detail. This major challenge is illustrated by showing the rapid drift and development of sea ice leads during a cold-air outbreak.

A 5 to 10 °C warm bias of the sea-ice surface temperature in global atmospheric reanalyses and weather forecasts is mainly caused by a missing representation of the snow layer on top of the sea-ice. Due to the low thermal conductivity of snow compared to sea-ice, a thin snow layer reduces the conductive heat flux much more efficiently than sea-ice, and thus insulates the cold atmosphere from the relatively warm ocean. An extended sea-ice parameterisation scheme that includes a prognostic sea-ice thickness and snow layer model has been developed and implemented in AROME-Arctic. It is the only model simulation with small deviations in the simulated surface temperatures.

3. References to the research (indicative maximum of six references)

- Batrak, Y., Müller, M. On the warm bias in atmospheric reanalyses induced by the missing snow over Arctic sea-ice. Nat Commun 10, 4170 (2019). https://doi.org/10.1038/s41467-019-11975-3
- Frogner, I-L, Singleton, AT, Køltzow, MØ, Andrae, U. Convection-permitting ensembles: Challenges related to their design and use. Q J R Meteorol Soc. 2019; 145 (Suppl. 1): 90– 106. https://doi.org/10.1002/qj.3525
- Müller, M., Y. Batrak, J. Kristiansen, M. Ø. Køltzow, G. Noer and A. Korslov, 2017. Characteristics of a convective-scale weather forecasting system in the Arctic. Mon. Wea. Rev., 145, doi/10.1175/MWR-D-17-0194.1
- Müller, M., M. Homleid. K.-I. Ivarsson, M. A. Ø. Køltzow, M. Lindskog, U. Andrae, T. Aspelien, L. Berggren, D. Bjørge, P. Dahlgren, J. Kristiansen, R. Randriamampianina, M. Ridal and O. Vignes, 2017: AROME - MetCoOp: A Nordic convective scale operational weather prediction model. Wea. Forecasting, 32, 609-627. doi/10.1175/WAF-D-16-0099.1
- Nipen T, I. Seierstad, C. Lussana, J. Kristiansen, and Ø. Hov, 2020: Adopting citizen observations in operational weather prediction. Bull. Amer. Meteor. Soc., 101, E43–E57, doi/10.1175/BAMS-D-18-0237.1
- Randriamampianina, R, Bormann, N, Køltzow, MAØ, Lawrence, H, Sandu, I, Wang, Z. Relative impact of observations on a regional Arctic numerical weather prediction system. Q J R Meteorol Soc. 2021; 147: 2212– 2232. https://doi.org/10.1002/qj.4018
- Sivle, A.D., S.D. Kolstø, P.J.K. Hansen, and J. Kristiansen, 2014: How Do Laypeople Evaluate the Degree of Certainty in a Weather Report? A Case Study of the Use of the Web Service yr.no. Wea. Climate Soc., 6, 399–412. doi/10.1175/WCAS-D-12-00054.1

4. Details of the impact (indicative maximum 750 words)
The Internet site and app Yr is a modern example of the value cycle at work. The research component is located at MET Norway with a limited area numerical weather prediction model developed through a long standing international partnership with data assimilation and ensemble prediction. The limited area model boundary conditions come from the routine ECMWF global model. The post-processing system is research driven and developed based on the user knowledge by the Yr-team. The work is led by meteorological experts across all disciplines at MET Norway including social sciences. The research based weather forecast services on Yr are automated allowing high frequency update of the forecasts. The data and informatics part of the translation to applications takes place at MET Norway. The

forecasts based on the limited area model for Scandinavia as well as the frontend products are made available as open data through a user-oriented API (application production interface), as are value added ECMWF forecast data with global coverage. The communication of forecasts and interaction with the general public and with specialised users in all fields of society is the basis for iterative improvement of the services.

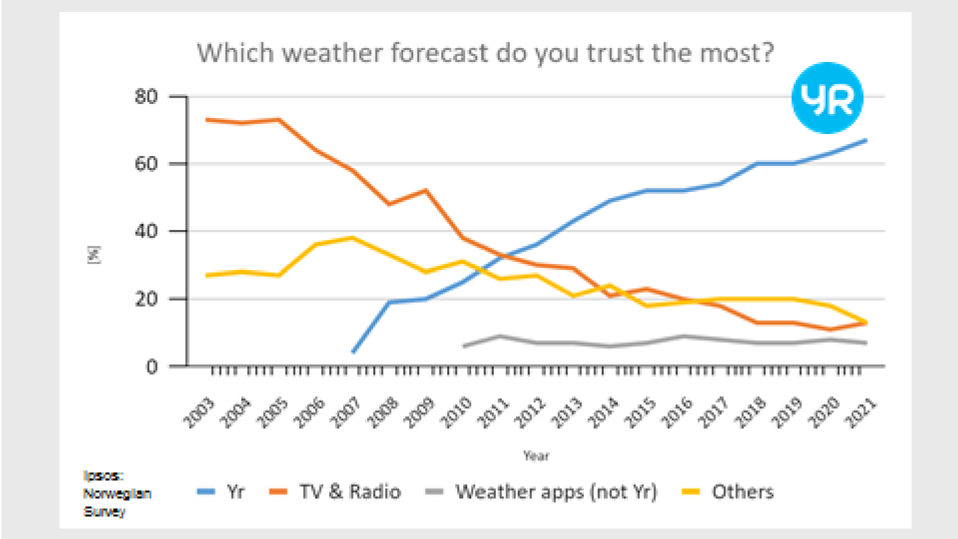
In this value cycle the research, development, operations and application of a dedicated numerical weather prediction model for the Arctic, AROME Arctic takes place, started in the WMO Polar Prediction Project and the Year of Polar Prediction (PPP and YOPP). The application experience further fostered developments such as fast sea ice and snow on sea ice predictions, which has improved both the backend weather forecasts and provided better data at the frontend for decision making and for all users of Yr.

MET Norway API is a digital public good that generates data and provides an interface to openly licensed world weather data. It provides free digital access to high-quality, reliable, and user-friendly 10-day weather forecast data for any geolocation in the world. The Yr value cycle includes research on citizen observations and their translation into applications. In the spring of 2018 MET Norway and Yr channelled a large amount of citizen observations into the post-processing of the numerical model forecasts, which for Norway (and the other Scandinavian countries as well as for the Baltic countries) meant a tenfold or more increase in the observational basis for temperature and precipitation. This factor is increasing. There is a near real-time transfer of the citizen data through a novel data quality control system which is based on spatial control of all observations at a given moment rather than time series control of individual sites. In this way as much as 80 (90) % of the private temperature (precipitation) observations are being retained and used in the post-processing at any given time.

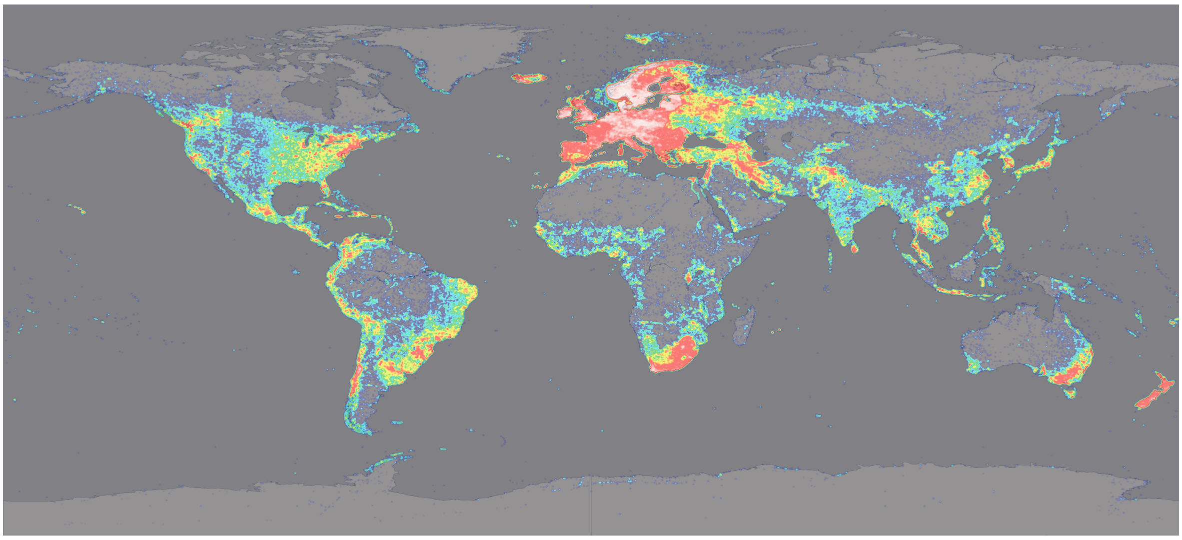
Yr does not generate revenue. Yr forecasts and associated global weather data are free to use for anyone and available through a smartphone interface. In this way a significant opportunity for value creation is offered nationally and internationally in real time across barriers of geography and economy with very low transactional costs. Yr is an integral part of the value cycle for weather forecasting at MET Norway. Many of the research projects at MET Norway are embedded in this value cycle. In this way lasting legacy of the research investment is achieved to the benefit for the users of MET Norway services. This value cycle includes links to international and national academia and research institutions. In this way academic excellence communicates with the end-user experience and knowledge that comes with the continuous service delivery by MET Norway.

5. Sources to corroborate the impact (indicative maximum of ten references)

Yr is a non-commercial collaboration between MET Norway and The Norwegian Broadcast Corporation (NRK). NRK is in charge of the continuous development of the user interfaces for electronic platforms in close dialogue with MET Norway experts.



Yearly user survey where a representative group of the Norwegian population is asked which weather forecast they trust the most. In 2022, Yr reached 70% (not shown).



Weekly Heatmap from summer 2015 showing the number of requests for Yr forecasts. The more reddish and white colours represented the largest density of requests.

Yr.no was the winner of two out of 14 WeatherApp-awards announced by WMO in December 2020 - the “Award for originality and innovation” and the “Award for submissions from public service NMHSs (shared with MeteoSwiss), https://public.wmo.int/en/media/news/wmo-announces-winners-of-weather-apps-awards-and-calendar-competition accessed 8 November 2021.

MET Norway R&D, impact case 2

Institution: Norwegian Meteorological Institute
Administrative unit: R&D MET Norway
Title of case study: Satellite-based monitoring of the global sea ice cover
Period when the underpinning research was undertaken: (2009-2022)
Period when staff involved in the underpinning research were employed by the submitting institution: (2009-2022)
Period when the impact occurred: (2017-2022)

1. Summary of the impact

MET Norway runs a 24/7 monitoring of the global sea ice cover based on satellite data. Climate information resulting from this monitoring reaches IPCC and WMO climate assessments, European policy makers, climate services, and the citizens at large.

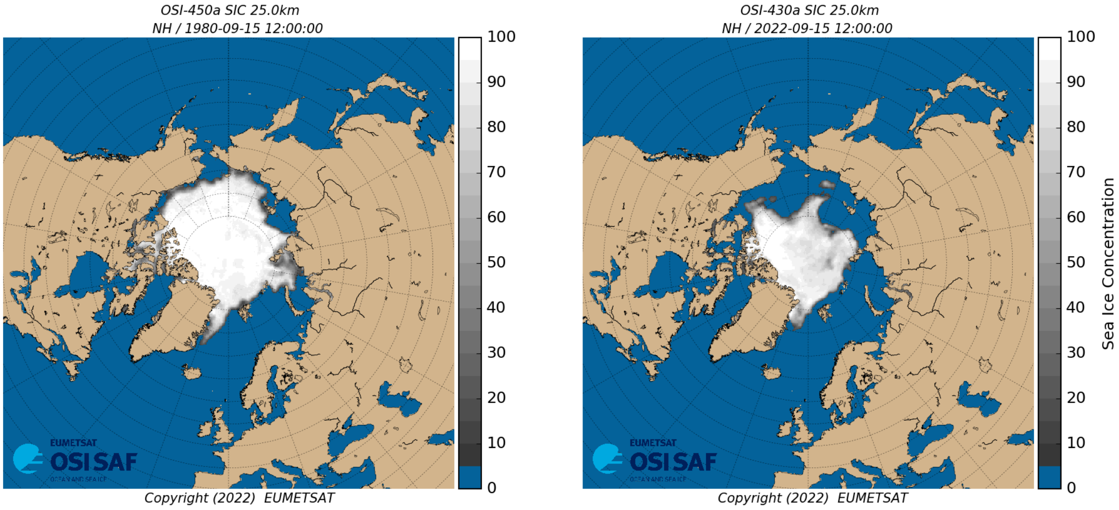
2. Underpinning research

To transform raw satellite images into climate information relevant for the society requires a long value chain. Over the years, MET Norway has developed such a value chain for the 24/7 monitoring of the global sea ice cover: every 100 minutes, a new satellite image is received at MET Norway and processed into a sea-ice information product, adding to over 40 years of sea-ice data we have collected so far.

Developing such a value chain involves both academic research (to improve the quality of the algorithms and resulting datasets) and technical development (to implement the algorithm onto high-performance computers and prepare multi-decadal datasets, but also to make the data available to all interested stakeholders). The required R&D activities to prepare such a value chain were realised thanks to funding from different institutions and programmes, including the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF, osi-saf.eumetsat.org), the Climate Change Initiative of the European Space Agency, the EU-funded Arctic Passion (2020-2026) or WMO Global Cryosphere Watch (GCW). Each time, the collaboration with European actors and especially the Danish Meteorological Institute strengthened MET Norway's position in Europe.

In the EUMETSAT OSI SAF, we developed the core algorithms for transforming raw satellite measurements of microwave brightness temperatures into maps of sea-ice concentration. The method includes dynamic tuning of the algorithms (to avoid artificial trends and jumps when changing satellite missions), atmospheric correction of the satellite signal using radiative transfer models, and uncertainties for each pixel. A first Climate Data Record was prepared and documented in Tonboe et al. (2016).

In the ESA CCI projects, we improved the core algorithms, especially their accuracy, temporal consistency, and spatial resolution. A new version of the Climate Data Record was prepared in coordination with OSI SAF, and documented in Lavergne et al. (2019). A series of scientific papers documented the qualities of the data record compared to other sources (Kern et al., 2019; 2021; 2022). This sea-ice data record contributed to the 6th IPCC Assessment Report cycle (2021-2022).



Above: *Maps of the sea-ice cover at the end of summer 1980 (left) and 2022 (right) showing the main trend of declining sea-ice area. Maps produced at MET Norway for the EUMETSAT OSI SAF and with R&D input from ESA CCI.*

In this period, we also developed our climate indicators and their graphical presentation online. MET Norway's sea-ice indicators are now available to all interested stakeholders (other scientists, news agencies, general public,...) on several of our webpages, including cryo.met.no that was developed since 2019. With contribution from the EU-funded Arctic Passion project (2020-2026), we are improving how to present this climate indicator online, with interactive visualisation.

Key researchers at MET Norway:
Steinar Eastwood, Senior Scientist, (1997 - present)
Thomas Lavergne, Senior Scientist, (2007 - present)
Signe Aaboe, Scientist, (2013 - present)
Atle Sørensen, Scientist, (2012 - present)
Amélie Neuville, Scientist, (2017-2020)
Michael Yartys, Student Trainee, (summer 2022)

3. References to the research

- *Scientific Paper:* Lavergne, T., Sørensen, A. M., Kern, S., Tonboe, R., Notz, D., Aaboe, S., Bell, L., Dybkjær, G., Eastwood, S., Gabarro, C., Heygster, G., Killie, M. A., Brandt Kreiner, M., Lavelle, J., Saldo, R., Sandven, S., and Pedersen, L. T.: Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records, The Cryosphere, 13, 49–78, https://doi.org/10.5194/tc-13-49-2019, 2019.
- *Climate Dataset:* OSI SAF (2017): Global Sea Ice Concentration Climate Data Record v2.0 - Multimission, EUMETSAT SAF on Ocean and Sea Ice, DOI: 10.15770/EUM_SAF_OSI_0008. http://dx.doi.org/10.15770/EUM_SAF_OSI_0008
- *Web pages:* https://cryo.met.no/en/sea-ice-index and https://cryo.met.no/en/bokeh/seaice
- *Scientific Paper:* Kern, S., Lavergne, T., Notz, D., Pedersen, L. T., Tonboe, R. T., Saldo, R., and Sørensen, A. M.: Satellite passive microwave sea-ice concentration data set intercomparison: closed ice and ship-based observations, The Cryosphere, 13, 3261–3307, https://doi.org/10.5194/tc-13-3261-2019, 2019.

4. Details of the impact

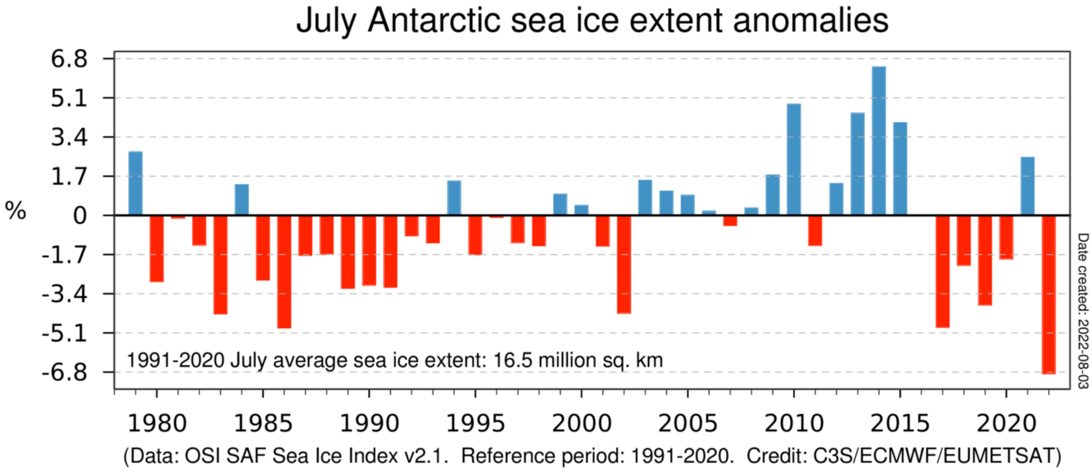
We outline here 4 key impacts of this research: contribution to IPCC assessments, contribution to WMO annual climate reports, contribution to operational climate services, and reaching-out to the citizens at large.

Five years ago, all stakeholders interested in sea-ice climate indicators would refer to the US data from the National Snow and Ice Data Center (NSIDC). There is still a way to go before a majority of them refer to our data instead, but the developments over the last 5 years are very encouraging, see below.

IPCC assessment report: The 6th Assessment Report of the International Panel on Climate Change (IPCC) was released in 2021-2022. The IPCC assessment reports are the authoritative compilation of knowledge concerning climate change, from the description of the physical basis (WG I), mitigation (WG II), and adaptation (WG III). For climate scientists, to be cited or used in IPCC reports is a key achievement. Our sea-ice data was used in several chapters of the WG I report (spec. Ch. 2 and Ch. 9), and the Lavergne et al. (2019) paper was cited. This contribution was facilitated by having the main author of Ch. 9 (D. Notz) a team member of the ESA CCI projects. Notz and his team helped define the sea-ice data product and gained confidence in our approach during the project. With our support, they computed several climate indicators, also from other data providers and made the choice to include our data in the AR6 WG I report (2021). Our data is also plotted in the WG I Summary for Policymakers (SPM) so that it was later presented in many fora (2019 onwards). It is difficult to be specific about the nature of impact or who the beneficiaries of our climate information through the IPCC reports are, but we experienced that the climate community at large knows our work better, and that the data is used and cited in more and more work since the IPCC report.

WMO State of the Global Climate reports: Through our contribution to the Global Cryosphere Watch (GCW) - a body of the World Meteorological Organization (WMO) specialised in all things cryosphere - we were invited to contribute to the writing of the last three annual WMO's State of the Climate Reports (SoC 2019, 2020, 2021). In these reports, our sea-ice climate indicators are plotted and contribute to the description of the past year sea-ice events (maximum, minimum, regional anomalies, etc…). The summary plots are created by the team at the UK Met Office, from our online sea-ice data. These summary plots and statements are then highlighted during the WMO press conference launching the annual reports and are seen by many. WMO reports are first published in English, then translated in other languages.

Climate information services: Because they span over 40 years and are updated on a daily basis, our online sea-ice data have been picked by several climate information services in Europe, particularly in the Copernicus programme. For example, the data is plotted and analysed in the monthly bulletins of the Copernicus Climate Change Service (C3S, since 2021) and the annual Ocean State Report of the Copernicus Marine Service (CMEMS, since 2019). Our data is also highlighted as part of the Arctic and Baltic Sea Ice indicator of the European Environmental Agency (EEA, since 2020), which they update on a yearly basis. C3S and EEA do their own plotting from our online data, while we provide graphs to CMEMS.



Above: *Antarctic sea-ice extent anomalies for the months of July, showing July 2022 as a record low value (last red bar to the right). Graphics made by the Copernicus Climate Change Service (C3S) based on climate indicator data produced by MET Norway in the context of the OSI SAF.*

General public: Finally, our sea-ice indicators reach the general public through our web pages, monthly weather reports, and through social media platforms. Sea-ice is a key indicator of climate change and its area undergoes very tangible trends (especially in the Arctic) that are clearly attributed to anthropogenic climate change. The link to climate change is easy to explain and understand (warmer temperatures melt the ice). Sea-ice area has large variations within the year as well as from day to day. All in all, it is an interesting indicator for the general public, one they follow the variations throughout the year. This explains why our sea-ice climate indicators are accessed on our web sites (e.g. https://cryo.met.no) and shared and commented upon on social media platforms such as Twitter and Mastodon. When significant events (e.g. record low values) have happened, our sea-ice data were presented on state TV (NRK) as part of the weather report. We are sometimes interviewed by Norwegian newspapers to comment on sea-ice conditions, based on our data.

5. Sources to corroborate the impact

- IPCC AR6 WG I report (our sea-ice data contribute to Chap. 2 and Chap. 9). For example Fig. 2-20 (https://www.ipcc.ch/report/ar6/wg1/figures/chapter-2/figure-2-20/) and Fig. 9-13 (https://www.ipcc.ch/report/ar6/wg1/figures/chapter-9/figure-9-13/) and Fig. 9-15 (https://www.ipcc.ch/report/ar6/wg1/figures/chapter-9/figure-9-15/)
- WMO State of the Climate (SoC) reports. For example Figure 10 in the “State of the Global Climate 2020 (WMO-No. 1264)” (https://library.wmo.int/doc_num.php?explnum_id=10618)
- Monthly climate bulletins from C3S with sea-ice graphs using sea-ice data from MET Norway (https://climate.copernicus.eu/sea-ice-cover-november-2022).
- The Sea Ice Extent Ocean Monitoring Indicator (OMI) of CMEMS: Arctic (https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/arctic-monthly-mean-sea-ice-extent-observations) and Antarctic (https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/antarctic-monthly-sea-ice-extent-observations-reprocessing)
- The EEA Arctic and Baltic sea ice indicators (https://www.eea.europa.eu/ims/arctic-and-baltic-sea-ice)
- Various websites showing our sea-ice indicator plots: https://cryo.met.no/en/sea-ice-index (English), https://cryo.met.no/nb/sjoe-is-indeks (Norwegian), http://polarportal.dk/havis-og-isbjerge/havisens-udbredelse/ (Danish)
- Various online Climate “Dashboards”, e.g. that of UK Met Office (https://climate.metoffice.cloud/sea_ice.html) or that of the French newspaper “Le

Monde” (https://www.lemonde.fr/les-decodeurs/article/2022/11/03/cop27-6-indicateurs-pour-mesurer-l-urgence-climatique_6148399_4355770.html).

- News items in Norwegian media, e.g. https://www.nrk.no/tromsogfinnmark/havisen-rundt-svalbard-har-smeltet-_-mangler-havis-pa-storrelse-med-svalbard-1.16058060

MET Norway R&D, 3

Institution: Norwegian Meteorological Institute
Administrative unit :Research and Development Department
Title of case study: Climate Future Assessment
Period when the underpinning research was undertaken: 2015-2022
Period when staff involved in the underpinning research were employed by the submitting institution: 2015-2022
Period when the impact occurred:2018-2022

1. Summary of the impact (indicative maximum 100 words)

Our NorESM (Norwegian Earth System Model) simulations and its analysis have formed an integral part of the 6th assessment report of the Intergovernmental Panel of Climate Change on the state of the climate. The results have strengthened the understanding of climate change and have added substantial further confidence on likely future climate change and its regional aspects, namely Arctic amplification. Such confidence allows for a better planning of the transformation of the global energy system into an economy without fossil fuels. The results are at the same time the basis for reports and assessments on climate adaptation.

2. Underpinning research (indicative maximum 500 words)

NorESM is a unique Norwegian climate model, and an essential tool for the Norwegian climate research community to contribute to CMIP (Climate model intercomparison project) and IPCC (Intergivernmental Panel on Climate Change) climate assessments. It is the basis for the participation and cooperation on climate research in numerous projects (institute based, NFR (Norwegian Research Council) & EU funded). It allows for the testing of ad-hoc and relevant climate science questions due to the modularity of NorESM model code basis (in particular Arctic climate, ocean, aerosol/chemistry but also other components) and the experience of the Norwegian Climate Modelling consortium, which is co-lead by the R&D of MET Norway, to set-up model simulations (e.g. in support of 1.5 degree IPCC report and multiple experiments for CMIP6 and IPCC/AR6).

The NorESM configurations NorESM2-LM and NorESM2-MM were finalized for CMIP6 participation in summer and fall of 2019, respectively, and the bulk of the experiment submission to CMIP6 was not completed before late 2019. 1400 model simulations were made for 90 different experiments proposed by CMIP6. These simulations where made publicly available via ESGF data nodes and were the basis of analysis.

A large range of scientific publications has been published already and further important scientific papers are under review or under preparation. Up to the end of 2022, about 600 peer-reviewed publications (Co-authorship by R&D MET in ca. 30) have been published where NorESM results have been used for the analysis of climate processes, climate scenarios and impact of climate change.

The international publication of the CMIP6 NorESM2 model results facilitated also considerable joint analysis studies with international cooperation partners. We found, for instance, fundamental differences in the Southern Ocean circulation and redistribution of ocean heat uptake, ultimately delaying the global surface warming in NorESM2 by several centuries. Such differences explain the existing diversity in climate model results and provide at the same time bounds and confidence on possible climate futures (Gjermundsen et al. 2021).

The climate simulations from NorESM are currently used for downscaling global scenarios to likely future local conditions in Norway in the frame of the European CORDEX initiative and in the course of the preparation of the renewed Klima i Norge 2100 report by METs R&D unit.

All the researchers named of being associated to the climate research section have been key. Leaders have been Michael Schulz (Deputy head of Climate modelling and Air pollution section), Inger Hansen Bauer and Anita Verpe Dyrrdal (Successive Heads of the Norwegian Climate Service Center), Jan Erik Haugena and Rasmus Benestad (Successive Heads of the Climat data analysis section).

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Earth System Dynamics ;Volum 12.(1) s. 253-293, peer reviewed article
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6) Dyrrdal, A.V., Stordal, F. and Lussana, C.
Evaluation of summer precipitation from EURO-CORDEX fine-scale RCM simulations over Norway.
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4. Details of the impact (indicative maximum 750 words)

The joint NorESM infrastructure producing the NorESM simulation results is cost-effective for the national and nordic partners to undertake earth system modelling. It allows for FAIR (past and future) climate data provision for: downscaling/climate services, assessment work, model intercomparison project science, university education.

It assembles and provides exchange fora for Norwegian climate scientists with respect to understanding of earth system modeling, code insight, calibration, publication, outreach. A recent user survey in 2022 revealed: 60 national experts from a range of 9 institutes use the model in 40 projects (10 EU, 21 RCN, 8 Internal, 2 Nordic). The total grant size of these projects amounts to 1900 MNOK (40% EU, 55% RCN, 5% rest). Projects have a duration of typically 3-5 years.

The scientific publications, making use of the NorESM model simulations, formed the basis for the 6th IPCC assessment report on climate change, 2021, The Physical Science Basis. Similarly, the United Nation's Paris Agreement Conference asked IPCC to compile a report on the specific benefits of 1.5 degree warming (versus 2 degrees), for which 40 publications where made using 125 model NorESM simulations, provided in a short time in the period 2017-2019.

It is of no doubt that the IPCC reports inform society with great care about the forthcoming climate change and its causes. The extent of such information is of general nature, influencing international wealth, economies, energy systems and political decisions taken to mitigate greenhouse gas emissions and those to prepare the societies for unavoidable climate adaptation.

The NorESM model simulations and its analysis where performed in the scope of two large NFR funded projects (INES and KeyCLIM). The Norwegian Climate Modelling Consortium behind these projects consisted of 6 Norwegian institutes (NORCE, MET Norway, NERSC, UiO, UiB, NERSC, NILU, Bjerknes Center). M. Bentsen (Norce) and M. Schulz co-lead the two projects. M. Schulz was also co-lead of the CMIP6 endorsed model intercomparison AerChemMIP, exploring the specific impacts of aerosols and reactive gases on climate, contributing to the international cooperation on the CMIP data provision and analysis.

The model simulation results are publicly available and form the basis for multiple climate assessments, such as the downscaling of the results to community level in Norway, as done in METs led Climate Service Center (a cooperation with NORCE, NVE and Bjerknes Center). Boundary conditions from global climate scenario simulations are used to derive more impact oriented information on the occurrence of precipitation extremes, flooding, drought etc.

5. Sources to corroborate the impact (indicative maximum of ten references)

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Klimaprofiler for fylker
2021
NCCS report no 2/2021
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Met NorwayR&D, 4

Institution: Norwegian Meteorological Institute
Administrative unit: Research and Development Department
Title of case study: Coastal ocean forecasting, Norkyst
Period when the underpinning research was undertaken: 2012 - 2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2012 - 2021
Period when the impact occurred: 2012 - 2021

1. Summary of the impact (indicative maximum 100 words)
A coastal ocean circulation model at unprecedented resolution "Norkyst" was developed in collaboration with the IMR and NIVA, and put into operational use for ocean forecasting in 2011. Norkyst is the national complement to the Copernicus Marine Service and now forms the backbone for all contingency models (search-and-rescue, oil spills, ship drift etc.). It is also the basis for "trafikklyssystemet", the tool used for regulating the growth of the salmon aquaculture industry. All output data are completely free and much used for R&D, ecosystem assessments, ship routing, sound speed profiles, and so on.

2. Underpinning research (indicative maximum 500 words)

MET Norway is responsible for operational ocean forecasting for the Norwegian coast and adjacent seas. The main tool for this is numerical ocean circulation models driven by input from NWP (Numerical Weather Prediction) and use of accessible ocean observations in data assimilation. Lack of near real time observations in the ocean (compared what is available in the atmosphere for NWP), and relatively coarse horizontal resolution of the models has been a limitation for the use of model results especially in coastal areas where the actual needs for ocean forecasts are the highest. The development and operationalization of the coastal ocean circulation model "Norkyst" is an answer to these needs. It is a result of several R&D projects to a large extent externally funded e.g from RCN and close cooperation with partners, IMR, NIVA and the universities of Oslo and Bergen. Substantial efforts have been made to improve the physical description of the upper ocean to strengthen transport estimates.

Norkyst-800 (800 m horizontal resolution) is used today as the main forecast tool for ocean forecasting for the coast of Norway. This includes e.g. forecasting of sea surface temperatures and ocean currents in oil spill preparedness modeling, Search-and-Rescue preparedness models, and plankton dispersion models. A key part of the Norkyst system is the 4D-variational (4D-Var) Data Assimilation scheme developed through research several research projects funded by a mixture of public and private organizations. Norkyst-DA assimilates satellite sea surface temperature, in-situ observations from e.g. ARGOS drifters, CTD profiles, Ferrybox data, in addition to HF-radar surface currents. Assimilation of sea level anomaly and SAR currents is currently in a development and testing stage.

Main topics for the R&D work on Norkyst has been:

- Land-ocean coupling at high spatial resolution
- Air-sea interactions with waves
- Transport modeling, salmon lice, cod eggs
- Ecosystem assessments
- Coastal ocean observations, gliders/HF-radars

A brief description of the system is given at ocean.met.no

Key researchers at MET Norway involved in Norkyst R&D in the period 2010 to present
Kai Håkon Christensen, Head of Division for Ocean and Ice
Pål Erik Isachsen, Senior Scientist
Ann Kristin Sperrevik, Scientist
Johannes Rørs, Senior Scientist
Arne Melsom, Senior Scientist,
Nils Melsom Kristensen, Scientist
Magne Simonsen, Scientist
Yvonne Gusdal, Scientist
Cecile Mauritzen, Senior Scientist
Lars Petter Røed, Senior Scientist
Gøran Bostrøm, Senior Scientist

3. References to the research (indicative maximum of six references)

Röhrs, J., Christensen, K.H., Vikebø, F.B., Sundby, S., Saetra, O., Broström, G., 2014. Wave-induced transport and vertical mixing of pelagic eggs and larvae. Limnol. Oceanogr. 59(4), 1213–1227. https://doi.org/10.4319/lo.2014.59.4.1213

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Myksvoll, M. S., Sandvik, A. D., Albretsen, J., Asplin, L., Johnsen, I. A., Karlsen, Ø., ... & Ådlandsvik, B. (2018). Evaluation of a national operational salmon lice monitoring system—From physics to fish. *PLoS One*, *13*(7), e0201338.

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Christensen, K. H., Breivik, Ø., Dagestad, K. F., Röhrs, J., & Ward, B. (2018). Short-term predictions of oceanic drift. *Oceanography*, *31*(3), 59-67.

Web page and access to data: https://ocean.met.no/models#norkyst
https://thredds.met.no/thredds/fou-hi/fou-hi.html

4. Details of the impact (indicative maximum 750 words)

Management of the salmon aquaculture industry.
This is a collaboration between MET Norway and IMR. The parasitic salmon louse inhibits growth of the huge Norwegian salmon industry by increasing wild salmon population mortality. The carrying capacity of the wild salmon stocks is the index for industrial sustainability. The salmon lice are dispersed along the Norwegian coast for weeks, and detailed information of the current is necessary. Thus, the results from NorKyst800 provides an invaluable contribution to parts of the management system “Trafikklyssystemet”. The salmon lice dispersion from

Norwegian fish farms are assessed weekly (lakselus.no) and the aggregated results are evaluated annually and with “traffic light colouring” every second year.

Preparedness to drift simulations in case of e.g. oil spill and other marine pollutants as well as for Search and Rescue.
The preparedness for oil spill in Norway is managed by the Norwegian Coastal Administration in cooperation with the The Norwegian Clean Seas Association for Operating Companies (NOFO). MET Norway plays an important role in this context by
1) maintenance and operation of the OpenDrift model system. OpenDrift is an open source code developed at MET Norway with modules for e.g. oil spills, search and rescue and marine plastic.
2) Norkyst as the operational ocean model providing the necessary input to OpenDrift.
For Search and Rescue, OpenDrift is used by the Norwegian rescue services to estimate the drift of ships or man overboard, together with detailed information of the surface currents from Norkyst.
In connection with the RCN SFF CERAD (Centre for Environmental Radioactivity) a module for calculation of the spread of radioactive pollution in the sea has been developed in a PhD study (MET Norway and NMBU). This has been implemented in OpenDrift and is now, linked to the operational Norkyst, a part of the nuclear preparedness system managed by DSA in case of an accident at the Norwegian coast.

Ocean and coastal forecasts for the general public including storm surge warnings are using Norkyst as the main ocean data information source. This can be followed on yr.no and havvarsel.no.
Storm surge warnings are given on yr, Weather warnings in Norway

5. Sources to corroborate the impact (indicative maximum of ten references)

- https://havvarsel.no
- https://yr.no (e.g. https://www.yr.no/en/coast/graph/1-174764/Norway/Vestland/Kinn/Kr%C3%A5kenes%20fyr)
- https://api.met.no
- https://www.regjeringen.no/no/tema/mat-fiske-og-landbruk/fiskeri-og-havbruk/1/oppdrettslaksen/stortingsmelding-om-vekst-i-havbruksnaringen/id2398853/
- http://thredds.nodc.no:8080/thredds/catalog/smittepress_new2018/catalog.html
- https://stromkatalogen.hi.no/
- OpenDrift: https://opendrift.github.io/

Nansensenteret - NERSC [1]

Institution: Stiftelsen Nansen senter for miljø og fjernmåling (NERSC), Bergen
Administrative unit: same
Title of case study: **Urban air quality assessment and modelling**
Period when the underpinning research was undertaken: 2011 - present
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 - present
Period when the impact occurred: 2011 - ongoing

1. Summary of the impact

High resolution model simulations of urban air pollution have been performed to quantify the near surface distribution and concentrations of air pollution (NO_2, $PM_{2.5}$ and PM_{10}) from the three major local sources including road traffic, wood burning ovens, and vessels in the port of Bergen. The municipality politicians, health and planning authorities and the Port of Bergen have assessed the impact of restrictions on emissions of pollution from local sources. Regulations includes requirements for clean burning ovens, periodic bans on car traffic to reduce emission under unfavourable weather conditions for high near surface air pollution, as well as general electrification of the Port of Bergen.

2. Underpinning research

Air quality is determined by a balance between the pollution emission rate and ability of the atmosphere to dilute (diffuse) the pollution. Emission rates are usually known as well as locations of the emitters. Atmospheric diffusion is however a complex process that depends on details of land use – land cover, dynamics and stability of the lowermost air layers, and topographical features. The worst air quality is observed in calm, layered atmosphere where pockets of polluted air could be transported over significant distances. In such conditions, common Gaussian diffusion models fail, and explicit numerical simulation of the atmospheric transport and turbulent diffusion is required. The key underpinning research achievement was development and implementation of the large-eddy simulation (LES) technique for the realistic air quality modelling. We use the open-source PALM modelling system that resolves the air motions at meter-scales over the whole Bergen municipality, using the regular grid of order of 10^8 cells. We run the model with real laser-based topography, actual emission sources, and for observed atmospheric conditions – obtained with our temperature profiler MTP5- HE.

The background research revealed the local system of atmospheric circulations – a complex but persistent interplay of breeze and valley air streams – that shapes the geographical pattern of the pollution transport and diffusion. This research suggested an accumulation and stagnation mechanism, that create highly polluted zones in the complex environment. We identified these zones within the Bergen municipality. At the following stage of research, we disclosed statistical relationships between this persistent geographical patten of pollution and large-scale atmospheric blockings. Blockings are reasonably well predictable in global weather and climate models. It created a scientific basis for high-resolution air quality assessment in seasonal, interannual, and even climate perspectives.

We used the advance in understanding of dynamics of the local air quality and its connections with global weather and climate for assessment of air pollution pathways and effects (as regulated nationally by *Forurensingsforskriften*). We evaluated the effects with respect to health-related thresholds for both the concentration, frequency, and annual accumulated values for the major air pollution constituents (including NO_2, $PM_{2.5}$ and PM_{10}).

Using public data, the local sources for air pollution (in Bergen) where quantified related to the road traffic on the main and side roads (NO_2, $PM_{2.5}$ and PM_{10}), burning of wood for domestic heating (mainly $PM_{2.5}$ and PM_{10}) and emissions for different types/size and periods of ships in the port (NO_2, $PM_{2.5}$ and PM_{10}). Also, some other point sources contribute with emissions as well as long range transport of pollutant during (un)favourable weather conditions.

Our knowledge on the local air quality, meteorology and emissions have been used in setting up the PALM system to simulate the spread and distribution of the near surface concentrations of the main air quality constituents and originating from the sources throughout the entire Bergen Municipality. Tracing the contributions from the different sources individually has allowed us to quantify the actual impact, spread, transport and concentrations origination from each of the air pollution sources. The transport of air pollution between different parts/districts of the municipality has also been quantified.

Professor Igor Ezau: Initiator, leader, main researcher and supervisor (2002 – 2021). Professor at University of Tromsø and adjunct position at NERSC since 2021.

PhD. student/researcher II **Dr. Tobias Wolf**: Since 2012, doctor dissertation in 2016 and resigned from NERSC in 2019. He was recruited as chief engineer in Oslo Municipality (Bymiljøetaten) responsible for air quality assessment and modelling.

Senior scientist and research coordinator **Lasse H. Pettersson**: Research applications, assessments, and stakeholder network and interaction. At NERSC since 1986 to present.

Researcher II **Dr. Victoria Miles**: Environmental and urban research studies. At NERSC since 2009.

3. References to the research

PEER REVIEW PUBLICATIONS:

Wolf, Tobias; Pettersson, Lasse H; Esau, Igor. (2021) Dispersion of particulate matter (PM2.5) from wood combustion for residential heating: Optimisation of mitigation actions based on large-eddy simulations. *Atmospheric Chemistry and Physics (ACP)* Volum 21(16) s. 12463-12477

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Wolf-Grosse, Tobias; Pettersson, Lasse H; Esau, Igor (2017): Tilrettelegging av produksjonsløype for risikovurdering av spredning av utslipp til luft for skip ved kai i Bergen havn. Bergen, Norge: Nansen senter for miljø og fjernmåling. Technical report (379). 9 s.

Wolf, Tobias; Pettersson, Lasse H; Esau, Igor (2016). Spredning og konsentrajonsdannelse av NO2 og PM2.5 i Bergen Sentrum - et studie med vekt på bidrag fra skip i havna. Nansen Environmental and Remote Sensing Center 2016 84 s. NERSC Technical Report (370).

4. Details of the impact

The air quality in Bergen – the so call “giftlokket” (the poison trap) – has been of concern for the inhabitants, politicians, and authorities of the entire municipality over more than 100 years. Regularly, the air quality at ground level is exceeding the thresholds for healthy air quality. To improve the air quality, measures reducing the emissions from the local sources has been implemented by the politicians – both for long term effects and for emergency mitigation during high pollution events. These includes temporarily bans on car traffic (even and odd dates), additional cleaning of streets, requirements and compensation for replacement of clean burning oven technology in private houses, restrictions on the number of and differentiated fees for ships in the harbour, and extensive land-electrification of the harbour, to mention some.

Based on local private endowments from the GC Rieber fund to increase the local knowledge on the complexity of the nears surface air quality the Nansen Center has undertaken several studies to increase the awareness and to make an impact on the local decisions and actions related to the air quality.

NERSC has installed and operated a vertical microwave temperature profiler (MTP) on the roof-top of Geophysical Institute in Bergen since 2011 (https://veret.gfi.uib.no/?action=mtp). The MTP provides continuous measurements and are important for detection of actual height of meteorological inversions (typically 200-350 m altitude), supplementing the meteorological observations around sea level and 643 meters altitude. The data are used scientifically, in local meteorology forecasting in media (værvarsel), municipal health and environmental authorities, and the citizens of Bergen, identifying many of the situations with high air pollution.

Through model simulations the relative contributions and total pollution level from each source have been quantified under various meteorological (both winter and summer inversion etc.) and emission scenarios (types of ships in port, present and clean burning oven technology) etc. Also, the transport of pollutants (e.g., from wood fire ovens) between the various districts of the municipality have been quantified. The results were first published in two open available reports in Norwegian (reports #370 and #392).

Based on the quantitative impact of emissions from ships in the harbor on the habited areas of the city, Bergen Port decided to establish an infrastructure for offering electricity from land to ships and implemented a differentiated tax /fee system – Environmental Port Index (EPI) for cruise ships. Meanwhile the Nansen Center developed a production line (report #379) to provide dedicated meteorological and pollution assessments of the directional impact of emission for ships located in the harbor during situations with poor air quality. The assessments were initiate when the municipality assessed the risks for high and asked the port (and road) authorities to take specific measures reducing the emissions from the harbor area.

From 1. January 2021 Bergen Municipality (based on a decision in 2017) introduced a general ban on use of 30.000 “old” ovens, not using clean burning technology. The municipality offered a partly compensation on NOK 5.000 for replacements of ovens in private houses throughout the entire municipality. Compensation for replacing around 10.800 ovens have been given. From 2023 this ban may be ceased by the politicians.

Based on our model simulations we concluded that particular the emissions of $PM_{2.5}$ from ovens in the city districts up-stream to the city centre had a particular high impact on the total level of pollutants in the municipality. Bergen has eight local districts (bydeler). According to our simulations, reducing the emissions in the four districts in the outskirts of Bergen, will only reduce the number of high pollution events by 5-6%, while targeting the improvements to the city close districts will eliminate the high pollution events (99-100%) and significantly reduce the frequency of moderate pollution events (72-82%), during different weather scenarios. Geographically targeted measures to reduce the emissions from burning of wood for heating in certain districts, would significantly improve the air quality (for 90% of the inhabitants), compared to a general improvement in all households.

5. Sources to corroborate the impact

Bergen Municipality: Public hearing on termination of bans for use of polluting fireplaces - **Oppheving av forbud mot forurensende ildsteder.** 15. December 2022.

Some relevant news stories:

Bergens Tidene: Fritt frem for forurensende fyring igjen. 8. December 2022.

Bergens Tidene: Forbud mot gamle ovner vil gi ni av ti bedre luft. 21. March 2019.

BA: Luftforurensingen i Bergen: Svart teppe av sot. 29. March, 2019

NRK Vestlandsrevyen: Vraking av gamle ovner. 20. March 2019

Bergens Tidende: Så mange bergensere rammes av forurensning fra vedfyring. 20. March 2019

Bergens Tidende: Cruiseskipenes bidrag til luftforurensingen i Bergen, 23. July, 2018.

TV2: Nyttvåpen mot dårlig byluft. 5. January 2016

NRK: Gjev vêret æra for betre luft i Bergen. 6. oktober, 2015

Fanaposten: Slik skal han forbedre luftvarslingene. 27 February 2015.

User contacts:

- Port of Bergen: Even Husby.
- Helsevernetaten (Health authorizes), Bergen municipality: Arild Jensen.

Funding sources:

- The **GC. Rieber funds** (endowments for several basic studies and a PhD. study of a local air quality issues in Bergen).
- Contracts with the **Port of Bergen** to investigate the impact of emissions for ships in the port.

- SERUS: Building Socio-Ecological Resilience through Urban Green, Blue and White Space. **Belmont-RCN** contract #311986
- URSA-MAJOR: URban Sustainability in Action: Multi-disciplinary Approach through Jointly Organized Research schools. **RCN-INTPART** contract #322317.
- The MTP was purchased under the Planetary Boundary Layer Feedback in the Earth's Climate System (PBL-feedback) funded by **RCN** (Research Council of Norway) contract #191516/V30.

Nansensenteret - NERSC [2]

Institution: Stiftelsen Nansen senter for miljø og fjernmåling (NERSC), Bergen
Administrative unit: same
Title of case study: **Operational Oceanography in the Nordic Seas and Arctic Ocean**
Period when the underpinning research was undertaken: 2011 - present
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 - present
Period when the impact occurred: 2011 - present

1. Summary of the impact

The state-of-the-art model and data assimilation systems for the Nordic Seas and Arctic called TOPAZ and neXtSIM have taken all the steps from basic research tools to a collaborative operational forecasting activity fitting both the requirements of the European Copernicus Marine Services and the national mandate at MET Norway. The provision of operational forecasts for the Nordic Seas and Arctic Ocean physics and biogeochemistry, and the related reanalyses using advanced models and data assimilation techniques, have made the Copernicus Marine Services a unique provider of multidisciplinary reanalysis data and forecasts for a large and diverse group of users.

2. Underpinning research

Data assimilation techniques are used to make a numerical model honour measurements and produce robust and valuable forecasts. NERSC has introduced the Ensemble Kalman Filter (EnKF) and demonstrated its value for near-real-time forecasts of the Nordic Seas and Arctic ocean and sea ice with our TOPAZ forecasting system. In 2010, the transition of the TOPAZ forecasting system to MET Norway was completed and NERSC could concentrate on the corresponding TOPAZ reanalysis (Sakov et al. 2012, Xie et al. 2017). A reanalysis is a more demanding exercise than the forecast in view of the continuity required for climate studies, the stability of the data assimilation techniques and the computational costs (millions of CPU hours). Refinement of the EnKF and the assimilation of large datasets from remote sensing and ocean profiles have allowed the delivery of a 30-years reanalysis to the Copernicus Marine Services in 2021. Within the TOPAZ system our three-dimensional ocean model HYCOM is run at a horizontal resolution of about 10 kilometers and with 28 layers an advanced hybrid vertical coordinate system. The vertical layering is determined by water density in the deep waters and reverts to traditional fixed levels near the surface. Similarly, a reanalysis of the biogeochemical state of the Arctic Ocean and North Atlantic has been produced (Simon et al. 2015), benefitting from specific developments of data assimilation and has become the official Arctic multi-year biogeochemical ocean product in the European Copernicus Marine Service.

Data assimilation has, however, limitations when the simulation model has shortcomings. For example, it is well known that the sea ice models that have been used cannot reproduce the very intermittent and local deformations of sea ice (cracks, leads and ridges that form suddenly), so such features cannot be forecasted even with data assimilation. NERSC has therefore initiated the development of the next generation Sea Ice Model (neXtSIM) based on a brittle sea ice rheological model, meaning that the sea ice is treated as a solid rather than a fluid. The numerical basis of the neXtSIM model was set in an adaptive Lagrangian mesh, which is also unique in operational forecasting and climate modelling communities. NERSC has developed the sea ice model code from scratch (Bouillon and Rampal, 2015) and brought it all the way to operational forecasts, included in the Copernicus Marine Services in 2019.

Research Leader Laurent Bertino: main researcher, data assimilation and team management (2002-present).
Research Leader Annette Samuelsen: research on biogeochemical modelling and team management (2005-present).
Researcher Pierre Rampal: researcher on sea ice modeling and team management (2012-2020). Adjunct position since 2021.
Research Leader Einar Ólason: researcher on sea ice modeling and team management (2014-present).
Researcher Jiping Xie: researcher on data assimilation (2014-present).
Researcher Timothy Williams: researcher on sea ice modelling (2011-present).
Researcher Sylvain Bouillon: post-doc then researcher on sea ice modelling (2013-2016).

3. References to the research

PEER REVIEW PUBLICATIONS:

Bertino, L., & Lisaeter, K. A. (2008). **The TOPAZ monitoring and prediction system for the Atlantic and Arctic Oceans**. *Journal of Operational Oceanography*, *1*(2), 15–18. https://doi.org/10.1080/1755876X.2008.11020098

Karina von Schuckmann, Pierre-Yves Le Traon, Enrique Alvarez-Fanjul, Lars Axell, Magdalena Balmaseda, Lars-Anders Breivik, Robert J. W. Brewin, Clement Bricaud, Marie Drevillon, Yann Drillet, Clotilde Dubois, Owen Embury, Hélène Etienne, Marcos García Sotillo, Gilles Garric, Florent Gasparin, Elodie Gutknecht, Stéphanie Guinehut, Fabrice Hernandez, Melanie Juza, Bengt Karlson, Gerasimos Korres, Jean-François Legeais, Bruno Levier, Vidar S. Lien, Rosemary Morrow, Giulio Notarstefano, Laurent Parent, Álvaro Pascual, Begoña Pérez-Gómez, Coralie Perruche, Nadia Pinardi, Andrea Pisano, Pierre-Marie Poulain, Isabelle M. Pujol, Roshin P. Raj, Urmas Raudsepp, Hervé Roquet, Annette Samuelsen, Shubha Sathyendranath, Jun She, Simona Simoncelli, Cosimo Solidoro, Jonathan Tinker, Joaquín Tintoré, Lena Viktorsson, Michael Ablain, Elin Almroth-Rosell, Antonio Bonaduce, Emanuela Clementi, Gianpiero Cossarini, Quentin Dagneaux, Charles Desportes, Stephen Dye, Claudia Fratianni, Simon Good, Eric Greiner, Jerome Gourrion, Mathieu Hamon, Jason Holt, Pat Hyder, John Kennedy, Fernando Manzano-Muñoz, Angélique Melet, Benoit Meyssignac, Sandrine Mulet, Bruno Buongiorno Nardelli, Enda O'Dea, Einar Olason, Aurélien Paulmier, Irene Pérez-González, Rebecca Reid, Marie-Fanny Racault, Dionysios E. Raitsos, Antonio Ramos, Peter Sykes, Tanguy Szekely & Nathalie Verbrugge. **The Copernicus Marine Environment Monitoring Service Ocean State Report.** Journal of Operational Oceanography,Volume 9, 2016. https://doi.org/10.1080/1755876X.2016.1273446

Lisæter, K. L., Rosanova, J., & Evensen, G. (2003). **Assimilation of ice concentration in a coupled ice-ocean model, using the Ensemble Kalman filter.** Ocean Dynamics, 53(4), 368–388. https://doi.org/10.1007/s10236-003-0049-4

Rampal, P., Dansereau, V., Olason, E., et al. **On the multi-fractal scaling properties of sea ice deformation.** The Cryosphere, 2019, DOI:10.5194/tc-13-2457-2019.

Samuelsen A., Daewel U., Wettre C., **Risk of oil contamination of fish eggs and larvae under different oceanic and weather conditions**, *ICES Journal of Marine Science*, Volume 76, Issue 6, November-December 2019, Pages 1902–1916, https://doi.org/10.1093/icesjms/fsz035

Simon, E., Samuelsen, A., Bertino, L., & Mouysset, S. (2015). **Experiences in multiyear combined state-parameter estimation with an ecosystem model of the North Atlantic and Arctic Oceans using the Ensemble Kalman Filter.** *Journal of Marine Systems*, *152*, 1–17. https://doi.org/10.1016/j.jmarsys.2015.07.004

Williams, T., Korosov, A., Rampal, P., & Ólason, E. (2021). **Presentation and evaluation of the Arctic sea ice forecasting system neXtSIM-F.** *The Cryosphere*, *15*, 3207–3227. https://doi.org/10.5194/tc-15-3207-2021

Xie, J., Bertino, L., Counillon, F., Lisæter, K. A., & Sakov, P. (2017). **Quality assessment of the TOPAZ4 reanalysis in the Arctic over the period 1991–2013.** *Ocean Science*, *13*(1), 123–144. https://doi.org/10.5194/os-13-123-2017.

PUBLIC REPORTS

Pettersson, Lasse H., Laurent Bertino og Johnny A. Johannessen (2020): **Copernicus marine tjenester og Miljødirektoratets økokyst- og havforsuringsprogrammer.** NERSC teknisk rapport no. 404. Miljødirektoratets rapportserie: M-1873|2020. Desember 2020.

Wakamatsu, T, V.C. Yumruktepe, A. Samuelsen and L. Bertino, **QuID For Arctic Biological Reanalysis Product ARCTIC_MULTIYEAR_BGC_002_005**, Issue 1.2, Sep. 2022. https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-ARC-QUID-002-005.pdf

Xie J., L. Bertino, Counillon, F., Raj, R.P., **QuID for Arctic Ocean Physical Multi Year Product ARCTIC_MULTIYEAR_PHY_002_003**, Issue 1.2, Jul 2022. https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-ARC-QUID-002-003.pdf

Bertino, L., T. Lavergne, A. Samuelsen, et al. **Synthesis on the visions of the evolution of the Copernicus services**, KEPLER Deliverable 5.1, June 2020. 27p. https://kepler-polar.eu/work-packages/wp5/

4. Details of the impact

TOPAZ and neXtSIM are used routinely to produce daily updated operational forecasts of ocean, sea ice and biogeochemical variables and reanalyses (updated every year), freely available through the Copernicus Marine Services, the official European service for operational oceanography products. The TOPAZ forecasting system was transferred to the regular operational forecasting services of MET Norway in 2008 and co-developed with them ever since. NERSC provides the neXtSIM sea ice forecasts and the reanalyses of the ocean physical and biogeochemical variables. Our Arctic Copernicus service has 130 external users, of which 40 are downloading data daily. See the 22 Arctic use cases.

All forecast and reanalysis systems assimilate satellite and in situ data, keeping the forecasts and reanalysis products on track. This allows space agencies to **evaluate the potential impact of future satellite missions**. NERSC has provided 5 such studies to the European Space Agency (ESA) in the past 10 years related to sea level, ocean colour, ocean salinity, ocean surface currents, and sea ice thickness and drift. NERSC collaborated with the IMR to optimize the deployment of autonomous robotic measurement devices, as part of the NorArgo infrastructure in 2019.

Our Copernicus Marine Service Arctic forecasts is used by **civilian and naval military information systems,** such as in BarentsWatch. The French Navy Hydrographic and Oceanographic Service (SHOM) has also used the neXtSIM forecasts to plan a cruise in the Greenland Sea between 19th August and 3rd September 2017. The forecast was particularly important to plan the cruise days in advance because an ice island was drifting towards the area where moorings were deployed. SHOM followed-up in 2021 ordering a higher resolution ocean and sea ice forecasting system. Our sea ice forecasts have been included in the commercial NavPlanner **e-navigation software** from the Norwegian company NAVTOR AS in 2017 during the SWARP project, assisting vessels to avoid ice-infested waters. Sintef AS has also used surface currents data for ship routing (RUTESIM project, 2021).

Our forecasts of sea ice and surface currents has also been used to calculate the deflection and attenuation of surface waves in forecasts and hindcasts at the ECMWF, Ifremer, and MET Norway.

Forecasts and reanalyses of surface currents and sea ice motions are used for drift calculations by public bodies and private companies for **preparedness and impact studies of pollutions at sea** and their **impact on the ecosystem**. Drift calculations are also used for **Search and Rescue operations**. Our systems will be used in case of major catastrophes in the Nordic Seas and Arctic. "What if" studies have studied the conjunction of oil leakages and fish eggs (Samuelsen et al. 2019). The RPS ASA consulting company has also evaluated the spreading of a hypothetical oil spill in the Arctic for WWF Canada in 2014. The neXtSIM model has been used to calculate trajectories of oil spills in sea ice within the ART joint industry project (2013-2015). neXtSIM's ability to simulate scale-dependent diffusion properties of sea ice was crucial for that.

The forecast of sea ice drift has also been used to assist **navigation of icebreakers** in sea ice: the forecast of the drift helps ordering high-resolution satellite radar data three days in advance. Our TOPAZ short-term forecast has been used by the SIDFEx consensus forecast during the Year of Polar Prediction in 2019.

The TOPAZ large-scale ocean forecasting system is part of a value chain between providers of ocean and sea ice information and users along the coast. MET Norway has since 2015 used the TOPAZ system daily for **dynamical downscaling** to a higher resolution model covering all the coast of Norway at a higher resolution. Another model is used around Svalbard. These coastal models serve the national preparedness, including storm surge forecasting, pollution and search and rescue operations. Applications also include e.g. the "traffic light" system for salmon/sea lice in Norwegian aquaculture performed by the Institute of Marine Research (IMR).

We applied the ocean model HYCOM to the South China Sea providing long time series of ocean data for **design criteria of offshore installations**. The 18-year reanalysis assimilated satellite altimeter data and was licensed in 2014 for the SeaFINE Joint Industry Project partners. The TOPAZ Ocean modelling system has been set up for the Indian and Atlantic Oceans and used in several oceanographic research studies of regional relevance in cooperation with the Nansen Centres in e.g. India and South Africa.

5. Sources to corroborate the impact

User contacts:

- MET Norway: Lars Anders Breivik, Director of Research larsab@met.no
- NAVTOR AS: Bjørn Åge Hjøllo, technical director. bjorn.hjollo@navtor.com
- Mercator Ocean International: Pierre Bahurel, CEO. pbahurel@mercator-ocean.fr
- TOTAL E&P: Claire Channelière. claire.channelliere@total.com
- French naval hydrographic and oceanographic service SHOM: Camille Daubord. Tél. +33 2 56 31 25 57. camille.daubord@shom.fr
- OceanWeather Inc.: Andrew Cox, andrewc@oceanweather.com
- European Space Agency: Craig Donlon, craig.donlon@esa.int

Funding sources:

- Mercator Ocean International. Copernicus Marine Services (2015-present)

- EU FP7 project GREENSEAS (2011-2014) MyOcean2 (2012-2014), SANGOMA (2012-2016), SWARP (2014-2017), EU H2020 project MyOcean-FollowOn (2014), KEPLER (2019-2021). ERA-NET project SEAMAN (2013-2016).
- OceanWeather Inc. SeaFINE JIP (2010 and followed-up in 2012).
- TOTAL E&P. International Association of Oil and Gas Producers Oil-in-Ice Arctic Response Technology JIP (2013-2015).
- NFR projects Retrospect (2017-2019), REDDA (2016-2019), SIMECH (2014-2016), FRASIL (2017-2021), RUTESIM (2020-2021), NorArgo (2014-2018).
- ESA: Ocean Colour CCI (2014-2017), Arctic+Salinity (2019-present), GARCA (2014-2017), SMOSIce (2014-2016).
- NordForsk Center of Excellence EmblA (2014-2018).
- French Navy Hydrographic and Oceanographic Service - SHOM (2017-2021).

Nansensenteret - NERSC [3]

Institution: Stiftelsen Nansen senter for miljø og fjernmåling (NERSC), Bergen	
Administrative unit: same	
Title of case study: **Improved Climate Predictions**	
Period when the underpinning research was undertaken: 2011 - present	
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 -	
Period when the impact occurred: 2011 - present	

1. Summary of the impact

What happens over the next weeks, months, and years is of immediate concern, as it affects our daily lives in many ways. Policy- and decision-makers demand such information **–** vital to managing human activity sustainably and preparing the societal transformation **–** that bridges the time gap between weather forecasts and long-term climate change projections. We have developed such climate prediction capabilities in Norway, and we contribute to coordinated experiments (Coupled Model Intercomparison Project-CMIP), operational predictions (WMO Lead Centre for Annual-to-Decadal Climate Prediction), and the research centre for innovation "SFI Climate Futures", which develops tailored climate predictions for a set of Norwegian stakeholders.

2. Underpinning research

Climate predictions are achieved by making use of observations to reduce uncertainty in climate models and provide model simulations in near time (up to a decade) with refined accuracy. Predictability arises when the slowly varying components of the climate system, like the ocean, significantly influence the others (such as the atmosphere) and especially when two-way interaction reinforces the variability. In 2011, climate prediction was in its infancy and no climate prediction system existed in Norway. The strategic project SKD-PRACTICE (2011–2014) established a prototype of the Norwegian Climate Prediction Model (NorCPM) tested in an idealised configuration. NorCPM combines the Norwegian Earth System Model and the ensemble Kalman Filter data assimilation method; an advanced data assimilation method that was introduced at NERSC in the 1990s and has been further developed and applied to other fields of application since. NorCPM is developed with partners of the Bjerknes centre. NERSC leads the development of the data assimilation method and brings knowledge on mechanisms of predictability. The demonstration of NorCPM with real data was provided during the NRC-EPOCASA (2014-2017). Its unique features (assimilation in isopycnic coordinate, flow-dependent covariance) were shown to have strong assets [*Counillon et al. 2016*]. The system was found to be competitive with other predictions systems [*Wang et al. 2019*] even though it only used sea surface temperature observation at that time. NorCPM was later further developed to use hydrographic profiles [Wang et al. 2017] within the EU-Blue Action project (2016-2021) and sea ice observations [*Kimmritz et al. 2019*] in NRC-SNOWGLACE. The Trond Mohn Foundation financed Bjerknes Climate Prediction Unit (2018-2024) secured long-term funding for prediction activities in Bergen, including the *Climate Dynamics and Prediction group* at NERSC, and allowed Norway to contribute to the Coupled Model Intercomparison Project version 6 Decadal Prediction Project; and other international predictions experiments (WMO Lead Centre for Annual-to-Decadal Climate Prediction). Knowledge gained helped us better understand mechanisms of predictability in our region of interest [*Langehaug et al. 2020*] and to improve their representation in our models. It was shown that our current generation of Earth System Model underestimates the amplitude of the predictable signal, but that a postprocessing technique using a very large ensemble can skilfully predict the climate in Europe up to a decade in advance [*Smith et al. 2020*]. We have continued improving our data assimilation methods to further enhance prediction skill (e.g. hybrid covariance, novel vertical localisation), and combined data assimilation with machine learning techniques to match performance of a system at high resolution at a reasonable computational cost. Finally, data assimilation was used to efficiently train model parameters and mitigate model biases [*Singh et al. 2021;* in the EU-TRIATLAS 2019-2023]. NorCPM is currently being evolved to subseasonal-to-seasonal time scales through initialization of the land and atmospheric components. NorCPM contributes to the predictions used in the centre for research innovation Climate Futures (2020-2028), which delivers operational predictions every months to the public (https://klimavarsling.no) and tailored prediction to a set of Norwegian stakeholders in shipping, insurance, renewable energy, agriculture, aquaculture, and fisheries.

Dr. Francois Counillon: has a PhD in data assimilation for operational oceanography and developed the Arctic forecasting system of the marine Copernicus service. He has developed the first versions of the NorCPM and leads now data assimilation development in BCPU team. He also leads the *Climate Dynamics and Prediction group* at NERSC since 2020. He coordinates the climate prediction activities at NERSC.

Dr. Helene Langehaug: defended her PhD in 2011 on water masses transformation in the Nordic Seas and she has since built expertise on understanding and assessing model of predictability in the Nordic Seas and Arctic Ocean. She is now a senior researcher at NERSC and leads the *Assessment of the limit of predictability* in BCPU team. She co-leads the *Climate Dynamics and Prediction group* at NERSC.

Dr. Yiguo Wang: was hired as a postdoc at NERSC in 04/2013. He becomes a researcher in 2017 and as a senior researcher in 2022. He is now the main developers of the ocean data assimilation in NorCPM. He was granted a Young Research Talent grant in 2020 (1M€) from the Norwegian Research Council (NRC) and an additional NRC-project bilateral project with China in 2021 (1M€), both dealing with enhanced coupled reanalysis and climate prediction.

Dr. Madlen Kimmritz: was hired as a postdoc (03/2016—2018) in the NRC-SNOWGLACE project and developed the capability to assimilate sea ice observation and improve sea ice prediction with NorCPM. She continues as a researcher in 2018 within NRC-Seasonal-forecast-engine until she left NERSC in 02/2020.

Dr. Tarkeshwar Singh: was hired as a postdoc (03/2020 until present) to work on parameter estimation with ensemble data assimilation method. He has demonstrated the feasibility and efficiency of the approach and apply the approach to several components of the NorESM (biogeochemistry, atmosphere).

MSc Edson Freire Silva: was hired as a INSTSTIP PhD student (in 11/2020) to develop climate prediction of harmful algae bloom along the Norwegian coast using machine learning techniques.

Prof. Noel Keenlyside: has a 20% position at NERSC since 12/2012. He was pioneering the field of climate prediction in 2009 with one of the first attempt and he leads the lead the BCPU team and coordinate the prediction activity at the BCCR.

Prof. Dr. Yongqi Gao: had expertise in climate dynamics and teleconnection. He was leading the *Climate Dynamics and Prediction group* at NERSC until 2020 and was instrumental in securing funding for climate prediction activity (EU-Blue Action, Nordic Center of excellence ARCPATH, NRC-SNOWGLACE, JPI-ROADMAP etc.). He helped gain understanding on the mechanisms of predictability and develop collaboration with partners in China **–** in particular with the Nansen-Zhu International Research Centre. Gao passed away in 2021.

3. References to the research

PEER REVIEW PUBLICATIONS:

All names of NERSC researchers are in Bold

1. **Counillon F**, **Keenlyside N**, Bethke I, **Wang Y**, **Billeau S**, Shen M-L, Bentsen M. Flow-dependent assimilation of sea surface temperature in isopycnal coordinates with the Norwegian climate prediction model. Tellus A. 2016. DOI: 10.3402/tellusa.v68.32437. *First demonstration of NorCPM with real data. Major indices of climate variability can be controlled by assimilating SST, thanks to assimilation carried in isopycnal coordinate and advanced ensemble data assimilation.*
2. **Wang, Y.**, **Counillon, F.**, **Keenlyside, N.**, Svendsen, L., Gleixner, S., **Kimmritz, M.**, Dai, P. and **Gao, Y.**, 2019. Seasonal predictions initialised by assimilating sea surface temperature observations with the EnKF. *Climate Dynamics, 2019*. *Demonstrates competitive seasonal predictions skill against state-of-the-art prediction systems by assimilating only sea surface temperature (SST) with advanced data assimilation.*
3. ***Singh, T.***, ***Counillon, F.***, *Tjiputra, J.*, ***Wang, Y.***, *Gharamti, M.E, 2022. Estimation of Ocean Biogeochemical Parameters in an Earth System Model Using the Dual One Step Ahead Smoother: A Twin Experiment. Front. Mar. Sci. 9:775394. doi: 10.3389/fmars.2022.775394. A first demonstration of the capability of Data assimilation to efficiently estimate parameter within a full Earth System model.*
4. **Kimmritz M.**, **Counillon F.**, Bitz C.M., Massonnet F., Bethke I., **Gao Y.** Optimising assimilation of sea ice concentration in an Earth system model with a multicategory sea ice model, Tellus A., 2018. DOI: 10.1080/16000870.2018.1435945. *First demonstration of strongly coupled DA of ocean and sea ice within an Earth System model and shows the crucial role of sea-ice multicategory updates.*
5. Smith, D., ..., **Counillon**, **F.**, **Keenlyside, N.**, **Wang, Y.** North Atlantic climate far more predictable than models imply, Nature, 2020. https://doi.org/10.1038/s41586-020-2525-0. *Shows that winter climate of Europe can be predicted up to ten years in advance. This was possible by performing a huge number of prediction experiments to unmask the predicable dynamics hidden by large errors in modelling scale interactions.* BCPU contributed with providing data and editing the text.
6. **Langehaug, H.R.**, Ortega, P., **Counillon, F.**, Matei, D., Maroon, E., **Keenlyside, N.**, Mignot, J., **Wang, Y.**, Swingedouw, D., Bethke, I. and Yang, S., 2022. Propagation of Thermohaline Anomalies and their predictive potential along the Atlantic water pathway. Journal of Climate, 35(7), pp.2111-2131. https://doi.org/10.1175/JCLI-D-20-1007.1. *Investigate the dominant mechanism of predictability in the Nordic Seas in predictions systems contributing to the EU-Blue action consortium.*

4. Details of the impact

The Bjerknes Climate Prediction Unit (BCPU) core research spans all four research themes of the Bjerknes Climate Research Centre (BCCR), and benefits from integration in the BCCR's Dissemination and Outreach plans and established communication channels (e.g., relevant media contacts, agreements with schools, regular open days and science fairs, tailored talks for policymakers or specific societal groups). The operational seasonal forecast (https://klimavarsling.no) **–** to which NorCPM contributes **–** is regularly reported in Norwegian newspaper, thus raising awareness of climate prediction to the public and increasing our visibility to regional and national stakeholders and authorities. Similarly, the *Climate Futures research center for innovation (SFI)* proposed proof of concept of the benefit of climate predictions to number of stakeholders – insurance, agriculture, shipping, fisheries, aquaculture, renewable energy. Activities in the SFI project are quickly expanding, and NERSC now leads the ocean Sustainable Food Production node.

NorCPM has become an internationally recognized climate prediction system. The model system contributed to CMIP6 Decadal Climate Prediction Project, and every year it contributes to the World Meteorological Organisation's quasi-operational multi-annual predictions. The NorCPM infrastructure is now included in the Norwegian Earth System code repository (https://github.com/NorESMhub). The system is thus becoming accessible to the wider community of climate modelers in Norway and beyond, which may foster new research avenues. Data produced by the NorCPM system are made publicly available as soon as the model version is published. This include the CMIP6 DCPP data set (www.dkrz.de/WDCC/ui/cerasearch/cmip6?input=CMIP6.CMIP.NCC.NorCPM1) but also interim versions available on the Research Data Archive (e.g. 10.11582/2016.00002, 10.11582/2019.00029, ...). The team has a strong academic profile and publish actively in high impact factor journals (between 2-3 paper per year in average). We are involved in international expert panels (CLIVAR GSOP, CLIVAR-TBI, WCRP-EPESC), and organizing international workshops and summer research schools.

The BCPU has established a strong and stable financial situation with projects funded by the EU, Norwegian Research Council, NordForsk, and private donations. The group has had a steady controlled growth, and the position of the group at NERSC is secure for the coming years. Having access to its own Earth system model and prediction system allows for innovative experimental design, and makes the Norwegian research community attractive for international partnerships and calls (e.g., EU programs). In 2022 the total budget of the project portfolio in which the BCPU team is involved (not only BCPU budget) increased by more than €100M, highlighting the importance that this research has fostered.

5. Sources to corroborate the impact

Some relevant news stories:

- https://bcpu.w.uib.no (website that gathered prediction activity in the Bjerknes Climate Prediction Unit)
- https://www.climatefutures.no website of the research-based centre for innovation
- https://klimavarsling.no operation prediction to which NorCPM contributes (e.g. described here)
- BCPU contributes to the UK Met Office's Global Annual to Decadal Climate Update, Example of press release from the latest forecast https://public.wmo.int/en/media/press-release/wmo-update-5050-chance-of-global-temperature-temporarily-reaching-15°c-threshold
- https://www.data-assimilation.no ; We contribute to the Data assimilation center in Norway.

Example of scientific result that get caught up by national media:

- https://www.nrk.no/norge/klimarapport-varslar-auka-temperatur-dei-neste-fem-ara-1.15083785 .

- https://www.bt.no/nyheter/lokalt/i/QlzGnx/vil-gi-deg-svar-paa-om-det-blir-kalde-eller-varme-vintre-ti-aar-frem-i-t

Source code:

https://github.com/NorESMhub

Events:

- https://blue-action.eu/events/past-events/workshop-climate-prediction-in-the-atlantic-arctic-sector (workshop organized every other years)
- https://bjerknes.uib.no/en/article/news/symposium-honour-memory-late-prof-yongqi-gao (special event in the memory of our late colleague)
- https://www.data-assimilation.no/workshops/EnKF-WS-2023 (international workshop co-organized every year on theoretical development of the EnKF method)

Summer research school:

- https://www.nersc.no/news/announcement-crash-course-data-assimilation (organized every other year)

Impact case guidelines

Each case study should include sufficiently clear and detailed information to enable the evaluation committee to make judgements based on the information it contains, without making inferences, gathering additional material, following up references or relying on members' prior knowledge. References to other sources of information will be used for verification purposes only, not as a means for the evaluation committee to gather further information to inform judgements.

Timeframes

- The impact must have occurred between 2011 and 2021
- Some of the underpinning research should have been published in 2010 or later
- The administrative units are encouraged to prioritise recent cases

Page limit

Each completed case study template will be limited to **five pages** in length. Within the annotated template below, indicative guidance is provided about the expected maximum length limit of each section, but institutions will have flexibility to exceed these so long as the case study as a whole remains no longer than **five pages** (font Arial size 10,5 or similar). Please write the text into the framed template under the sections 1–5 below. The guiding text that stands there now, can be deleted.

Maximum number of cases permitted per administrative unit

For up to 10 researchers: one case; for 10 to 30 researchers: two cases; for 30-50 researchers: three cases; for 50-100 researchers: four cases, and up to five cases for units exceeding 100 researchers.

Naming and numbering of cases

Please use the standardised short name for the administrative unit, and the case number for the unit (1,2,3, etc) in the headline of the case. Each case should be stored as a separate PDF-document with the file name: [Administrative unit short name] [case number]

Publication of cases

RCN plans to publish all impact cases in a separate evaluation report. By submitting the case the head of the administrative units consents to the publication of the case. Please indicate below if a case may not be made public for reasons of confidentiality.

If relevant, describe any reason to keep this case confidential:

ATMOS – case 1

Institution: NILU
Administrative unit: ATMOS
Title of case study: Ash forecasts for aviation in the actual event of a volcanic eruption
Period when the underpinning research was undertaken: 2008-now
Period when staff involved in the underpinning research were employed by the submitting institution: Stohl (2004-2020), Eckhardt (2006-now), Prata (2006-2018), Kristiansen (2009-2017)
Period when the impact occurred: 2010-2011

1. Summary of the impact

After the eruption of the Eyjafjallajökull volcano the aviation transport sector was widely closed down. This resulted in high costs and stressful travel experiences of many passengers. For the eruption of the Grimsvotn volcano in 2011 assessments of the atmospheric distribution of the volcanic ash could be performed by ATMOS which was a basis for the decision to leave the air space over Norway open contrary to the international recommendation.

This was only possible because ATMOS has experts in both transport modelling and remote sensing. Since 2008 they work on developing accurate emission profiles and improve atmospheric ash prediction with transport models and remote sensing products.

2. Underpinning research

For describing the distribution of volcanic ash in the atmosphere during and after an eruption it is essential to have information on the exact emission time and emission altitude. This is very challenging as usually there are very little observations around the volcano and the high ash concentrations and clouds limit the ability to observe the exact distribution.

The information on the emission source term is then used as an input for atmospheric transport modelling. To have the most accurate representation of the transport process, accurate parametrisations for calculating the removal and detailed information on the size distribution of the ash is needed. To complement this model framework as many and as accurate as possible observations are needed to compute and derive all necessary input parameters.

When doing the analysis with a combination of above the result is a four-dimensional gridded dataset which describes for every timestep (hourly resolution) the concentration and particle size of volcanic ash. By knowing the threshold of ash concentration, which is still safe to fly through, potential flight routes around dangerous air space can be determined. In addition to the model output expert knowledge has been used to assess both the accuracies and uncertainties in the satellite retrievals over the area of concern.

The basis for this complex research framework and the ATMOS researchers who developed it are the transport model FLEXPART, inversion framework development and expertise on satellite retrievals. Since the late 1990s Andreas Stohl, ATMOS senior researcher (2004-2020) develops the Lagrangian Particle Transport model FLEXPART which is actively used, validated, and developed at ATMOS, see e.g.

Pisso, I., Sollum, E., Grythe, H., Kristiansen, N. I., Cassiani, M., Eckhardt, S., Arnold, D., Morton, D., Thompson, R. L., Groot Zwaaftink, C. D., Evangeliou, N., Sodemann, H., Haimberger, L., Henne, S., Brunner, D., Burkhart, J. F., Fouilloux, A., Brioude, J., Philipp, A., Seibert, P., and Stohl, A.: The Lagrangian particle dispersion model FLEXPART version 10.4, Geosci. Model Dev., 12, 4955–4997, https://doi.org/10.5194/gmd-12-4955-2019, 2019.

Eckhardt, S., Cassiani, M., Evangeliou, N., Sollum, E., Pisso, I., and Stohl, A.: Source–receptor matrix calculation for deposited mass with the Lagrangian particle dispersion model FLEXPART v10.2 in backward mode, Geosci. Model Dev., 10, 4605–4618, https://doi.org/10.5194/gmd-10-4605-2017, 2017.

Stohl also worked on inverse algorithms, which made it possible to establish the first case of an inverse determination of an volcanic ash profile in 2008 by Eckhardt et al. Sabine Eckhardt (2006-now) is a senior researcher at ATMOS working intensely with application and development of the FLEXPART model. Nina Iren Kristiansen (2009-2017) was a PhD student focussing on her thesis on modelling volcanic ash clouds and validating and improving it with satellite observations. Fred Prata (2006-2015), senior scientist in ATMOS has been the core competence for determination of volcanic ash by remote sensing. He provided the remote sensing data for the volcanic ash assessments and the inversion framework, which were applied in 2010 during the Eyjafjalljøkul eruption and 2011 for the Grimsvotn eruption.

All algorithm developed during that time period are still in use and an improved version is used for the operational ash warning system together with the Norwegian Meteorological institute. In addition to the ATMOS researchers named above the group has been extended to ensure availability during a potential future eruption.

3. References to the research

Eckhardt, S., Prata, A. J., Seibert, P., Stebel, K., and Stohl, A.: Estimation of the vertical profile of sulfur dioxide injection into the atmosphere by a volcanic eruption using satellite column measurements and inverse transport modeling, Atmos. Chem. Phys., 8, 3881–3897, https://doi.org/10.5194/acp-8-3881-2008, 2008.

Kristiansen, N. I., A. Stohl, A. J. Prata, A. Richter, S. Eckhardt, P. Seibert, A. Hoffmann, C. Ritter, L. Bitar, T. J. Duck, and K. Stebel (2010): Remote sensing and inverse transport modelling of the Kasatochi eruption sulfur dioxide cloud. J. Geophys. Res. 115, D00L16, https://doi.org/10.1029/2009JD013286.

Stohl, A., Prata, A. J., Eckhardt, S., Clarisse, L., Durant, A., Henne, S., Kristiansen, N. I., Minikin, A., Schumann, U., Seibert, P., Stebel, K., Thomas, H. E., Thorsteinsson, T., Tørseth, K., and Weinzierl, B.: Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: the 2010 Eyjafjallajökull eruption, Atmos. Chem. Phys., 11, 4333–4351, https://doi.org/10.5194/acp-11-4333-2011, 2011.

Moxnes, E. D., N. I. Kristiansen, A. Stohl, L. Clarisse, A. Durant, K. Weber, and A. Vogel (2014): Separation of ash and sulfur dioxide during the 2011 Grimsvötn eruption. J. Geophys. Res. 119, https://doi.org/10.1002/2013JD021129.

Kristiansen, N. I., A. J. Prata, A. Stohl, and S. A. Carn (2015): Stratospheric volcanic ash emissions from the 13 February 2014 Kelut eruption. Geophys. Re. Lett. 42, 588-596, https://doi.org/10.1002/2014GL062307

Prata, A. J., N. Kristiansen, H. E. Thomas, and A. Stohl (2018): Ash metrics for European and trans-Atlantic air routes during the Eyjafjallajoekull eruption 14 April to 23 May 2010. J. Geophys. Res. 123, 5469-5483, https://doi.org/10.1002/2017JD028199.

4. Details of the impact

ATMOS research activities have a strong focus on both observations (remote sensing and surface observations) and modelling. An experienced, internationally acknowledged research group of senior researchers and some PhDs and postdocs have this as a core topic and develop tools and skills in this field ongoing.

Because of its international credibility ATMOS succeeded in preventing financial damage through the volcanic eruption of Grimsvotn in 2011 by suggesting leaving the airspace open.

ATMOS could already prove their competence on accurate modelling and observation of volcanic ash during the Eyjafjalljøkul eruption. The results ATMOS achieved have been clearly more detailed and more accurate than what the Norwegian meteorological institute could provide with their standard model, but also exceeded the quality and accuracy of the London Volcanic Ash Advisory Center (London VAAC) published.

There are two reasons why ATMOS had this leading competence at this time. On the one hand ATMOS hired a world leading expert on satellite retrievals, specialized on volcanic observations, Fred Prata as a senior scientist. He acquired several ESA and EU projects which had a focus on volcanic emission description. Through one project a doctoral student, Nina Iren Kristiansen was and trained on atmospheric modelling of volcanic emissions. She took a central role at NILU for the production of results during the volcanic eruptions. The other reason that ATMOS was so well prepared has been that already in 2008 (Eckhardt et al., 2008) the researchers developed the first algorithm to determine the vertical profile and timing of volcanic emissions by using both satellite data and ATMOS's transport model FLEXPART.

To know the exact initial distribution of the ash is crucial for accurate forecasts of atmospheric ash distribution. Based on this it was possible in 2010 to efficiently improve and adapt the method to apply it for the Eyjafjalljøkull eruption (Stohl et al., 2011). Exactly this method was then applied for the Grimsvotn eruption to give an accurate information about areas in the Norwegian air space where it was safe to fly. This high competence of ATMOS resulted in membership to the national "agency group" for volcanic ash which gave this recommendation, despite the recommendation of London VAAC.

Many delays cancelled flights and millions of Norwegian kroners could be saved by holding the air space open. After this, in 2016, an operational system for volcanic ash warning has been developed together with the Norwegian meteorological institute. Regular common exercises between these two institute ensure a working system in case of another eruption.

5. Sources to corroborate the impact

There is a master thesis at the university of Oslo publish which gives a detailed description of what happened during the Grimsvotn eruption (in Norwegian only):

https://www.duo.uio.no/bitstream/handle/10852/13395/MA_Nilsen_Rannveig_Baaserud.pdf

In the annual NILU report for 2011 is described how the Minister of Transport Magnhild Meltveit Kleppa gratefully acknowledges NILU's contribution to prevent aviation complications.

https://www.nilu.com/wp-content/uploads/2022/06/NILU-aarsmagasin2012-eng-web.pdf

(page 28)

Personal reference:

Ira Schaug-Pettersen, Senior Inspector, Civil Aviation Authority Norway (ira.schaug-pettersen@caa.no).

Impact case guidelines

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Timeframes

- The impact must have occurred **between 2011 and 2021**
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- The administrative units are **encouraged to prioritise recent cases**

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Publication of cases

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If relevant, describe any reason to keep this case confidential:

MILK – Case 1

Institution: NILU
Administrative unit: MILK
Title of case study: Regulation of the "forever chemicals" PFAS
Period when the underpinning research was undertaken: 2011-continuous
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-continuous
Period when the impact occurred: 2011-2023

1. Summary of the impact

Per- and polyfluoroalkyl substances (PFAS) are chemicals with extreme environmental persistence and multiple adverse effects. NILU together with national and international collaborators have shown that PFAS compounds are ubiquitous in environmental and human matrices. This has led to the introduction of regulations on individual PFAS compounds during the last decade. As the PFAS class contains a wide range of compounds and there is a lack of transparency from industry concerning which PFAS are produced, and in what quantities, NILU together with national and international scientists have proposed a new framework to reduce harmful chemicals like PFAS added to consumer goods, and to phase out non-essential PFAS (Cousins et al, 2019). They argue that the high persistence is sufficient concern for chemical management as a chemical class, and for all "non-essential" uses of PFAS to be phased out (Cousins et al., 2020).

In February 2023, Norway together with Sweden, Denmark, The Netherlands and Germany proposed a European ban of the large group of PFAS of approximately 10 000 PFAS compounds[1].

2. Underpinning research

The nature of the impact is the scientific evidence of occurrence, biomagnification and potential risk of PFAS in the environment and humans. This has been documented from several research projects, monitoring programmes, PhD thesis, reports and scientific publications.
MILK has been involved in several projects investigating the occurrence of PFAS compounds :

- PERFORCE3 - H2020 ITN project https://perforce3-itn.eu/ , https://perforce3-itn.eu/esr-projects/esr-8/
- EU PerFood – FP7 project https://ibed.fnwi.uva.nl/perfood/
- Several PhD students and thesis investigating the presence and potential health risks (e.g. epidemiological population studies):
  - Linda Hanssen (2007-2011). "Human biomonitoring of perfluoroalkyl substances and cyclic volatile methylsiloxanes, 2013."
  - Therese Haugdahl Nøst, Tromsø population studies (2011-2014). "Understanding temporality in human concentrations of organic contaminants -Considering human concentrations over time and through life in perspective of historic production and use", 2014.
  - Vivan Berg,"Concentrations and predictors of persistent organic pollutants in pregnant women and associations with maternal and infant thyroid homeostasis. The Northern Norway Mother-and-Child Contaminant Cohort Study", 2015.
  - Saminor population study: https://uit.no/research/saminor_en

[1] https://www.regjeringen.no/no/aktuelt/norge-foreslar-forbud-av-miljogiften-pfas/id2962234/

- Tromsø population study The Tromsø Study | UiT
- MISA, The Northern Norway Mother-and-Child contaminant Cohort Study, Miljø i svangerskapet og i ammeperioden (MISA) | UiT

Ongoing programs funded by the Norwegian Environment Agency where MILK is the project leader with analysis of PFAS compounds in various environmental samples, with emphasis on investigating chemical properties such as bioaccumulation and potential biological effects of the various PFAS compounds:

- Environmental pollutants in the terrestrial and urban environment (2014- ongoing)

Miljøgifter i bydyr (MILBY) - Miljødirektoratet (miljodirektoratet.no)

- Screening programs (NILU and NIVA)

https://www.miljodirektoratet.no/publikasjoner/2021/januar-2021/screening-programme-2019/

- Atmospheric contaminants (1993-ongoing)

Monitoring of environmental contaminants in air and precipitation: Annual report 2021 - Miljødirektoratet (miljodirektoratet.no)

☐ Names of the key researchers and what positions they held at the administrative unit at the time of the research

All employed at NILU at present time:
Dorte Herzke, Senior scientist, Department of Environmental Chemistry (1999-)
Linda Hanssen, Senior scientist and Head of section, Department of Environmental Chemistry (2012-)
Vladimir Nikiforov, Senior scientist, Department of Environmental Chemistry (2014-)
Torkjel Sandanger, Senior scientist, Department of Environmental Chemistry (2006-)
Lara Cioni, PhD student, Department of Environmental Chemistry (2020-)
Pernilla Bohlin Nizzetto, Senior Scientist, Department of Environmental Chemistry (2014-)

Therese H. Nøst, PhD student and scientist, Department of Environmental Chemistry – Scientist, Department of Environmental Chemistry (2014-2019)

3. References to the research

Herzke, D., Nikiforov, V., Yeung, L. W., Moe, B., Routti, H., Nygård, T., ... & **Hanssen, L.** (2023). Targeted PFAS analyses and Extractable Organofluorine–Enhancing our Understanding of the presence of unknown PFAS in Norwegian wildlife. *Environment International*, *171*, 107640. https://doi.org/10.1016/j.envint.2022.107640

Jouanneau, W., Léandri-Breton, D. J., **Herzke, D**., Moe, B., **Nikiforov, V.** A., Pallud, M., ... & Chastel, O. (2023). Does contaminant exposure disrupt maternal hormones deposition? A study on per-and polyfluoroalkyl substances in an Arctic seabird. *Science of The Total Environment*, 161413. https://doi.org/10.1016/j.scitotenv.2023.161413

Cioni, L., Nikiforov, V., Coêlho, A. C. M., **Sandanger, T. M., & Herzke, D.** (2022). Total oxidizable precursors assay for PFAS in human serum. Environment International, 170, 107656. https://doi.org/10.1016/j.envint.2022.107656

Cousins, I. T., Goldenman, G., **Herzke, D**., Lohmann, R., Miller, M., Ng, C. A., ... & DeWitt, J. C. (2019). The concept of essential use for determining when uses of PFASs can be phased out. *Environmental Science: Processes & Impacts*, *21*(11), 1803-1815. DOI: 10.1039/C9EM00163H

Cousins, I. T., DeWitt, J. C., Glüge, J., Goldenman, G., **Herzke, D.,** Lohmann, R., ... & Wang, Z. (2020a). The high persistence of PFAS is sufficient for their management as a chemical class. *Environmental Science: Processes & Impacts*, *22*(12), 2307-2312. DOI: 10.1039/D0EM00355G

Cousins, I. T., DeWitt, J. C., Glüge, J., Goldenman, G., **Herzke, D**., Lohmann, R., ... & Wang, Z. (2020b). Strategies for grouping per-and polyfluoroalkyl substances (PFAS) to protect human and environmental health. *Environmental Science: Processes & Impacts*, *22*(7), 1444-1460. DOI: 10.1039/D0EM00147C

Hansen, S., Vestergren, R., **Herzke, D.**, Melhus, M., Evenset, A., **Hanssen, L.**, ... & **Sandanger, T. M.** (2016). Exposure to per-and polyfluoroalkyl substances through the consumption of fish from lakes affected by aqueous film-forming foam emissions—A combined epidemiological and exposure modeling approach. The SAMINOR 2 Clinical Study. *Environment International*, *94*, 272-282. https://doi.org/10.1016/j.envint.2016.05.030

Glüge, J., Scheringer, M., Cousins, I. T., DeWitt, J. C., Goldenman, G., **Herzke, D**., ... & Wang, Z. (2020). An overview of the uses of per-and polyfluoroalkyl substances (PFAS). *Environmental Science: Processes & Impacts*, *22*(12), 2345-2373. DOI: 10.1039/D0EM00291G

Bustnes, J. O., Bårdsen, B. J., **Herzke, D**., Bangjord, G., Bourgeon, S., Fritsch, C., & Eulaers, I. (2022). Temporal Trends of Organochlorine and Perfluorinated Contaminants in a Terrestrial Raptor in Northern Europe Over 34 years (1986–2019). *Environmental Toxicology and Chemistry*, *41*(6), 1508-1519.https://doi.org/10.1002/etc.5331

Nøst, T. H., Vestergren, R., Berg, V., Nieboer, E., Odland, J. Ø., & **Sandanger, T. M**. (2014). Repeated measurements of per-and polyfluoroalkyl substances (PFASs) from 1979 to 2007 in males from Northern Norway: assessing time trends, compound correlations and relations to age/birth cohort. *Environment international*, *67*, 43-53. https://doi.org/10.1016/j.envint.2014.02.011 (Tromsøundersøkelsen)

Berg, V., **Nøst, T. H.,** Huber, S., Rylander, C., Hansen, S., Veyhe, A. S., ... & **Sandanger, T. M.** (2014). Maternal serum concentrations of per-and polyfluoroalkyl substances and their predictors in years with reduced production and use. Environment international, 69, 58-66. https://doi.org/10.1016/j.envint.2014.04.010 (MISA - The Northern Norway Mother-and-Child contaminant Cohort Study)

Berg, V., **Nøst, T. H**., Hansen, S., Elverland, A., Veyhe, A. S., Jorde, R., ... & **Sandanger, T. M**. (2015). Assessing the relationship between perfluoroalkyl substances, thyroid hormones and binding proteins in pregnant women; a longitudinal mixed effects approach. *Environment international*, *77*, 63-69. https://doi.org/10.1016/j.envint.2015.01.007 (MISA - The Northern Norway Mother-and-Child contaminant Cohort Study)

Berg, V., **Sandanger, T. M., Hanssen, L.,** Rylander, C., & Nøst, T. H. (2021). Time trends of perfluoroalkyl substances in blood in 30-year old Norwegian men and women in the period 1986–2007. *Environmental Science and Pollution Research*, *28*, 43897-43907. https://doi.org/10.1007/s11356-021-13809-6 . (Tromsø population study)

4. Details of the impact

Several reports and publications (see publication list) on the occurrence, persistency, bioaccumulation and risk of PFAS in environment and humans. These publications and reports have been a result of many national projects and programs in addition to EU projects over several of years. The scientific findings from these projects and programs have been communicated in national and international meetings and for authorities, and have been essential knowledge and evidence for the authorities to the proposal to ban PFAS compounds.

5. Sources to corroborate the impact

- Dorte Herzke, NILU, took part in a press conference at the Ministry for Climate and Environment, Norway, February 7, 2023, where she gave a presentation about the ubiquitous presence of PFAS in the environment and humans. The press conference was related to the proposal from authorities in Denmark, Germany, the Netherlands, Norway and Sweden to reduce the PFAS emissions into the environment and make products and processes safer for people.

- Press conference (in Norwegian):
https://www.regjeringen.no/no/aktuelt/invitasjon-til-fremleggelse-av-forslag-om-a-forby-miljogifter-i-blant-annet-sports-og-kjokkenartikler/id2961810/
- ECHA news February 7 2023:
https://echa.europa.eu/da/-/echa-publishes-pfas-restriction-proposal

- The complementary competence at NILU with analytical chemistry and modelling, in collaboration of the University of Tromsø (ISM) with the epidemiology competence have given us important knowledge about the contaminant burden in the humans related to the emission of contaminants, the time of birth, the gender, and the ban and stop of emission of chemicals. The ban of chemicals is of utmost importance in order to reduce the exposure of chemicals for both human and environment, as now proposed for the large and complicated PFAS group.

Most important publications for the impact to regulation of PFAS:

Cousins, I. T., DeWitt, J. C., Glüge, J., Goldenman, G., **Herzke, D.,** Lohmann, R., ... & Wang, Z. (2020). The high persistence of PFAS is sufficient for their management as a chemical class. *Environmental Science: Processes & Impacts*, *22*(12), 2307-2312. DOI: 10.1039/D0EM00355G

Ng, C., Cousins, I. T., DeWitt, J. C., Glüge, J., Goldenman, G., **Herzke, D**., ... & Wang, Z. (2021). Addressing urgent questions for PFAS in the 21st century. *Environmental science & technology*, *55*(19), 12755-12765. https://doi.org/10.1021/acs.est.1c03386

Glüge, J., London, R., Cousins, I. T., DeWitt, J., Goldenman, G., Herzke, D., ... & Scheringer, M. (2021). Information requirements under the essential-use concept: PFAS case studies. *Environmental science & technology*, *56*(10), 6232-6242. https://doi.org/10.1021/acs.est.1c03732

Norce Climate & Environment impact case 1:

Norwegian Bioprocessing and Fermentation Centre - NBioC

Institution: NORCE
Administrative unit: Climate & Environment Division
Title of case study: Norwegian Bioprocessing and Fermentation Centre - NBioC
Period when the underpinning research was undertaken: 2018- and ongoing
Period when staff involved in the underpinning research were employed by the submitting institution: Ongoing
Period when the impact occurred: Still occurring

1. Summary of the impact

The Norwegian Bioprocessing and Fermentation Centre - NBioC is a national centre and open research infrastructure for the development of new bioresources and bioproducts supporting Norway's strategy on the (bio) circular economy. Its main goal is to contribute to economic and social development by being a key-enabler for the emerging bioeconomic value-chain on bioprocessing and fermentation, hence supporting a fast-track to innovation. As NORCE hosts the infrastructure it builds on and do enable inhouse expertise within industrial biotechnology and has and will continue to facilitate collaboration with partners on industrial scale processes and commercial development of novel products for external users.

2. Underpinning research

NBioC is funded by the Research Council of Norway and NORCE is the host for the centre, which is located in Stavanger and organised under the research group Industrial Biotechnology. The Industrial Biotechnology group has for several years had its focus on the use of new and sustainable bioresources to produce feed, food and biochemicals through fermentation, and on value creation from waste streams and by-products. This includes the use of alternative carbon sources and Norwegian natural resources for bioproduction (such as marine biomass, waste and side streams, industrial discharge and single carbon gases CO2 and methane from natural and industrial sources). The objective is production of biomass for food/feed (including aquaculture feed), enzymes and biochemicals. Previous projects within these fields and collaboration with public and private institutions led to the application for hosting the infrastructure, in line with the goal to develop national competence and build strong partnership/network within fermentation and scaling up, focusing on gas fermentation. Accordingly, NBioC builds on competence and expertise within the research group, on previous projects and collaboration with a variety of partners ranging from universities, research institutes and industry.

NBioC was established to be a key-enabler for the emerging bioeconomic value-chain on bioprocessing and fermentation. For NbioC the starting point is the potential within microorganisms to produce high-value products and biomass. In this context, NBioC do foster scaling up of fermentation processes, a crucial field of research, development and innovation (RDI), with state-of-the-art infrastructure from laboratory to pilot scales. More specifically to a) use of a broad range of sustainable feedstocks including gasses by developing new fermentation processes, process optimisation, and scale up through modelling from laboratory to pilot and industrial scale, and b) design and production of biomass, food/feed ingredients, chemicals and enzymes through gas and traditional fermentation. NBioC support R&D on sugar-based fermentation using low value biomass and nutrients from side streams as feedstock, and gas-based fermentation using C1 gas from natural gas and biogas sources (CO_2, CH_4), as a source of carbon for the production of biomass or biochemicals. The aim is to enable the development, optimisation, scaling-up and piloting to produce enzymes, protein and/or fatty acids rich biomass, and a wide array of platform chemicals key-enabler for the emerging bioeconomic value-chain on bioprocessing and fermentation, ranging from basic research (TRL1) to pilot-scale demonstration (TRL6), hence supporting a fast-track to innovation.

Names of the key researchers and what positions they held at the administrative unit at the time of the research:
The infrastructure was enabled through competence and expertise in the research group with the following personnel as key contributors:

Susanne Gitlesen, Senior Scientist
Catherine Boccadora, Senior Scientist
Anne Krøvel, Senior Scientist,
Thomas Kruse, Researcher
Renate Kvingedal, Research Director
Hans Kleivdal, Deputy EVP

3. References to the research

As this impact case is an infrastructure we here only point to some examples of publications (after 2019):

Gaykawad S.S., Ramanand S.S., Blomqvist J., et.al., (2021): Submerged Fermentation of Animal Fat By-Products by Oleaginous Filamentous Fungi for the Production of Unsaturated Single Cell Oil. Fermentation (7), 300. doi.org/10.3390/fermentation7040300

García-Moyano A, Larsen Ø, Gaykawad S, et.al., (2021): Fragment exchange plasmid tools for CRISPR/Cas9-mediated gene integration and protease production in Bacillus subtilis. Appl Environ Microbiol (87): e02090-20. https://doi.org/10.1128/AEM.02090-20

4. Details of the impact

Examples of impacts: NBioC has facilitated following projects and industry capacity:

- **The H2020 project PyroCO2** (2021- 2026) is led by Sintef with NORCE as a key research partner and co-lead in WP2: From Feedstock to Acetone: Bioprocess Development & Optimisation. The work includes developing sustainable industrial processes to produce chemicals and bio-based products by converting low value compounds into high value products, for example using greenhouse gasses or industrial waste or by-products to produce high quality protein, lipids, or platform chemicals through microbial fermentation. This will be done by developing a kinetic model based on laboratory-scale fermentation experimental results, and the model being tested, refined, and validated by comparing predictions with data obtained from intermediate scale fermentations. NORCE are currently establishing the integrated process up to pilot scale using the NBioC infrastructure and will design the 150 m3 demonstration plant at Herøya industry park in collaboration with chemical industry partners. See PyroCO2

- **SFI - Industrial Biotechnology** (2021- 2024) is led by Sintef with NORCE and is a research-based innovation centre aiming to boost the competitiveness of the Norwegian biotech industry. as key partner in project 5: Gas value chain -gas production and gas to product. The objective is to develop gas fermentation process and technology. The aims are to 1) optimize reactor models and large-scale reactor designs with a focus on gas mas transfer, 2) first version of a model for a lab scale reactor, 3) Syngas usable for production of proteins, materials, and/or fuels, 4) Report on gas sources for microbial processes and required safety regulation and 6) Mass, water and energy balances for a lab scale process. The NBioC infrastructure is in this project an important infrastructure See https://sfi-ib.com/

- **BMFish Feed** (2020- 2025). Development of bacterial feed with a tailored high-lipid content for use as feed additive in aquaculture. Using the omega-3 production side streams as feedstock for production of a lipid-rich bacterial meal (BM) for fish feed additives with the aims to, 1) process development (mixed microbial culture fermentation, 2) up-scaling, 3) LCA, 4) TEA and 5) RRI.

- **HCO2Feed** (2019- 2020). The aim of this pre-project is to evaluate a fermentation process to utilise CO_2 and H_2 to produce a high-quality protein rich biomass for the use in aquaculture industry. Project Sub goals: Establish fermentation technology for detonating gas; Investigate microorganism growth rate at different hydrogen saturation; Evaluate the biomass as a high-quality protein feed ingredient Perform a first technical economical assessment.

- **Spin-off company Gas2feed AS** founded by NORCE and co-investors in 2020 based on research conducted by NORCE. By using microbial fermentation, G2F capture and convert CO_2 into nutritional proteins for the use in aquaculture. G2F is currently upscaling the technology and process together with NORCE using the NBioC infrastructure. For more information, see Turning air to food | Gas 2 Feed | Norway (g2f.no).

5. Sources to corroborate the impact

Kirsti Landsverk, RCN -Infrastructure department

Håvard Sletta, Sintef

Jarle Dragvik, Gas2feed

Norce Climate & Environment impact case 2:
Capacity building in ODA countries

Institution: NORCE
Administrative unit: Climate & Environment Division
Title of case study: Capacity building in ODA countries
Period when the underpinning research was undertaken: 2003- 2016
Period when staff involved in the underpinning research were employed by the submitting institution: 2003- present
Period when the impact occurred: 2003- present

1. Summary of the impact

NORCE's research group Gene technology, Environment and Society (GEMS) activities were considered by the Norwegian authorities as an important contribution to the fulfilment of the obligations of the Cartagena Protocol under the Convention on Biological Diversity. In the period 2008-2014 GEMS delivered comprehensive courses, workshops, reports as well as training and education in cooperation with international partners. The program was extended for 2015-2016 with the focus on synthetic biology. The impact includes knowledge and training in gene technology issues (e.g., molecular biology, risk assessment, legal and social aspects), personnel exchange, funding of research projects, and appointment in expert committees.

2. Underpinning research

GEMS (formerly GenØk - Centre for Biosafety) is the national competence centre in biosafety. The group conducts research on environmental, health and social consequences of genetic engineering and genetic modification. GEMS also conducts advisory and communication activities within their area of competence. Based on this competence the research group has received funding for capacity building activities in ODA (Official Development Assistance) countries.

Capacity building activities funded by Norad (the Norwegian Agency for Development Cooperation) (2008-2012). This programme was organised in the first round "to contribute to a sustainable management of biological diversity and natural resources," and the goal of the second phase project was "safe use of modern biotechnologies according to the goal to ensure a sustainable management of biological diversity and natural resources". The following activities were carried out:

- Courses: A theoretical and hands-on course for senior scientists, policy makers and regulators, NGO/civil society Leaders. The 2-week course combined lectures, group discussions, casework and practical laboratory sessions. 40 participants from ODA-countries were given full sponsorship, and there were 20 places available for self-sponsored participants. 10 of these courses were held in Tromsø, Norway.
- International biosafety courses and workshops held in Bogor (Indonesia, 2006), Lima (Peru, 2007), Bloemfontein (South-Afrika, 2009), Florianopolis (Brazil, 2010), Hyderabad (India, 2011), Dar es Salaam (Tanzania, 2012), Florianopolis (Brazil, 2013), Chisinau (Moldova, 2014), Montevideo (Uruguay, 2014 - partly funded by Ministries in Uruguay).
- Course curriculum developed to meet regional needs in collaboration with universities in ODA-countries. Courses included laboratory modules, teaching, case- and group-work. Presenters were from universities, research institutes, industry, and governmental agencies.
- Conference: Setting the Stage; Agriculture in Perspective, Agriculture for the Future; (2012) in Penang, Malaysia
- Master module in biosafety (web-based course), offered by UiT- The Arctic University of Norway in the spring of 2008 for national and international students.
- Biosafety First book, and Biosafety assessment Tool (BAT) - an online tool for developing GMO risk assessments.

- Initiation of research hubs. Collaboration with research institutions in Zambia, China, South Africa, Malaysia, and Brazil.

Synthetic biology courses: In 2015 under the CBD COP 12, national representatives were urged to establish effective measures to regulate the environmental release of any organisms, components or products resulting from synthetic biology techniques. GEMS received funding from the Norwegian Ministry of Foreign Affairs for in collaboration with NIBIO to arrange two courses at universities in Potchefstroom (South Africa, 2015) and Bogor (Indonesia, 2016). These courses (each over 6 days) were designed to provide knowledge and training in biosafety issues, innovation possibilities and sustainable use of genetic resources with particular attention given to synthetic biology. Participants offered full sponsorship included senior scientists, policy makers and regulators, NGO/Civil society leaders, from the regions, and the course curriculum was developed together with the university partners.

The capacity building projects was expanded through:
- **NOREC (FK Norway)** personnel exchanges with research partners at Universities in Brazil, South Africa, China, and Zambia (2007- 2018). The aim by these exchanges was to achieve increased understanding of research and culture, as well as to promote work towards the sustainable development goals.

Names of the key researchers and what positions they held at the administrative unit at the time of the research
As some of this capacity building courses was held many years ago, and since some of the key personnel now are retired, we here only mention those that still works in NORCE and that continue to be involved in capacity building activities (name and role then and now which is given in brackets):
Dr. Anne Ingeborg Myhr – Senior Scientist /Director (from 2013) (now SVP Biotechnology and Circular Economy) (employed from 2003)
Katrine Jaklin – Project Manager Capacity Building / Head of Administration (now senior adviser communication) (employed from 2004)
Dr. Sarah Agapito - Scientist (now Research Professor) (employed from 2013)
Dr. Arinze Okoli - Scientist (employed from 2010)
Dr. Idun Grønsberg - Scientist (employed from 2003)
Dr. Odd-Gunnar Wikmark – Scientist (now Research Director) (employed from 2010)

Key contextual information about this area of research.
Key contextual information for this kind of activities can only partly be identified through Norad as the same funding opportunities is not possible after a reorganisation in Norad. Most similar is the Norad NORHED program, which unfortunately only universities can apply to. The RCN (e.g., INTPART and bi-lateral calls), and GEF and FAO offers possibility of funding of parts of the activities. Information about regulatory processes can be found under CBD and the Cartagena Protocol (for example the Biosafety Clearing House).

3. References to the research

As this impact case is on capacity building, we will here give a) references to reports and evaluation of the activities, and b) publications based on the activities and initiated collaboration.

Reports and evaluation
- a) Reports about capacity building projects can be requested from NORAD
- b) Overview of projects and funding from NORAD, including Ministry of Foreign Affairs and NOREC LINK
- *c)* Evaluation of capacity building activities by KPMG (2016): End Review of GenØk's Biosafety Capacity Building Program, LINK

Publications
The research hubs that achieved funding used this for scholarships, other expenses and published several articles (see below). The funding GEMS achieved was not for intended for research but on our own imitative two reports were published:

Wikmark, O-G, Brautaset, T. Agapito-Tenfen, S., Okoli, A. S., Myhr, A. I., Binimelis, R., Ching, L. L. (2016) Synthetic biology – biosafety and contribution to addressing societal challenges. Biosafety Report 02/16, DOI: 10.13140/RG.2.2.29987.25121 LINK

Agapito-Tenfen, S., and Wikmark, O.-G. (2015) Current status of emerging technologies for plant breeding: Biosafety and knowledge gaps of site directed nucleases and oligonucleotide-directed mutagen. GenØk Biosafety Report 2015/02 LINK

4. Details of the impact

In 2016, ***KPMG presents the end review*** of the Capacity Building Programme (2008 – 2012 and 2013 – 2014). The findings were:

The programme has had a significant impact in strengthening cooperating countries capacity to implement international agreements

- More than 500 key stakeholders have been trained and 35 of these held in 2015, official positions at the national and international level under the Cartagena Protocol. This has considerably strengthened the contribution of ODA countries in international processes. According to the Head of the Biosafety Division of the CBD Secretariat, GenØk has been "a very important component feeding services to all developing countries under the Cartagena Protocol."

The GenØk programme has played an important role by improving ODA countries' capacity to perform risk assessments and safety evaluations regarding biosafety.

- GenØk support has both helped build the capacity to perform risk assessments and enabled citizens to demand that risk assessments are performed in a responsible way. This has led to observably strengthened national processes in, for example, South Africa and Uruguay.

GenØk has provided pivotal support to key partners for the strengthening of research and teaching capacities and for knowledge sharing through collaborative networks.

- While the earlier partnerships in China and Zambia have not succeeded in providing a sustained strengthening of research capacities, the subsequent partnerships with NWU in South Africa and the Federal University of Santa Catarina (UFSC) have been very successful. Both universities refer to GenØk's support as a "game changer". They have both established regional research networks and have demonstrated ability independently to raise funding for research that will help them sustain their programmes.

At the overall level is it clear that GenØk has made a significant contribution to the safe use of modern technologies. GenØk's holistic approach and wide reach puts the institution in a unique position in the global field of biosafety.

- All respondents concur that no other institutions would have taken the place of GenØk had the programme not existed. GenØk is a unique type of institution, combining science with a socio-economic approach and engaging with a wide range of stakeholders. GenØk is also one of very few institutions with such a scientific competency and capacity that is not financed by the GMO industry.

KPMG did also find weaknesses as for example high cost for Tromsø courses, weaknesses in planning as for example no risk assessment integrated in the process of selecting partners, and that the programme were essentially organized as clusters instead of projects.

An evaluation of the ***courses on synthetic biology*** in 2015 and 2016 identified the following impacts: The regional courses have contributed to build awareness and educate people on important aspects that need to be considered, and on how to find useful scientific information in order to make informed choices on national legislation development. Participants claimed that they had increased their capacity to ensure safe use of synthetic biology and products thereof, while participants from governmental offices claimed increased competence in assessing applications for use and introduction of synthetic biology and products thereof. The evaluation reports show that 85% of the participants in the Southern African course agreed that they would better follow and participate in the national and international debates on synthetic biology, whereas 50% of the Asian participants agreed.

The network built has been used to build partnership for funding of research projects as for example by the RCN, and two of these are ***bi-lateral projects***:

SANCOOP- Project Grant Number 234196: (2014-2017). South Africa-Norway Cooperation: Development of efficient bio-flocculants by exploring the microbial diversity of South African Eastern Cape Province for Novel Bioflocculants. Funder: RCN.

SANOOCEAN -Project Grant Number 288073 (2019-2023). South Africa-Norway Cooperation: Microplastics in wastewater as a carrier and dispersal route of antibiotic resistance in oceans. Funder: RCN

The ***NOREC exchange project*** is still running and was planned to continue in 2020 but has been postponed to 2023 because of the Covid-19 pandemic.

The unique experience by these capacity building activities has also build competence internally about international regulation and an awareness of challenges and opportunities by using modern gene technologies at the global scale. As a respond GEMS researchers have been appointed to several ***UN technical experts' groups*** as for example the Ad Hoc Technical expert groups under CBD on a) socio-economic considerations, b) risk assessment and management, and c) on synthetic biology. Several side-events has been arranged at the COPMOP meetings under CBD either to present the capacity building activities or other relevant projects.

5. Sources to corroborate the impact

Prof Johnnie van den Berg, North-West University in Potchefstroom, South Africa
Prof. Calos Bezuidenhout, North-West University in Potchefstroom, South Africa
Prof. Damayanti Buchori, Bogor Agricultural University, Indonesia
Prof. Rubens Nodari, Federal University of Santa Catarina, Brazil
Casper Linnestad. Senior Adviser at Norwegian Ministry of the Environment. Norwegian Ministry of the Environment
Helle Biseth, Senior Adviser, Department of Climate and Environment, NORAD, Norway

NORCE Climate & Environment impact case 3:
SFI – Climate Futures

Institution: NORCE	
Administrative unit: Climate & Environment Division, Department of Climate Dynamics	
Title of case study: Climate Futures (a center for research driven innovation)	
Period when the underpinning research was undertaken: Started in 2017. Still running.	
Period when staff involved in the underpinning research were employed by the submitting institution: Throughout the period**.**	
Period when the impact occurred: The impact is three folded, and still occurring	

1. Summary of the impact

The specific impact here relates to the development climate forecasts on timescales from 10 days to 10 years. The forecasts represent an innovation space that provides actionable knowledge for private and public actors alike. Specifically, these climate forecasts are tailormade for businesses, governmental agencies, and local authorities within four broad themes: smart shipping, resilient societies, renewable energy, and sustainable food. With roughly 30 partners, whereof several research institutions, the impact of the realization of Climate Futures (CF), which started in 2020, reaches beyond 2021, but still marks a major shift in how this department interacts with stakeholders.

2. Underpinning research

The awareness of climate risks has been growing steadily since the IPCC' Assessment Report 4 (AR4), which was published in 2007. This understanding reached a new level with Mark Carney´s Lloyds talk in 2015 and the signing of the Paris Accords. In subsequent years, companies started investigating how they better can navigate climate risk while maintaining their level of business ambitions. The solution to many of climate challenges reside in knowing how to act prior to the occurrence of single phenomena (e.g. hurricanes) or the escalation of a persistent trends (e.g. warming temperatures), which again can result in a third phenomenon played out on an intermediate time scale. Producing various types of forecasts (demand for potato, insurance claims, prolonged port stays by tankers or energy demand) are at the core of CF. Yet, these user driven forecasts hinge on several methodological steps, including the usage of multi-model forecasts producing several hundred of individual forecasts that are post-processed and bias-corrected before being included in the development of risk mitigation and delivery of new services and products.

As we increasingly understand the mechanisms that drive the enormously complex climate system, both dynamical and empirical models are steadily improving. At the same time, increased computational power, enhanced observations and remote sensing, and advanced statistical methods to blend models and observations are driving a big data fuelled revolution in climate prediction.Through designated co-production (representing a novel methodological approach), we're enabling a careful, but speedy, transformation of research into innovative practical applications and services as those referenced above. Our team collaborates with other national experts in handling big data, statisticians, climatologists, climate modellers, and climate service practitioners. Working in a complementary fashion with the international research community, we continue to improve our own models and, taking existing seasonal forecast ensembles and employing innovative empirical-statistical approaches to make the forecasts better and more relevant for our users.

This work started prior to the realization of CF with a project called *Seasonal Forecasting Engine* (SFE) which was funded by the RCN and ran from 2017-2021. This overlapped with the establishment of the CF-consortium which started late 2017 and led to the start of the center in October 2020.

Names of the key researchers and what positions they held at the administrative unit at the time of the research.

Erik Kolstad, PI and Research Professor (2017-present)
Øyvind Paasche, Senior Researcher (2017-present)
Stefan Soblowski, Research Professor (2017-present)
Silje Sørland, Senior Researcher (2017-present)
Etienne Dunn-Sigouin, Senior Researcher (2017-present)
Iseling Medhaug, Project Coordinator (2017-present)
Ole Wulff, Senior Researcher (2017-present)

A key aspect of this research is that is can access and assimilate data hosted by the private companies themselves. The same is true for governmental agencies and authorities, but they are often publicly available.

3. References to the research

Alex Lenkoski, Erik Wilhelm Kolstad & Thordis Linda Thorarinsdottir
A Benchmarking Dataset for Seasonal Weather Forecasts
Published by Norwegian Computing Central 2022.

Erik W. Kolstad, C. Ole Wulff, Daniela I. V. Domeisen, & Tim Woollings
Tracing North Atlantic Oscillation Forecast Errors to Stratospheric Origins
Online Publication: 24 Sep 2020
DOI: https://doi.org/10.1175/JCLI-D-20-0270.1
Page(s): 9145–9157

Erik W. Kolstad, Oda N. Sofienlund, Hanna Kvamsås, Mathew A. Stiller-Reeve, Simon Neby, Øyvind Paasche, Marie Pontoppidan, Stefan P. Sobolowski, Håvard Haarstad, Stina E. Oseland, Lene Omdahl, & Snorre Waage
Trials, Errors, and Improvements in Coproduction of Climate Services
Print Publication: 01 Aug 2019
DOI: https://doi.org/10.1175/BAMS-D-18-0201.1
Page(s): 1419–1428

Marius Årthun, Erik W. Kolstad, Tor Eldevik, Noel S. Keenlyside
Time Scales and Sources of European Temperature Variability
First published: 12 March 2018 | https://doi.org/10.1002/2018GL077401

Erik W. Kolstad & Marius Årthun
Seasonal Prediction from Arctic Sea Surface Temperatures: Opportunities and Pitfalls
Print Publication: 15 Oct 2018
DOI: https://doi.org/10.1175/JCLI-D-18-0016.1

4. Details of the impact

The numerical weather prediction (NWP) output on which the different types of forecasts afforded by CF require substantial postprocessing, as they are subject to systematic errors in both mean and spread. We supply a multi-model, multi-variable global dataset using five forecasting systems from the Copernicus climate data store (CDS) which can help serve these purposes. Our dataset is constructed using a straightforward anomaly standardization methodology with a leave-year-out cross validation design. In addition, validating observations from the ERA5 dataset are supplied, enabling rapid verification of system performance. By enabling availability to these forecasts, frequently updated, they form the basis for a series of products and services that CF currently are developing with the partners in the center.

One example that can be highlighted here, and which underscores the different levels of impact that the activity of CF has on different segments of Norwegian industry is briefly described in the following:

The first step in coproducing forecasts is establishing a constructive and open dialog with the partners in question, which in this case is seafood production. This is a major industry in Norway being the second largest after oil and gas. The potential for upscaling is therefore deemed large, also for sea food production abroad given that the methods and applications employed here are universal.

When the dialogue phase, a key part of the process is concluded, we start the methodological work with constructing the actual forecasts. Predicting changes in coastal water masses require postprocessing and ‘ground truthing’ the raw forecasts drawn from 5-7 global models (totaling up to 300 runs) to observational data sets before delivering the actual forecasts. In this case, the forecasts were implemented in a specific software that another of the partners in the center has developed and which is used by the seafood producer in daily decision making with respect to feeding and delousing etc. To this impact case we are working on adding other variables such as salinity and freshwater runoff from land. Given that this is still work in progress (ongoing since the start of the Seasonal Forecast Engine project which started in 2017) we have still not reached a point where we assess the value of how these forecasts have contributed to decision making and hence to improved productivity, sustainability, and economic margins.

5. Sources to corroborate the impact

André Teigland, Director at Norwegian Computing Centre
Karsten Kristiansen, Director Skadeerstating, Tryg
Tore Søiland, special adviosr, RCN.
Tore Norheim Hagtun, Co-funder, Clarify

NORCE Climate & Environment impact case 4: Development and implementation of the Norwegian Climate Service Centre (NCCS)

Institution: NORCE	
Administrative unit: Climate and Environment Division	
Title of case study: Development and implementation of the Norwegian Centre for Climate Service (NCCS)	
Period when the underpinning research was undertaken: 2013 - present	
Period when staff involved in the underpinning research were employed by the submitting institution: 2013 - present	
Period when the impact occurred: 2015 - present	

1. Summary of the impact

The novel products and services made readily available by NCCS concerning climate and hydrological data have fundamentally altered the accessibility that municipalities and counties, as well as additional public and private actors, have to scientific information. By establishing this conduit between the NCCS science community and users, a major leap forward has been made in the possibilities that national, regional, and local administrative units have in crafting climate change adaptation policies and management plans and consequently reduce the unwarranted negative effects that ongoing and future climate change can have on nature and society.

2. Underpinning research

The Norwegian Climate Service Centre (NCCS) is a national science provider jointly run by key research organizations in Norway. The consortium includes the Norwegian Meteorological Institute (MET), the Norwegian Water Resources and Energy Directorate (NVE), NORCE – Norwegian Research Centre, and the Bjerknes Centre for Climate Research. The NCCS is mainly funded by the Norwegian Environment Agency although partners contribute with in-kind resources. The main purpose of NCCS is to provide national, regional and local decision-makers (especially municipalities and counties) in Norway with locally relevant information on climate trends and change as well as climate change adaptation.

It does so through two main streams of publications: (I) Historical, present and future projections for climate up to the year 2100, and (ii) regional climate factsheets:

Historical, present and future projections for climate up to the year 2100 (Climate in Norway 2100, Climate in Svalbard 2100): These reports were produced and subsequently delivered in 2009 and 2015, with a third installment under development and to be made available in 2025. Based on input data from IPCC´s and the World Climate Research Programme (WCRP) dataset of 10 Euro-CORDEX projections (12x12km^2), NCCS undertakes local downscaling and impact modelling to provide a common assessment of climate change projections for Norway up to 2100. The reports provide critical information on the main features of how we expect global warming to be manifested in Norway where it forms a basis for decision-making about local and regional climate adaptation measures. Key impact variables that are modelled and assessed include air temperature, precipitation, wind, runoff, drought, flooding, snow, glaciers and frozen lakes, permafrost, avalanches landslides, sea level, ocean climate, and sea ice.

Climate factsheets (climate profiles) for each Norwegian region: The brief reports, which in themselves represent novel ways of conveying science-based climate information, were produced in 2017 and 2021 to provide local and regional land use planners and managers with information about the main climate related concerns for each region. These profiles provide actionable foresight on local climate change and climate change allowances, including climate factors for heavy precipitation, river floods and storm surges.

NCCP also produces and communicates climate and hydrological data for use in climate change adaptation and impact studies on the effect of climate change on nature and society. NCCS is involved in many research projects focusing on climate change and therefore provides the scientific community with key innovations in climate modelling.

Involved researchers at NORCE:
Trond Martin Dokken: EVP, Head of the Climate and Environment Division (2013- present)
Stephanie Meyer: Research Leader, Regional Climate, Department of Climate Dynamics. (2013- present)
Marie Pontoppidan: Research Leader, Forecasting Engine, Department of Climate Dynamics. (2016-Present)
Øyvind Paasche: SVP Climate Dynamics Department, (2021- present)
Eystein Jansen: Research Professor, Ocean Observations (2013- 2017)
Silje Sørland: Senior Scientist, Forecasting Engine, Department of Climate Dynamics (2020- 2022)

3. References to the research

Hege Hisdal, Dagrun Vikhamar-Schuler, Eirik J. Førland og Irene Brox Nilsen (eds.) (2021) Klimaprofiler for fylker: Et kunnskapsgrunnlag for klimatilpasning (Climate Profiles for Regions: A knowledge base for climate adaptation). NCCS report no. 2/2021. Link: https://klimaservicesenter.no/kss/rapporter/rapporter-og-publikasjoner_2

(Note: this report is the third instalment, where previous versions were produced in 2017 and 2015 for all regions in Norway. The link above also provides access to several background documents related to these publications).

I.Hanssen-Bauer, E.J.Førland, H.Hisdal, S.Mayer, A.B.Sandø, A.Sorteberg (eds.) (2019) Climate in Svalbard 2100 – a knowledge base for climate adaptation. NCCS report no.1/2019 Link: https://klimaservicesenter.no/kss/rapporter/rapporter-og-publikasjoner_2

I. Hanssen-Bauer, E.J. Førland, I. Haddeland, H. Hisdal, D. Lawrence, S. Mayer, A. Nesje, J.E.Ø. Nilsen, S. Sandven, A.B. Sandø, A. Sorteberg og B. Ådlandsvik (eds.) (2017) Climate in Norway 2100 – a knolwedge base for clinate adaptation. NCCS report no.1/2017 Link: https://klimaservicesenter.no/kss/rapporter/kin2100

I. Hanssen-Bauer, E.J. Førland, I. Haddeland, H. Hisdal, S. Mayer, A. Nesje, J.E.Ø. Nilsen, S. Sandven, A.B. Sandø, A. Sorteberg og B. Ådlandsvik (eds.) (2015) Klima i Norge 2100: Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015. NCCS report no. 2 2015 Link: *https://klimaservicesenter.no/kss/rapporter/rapporter-og-publikasjoner_2*

(Note: this report is the second instalment, where previous version was produced in 2009 The link above also provides access to the 2009 report).

M.J.R. Simpson, J.E.Ø. Nilsen, O.R. Ravndal, K. Breili, H. Sande, H.P. Kierulf, H. Steffen, E. Jansen, M. Carson, O. Vestøl (2015) Seal level Change for Norway: past and Present Observations and Projections to 2100. NCCS Report no.1/2015. Link: https://klimaservicesenter.no/kss/rapporter/rapporter-og-publikasjoner_2

4. Details of the impact

The fundamental impacts of the NCCS are based on its structural context and the material it delivers to Norwegian public authorities at the national, regional, and local levels. Structurally, it is comprised of the leading climate scientists and institutions involved in global and regional climate modelling in Norway, and who participate in national and international cooperation on the production of climate and hydrological climate data and derived services. Likewise, the structural nature of NCCS provides specific avenues for consultation and knowledge exchange with end users of the information – local, regional, and national policymakers, planners and managers, and key sector stakeholders responsible for land use planning and development. These stakeholders are consulted to ensure their needs are needs are included in the results that the NCCS publishes. This structure provides the basis for a conduit between global climate modelling and practical scientific results that function as a basis for development and monitoring of local and regional climate adaptation strategies by end users.

In terms of material results, the NCCS scientific community is versed in developing highly relevant and cost-effective models to translate (downscale or regionalize) global climate model output, such as those communicated in main IPCC reports and based on global standard Climate data (e.g. WCRP). Through the publication of the *Climate in Norway 2100 and Climate in Svalbard 2100* series, an overarching scientific basis for forecasting future Norwegian Climate is comprehensively provided through obtaining and downscaling climate and hydrological data, which can be used downstream by a wide range of Norwegian scientists. Further, and more importantly, this information is both synthesized and made more practical through county factsheets for each Norwegian county. Norwegian decision-makers and planners are therefore provided with easy access to Norwegian climate and hydrological observations, projections, and derived products. Again, the ongoing dialogue with end users in the development of the county factsheets ensures that the output is tailored to the needs of managers responsible for developing and implementing local climate adaptation strategies.

5. Sources to corroborate the impact

Hege Hisdal, NVE

Herdis Laupsa, Norwegian Environmental Agency

Roar Skålin, Met Norway

NORCE Climate & Environment impact case 5: Closing knowledge gaps and informing society on Ocean Acidification

Institution: NORCE
Administrative unit: Climate & Environment Division, Department of Climate Dynamics
Title of case study: Closing knowledge gaps and informing society on Ocean acidification
Period when the underpinning research was undertaken: 2011 – present
Period when staff involved in the underpinning research were employed by the submitting institution: 2011 – present
Period when the impact occurred: 2013 – present

1. Summary of the impact

The biogeochemical observational work in the Ocean Observations group at NORCE Climate and Environment has been built up and ever since the early days of the Bjerknes Centre for Climate Research (BCCR) and is presently at a national and international forefront. One of the main outcomes is knowledge of changes in ocean acidification (OA). Members of the group are now among the main experts nationally, and highly recognised internationally, and frequently coordinate reports on OA for the Norwegian Environmental Agency, and inform the public via fact sheets, science fairs, and with interactions with schools.

2. Underpinning research

OA is the consequence of the ocean's increasing load of anthropogenic carbon dioxide (C_{ant}), resulting in a decrease in pH of the seawater. The OA observational work within the group is traditionally focused on the Nordic Seas and the North Sea, but more recently also on Norwegian fjords. NORCE is one of the main partners in the Ocean acidification programme, financed by the Norwegian Environmental Agency (together with University of Bergen, Institute of Marine Research, and NIVA). Using data from this programme, and from different scientific cruises in the region (available via the carbon-based data product GLODAP (which NORCE scientists contribute to), several reports and papers have been published since 2013, identifying changes and trends in OA. Despite many years of research there are still many knowledge gaps in terms of pathways and variability of the C_{ant} in the ocean interior, and drivers of the uptake variability, but the largest gaps are in coastal and fjord environments. NORCE has contributed to decrease this knowledge gap, through several scientific publications, and reports for the Norwegian Environmental Agency.

The results show significant trends of decreasing pH in most ocean regions studied, and that the dominant driver for most regions is the increasing concentrations of C_{ant} (e.g., Skjelvan et al., 2013). For fjord systems we have a rather poor understanding in terms of OA due to lack of observations. In addition, there is a high degree of seasonality, which complicates the identification of interannual trends (e.g., Skjelvan and Omar, 2015; Omar et al., 2016). Knowledge of OA is one of UN's Sustainable Development Goals (SDG 14.3).
OA has also been frequently communicated to the general public, often via school projects.

Dates of when it was carried out.
2013 – present.

Names of the key researchers and what positions they held at the administrative unit at the time of the research

Ingunn Skjelvan, Senior Researcher, Ocean Observations (2011– present)
Abdirahman, M., Omar, Senior Researcher, Ocean Observations (2011– present)
Emil Jeansson, Research Director, Ocean Observations (2011– present)

NORCE, via the Ocean Observations group, is since 2016 coordinating the Ocean Thematic Centre (OTC) of ICOS (Integrated Carbon Observation System). The work of the OTC is to be a service unit for the marine observational network, to facilitate and maintain the high-quality carbon data produced. These data and their high quality are critical to be able to detect and quantify changes in OA. The OTC lead has contributed to put NORCE in a leading role on ocean carbon cycle research in Europe.

3. References to the research

Skjelvan, I., et al., Monitoring ocean acidification in Norwegian seas in 2020, Report, Norwegian Environment Agency, M-2056, 2021. https://www.miljodirektoratet.no/publikasjoner/2021/mai-2021/monitoring-ocean-acidification-in-norwegian-seas-in-2020/

Skjelvan, I., Jeansson, E., Norwegian Ocean Acidification data and UNs sustainable development goal (SDG) 14.3, An evaluation of data delivery to UNs SDG indicator on Ocean Acidification, Report (in Norwegian) for Miljødirektoratet, M-2089/5-2020, NORCE Climate, 2020. https://www.miljodirektoratet.no/publikasjoner/2021/august-2021/norske-havforsuringsdata-og-fns-barekraftsmal-14.3/

Omar, A.M., et al., 2019, Trends of Ocean acidification and pCO2 in the Northern North Sea, 2003–2015, JGR Biogeosc., 124, 3088-3103. https://doi.org/10.1029/2018JG004992

Omar, A.M., et al., 2016, Aragonite saturation states and pH in western Norwegian fjords: seasonal cycles and controlling factors, 2005–2009. Ocean Science, 12, 937, 951. https://doi.org/10.5194/os-12-937-2016

Skjelvan, I., Omar, A.M., Status of knowledge about ocean acidification in fjords at the west coast of Norway, Report (in Norwegian), Miljødirektoratet, M-426, 2015. https://www.miljodirektoratet.no/publikasjoner/2016/juni-2016/kunnskapsstatus-for-havforsuring-i-fjorder-langs-vestlandskysten/

Skjelvan, I., Jeansson, E., et al., Ocean acidification and uptake of anthropogenic carbon in the Nordic Seas, 1982-2013, Report (in Norwegian), Norwegian Environment Agency, M244, 2014. https://www.miljodirektoratet.no/publikasjoner/2015/februar/havforsuring-og-opptak-av-antropogent-karbon-i-de-nordiske-hav-1981-2013/

4. Details of the impact

The OA work conducted by NORCE and collaborators has significantly decreased the knowledge gaps on OA in Norwegian and adjacent ocean regions. The work done for the report in 2013 showed clear trends of reduced pH and the main drivers to these changes (Skjelvan et al., 2013). The report was written with the aim to address the general public and it formed the basis for the paper of Fransner et al. (2022; Acidification of the Nordic Seas, Biogeosciences, 2022, https://doi.org/10.5194/bg-19-979-2022). Another report was written for the Environmental Agency in 2020, with the aim to popularise the results from the paper by Fransner et al. Due to a delay in the finalising of the paper this report was not published until 2022. OA research in general is aimed to address the general public, and the main route of this communication goes via the Environmental Agency, and the Bjerknes Centre for Climate Research. Much of the outreach on OA has been conducted over the years, both on science fairs, and more directly via projects with schools. One of the latest ones were connected to the research communication project “Next Step” (https://bjerknes.uib.no/term/neste-steg), coordinated by the University of Bergen, where NORCE scientists were responsible for the OA parts, in collaboration with the Amalie Skram high school, where the students presented their work and showed some simple experiment in the main concert hall (the Grieg Hall).

NORCE informed the Norwegian Environmental Agency of the reporting of the SDG data and gave recommendations of how this could optimally be done within the present Norwegian network (Skjelvan and Jeansson, 2020). This had a clear impact since the procedure was implemented by the agency the year after. NORCE scientist (Skjelvan) is one of Norway's national experts in the OA working group (https://www.ospar.org/news/ocean-acidification-2020).

5. Sources to corroborate the impact

Gunnar Skotte, Norwegian Environmental Agency
Aurora Stenmark, Norwegian Environmental Agency

NORSUS Case number 2

Institution: NORSUS
Administrative unit:
Title of case study: Biogas
Period when the underpinning research was undertaken: 2013-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2021
Period when the impact occurred: 2016-2021

1. Summary of the impact (indicative maximum 100 words)

Results from application of models developed by NORSUS has had an important impact on the Norwegian Biogas industry, by providing decision support when developing biogas value chains, and as input to policy development. Examples: The decision to build The Magic Factory in Tønsberg, the largest biogas plant in Norway treating food waste and livestock manure contributing to an annual reduction of 13,986 tonnes CO2 equivalents per year. The development of national regulations and economic support systems: requirement to separate food waste in Norwegian municipalities proposed by the Environment Agency, and economic support per tonne of manure for biogas production managed by Agriculture agency.

2. Underpinning research (indicative maximum 500 words)

NORSUS has led several cross disciplinary research projects involving industry actors funded by the Norwegian Research Council. In the research project BioValueChain (2013-2017) national models for assessing the environmental impacts from production of biogas and biofertilizer from food waste and livestock manure, as well as economic models for calculating profitability of actors in the value chain was developed. The environmental model is based on life cycle assessment (LCA) methodology which was adapted specifically for biogas value chains and the types of decision the model is intended for. The economic models were developed for key actors in the biogas value chain: farmers and the biogas plant, in order to assess their economic viability and effects of various economic support systems.

Application of the models showed that anaerobic digestion (biogas production) of food waste represented the most beneficial treatment technology for food waste in terms of environmental impact, in a value chain perspective. In a Norwegian context, the biogas value chain configuration with the best environmental performance was to co digest food waste and manure, utilize biogas as a transport fuel and to utilize digestate as fertilizer to substitute mineral fertilizer. Furthermore, the research found that the most optimal value chain configuration represented the least economically profitable option for the actors in the value chain, indicating the need for an economic support system to reduce environmental impacts.

In the project Bærekratig Biogass (2017-2019) the models from BioValueChain were applied and refined, and the life cycle assessment methodology adapted for decision support of the different value chain actors, and increasing the knowledge about new feedstocks and the use of CO2 from upgrading of biogas. The results show that the use of CO2 from upgrading of biogas can be utilized cost efficiently if a greenhouse is located in close proximation to the biogas plant, and that it will result in reduced emissions. In addition, the models have been further refined and applied in several commissioned projects, both for regional initiatives to develop new biogas value chains, Innovation Norway and for authorities such as the Norwegian Environment Agency and Agriculture Agency.

In NORSUS a large range of researchers have participated in the biogas related projects: Ole Jørgen Hanssen (Senior Researcher), Kari-Anne Lyng (first as Researcher, then Senior Researcher), Ingunn Saur Modahl (Senior Researcher), Hanne Møller (Senior Researcher), Hanne Lerche Raadal (Senior Researcher), Kjersti Prestrud (Researcher), Pieter Callewaert (Researcher), Aina Stensgaard (Researher) and Simon Saxegaard (Researcher).

3. References to the research (indicative maximum of six references)

The development and application of the models for calculating the environmental impacts of biogas value chains, and the economic model to assess profitability for key actors are published in the three following scientific papers:

- Lyng, K.-A., Modahl, I S., Møller, H., Morken, J., Briseid, T. and Hanssen, O.J. (2015): The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains. International Journal of Life Cycle Assesment. DOI: http://link.springer.com/article/10.1007/s11367-015-0851-5
- Lyng, K.-A., Stensgård, A., Hanssen, O.J., Modahl, I.S., 2017. Relation between greenhouse gas emissions and economic profit for different configurations of biogas value chains. A case study on different levels of sector integration. Journal of Cleaner Production 182 (2018) 737-745. https://www.sciencedirect.com/science/article/pii/S0959652618304384
- Lyng, K.-A., Bjerkestrand, M., Stensgård, A.E., Callewaert, P., Hanssen, O.J., 2018. Optimising Anaerobic Digestion of Manure Resources at a Regional Level. Sustainability 10, 286. https://doi.org/10.3390/su10010286

Results from application of the models were used as decision support when deciding to build the biogas plant The Magic Factory in Tønsberg. The viability of the model was evaluated in a scientific paper:

- Lyng, K.-A, Modahl I.S., Møller, H and Saxegaard, S., (2021): Comparison of results from life cycle assessment when using predicted and real-life data for an anaerobic digestion plant. Journal of Sustainable Development of Energy, Water and Environment Systems, Volume 9, Issue 3, 1080373. http://dx.doi.org/10.13044/j.sdewes.d8.0373

Implications for policy development were assessed in scientific papers and in commissioned reports from Agriculture Agency and Environment Agency:

- Lyng, K.-A., Skovsgaard, L., Jacobsen, H.K. et al. Environ Dev Sustain (2019): The implications of economic instruments on biogas value chains: a case study comparison between Norway and Denmark https://doi.org/10.1007/s10668-019-00463-9
- Lyng, K.-A., Prestrud, K., Stensgård, A.E., 2019. Evaluering av pilotordning for tilskudd til husdyrgjødsel til biogassproduksjon. OR 04.10. Østfoldforskning. https://norsus.no/publikasjon/evaluering-av-pilotordning-for-tilskudd-til-husdyrgjodsel-til-biogassproduksjon/
- Syversen, F., Lyng, K.-A., Bjørnerud, S., Amland N., E., Callewaert, P., Prestrud, K. (2018): Utsortering og materialgjenvinning av biologisk avfall og plastavfall. Utredning av konsekvenser av forslag til forskrift for avfall fra husholdninger og liknende avfall fra næringslivet Mepex AS, Østfoldforskning. https://www.miljodirektoratet.no/hoeringer/2021/januar-2021/forslag-til-forskrift-om-utsortering-av-bioavfall-og-plastavfall-/

4. Details of the impact (indicative maximum 750 words)

The environmental models developed in the research projects were applied to assess different biogas configuration scenarios to treat the organic waste and manure resources available in Vestfold. These results were presented for local politicians, and the decision to build was done by 10 municipalities in Vestfold (10k-samarbeidet). The plant was planned based on the optimal scenario to obtain the largest reduction of environmental impacts. As the first of its kind in Norway, The Magic Factory is a large-scale biogas factory in Norway co treating food waste and manure. The plant was officially opened by the prime minister in September 2016. NORSUS has had a long-term collaboration with Greve Biogas, the plant owner, and performed research on the operation of the plant. In 2018 The Magic Factory was the first in Norway to utilise CO_2 from upgrading of biogas, by transporting the CO_2 in pipes from the upgrading facility to a greenhouse located nearby. In the greenhouse tomatoes are produced from CO_2 and digestate from the biogas factory. NORSUS has documented that the Magic

Factory contribute to annual net emissions reduction of 13,986 tonnes CO2 equivalents per year.

The models and the knowledge from the research projects were applied in two commissioned projects from the Environment Agency, first in the Evaluation of different political instruments to increase separation of organic and plastic waste, and afterwards in a project assessing the impacts of a new regulation requiring Norwegian households and companies producing household-like waste to separate organic waste, which was carried out together with Mepex. After that the Environment Agency proposed a change in the waste regulation in January 2021, and the change was implemented 1.1.2023. https://lovdata.no/dokument/LTI/forskrift/2022-06-07-971 The increase in the amount of food waste separated is expected to increase the biogas produced, which in turn leads to increased resource efficiency in terms of recycling of nutrients as well as reduction in greenhouse gas emissions as the biogas can substitute fossil fuels, and as digestate can substitute mineral fertilizer.

Biogas production from livestock manure is identified as one of the most important measures to reduce greenhouse gases from agriculture in Norway. Application of the economic models developed in the research projects showed that the main barriers are economic costs associated with additional storage requirements. A pilot scheme where farmer receives economic support per tonne manure treated in a biogas plant was introduced in 2014. NORSUS performed an evaluation of the pilot scheme commissioned by Agriculture Agency in 2019, and based on the evaluation the pilot scheme was transformed to a permanent support system. https://lovdata.no/dokument/SF/forskrift/2014-12-19-1815 Economic support for manure for biogas production is expected to result in more biogas plants considering manure as a relevant feedstock, which will lead to reduction of greenhouse gas emissions from storage of manure as well as increased biogas production which can substitute fossil fuels and reduce greenhouse gas emissions in transport. The perspectives and support systems have been communicated along with the perspectives of six other countries in an international report published by IEA Bioenergy Task 37 Energy from biogas. This has the potential to obtain impacts in other countries, including countries with less developed biogas value chains and support systems.

5. Sources to corroborate the impact (indicative maximum of ten references)

Ivar Kopperud Sørby from Greve Biogass/The Magic Factory explains how NORSUS contributed to the establishment and further development of the installation in a webinar to be found here: https://www.youtube.com/watch?v=gJGfAYiilxI&t=4174s , see from 1h17minutes into the recording.

News article on Greve Biogas webpage about the research project Bærekraftig Biogass and utilisation of CO2 as the first biogas plant in Norway: https://grevebiogass.no/aktuelt/november-2018/groenn-co2-fra-biogassanlegg-til-veksthus-norges-foerste/

Norwegian Environmental Agency proposal for changes in waste regulations, where the report from Mepex and Østfoldforskning (NORSUS) is cited in their consultation statement (høringsuttalelse): https://www.miljodirektoratet.no/hoeringer/2021/januar-2021/forslag-til-forskrift-om-utsortering-av-bioavfall-og-plastavfall-/

Assessment of policy instruments for biogas production in Norway performed by Norwegian Environment Agency where Østfoldforskning (NORSUS) is cited a number of times: https://www.miljodirektoratet.no/globalassets/publikasjoner/m1652/M1652.pdf

Report from a working group led by Norwegian Agriculture Agency assessing policy instruments for manure for biogas production, where NORSUS (Østfoldforskning) is largely cited, and where four of the reports from Østfoldforskning is in the reference list. NORSUS participated in the reference group for the work: https://www.regjeringen.no/contentassets/6a5da53b1ba243eb86a4e2314abe96a4/husdyrgjods el-til-biogass---gjennomgang-av-virkemidler-for-okt-utnyttelse-av-husdyrgjodsel-til-biogassproduksjon.pdf

News article in Bondebladet about how research from Østfoldforskning provides foundation for strategy development for biogas production from manure https://www.bondelaget.no/nyhetsarkiv/store-muligheter-for-bruk-av-norsk-husdyrgjodsel-til-biogassproduksjon

Other relevant publications:

Lyng, K.-A. (2020). Bruk av CO2 fra oppgradering av biogass. Beregning av potensiell klimaeffekt ved bruk i veksthus. Østfoldforskning, OR.24.20. https://norsus.no/en/publikasjon/potensiell-klimaeffekt-ved-bruk-av-co2-fra-oppgradering-av-biogass-i-veksthus/

Lyng, K.-A. & Saxegård, S. (2020). Livsløpsvurdering av produktene og tjenestene til Den Magiske Fabrikken: Avfalls- og gjødselhåndtering, biodrivstoff, biogjødsel og bio-CO2. NORSUS OR23.20. https://norsus.no/en/publikasjon/livslopsvurdering-av-produktene-og-tjenestene-til-den-magiske-fabrikken/

Brekke, A., Lyng, K.-A., Olofsson, J., Szulecka, J., Lyng, K.-A., Olofsson, J., Szulecka, J., 2019. Life cycle assessment : A governance tool for transition towards a circular bioeconomy? Book chapter in From Waste to Value | Valorisation Pathways for Organic Waste Streams in Circular Bioeconomies. Taylor Francis. https://doi.org/10.4324/9780429460289

Lyng, K.-A., Callewaert, P. og Prestrud, K. (2019): Kunnskapsgrunnlag for nasjonal strategi for husdyrgjødsel til biogassproduksjon. Del 2: Nasjonale scenarier. Østfoldforskning https://norsus.no/en/publikasjon/kunnskapsgrunnlag-for-nasjonal-strategi-for-husdyrgjodsel-til-biogassproduksjon-2/

Lyng, K.-A., Callewaert, P., Stabbetorp, E.M. og Prestrud, K. (2019): Kunnskapsgrunnlag for nasjonal strategi for husdyrgjødsel til biogassproduksjon. Del 1: Råstoffgrunnlag, gjødselbehov og synergier mellom sektorer. Østfoldforskning AS, OR 25.19. https://norsus.no/en/publikasjon/kunnskapsgrunnlag-for-nasjonal-strategi-for-husdyrgjodsel-til-biogassproduksjon/

Lyng, K.-A., 2018. Reduction of environmental impacts through optimisation of biogas value chains. Drivers, barriers and policy development. PhD thesis 2018:6, Norwegian University of Life Sciences.

Stensgård, A. E, Saxegård, S. A., Lyng, K-A og Hanssen, O.J. 2017: Følgeforskning: Den Magiske Fabrikken Miljø- og økonomianalyse. Østfoldforskning AS, OR 21.17

Raadal, H.L., Stensgård, A. E., Lyng, K-A. og Hanssen, O.J. 2016: Vurdering av virkemidler for økt utsortering av våtorganisk avfall og plastemballasje. Østfoldforskning, OR 01.16. https://www.miljodirektoratet.no/globalassets/publikasjoner/M522/M522.pdf

Lyng, K.-A., Brekke, A., 2019. Environmental Life Cycle Assessment of Biogas as a Fuel for Transport Compared with Alternative Fuels. Energies 12, 532. https://doi.org/10.3390/en12030532

NORSUS Case number 1

Institution: NORSUS
Administrative unit:
Title of case study: Food loss and waste
Period when the underpinning research was undertaken: 2010-present day
Period when staff involved in the underpinning research were employed by the submitting institution: 2010-present day
Period when the impact occurred: 2010-present day

1. Summary of the impact

Results from NORSUS' research on food waste has laid the foundation of the current Norwegian policy framework for food waste prevention (the negotiated agreement). It has also impacted the current EU framework on food loss and waste (FLW). The Research has contributed to the national and EU definition of FLW, methodology and guidance for quantification of FLW, and identification of FLW hotspots in the food supply chain as well as prevention and reduction strategies which in turn has contributed to an annual reduction in national food waste equivalent to 114 850 tons of CO2-eqvivialents and 2,2 billion NOK.

2. Underpinning research

NORSUS has led and participated in several national and international cross disciplinary research projects on FLW:

Quantification methodology, monitoring and statistics:
In the government and industry funded **ForMat project** (2010-2016), where NORSUS were the scientific responsible partner, NORSUS developed definitions, methodology, guidance documents for food waste quantification as well as food waste statistics for the Norwegian food industry, retailers, wholesalers and households.
In the EU funded project **FUSIONS** (2012-2016) NORSUS contributed to harmonization of food waste monitoring and a Common Food Waste Policy for EU27.
In the **Nordic Project on food waste prevention** (2013-2016) funded by the Nordic Council of Ministers, NORSUS developed definitions and quantification methodology for food losses in agriculture. Also, in the project, the total amount of waste in primary production in the Nordic countries was measured and estimated.
In the RCN and industry funded **KuttMatsvinn2020** project led by NORSUS, guidance and methodology for food waste quantification and national food waste statistics for the food service industry was developed.
In the Nordic project, **Monitoring FoodWaste and Loss in the Nordic region**, led by NORSUS and financed by the Nordic Council of Ministers (2020-2021) best practice for food loss and waste quantification and monitoring in the Nordic region was identified.

The above-mentioned research on monitoring and quantification has identified how food loss and waste should be quantified across the food value chain (both in the national, Nordic and European contexts). The research has also identified the hot spots of food loss and waste, what types of food is wasted, the economic and environmental impact of the food loss and waste, why food is lost/wasted and how food loss and waste can be prevented and reduced. The projects have also identified the food waste behaviour and attitudes for different consumer types. The research has contributed to put food waste on the Norwegian and European policy agendas and underpinned the importance of monitoring of food waste as well as actions towards food waste prevention.

Prevention and reduction:
In the **Nordic Project on food waste prevention** (mentioned above), NORSUS identified how different types of date labels affect food waste, how increased shelf life can prevent food waste from occurring and the need for supplementary date labelling and guidance that can reduce

food waste. The project also established a Nordic platform for redistribution and developed best practices for food redistribution.
In the RCN funded projects **Breadpack** (2013-2016) and **Greenpack** (2013 - 2015) different packaging strategies for reducing food waste were tested, analysed and documented.
In the SUSFOOD and RCN funded **AVARE** project different strategies for prevention and reduction of food waste in the food service sector were identified and evaluated.
In the RCN funded **BREAD** project (2019-2022) obstacles for responsible innovation in the food sector related to food waste prevention and reduction were investigated. One of the concrete outputs from the project was the *10 principles to reduce food waste together*, a industry-anchored framework that identifies several key challenges and solutions regarding how the food industry can halve food waste by 2030 through responsible innovation and collaboration.

The above-mentioned research on prevention and reduction, as well as some of the projects on monitoring and quantification, have developed concrete sector specific guidelines on how to reduce food waste, developed policy briefs and identified and prioritized different policy, industry and consumer actions towards halving food waste by 2030 (the SDG goal 12.3 and the goal of the negotiated industry agreement). The work has also contributed to the food waste reduction of 14 % within the Norwegian food sector.

In addition, NORSUS researchers have worked with a number of municipalities and counties to reduce food waste in their operations. NORSUS has carried out several projects to reduce food waste in the care sector in Norwegian municipalities Fredrikstad, Sandefjord, Bergen, Østre Toten, Voss, og Hamar. We have also carried out similar projects in the school sector in several Norwegian county municipalities Troms og Finnmark, Viken, Vestland and Innlandet. See e.g. Guide for reducing food waste in the care sector and Reduction of food waste in Sandefjord municipality

In NORSUS a wide range of researchers have participated in the FLW related projects: Ole Jørgen Hanssen (Senior Researcher, 2007-today), Aina Stensgård (Researcher, 2014-today), Hanne Møller (Senior Researcher, 2010-2020), Erik Svanes (Researcher, 2010-2016), Kjersti Prestrud (Researcher, 2018-2022), Pieter Callewaert (Researcher, 2018-today), Sigrid Møyner Hole (Senior researcher, 2022-today), Ellen-Marie Forsberg (Senior researcher/Director) and Ina Charlotte Berntsen (Researcher, 2022-today).

NORSUS is part of the EU platform on food losses and food waste, established in 2016.

3. References to the research

Scientific publications on food waste quantification methodology:

- Sara Corrado, Carla Caldeira, Mattias Eriksson, Ole Jørgen Hanssen, Hans-Eduard Hauser, Freija van Holsteijn, Gang Liu, Karin Östergren, Andrew Parry, Luca Secondi, Åsa Stenmarck, Serenella Sala. 2019. "*Food waste accounting methodologies: Challenges, opportunities, and further advancements".* Global Food Security, Volume 20. 2019, Pages 93-100, ISSN 2211-9124, https://doi.org/10.1016/j.gfs.2019.01.002.
- Malefors, Christopher, Pieter Callewaert, Per-Anders Hansson, Hanna Hartikainen, Oona Pietiläinen, Ingrid Strid, Christina Strotmann, and Mattias Eriksson. 2019. "*Towards a Baseline for Food-Waste Quantification in the Hospitality Sector—Quantities and Data Processing Criteria*" Sustainability 11, no. 13: 3541. https://doi.org/10.3390/su11133541.
- Hanna Hartikainen, Lisbeth Mogensen, Erik Svanes, Ulrika Franke. 2018. "*Food waste quantification in primary production – The Nordic countries as a case study*". Waste Management, Volume 71, Pages 502-511, ISSN 0956-053X. https://doi.org/10.1016/j.wasman.2017.10.026.
- Ole Jørgen Hanssen, Frode Syversen, Eivind Stø. 2016. "*Edible food waste from Norwegian households—Detailed food waste composition analysis among households in two different regions in Norway*". Resources, Conservation and Recycling, Volume

109, Pages 146-154, ISSN 0921-3449. https://doi.org/10.1016/j.resconrec.2016.03.010.

Scientific publications on food waste prevention and reduction strategies:

- Bergström, Pauline, Christopher Malefors, Ingrid Strid, Ole Jørgen Hanssen, and Mattias Eriksson. 2020. "*Sustainability Assessment of Food Redistribution Initiatives in Sweden*" Resources 9, no. 3: 27. https://doi.org/10.3390/resources9030027.
- Svanes, Erik, Sofie Oestergaard, and Ole Joergen Hanssen. 2019. "*Effects of Packaging and Food Waste Prevention by Consumers on the Environmental Impact of Production and Consumption of Bread in Norway*" Sustainability 11, no. 1: 43. https://doi.org/10.3390/su11010043.
- Mattias Eriksson, Christopher Malefors, Pieter Callewaert, Hanna Hartikainen, Oona Pietiläinen, Ingrid Strid. 2019 "*What gets measured gets managed – Or does it? Connection between food waste quantification and food waste reduction in the hospitality sector*". Resources, Conservation & Recycling: X, Volume 4, 100021, ISSN 2590-289X. https://doi.org/10.1016/j.rcrx.2019.100021.
- Østergaard, Sofie, and Ole Jørgen Hanssen. 2018. "*Wasting of Fresh-Packed Bread by Consumers—Influence of Shopping Behavior, Storing, Handling, and Consumer Preferences*" Sustainability 10, no. 7: 2251. https://doi.org/10.3390/su10072251.

In addition we have a number of reports.

4. Details of the impact

One of the results from the early stages of the ForMat project was the establishment of Matvett AS in 2012. Matvett is a key partner for NORSUS who has ensured industry uptake of large parts of the presented research. Matvett is the food and hospitality industry's organization for preventing food waste, and does this through collaboration with research organizations and the authorities, on behalf of the industry. Through close collaboration with Matvett, NORSUS' research has been implemented in various ways:

- Harmonised food waste monitoring and reporting across the food supply chain in Norway through yearly workshops, guidelines and tools.
- Various food waste prevention and reduction actions across the food value chain:
    - Systematic discounting of food products that are approaching the expiration date across all retailers in Norway (2017).
    - Changes in date labelling for a large number of food products with "Best before" instead of "Expires by" (2014-2016).
    - Harmonized supplementary date labelling in the food industry (2018)
    - Courses for employees in the food service sector on food waste (2019).
    - Collaboration on allocation of shelf life for minimal food waste through STAND

In addition to the overarching implementation via Matvett, several of the research projects mentioned in section 2 have been executed in close collaboration with industry. Breadpack and Greenpack was conducted in close collaboration with the industry (BAMA and Cernova). The packaging strategies tested within the two projects were implemented by the industry afterwards.

The research has also had a strong impact on the Norwegian policy framework on food waste. The ForMat project laid the foundation of an intentional agreement in 2015 for a food waste agreement. NORSUS was commissioned to develop a report on the data basis for food waste and proposals for the organization of reporting food waste in Norway, which in turn laid the foundation of the Recommendation for the development of food waste statistics in Norway that led to the establishment of the negotiated agreement on food waste reduction between the authorities and food industry organizations in Norway (2017).
The research from the various project has also documented the environmental and economic impact from food waste. Due to these analyses, food waste has been set high on the environmental policy agenda in Norway. Norway is one of few countries that has included food waste into the country climate mitigation strategy. The Norwegian environmental agency

contracted NORSUS to preform a cost benefit analysis (CBA) of halving food waste according to the negotiated agreement. This was done for the first time in 2016, and since then NORSUS has performed three CBAs, where the latest one was implemented into the national roadmap for climate mitigation KlimaKur2030, where food waste reduction is one of the main climate actions for agriculture. Food waste is also implemented within the Norwegian government's National strategy for a green, circular economy, where NORSUS' research on food waste forms the knowledge base, and in the Climate Plan for 2021-2030 where NORSUS' analyses for KlimaKur, the ForMat project and the KuttMatsvinn2020 project are referred to.

The ForMat project is also credited for contributing to the establishment of the first Norwegian Food Bank in 2013. Today Norway has 13 Food Banks saving more than 5,000 tonnes of food from going to waste that are redistributed to more than 480 non-profit organizations that help people in vulnerable life situations. The industry's work under the negotiated agreement has been crucial for this development.

The FUSIONS project and the subgroup on FLW monitoring within the EU platform on FLW laid the groundwork for the common methodology and minimum quality requirements for the uniform measurement of levels of food waste defined by the Commission Delegated Decision (EU) 2019/1597 of 3 May 2019 supplementing Directive 2008/98/EC of the European Parliament and of the Council.

The research has benefited many different actors, including: the various industry partners (retailers, wholesalers, food service and food industry), the Norwegian food banks, Norwegian society (reduced environmental impact) and the Norwegian government and the European Commission.

5. Sources to corroborate the impact (indicative maximum of ten references)

The final report from the ForMat-project, including the foreword by Governmental representatives and Knut Maroni (the CEO of FoodDrinkNorway at the time) and Sverre Leiro (the CEO and board member of the retail chain NorgesGruppen at the time) (page 4 to 5).

The national roadmap for climate mitigation KlimaKur2030, where reports from NORSUS (then Østfoldforskning) is cited several times and is one of the main scientific contributors for the food waste assessment.

The Norwegian government's National strategy for a green, circular economy, where NORSUS' research on food waste forms the knowledge base.

The Norwegian government's Climate Plan for 2021-2030 where NORSUS' analyses for KlimaKur, the ForMat project and the KuttMatsvinn2020 project are referred to.

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NORSUS Case number 2

Institution: NORSUS
Administrative unit:
Title of case study: Biogas
Period when the underpinning research was undertaken: 2013-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2013-2021
Period when the impact occurred: 2016-2021

1. Summary of the impact (indicative maximum 100 words)
Results from application of models developed by NORSUS has had an important impact on the Norwegian Biogas industry, by providing decision support when developing biogas value chains, and as input to policy development. Examples: The decision to build The Magic Factory in Tønsberg, the largest biogas plant in Norway treating food waste and livestock manure contributing to an annual reduction of 13,986 tonnes CO2 equivalents per year. The development of national regulations and economic support systems: requirement to separate food waste in Norwegian municipalities proposed by the Environment Agency, and economic support per tonne of manure for biogas production managed by Agriculture agency.

2. Underpinning research (indicative maximum 500 words)
NORSUS has led several cross disciplinary research projects involving industry actors funded by the Norwegian Research Council. In the research project BioValueChain (2013-2017) national models for assessing the environmental impacts from production of biogas and biofertilizer from food waste and livestock manure, as well as economic models for calculating profitability of actors in the value chain was developed. The environmental model is based on life cycle assessment (LCA) methodology which was adapted specifically for biogas value chains and the types of decision the model is intended for. The economic models were developed for key actors in the biogas value chain: farmers and the biogas plant, in order to assess their economic viability and effects of various economic support systems.

Application of the models showed that anaerobic digestion (biogas production) of food waste represented the most beneficial treatment technology for food waste in terms of environmental impact, in a value chain perspective. In a Norwegian context, the biogas value chain configuration with the best environmental performance was to co digest food waste and manure, utilize biogas as a transport fuel and to utilize digestate as fertilizer to substitute mineral fertilizer. Furthermore, the research found that the most optimal value chain configuration represented the least economically profitable option for the actors in the value chain, indicating the need for an economic support system to reduce environmental impacts.

In the project Bærekratig Biogass (2017-2019) the models from BioValueChain were applied and refined, and the life cycle assessment methodology adapted for decision support of the different value chain actors, and increasing the knowledge about new feedstocks and the use of CO2 from upgrading of biogas. The results show that the use of CO2 from upgrading of biogas can be utilized cost efficiently if a greenhouse is located in close proximation to the biogas plant, and that it will result in reduced emissions. In addition, the models have been further refined and applied in several commissioned projects, both for regional initiatives to develop new biogas value chains, Innovation Norway and for authorities such as the Norwegian Environment Agency and Agriculture Agency.

In NORSUS a large range of researchers have participated in the biogas related projects: Ole Jørgen Hanssen (Senior Researcher), Kari-Anne Lyng (first as Researcher, then Senior Researcher), Ingunn Saur Modahl (Senior Researcher), Hanne Møller (Senior Researcher), Hanne Lerche Raadal (Senior Researcher), Kjersti Prestrud (Researcher), Pieter Callewaert (Researcher), Aina Stensgaard (Researher) and Simon Saxegaard (Researcher).

3. References to the research (indicative maximum of six references)

The development and application of the models for calculating the environmental impacts of biogas value chains, and the economic model to assess profitability for key actors are published in the three following scientific papers:

- Lyng, K.-A., Modahl, I S., Møller, H., Morken, J., Briseid, T. and Hanssen, O.J. (2015): The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains. International Journal of Life Cycle Assesment. DOI: http://link.springer.com/article/10.1007/s11367-015-0851-5
- Lyng, K.-A., Stensgård, A., Hanssen, O.J., Modahl, I.S., 2017. Relation between greenhouse gas emissions and economic profit for different configurations of biogas value chains. A case study on different levels of sector integration. Journal of Cleaner Production 182 (2018) 737-745. https://www.sciencedirect.com/science/article/pii/S0959652618304384
- Lyng, K.-A., Bjerkestrand, M., Stensgård, A.E., Callewaert, P., Hanssen, O.J., 2018. Optimising Anaerobic Digestion of Manure Resources at a Regional Level. Sustainability 10, 286. https://doi.org/10.3390/su10010286

Results from application of the models were used as decision support when deciding to build the biogas plant The Magic Factory in Tønsberg. The viability of the model was evaluated in a scientific paper:

- Lyng, K.-A, Modahl I.S., Møller, H and Saxegaard, S., (2021): Comparison of results from life cycle assessment when using predicted and real-life data for an anaerobic digestion plant. Journal of Sustainable Development of Energy, Water and Environment Systems, Volume 9, Issue 3, 1080373. http://dx.doi.org/10.13044/j.sdewes.d8.0373

Implications for policy development were assessed in scientific papers and in commissioned reports from Agriculture Agency and Environment Agency:

- Lyng, K.-A., Skovsgaard, L., Jacobsen, H.K. et al. Environ Dev Sustain (2019): The implications of economic instruments on biogas value chains: a case study comparison between Norway and Denmark https://doi.org/10.1007/s10668-019-00463-9
- Lyng, K.-A., Prestrud, K., Stensgård, A.E., 2019. Evaluering av pilotordning for tilskudd til husdyrgjødsel til biogassproduksjon. OR 04.10. Østfoldforskning. https://norsus.no/publikasjon/evaluering-av-pilotordning-for-tilskudd-til-husdyrgjodsel-til-biogassproduksjon/
- Syversen, F., Lyng, K.-A., Bjørnerud, S., Amland N., E., Callewaert, P., Prestrud, K. (2018): Utsortering og materialgjenvinning av biologisk avfall og plastavfall. Utredning av konsekvenser av forslag til forskrift for avfall fra husholdninger og liknende avfall fra næringslivet Mepex AS, Østfoldforskning. https://www.miljodirektoratet.no/hoeringer/2021/januar-2021/forslag-til-forskrift-om-utsortering-av-bioavfall-og-plastavfall-/

4. Details of the impact (indicative maximum 750 words)

The environmental models developed in the research projects were applied to assess different biogas configuration scenarios to treat the organic waste and manure resources available in Vestfold. These results were presented for local politicians, and the decision to build was done by 10 municipalities in Vestfold (10k-samarbeidet). The plant was planned based on the optimal scenario to obtain the largest reduction of environmental impacts. As the first of its kind in Norway, The Magic Factory is a large-scale biogas factory in Norway co treating food waste and manure. The plant was officially opened by the prime minister in September 2016. NORSUS has had a long-term collaboration with Greve Biogas, the plant owner, and performed research on the operation of the plant. In 2018 The Magic Factory was the first in Norway to utilise CO_2 from upgrading of biogas, by transporting the CO_2 in pipes from the upgrading facility to a greenhouse located nearby. In the greenhouse tomatoes are produced from CO_2 and digestate from the biogas factory. NORSUS has documented that the Magic

Factory contribute to annual net emissions reduction of 13,986 tonnes CO2 equivalents per year.

The models and the knowledge from the research projects were applied in two commissioned projects from the Environment Agency, first in the Evaluation of different political instruments to increase separation of organic and plastic waste, and afterwards in a project assessing the impacts of a new regulation requiring Norwegian households and companies producing household-like waste to separate organic waste, which was carried out together with Mepex. After that the Environment Agency proposed a change in the waste regulation in January 2021, and the change was implemented 1.1.2023. https://lovdata.no/dokument/LTI/forskrift/2022-06-07-971 The increase in the amount of food waste separated is expected to increase the biogas produced, which in turn leads to increased resource efficiency in terms of recycling of nutrients as well as reduction in greenhouse gas emissions as the biogas can substitute fossil fuels, and as digestate can substitute mineral fertilizer.

Biogas production from livestock manure is identified as one of the most important measures to reduce greenhouse gases from agriculture in Norway. Application of the economic models developed in the research projects showed that the main barriers are economic costs associated with additional storage requirements. A pilot scheme where farmer receives economic support per tonne manure treated in a biogas plant was introduced in 2014. NORSUS performed an evaluation of the pilot scheme commissioned by Agriculture Agency in 2019, and based on the evaluation the pilot scheme was transformed to a permanent support system. https://lovdata.no/dokument/SF/forskrift/2014-12-19-1815 Economic support for manure for biogas production is expected to result in more biogas plants considering manure as a relevant feedstock, which will lead to reduction of greenhouse gas emissions from storage of manure as well as increased biogas production which can substitute fossil fuels and reduce greenhouse gas emissions in transport. The perspectives and support systems have been communicated along with the perspectives of six other countries in an international report published by IEA Bioenergy Task 37 Energy from biogas. This has the potential to obtain impacts in other countries, including countries with less developed biogas value chains and support systems.

5. Sources to corroborate the impact (indicative maximum of ten references)

Ivar Kopperud Sørby from Greve Biogass/The Magic Factory explains how NORSUS contributed to the establishment and further development of the installation in a webinar to be found here: https://www.youtube.com/watch?v=gJGfAYiilxI&t=4174s , see from 1h17minutes into the recording.

News article on Greve Biogas webpage about the research project Bærekraftig Biogass and utilisation of CO2 as the first biogas plant in Norway: https://grevebiogass.no/aktuelt/november-2018/groenn-co2-fra-biogassanlegg-til-veksthus-norges-foerste/

Norwegian Environmental Agency proposal for changes in waste regulations, where the report from Mepex and Østfoldforskning (NORSUS) is cited in their consultation statement (høringsuttalelse): https://www.miljodirektoratet.no/hoeringer/2021/januar-2021/forslag-til-forskrift-om-utsortering-av-bioavfall-og-plastavfall-/

Assessment of policy instruments for biogas production in Norway performed by Norwegian Environment Agency where Østfoldforskning (NORSUS) is cited a number of times: https://www.miljodirektoratet.no/globalassets/publikasjoner/m1652/M1652.pdf

Report from a working group led by Norwegian Agriculture Agency assessing policy instruments for manure for biogas production, where NORSUS (Østfoldforskning) is largely cited, and where four of the reports from Østfoldforskning is in the reference list. NORSUS participated in the reference group for the work:
https://www.regjeringen.no/contentassets/6a5da53b1ba243eb86a4e2314abe96a4/husdyrgjods

el-til-biogass---gjennomgang-av-virkemidler-for-okt-utnyttelse-av-husdyrgjodsel-til-biogassproduksjon.pdf

News article in Bondebladet about how research from Østfoldforskning provides foundation for strategy development for biogas production from manure https://www.bondelaget.no/nyhetsarkiv/store-muligheter-for-bruk-av-norsk-husdyrgjodsel-til-biogassproduksjon

Other relevant publications:

Lyng, K.-A. (2020). Bruk av CO2 fra oppgradering av biogass. Beregning av potensiell klimaeffekt ved bruk i veksthus. Østfoldforskning, OR.24.20. https://norsus.no/en/publikasjon/potensiell-klimaeffekt-ved-bruk-av-co2-fra-oppgradering-av-biogass-i-veksthus/

Lyng, K.-A. & Saxegård, S. (2020). Livsløpsvurdering av produktene og tjenestene til Den Magiske Fabrikken: Avfalls- og gjødselhåndtering, biodrivstoff, biogjødsel og bio-CO2. NORSUS OR23.20. https://norsus.no/en/publikasjon/livslopsvurdering-av-produktene-og-tjenestene-til-den-magiske-fabrikken/

Brekke, A., Lyng, K.-A., Olofsson, J., Szulecka, J., Lyng, K.-A., Olofsson, J., Szulecka, J., 2019. Life cycle assessment : A governance tool for transition towards a circular bioeconomy? Book chapter in From Waste to Value | Valorisation Pathways for Organic Waste Streams in Circular Bioeconomies. Taylor Francis. https://doi.org/10.4324/9780429460289

Lyng, K.-A., Callewaert, P. og Prestrud, K. (2019): Kunnskapsgrunnlag for nasjonal strategi for husdyrgjødsel til biogassproduksjon. Del 2: Nasjonale scenarier. Østfoldforskning https://norsus.no/en/publikasjon/kunnskapsgrunnlag-for-nasjonal-strategi-for-husdyrgjodsel-til-biogassproduksjon-2/

Lyng, K.-A., Callewaert, P., Stabbetorp, E.M. og Prestrud, K. (2019): Kunnskapsgrunnlag for nasjonal strategi for husdyrgjødsel til biogassproduksjon. Del 1: Råstoffgrunnlag, gjødselbehov og synergier mellom sektorer. Østfoldforskning AS, OR 25.19. https://norsus.no/en/publikasjon/kunnskapsgrunnlag-for-nasjonal-strategi-for-husdyrgjodsel-til-biogassproduksjon/

Lyng, K.-A., 2018. Reduction of environmental impacts through optimisation of biogas value chains. Drivers, barriers and policy development. PhD thesis 2018:6, Norwegian University of Life Sciences.

Stensgård, A. E, Saxegård, S. A., Lyng, K-A og Hanssen, O.J. 2017: Følgeforskning: Den Magiske Fabrikken Miljø- og økonomianalyse. Østfoldforskning AS, OR 21.17

Raadal, H.L., Stensgård, A. E., Lyng, K-A. og Hanssen, O.J. 2016: Vurdering av virkemidler for økt utsortering av våtorganisk avfall og plastemballasje. Østfoldforskning, OR 01.16. https://www.miljodirektoratet.no/globalassets/publikasjoner/M522/M522.pdf

Lyng, K.-A., Brekke, A., 2019. Environmental Life Cycle Assessment of Biogas as a Fuel for Transport Compared with Alternative Fuels. Energies 12, 532. https://doi.org/10.3390/en12030532

NVE_HD Case 1

Institution:
Administrative unit:
Title of case study: Flood, landslide and snow avalanche Early Warning Systems for a safer society
Period when the underpinning research was undertaken: 2011-2021
Period when staff involved in the underpinning research were employed by the submitting institution: 2011-2021
Period when the impact occurred: 2011-2021

1. Summary of the impact

A safer and more resilient society from risks posed by floods, landslides and snow avalanches is the goal of this reported path of R&D at the NVE_HD.

R&D at the NVE_HD has been instrumental for the establishment of high-quality snow avalanche and landslide early warning systems (EWS) and to further develop the existing flood EWS during the last decade. R&D has ensured important steps forwards in terms of process knowledge, model development, ensemble forecasting, crowdsourcing, digital communication, and lately also operational use of artificial intelligence. Efficient integration of R&D results in operational services, was possible through interplay of personnel from research, operational forecasting, and IT. A significant step was the SeNorge data series developed in collaboration with MET.no, providing observed and modelled data and forecasts of temperature, precipitation, and hydrological variables in a distributed field (1 km^2-resolution) available in an expert decision system and to the public. Our EWSs are used by all emergency response authorities, and as a tool to prompt individuals to take actions for damage reduction – e.g., by insurance companies using SMS to notify customers.

2. Underpinning research

NVE has operational responsibility for risk management related to floods, and (from 2009) for snow avalanches and landslides. Establishing and continuously improving knowledge-based state of the art warning systems has been a main goal of our R&D. The underpinning research has involved several PhD's and efforts from IT personnel.

SeNorge data series:

The nation-wide operational EWSs require models that simulate the state of the hydrological system and fluxes of water at high temporal and spatial resolution in gauged and ungauged catchments. Observed hydrometeorological data from NVE and MET.no are interpolated and used as model forcing data, providing spatially distributed datasets for historical, real time and forecasts of meteorological and hydrological variables and indices. These time series, at 24 hours and partly 3 hours temporal resolution going back to 1957, constitute the SeNorge.no common data source for our operational services. R&D has resulted in improved versions of the SeNorge data set (e.g., Huang 2019, Saloranta 2016).

Flood forecasting:

The national flood EWS started in 1989. Distributed hydrological models were developed at temporal and spatial scales relevant for decision systems (e.g., Huang et al. 2019), including the DDD model designed to keep the number of calibration parameters to a minimum (Skaugen and Onof, 2014). Forecasting further incorporates ensemble prediction (Hegdahl 2021). Output of the models are streamflow, but also a large number of parameters relevant for landslide and avalanche EWS such as subsurface water conditions (e.g., Skaugen and Mengistu, 2016) and snow conditions/melt (e.g., Saloranta. 2016). Return periods for floods are derived using statistical models (e.g. Kobierska et al., 2018) and are used as thresholds for various warning levels. The following staff contributed to the R&D: Stein Beldring, Kolbjørn Engeland (2013-), Helene B. Erlandsen (PhD 2018-2020), Trine Jahr Hegdahl (2015- including PhD), Shaochun Huang (2016-), Elin Langsholt, Deborah Lawrence, Hong Li [now: Anna Hansen] (2016-), Jan Magnusson (2015-2019), Thomas Skaugen.

Landslides and snow avalanches:

Landslides and snow avalanche EWS became operational in 2013. The services were developed as a joint initiative across public agencies between NVE, MET.no and the Norwegian Public Road Administration (NPRA) and are based on five pillars: automatic hydrological and meteorological stations, database of mass movement incidents, hydro-meteorological forecasting models, thresholds or return periods, and a trained group of forecasters.

Landslide EWS includes rainfall- and snowmelt-induced landslides (debris flows, debris avalanches, soil slides and slushflows). Krøgli et al. (2018) presented the thresholds developed for landslide warning, based on statistical analyses of historical landslides and simulated hydro-meteorological variables. The following staff contributed to the R&D: Hervé Colleuille, Graziella Devoli, Inger Karin Engen, Ingeborg K. Krøgli (-2019), Monica Sund (2012-), Søren Boje (-2019).

Snow avalanche EWS: Saloranta (2016) were instrumental for improving the simulations of snow at high resolution with national coverage in Norway. Techel et al. (2020) provided an important basis for creating a standard for defining avalanche danger in the EWS (work lead by Karsten Müller at NVE). Results from Engeset et al. (2018) improved communication of forecasts on Varsom.no and and Landrø et al. (2019) made recommendations used by educators and forecast users to develop skills in avalanche risk management. Larsen et al. (2020) allowed the development of the first ever nationwide detailed avalanche terrain exposure map and associated properties. The following staff contributed: Rune Engeset, Markus Landrø, Håvard Toft Larsen (2018-), Karsten Müller, Tuomo Saloranta.

3. References to the research

- **Engeset, R.V.**, Pfuhl, V. G., Landrø, M., Mannberg, A. & Hetland, A. (2018) Communicating public avalanche warnings – what works? Natural Hazards and Earth System Sciences, 18, 2537–2559, https://doi.org/10.5194/nhess-18-2537-2018.
- **Hegdahl, T.J.** (2021). Hydrological ensemble prediction systems: from evaluating daily streamflow forecasts to exploring the impact of selected flood events in a future climate. PhD Thesis, University of Oslo.
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- **Kobierska, F**., **Engeland, K**., Thorarinsdottir, T. (2018) Evaluation of design flood estimates – a case study for Norway. Hydrology Research, 49 (2): 450–465. https://doi.org/10.2166/nh.2017.068
- **Krøgli, I. K., Devoli, G., Colleuille, H., Boje, S., Sund, M., and Engen, I. K**.(2018) The Norwegian forecasting and warning service for rainfall- and snowmelt-induced landslides, Nat. Hazards Earth Syst. Sci., 18, 1427-1450, https://doi.org/10.5194/nhess-18-1427-2018, 2018.
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- **Larsen, H. T**., Hendrikx, J., Slåtten, M. S., & **Engeset, R. V.** (2020) Developing nationwide avalanche terrain maps for Norway. Natural Hazards, 103, 2829–2847, https://doi.org10.1007/s11069-020-04104-7.
- **Saloranta, T. M.** (2016) Operational snow mapping with simplified data assimilation using the seNorge snow model. Journal of Hydrology, 538, 314-325, https://doi.org/10.1016/j.jhydrol.2016.03.061.
- **Skaugen, T.** and **Mengistu, Z.** (2016) Estimating catchment scale groundwater dynamics from recession analysis- enhanced constraining of hydrological models. Hydrol. Earth. Syst. Sci. 20, 4963-4981, https://doi.org/10.5194/hess-20-4963-2016
- **Skaugen, T**. & Onof, C. (2014). A rainfall-runoff model parameterized from GIS and runoff data. *Hydrological processes*, *28*(15), 4529-4542. https://doi.org/10.1002/hyp.9968
- Techel, F., **Müller, K.** & Schweizer, J. (2020) On the importance of snowpack stability, the frequency distribution of snowpack stability, and avalanche size in assessing the avalanche danger level. The Cryosphere, 14, 3503–3521, https://doi.org/10.5194/tc-14-3503-2020

4. Details of the impact

The impact of our EWS is a safer and more resilient society with respect floods, landslides and snow avalanches. Our contribution is based on NVE having the national operational responsibility for risk management related to floods, and (from 2009) for avalanches and landslides. This operational responsibility is implemented at NVE_HD into the EWS described above, and we run continuous evaluations, research and development tasks in order to improve the precision and usefulness of the forecasting and warning systems.

NVE_HD is thus responsible for a value-chain from research, through dissemination, uptake, and implementation of the EWS tools (in addition, other aspects of the value chain are the responsibility of another NVE department). Our tools contribute to emergency preparedness and a reduction in the damages caused by natural hazards. The advantages of responsibility for such a value-chain are obvious; however, it has also caused research to feed directly into uptake in models and systems, and more or less direct implementation in the EWS – sometimes leading to dissemination in reports rather than peer-review publications.

NVE established a flood warning system in 1989. This provided valuable background experiences for setting up, in more recent years, the warning systems for landslides and snow avalanches that were launched operationally within quite short time by NVE_HD (live from January 1. 2013). It should be noted that NVE_HD was one of few countries in the world to implement a nation-wide landslide EWS. From workshops held in 2016 (Devoli, 2017) and 2019 (Calvello et al., 2020a) we promoted the creation of a network of researcher and stakeholders working with landslide EWS around the world. The LandAware network (Calvello et al., 2020b was finally established in 2020 and aims to assist other regions around the world with the organization of landslide EWS; this aspect is also causing significant impact.

Beneficiaries of our EWS and products are emergency response authorities, municipalities and infrastructure owners, ski tourists and the public, who ultimately contribute to the desired impact. Between warnings and a safer society, however, lies an important issue: namely the capacity of organizations and individuals to understand, process and respond correctly on early warnings. To fill this gap, NVE_HD has worked with stakeholder involvement and contributed to research on decision-making – especially for snow avalanches and more recently in particular to develop impact-based flood and snow avalanche warnings. Snow avalanches are unique in that they also are released by tourists or professionals, travelling on skis or snowmobiles, in addition to spontaneous release.

All warnings are issued on Varsom.no. The platform is used to publish daily warnings about natural hazards in Norway. The warnings issued from NVE include: Snow avalanches, floods, landslide (debris flows/slush flows), rock avalanches, and (lake and river) ice warnings. All extreme weather warnings from MET.no are also issued here to gain synergies and easy overview and access to all relevant warnings at one platform. The Varsom app also include tweets, news and educational material. Presently, the spatial resolution of the warnings is at the municipal level (for floods and landslides) and for 24 predefined warning regions for snow avalanches. Flood and landslide warnings use a color code (four levels – CAP-standards), where green signals no warning, yellow for flood represents a return period between mean and 5-year flood, orange between 5 and 50-year flood, and red above 50-year flood. Flood warnings may also be issued if other conditions (such as ice in channels, or stormwater due to snowmelt and frozen ground) imply potential flood damage. More detailed warnings about water levels in lakes and rivers may be issued during severe flood events depending on available observations and models. The landslide warnings use the same four levels as flood warning systems. The warnings are not statistically linked to return periods, but empirical thresholds for hydrometeorological conditions and landslide occurrence based on historical sources. Snow avalanche warnings follow the European Avalanche Danger Scale of five levels. In this way, we attempt to keep warnings simple, intuitive and in line with international standards. In the case of snow avalanches, this is particularly important to convey information to foreign ski tourists in Norway.

It is difficult to judge quantitatively if society has become safer after the introduction of our EW but reports from road authorities and municipalities after an event, often emphasize that the warnings enabled measures to be taken and damages to be minimized. The same information is conveyed from the NVE Region offices, who are responsible for direct communication with municipalities etc. during events. The following information further corroborates our claim.

An evaluation of NVE (Jakobsen et al. 2016) claims that stakeholders are satisfied with our EWS and that NVE provide high quality knowledge dissemination.

A user survey conducted in 2017 (Hisdal, 2017) confirms that a large majority of the target group considered the warnings useful or very useful and have quite high or very high confidence in the issued warning level. In-depth interviews show that warnings contribute to higher consciousness about snow avalanches and more knowledge on landslides.

A new evaluation of the flood and landslide EWS (Colleuille and Engen, 2020) indicate that the landslide services have succeeded as a tool for the road and railway authorities, and for municipalities and emergency agencies in increasing awareness, preparedness, and risk reduction. Respondents showed more confidence in landslide warnings compared to the 2017 survey, and a vast majority of recipients consider taking measures for damage reduction when they receive warning about floods, landslide hazard and intense rain. When a warning is issued, their visibility is also improved by media attention, especially of course in terms of large events.

Insurance companies refer to our flood EWS on their web pages, and some automatically send SMS to customers in municipalities where warnings have been issued, and some municipalities provide links to varsom.no.

Our warning systems are among those considered critical societal functions and capabilities in a report from Norwegian Directorate for Civil Protection (DSB).

5. Sources to corroborate the impact

- Calvello M, Devoli G, Freeborough K, Gariano SL, Guzzetti F, Reeves HJ, Stähli M (2020a). LEWS2020 workshop on regional Landslide Early Warning Systems – experiences, progresses and needs. EGU General Assembly 2020, EGU2020-9917. https://doi.org/10.5194/egusphere-egu2020-9917
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- Devoli G. (2017). Workshop «regional early warning systems for rainfall- and snowmelt-induced landslides. Need for an international forum?» NVE rapport 4/2017.
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NVE_HD Case 2

Institution: The Norwegian Water Resources and Energy Directorate (NVE)
Administrative unit: Department of Hydrology
Title of case study: Services for climate change adaptation in Norway with emphasis on hydrology and the cryosphere
Period when the underpinning research was undertaken: 2011–ongoing
Period when staff involved in the underpinning research were employed by the submitting institution: 2011–ongoing
Period when the impact occurred: 2015–ongoing

1. Summary of the impact

Norway's attention towards and knowledge about ongoing climate change, and the momentum and capacity of our society for climate change adaptation has improved as an effect of our research. NVE's monitoring and research on climate change effects on e.g., floods, glaciers and stormwater in Norway have raised public awareness. County-wise climate factsheets with climate change allowances, based on research on climate change impacts on hydrology at the NVE_HD, has provided municipalities with knowledge and tools for adaptation to climate change and resilient land use planning in both rural and urban settings. Reference to the report Climate in Norway 2100 and the county-wise climate fact sheets are made in the governmental planning instructions for climate adaptation.

2. Underpinning research

NVE_HD has conducted research on climate change impacts on hydrology and the cryosphere throughout the reporting period (2011 until now). The research covers contributions to global hydrology (amongst others through participation in the ISI-MIP collaboration), and observed and projected effects on the hydrology of Norway in particular. Several of NVE's studies have been cited in the IPCC AR6, namely Andreassen et al., 2020 (WGI, chapter 9), Nilsen et al, 2021 (WG II, chapter 13), Madsen, Lawrence et al., 2014 (WGII, chapter 13), Vormoor et al., 2016 (WGII, chapter 4), and in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (M. Jackson lead author in chapter 2, see Hock et al., 2019). In the IPCC AR5 report, more than ten papers were cited, including a report on climate change effects on floods in Norway as this was one of very few studies on this topic at that time.

Climate and hydrological projections, including method for downscaling and bias-adjustment.

NVE_HD was responsible for producing nationwide hydrological projections in the government-commissioned report Climate in Norway 2100 issued in 2015. NVE took on the sole responsibility to downscale and bias-adjust the climate input data for our hydrological models, from an ensemble of ten regional climate models at 1x1 km resolution, described in NVE Report 59/2016. The effort altogether resulted in a set of high-resolution gridded climate and hydrological projections for Norway. The following staff contributed: H. Hisdal (hydrologist and section head), I. Haddeland (hydrologist, researcher), L. M. Andreassen (glaciologist, researcher), D. Lawrence (hydrologist, researcher), W.K. Wong (hydrologist, researcher). I. Haddeland worked at NVE until 2015 and 2019-2022. Further research for an updated version of the report Climate in Norway 2100 has been carried out amongst others in several NFR-projects. This includes studies of downscaling methods (Yuan et al. 2019, 2021), improved evapotranspiration modelling (Erlandsen et al. 2017, 2019, 2021; Huang et al. 2019), and changes in the magnitude and frequency of flash floods (Lawrence et al. 2014).

Ensemble methods to assess and account for uncertainty in hydrological projections.

The estimation of likely future changes in hydrological variables is dependent on an extensive chain of models and methods to generate site-specific projections relevant for climate change adaptation and risk reduction. Different climate models, bias correction techniques and methods for hydrological modelling and analyses give widely varying projections for future changes in e.g., flood quantiles. NVE-HD has undertaken and contributed to both national and international research and collaboration on this topic (including participation in the FloodFreq COST action and several NFR projects), with the aims of identifying the relative importance of ensemble components in the estimation of hydrological extremes (Lawrence et al., 2020), assessing the effect of bias correction methods and extreme value analysis on changes in extremes (e.g., Sunyer et al., 2015), and developing alternative methods for interpreting changes directly from atmospheric variables derived from GCMs (e.g., Huang et al., 2021).

Extensive field monitoring program for changes in glacier area/mass balance. NVE_HD monitors glaciers in Norway through seasonal measurements of surface mass balance measurements on 10 glaciers and one ice patch. Front variation is measured annually on about 40 glaciers. Geodetic mass balance is assessed by repeat surveys of surface elevation derived from aerial photography, laser scanning and satellite data. Mass balance glaciers are surveyed every 10 years and routinely reanalysed (Andreassen et al., 2016). NVE has analysed changes in area, volume and length from remote sensing of many of the glaciers and compared this with the smaller sample of field measurements (e.g., Andreassen et al., 2020).

Climate reports

Climate in Norway 2100 was issued in 2015; see NVE staff contributing to this report above. Two technical reports on projections for flooding have also been issued (Lawrence and Hisdal 2011; Lawrence 2016) for use by technical specialists. After the publication of Climate in Norway 2100, NVE led the work on county-wise climate factsheets (published 2015–2021; published collectively as NCCS report 2/2021). H. Hisdal, D. Vikhamar-Schuler (meteorologist, researcher) and I. B. Nilsen (hydrologist, researcher) edited the factsheets. Vikhamar-Schuler worked at NVE in 2016–2018. In 2019, Climate in Svalbard was published, along with Climate factsheet Longyearbyen. Contributors: H. Hisdal, W. K. Wong, D. Vikhamar-Schuler, S. Beldring, R. Engeset, H. Li, T. Saloranta, M. Sund, I. B. Nilsen.

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4. Details of the impact

Transforming Norway to a resilient society towards the effects of climate change, is very much an ongoing task, e.g., sparked by a White paper on climate change adaptation 2012-2013. Our work has contributed significantly to both raising awareness and momentum for the necessity to act on climate change issues and to give practitioners state-of-the-art tools for climate adaptation related to hydrometeorological challenges. The impact of our research is thus that the train of societal transformation is moving, and on the right track.

NVE_HD's work spans the entire value-chain, from research to implementation, of the efforts to create a climate-resilient society. We contribute with our own monitoring and analyses to document climate change effects on hydrology and avalanches/landslides, disseminate the ongoing changes, and ultimately aid uptake of climate knowledge in society. We further interact with coordinated international scientific efforts such as CORDEX, as well as national institutions, to produce hydrological projections and analyses. Towards the end of the value-chain, we work with stakeholders and public actors to enable implementation of climate change adaptation measures.

Changes within the cryosphere are easy to comprehend for the public, and combined with Norwegian outdoor and sports traditions, glaciers and snow are very much at the center of media attention. This regards changes in the size of glaciers and ice patches (e.g. NRK: 20 isbreer i Norge er nå borte), the coupled spectacular glacial archaeological artefacts that appear, which places Norway as the global center of gravity for glacial archaeology (e.g. NRK: Skjulte skatter smelter fram fra breene, NVE: FonnSat – Fonner, areologi og satelittdata) which are striking effects of climate change. Decreasing number of snow-days over large areas cause concern for the future of our skiing traditions, but also for a thriving tourism industry. For these reasons, an NVE report on future snow depth in Norway (Saloranta and Andersen, 2018) has attracted widespread media attention (e.g., NRK: Klimaendringene gir økte temperaturer; Nettavisen: dyster beskjed om fremtidens påske). It is the data from our monitoring and analyses that enable the documentation of these changes, and it is our researchers that present the results to the public – whether the focus is the past, present or future, or the downstream implications of these changes with respect to hydropower potential or for future flooding. Our researchers have also contributed to the IPCC processes and reports, and the impact also comes from the vast influence of these reports.

NVE and partners in the Norwegian Centre for Climate Services (NCCS) produce and disseminate a knowledge-base of climate information. Hydrological and cryospheric climate information for Norway is disseminated through a variety of channels:

- Maps are available at NCCS and SeNorge (click temakart/klimakart), and picture files can be accessed through an API distributing WMS maps of climate projections.
- Data is available for download from NCCS Download griddata.
- The data is displayed on websites run by e.g. The Norwegian Directorate for Civil Protection and The Norwegian Agency for Local Governments.
- The web tool nevina.nve.no is used for calculating low flow indexes and flood values (this tool can also handle climate change allowances). Nevina is used by practitioners in e.g., the hydropower and stormwater management sector.

Many of these climate services have emerged through a research collaboration with other research institutions, notably the Norwegian Meteorological Institute, and the two other project partners in NCCS: NORCE and Bjerknes Centre for Climate Research. Climate change allowances for floods were developed at NVE (Lawrence and Hisdal 2011; Lawrence 2016) and are being used in the development of new hazard maps for floods and further in municipal zoning plans as well as infrastructure design. These services and tools aid decision-making for climate change adaptation and planning. Other collaborators contribute to communication of flood hazard, such as CICERO (Hegdahl et al., 2020).

NVE actively uses mass media as a dissemination channel. In a collaboration with the Norwegian Broadcasting Corporation, results from bias-adjusted climate projections, hydrological and cryospheric projections have been disseminated through NRK: Klima/kommune. The feature article has reached at least 900 000 page views. NRK also made the feature Jakten på klimaendringene which used results from our studies of observed changes in hydrology. Both feature articles won awards.

As an example of an impactful product and an important dissemination channel, we highlight climate factsheets (Hanssen et al., 2013, Hisdal et al., 2021). These are tools we provide for municipalities and practitioners to aid them in their efforts for climate adaptation. All sectors have a responsibility for climate adaptation in their respective sectors, and further, municipalities have the main responsibility for adaptation (according to the White paper on climate change adaptation). The municipalities need to take this into consideration in planning, according to e.g. the Norwegian planning and building act and the associated technical regulations TEK17 2017, as well as through a planning instruction on climate adaptation and the associated guidelines issued by the Norwegian Environment Agency in 2019.

Climate factsheets were published successively (2015 –2017) and have later been updated, to provide information for each county in Norway. They are accessible online through NCCS and are referenced in guidelines for the planning referenced above. Practitioners have gradually become familiar with the factsheets (Hauge 2017; Rusdal and Aall 2019; Hauge et al., 2020; Klemetsen and Dahl, 2020), and have been topics at workshops such as Klimathon (Neby 2019; Kvamsås et al., 2021). They are used as a knowledge base for developing risk and vulnerability assessments (Klemetsen and Dahl, 2020), infrastructure design and municipal planning. In a report on Norway's climate change adaptation work, however, the Office of the Auditor General of Norway revealed that knowledge bases such as the climate factsheets still have potential to reach wider user groups (Riksrevisjonen, 2022).

For the climate factsheets, MET provided information on atmospheric variables, including climate change allowances for heavy rainfall, and contributed to writing chapter 1 in the factsheets. The Norwegian Mapping Authority and the Norwegian Directorate for Civil Protection defined climate change allowances for storm surges (chapter 5). The other chapters in the climate factsheets have been created and written by NCCS-affiliated staff at NVE_HD (Hisdal, Vikhamar-Schuler, Nilsen) with input from the flood- and hazard mapping staff at NVE.

Presentations at seminars such as Klimathon (Neby, 2019), courses Vær smart and webinars arranged by the Norwegian Environment Agency, reveal that the climate factsheets have been used by government agencies responsible for infrastructure, municipalities, consultants, and impact researchers. The main uses include local land use planning and zoning, water management and emergency preparedness. Although the main target group of climate factsheets comprise spatial planning practitioners in municipalities, other local practitioners and their hired consultants, government agencies and education institutions use the climate factsheets.

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