MOZEES
Mobility Zero Emission Energy Systems

FME FORSKNINGSSENTER FOR MILJØVENNLIG ENERGI
Norges forskningsråd

Annual Report 2019

Table of contents

Message from the Chair of the Board

In 2019 the MoZEES Centre operation came up to full speed with a turnover of about 40 MNOK. A substantial number of about 80 researchers and students, and 25 technology experts from the industry Partners have been active in different research tasks. In addition, MoZEES' outreach through publications, scientific presentation, international cooperation, and open workshops and meetings increased significantly.

I am certain that the many research results and outreach activities will continue to strengthen the development of better technologies and solutions, and to support decision makers in the strive to implement zero emission heavy-duty transport. A good example of such a valuable contribution is the common work carried out in the MoZEES maritime case study, including an important publication on the risk assessment of hydrogen driven high-speed passenger ferries.

The Centres for Environment-friendly Energy Research are important instruments in the Government's strategy to meet the Paris agreement. In the coming years, we know that large reductions in CO2 emissions are required in the heavy-duty transport sector. This challenge opens new possibilities for companies active in the Centre and inspires us all to further research and innovation. The MoZEES Board hopes that from the Centre activities the Partners also find interesting opportunities to generate spin-off projects strengthening their business and the Centre further.

I am proud of the achievements obtained in the MoZEES Centre so far. I would like to thank all Partners for their important contributions, and Director Dr. Øystein Ulleberg and his team for all their efforts and good cooperation in 2019.

Rune Bredesen
Chairman of the Board

Letter from the Center Director

Another exciting year has passed for MoZEES and all our partners that are involved in environmental-friendly technology and zero emission transport. The phrase "Zero Emission" is now popping up everywhere, particularly when we talk about transport applications. The established automakers in the world have committed to mass produce battery electric passenger vehicles in only a couple of years from now, and other large multi-national companies are now making substantial investments in hydrogen and fuel cells for heavy-duty transport. In Norway there are clear goals for zero emission road transport, and we are continuing to see an increased interest for zero-emission maritime transport applications. How is MoZEES contributing to these developments? Here are some highlights from 2019. Since we are approaching a mid-term review, I decided to write a somewhat longer letter and summary of our activities.

MoZEES battery research focuses on the next generation high energy Li-ion batteries based on anodes with a high silicon (Si) content and spinel cathodes (LNMO). Our industry partners Elkem and Cenate have contributed with Si-materials, while LNMO-materials have been sourced from other commercial and research partners. Pre-lithiation of Si-anodes and different binders for Si-based electrodes have been studied at IFE and liquid electrolytes for Si-anodes have been studied at NTNU, while UiO has synthesized and characterized new LNMO-compositions with high contents of nickel (Ni). NTNU has established a collaboration with Uppsala University on surface coating of LNMO and there is also an activity at SINTEF and NTNU on modified cathode NMC-materials with high Ni-contents. I hope we soon are ready to make, and test full cells based on our own materials.

The MoZEES hydrogen research focus on the development of high performance electrocatalysts, low-cost bipolar plates and membranes and improvement of testing protocols for high pressure composite hydrogen pressure vessels. Alternative Ruthenium-based catalysts for use in acidic PEM-electrolyzers have successfully been synthesized by SINTEF and will be tested *in situ* in 2020. There is also research going on at NTNU with focus on durability of various steels for use in alkaline water electrolyzers and some activity at SINTEF on coating of bi-polar plates. Our industrial partners Johnson Matthey, Nel and Teer Coatings are all involved and interested in this research, while Hexagon closely follows our research on hydrogen storage tanks. UiO is responsible for some fundamental research and synthesis of proton conductive polymers based on PBI and PEEK membranes suitable for intermediate temperature (120°C) fuel cells. It will be exciting to see the performance of these new materials and components when tested in cells and stacks.

The applied research in MoZEES focus on the optimization of battery and hydrogen systems, suitable for operation in heavy-duty road, rail, and maritime applications. Modelling tools for optimization of design and operation of PEM fuel cells and water electrolyzers systems have been developed at IFE and have been partially validated using experimental PEMFC-stack and PEMWE-system testing data from SINTEF and Nel, respectively. A Li-ion battery reference cell (tailor-made pouch cells) with a known chemistry was acquired by FFI and IFE and forms the common basis for all future experiments and analyses on battery cell degradation and lifetime within MoZEES. This is supplemented by experimental work on Li-ion battery safety at USN, where data from an explosion test rig has been used to validate CFD-models to predict the effect of battery gas explosions. USN has also started work on hydrogen safety, with focus on hydrogen release, dispersion, and jet fires in semi-closed spaces. These research topics are highly relevant for the public and industrial partners in MoZEES, as they are now involved in the further scale-up and use of battery and hydrogen technology in different transport applications. MoZEES is really contributing to the development of durable and safe solutions.

Another important activity in MoZEES is to identify the market potential, business cases, and policy prerequisites for innovative and energy efficient transport concepts based on battery- and/or hydrogen electric solutions. In MoZEES there is a specific focus on markets that are supported by demanding national climate and transport policy goals, and applications where Norwegian industries and technology companies can assume a leading position. Four transportation sub-systems have been identified as particularly interesting: (1) Urban mobility and logistics, (2) Coastal line vessels and ferries, (3) Long-haul freight and passenger transport, and (4) Transportation terminals. Several studies on these topics have been completed, and we are now in position to develop meaningful roadmaps that can fast-track the implementation of zero-emission transport. I really hope our efforts can lead to some new firm contracts on zero-emission high-speed ferries in the next couple of years. I also hope we will be able to establish a large national project on zero emission trucks.

In addition to function as a research center, MoZEES also serves as a great meeting place and network arena. In January there was organized an internal workshop at TØI with about 40 participants and focus on the application of battery and hydrogen technology for maritime and heavy-duty transport. In February there was for the second year in a row organized a two-day meeting on batteries (MoZEES Battery Days 2019, including a battery course at IFE) with ca. 40 participants, including members from the MoZEES Board and Scientific Committee. The Annual meeting in April attracted more than 80 participants. In May, June and July several of the MoZEES partners contributed with presentations at several large international conferences in Europe, such as EVS32, ICE2019, and EFCF 2019. In October there was a MoZEES Heavy Duty Transport Workshop in Oslo, which was an open meeting with more than 60 participants, including many commercial players.

In addition to the many presentations at conferences, seminars, and meetings (more than 60 contributions), there was in 2019 published 5 reports and 12 articles in peer-reviewed journals, and more are on the way. MoZEES has in collaboration with The Norwegian Academy of Science and Letters (DNVA) also contributed to the publication of an EASAC-report (European Academies' Science Advisory Council) on Decarbonisation of Transport in Europe. This report will form the basis for further discussions and national meetings with focus on road maps and policy for zero emission transport.

In 2019 there were about 80 researchers and students active in different research tasks in the center, including 11 professors, 20 senior researchers and 25 young researchers. In addition, about 25 technology experts from the industry partners, 10 PhD-students, and 2 post. doc. (directly funded by the center) have participated and contributed to the research in MoZEES. In addition, there were 7 master students that performed projects related to relevant research tasks, from cathode materials for NMC-batteries (NTNU) to PEM-fuel cell membranes (UiO) to battery and hydrogen safety (USN). In general, more and more students would like to be associated with the Center, as this gives the students a larger network and access to additional supervision from research institutes and industry partners in MoZEES. The PhD-students and post. doc. fellows are now organized in a so-called MoZEES Research Training Network headed by UiO. In June the FMEs MoZEES and Bio4Fuels hosted a PhD Summer School on sustainable transport, with many guest lecturers from universities, research institutes, and pubic and industrial user partners in MoZEES.

Finally, there has also been established a Scientific Committee in MoZEES, with members from the University of Uppsala, RWTH University Aachen, Fraunhofer ISE and University of California at Davis. The Scientific Committee provides advice on the scientific work to ensure that the research in MoZEES is on a high international level. A separate Innovation Committee will be established in 2020.

I would like to thank everyone that has contributed to the great progress in MoZEES so far, and I am really looking forward to taking our research to the next level: Testing, Demonstration, Production, Application, and Implementation.

Øystein Ulleberg
Center Director

About MoZEES

MoZEES is a Center for environment-friendly energy research with focus on battery and hydrogen technologies for zero-emission transport on road, rail, and sea.

Background & Motivation

Norway has access to vast amounts of renewable power, some of which can be used to produce electricity and hydrogen for transport. Ambitious national and regional climate policies on low and zero emission transport are currently being implemented, including economic support for the introduction of battery and hydrogen fuel cell electric vehicles. There is also a strong national policy to stimulate existing and new businesses to create new "green jobs". Hence, there is now a need to couple national and regional climate policies with long-term industry-driven business development strategies.

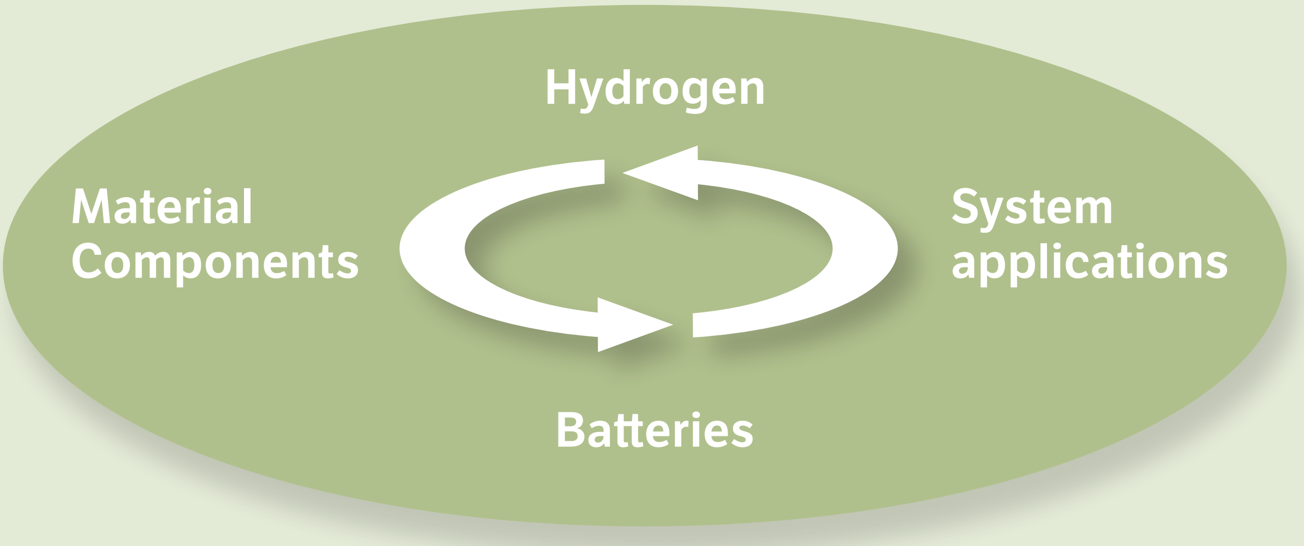
Battery and hydrogen technologies have been demonstrated for use in zero emission transport systems in many countries and regions around the world. However, further developments are needed before these technologies can be introduced into other transport sectors, such as heavy-duty transport by road, rail, or sea. MoZEES will focus on battery and hydrogen value chains, systems, and applications where Norway can take leading position in the future.

Main Objectives

The main objective with MoZEES is to be a Center for environment-friendly energy research with focus on new battery and hydrogen materials, components, technologies, and systems for heavy-duty zero-emission transport applications. The Center will contribute to the design and development of safe, reliable, and cost competitive zero-emission transport solutions. There will also be a strong focus on education and international collaboration.

Markets

The maritime sector has been identified as an important area where Norway can and should develop new zero emission technologies, systems, and solutions, both for domestic and international markets. One of the main ambitions in MoZEES is therefore to show how zero emission technologies can be a viable technical and economical alternative for the maritime sector,



both in Norway and abroad. MoZEES will also support R&D performed by the commercial User Partners that intend to participate in the international battery and hydrogen technology value chains.

Mission of the Center

In summary, the Center will add value to the society and user partners in the following way:

- Innovation: The Center will promote research that supports industrial R&D and other innovation activities undertaken by the User Partners, including: (1) Synthesis and fabrication of materials and components (2) Application and system integration of key technologies, (3) Design of integrated zero-emission transport systems and infrastructures (road, rail and sea).

- International Research Network: The Center will be an international contact point for research on batteries and hydrogen for use in transport. The Center will also serve as a network and meeting place for researchers and students to discuss interdisciplinary issues, ranging from basic to applied research.

- National Research Infrastructures: The Center will maximize the use of existing and planned research infrastructure already funded by the RCN and various EU programs. The use of existing research infra structures among the Research and User Partners will provide a solid foundation for the initial growth phase of the Center's activities.

- Guidelines and Roadmaps: The Center will provide authorities and certifying bodies with guidelines for safe battery and hydrogen systems and road maps for technology development and application into transport applications (road, rail and sea).

Partners

Industry and Public Partners

National Research Partners

tøi Institute of Transport Economics
Norwegian Centre for Transport Research

UiO University of Oslo

USN University of South-Eastern Norway

NTNU Norwegian University of Science and Technology

IFE Institute for Energy Technology

SINTEF

FFI Forsvarets forskningsinstitutt
Norwegian Defence Research Establishment

International Research Partners

UPPSALA UNIVERSITET

UC DAVIS UNIVERSITY OF CALIFORNIA

RWTH AACHEN UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

Members of the Center Management Team


Øystein Ulleberg (IFE)


Ragnhild Hancke (IFE)


Ann Mari Svensson (NTNU)

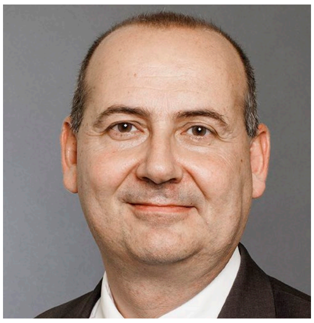

Magnus Thomassen (SINTEF)


Erik Figenbaum (TØI)


Katinka Elisabeth Grønli (UiO)

Members of the Executive Board


Arve Holt (IFE)


Patrick Bernard (Saft)


Ragnhild Wahl (Jernbanedir.)


Jorunn Voje (Elkem)


Gunnar Lindberg (TØI)


Anders Søreng (NEL Hydrogen)

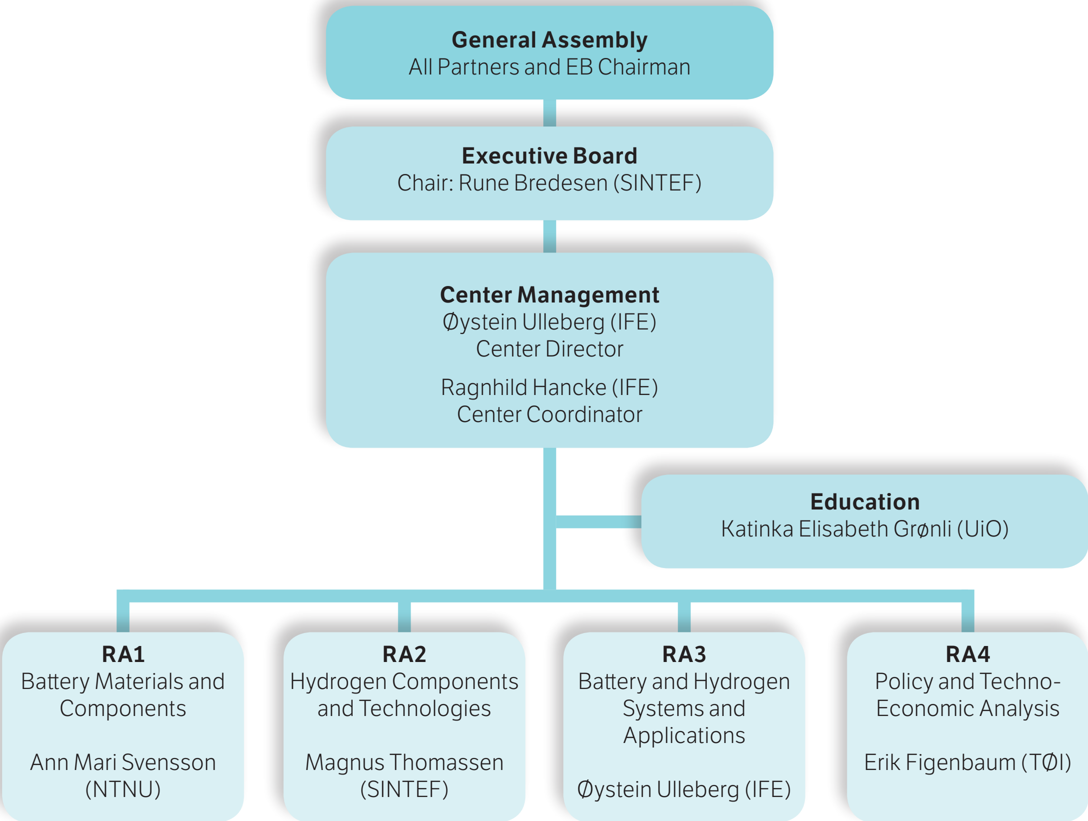

Per Ivar Helgesen (ENOVA)


Matko Barisic (ABB)


Rune Bredesen (SINTEF)


Jostein Mårdalen (NTNU)

Organisation



The Management Team and members of the Executive Board gathered at the MoZEES Annual Meeting 2019 (Photo: J.A. Wilhelmsen)

Education

MoZEES aspires to integrate our educational activities with the scientific development of the Center. Our three academic partners (UiO, NTNU and USN) offer basic educational programs and PhD programs at relevant departments. A major goal of the Center is to supply outstanding candidates for future positions in the transport and energy sector. This is enhanced by the active participation of user partners in all tasks at the Center, and in the development of our cross-disciplinary training network and activities.

As of March 2020, the Center engages 10 PhD fellows and 2 post docs/researchers. In addition, there are a number of young researchers and master students linked to MoZEES through associated projects. They have been integrated in local research environments and introduced to their closest collaborative partners in their respective Research Areas. Several of the PhD students have an industrial specialist as a co-supervisor. Most participated at the second Annual Meeting in April 2019, and four contributed with presentations of their own research in the main program.

MoZEES Research Training Network (RTN):
The Center has developed a dedicated research-training network to ensure active interaction between students and researchers across the different tasks and institutions as well as with relevant user partners.

RTN ACTIVITIES IN 2019:

• *MoZEES RTN had a dedicated session on outreach at the MoZEES Annual Meeting in April 2019. RTN members participated in a workshop on writing opinions/chronicles.*

• *In collaboration with FME Bio4Fuels MoZEES RTN organized an interdisciplinary Ph.D. summer school on the energy transition in the transport sector. The summer school was held at Quality Hotel Leangkollen in Asker from June 17th - June 21st. The one-week programme was designed to be both interdisciplinary and interactive, with a mixture of expert talks, lectures and group work focusing on various aspects of sustainable transport. In order to get 5 credits, the participants had to write an opinion/chronicle related to the topic of the summer school. One of the chronicles was published on forskning.no.*

• *In 2017 MoZEES RTN established their own webpage where the members are presented, and a blog that is run by the network itself. In 2019 the activity on the blog increased with contributions from almost all the members of the RNT.*

• *We congratulate Halvor Høen Hval with numerous pitches on why he wants to make batteries safe gskonferansen 2019' where he won, then he went to the final of the National Researcher Grand Prix before he also pitched at UiO:Energy Forum 2019.*

The MoZEES Mobility Program:
In 2018 we developed and adopted principles and a funding scheme for International and Industry Exchange for PhDs and young researchers. The MoZEES Mobility Program is designed to promote research exchange with International research partners and with the user partners of the center, aiming to foster increased interactions and mobility of candidates. In 2019, one grant was given:

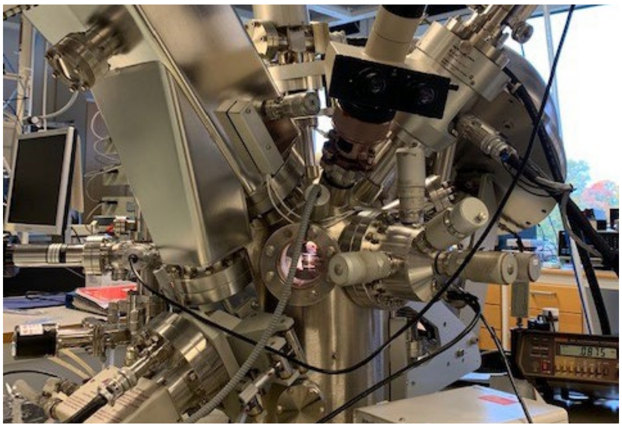
• *PhD fellow Elise Ramleth Østli was granted support for a 6-month stay at Uppsala University.*

International Research Exchange with support from MoZEES Mobility Program

During 2019 PhD student Elise Ramleth Østli spent 6 months at Ångström Advanced Battery Centre in Uppsala University. The Ångström Advanced Battery Center (ÅABC) in Uppsala has a wide variety of ongoing battery research, ranging from Na-ion batteries to polymer electrolytes for Li-ion batteries. A popular characterization technique amongst the ÅABC researchers is X-ray photoelectron spectroscopy (XPS) which is a powerful technique to get information about surfaces. The motivation for Elise Østli's stay at Uppsala was to learn more about how how surface coating of the cathode material $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO) can improve this material, and how XPS can be used to understand the coating's effect.

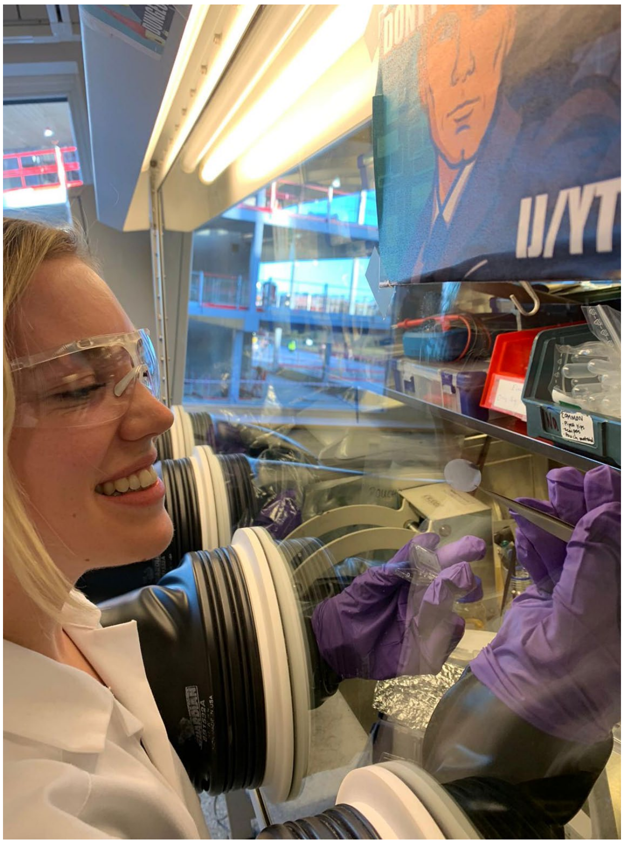
At ÅABC there is already research activity on LNMO as a high-voltage cathode material, both looking at new binders/polymer coatings and new electrolytes in combination with transition metal ion dissolution. However inorganic coatings on LNMO to stop transition metal ion dissolution is not currently being investigated within the group, making Østli's project fit in without overlapping with existing projects. This has created a good synergy where experience from all parties can be shared, thus ensuring a fruitful collaboration also in the future. Closer connections between the battery group at NTNU and at the ÅABC will benefit all, and collaborations in the future beyond the current study is highly likely.

The in-house XPS at the ÅABC



LNMO coated with 5 (left) and 10 (right) monolayers of Al_2O_3, which is one of the coating materials investigated. The coating is done by atomic layer deposition (ALD), which is a great technique for making such thin coatings.

"Being both the birthplace of the XPS-technique and having a world leading research group on battery materials, Uppsala was the perfect place for me to go for exchange, Elise Says"



The Research Training Network

Dr Alok Mani Tripathi *is employed as a doctoral researcher at the University of Oslo he performs in operando diagnostics of Li-ion batteries. This work is relevant for all the battery research in MoZEES as it will give a better understanding of the behavior and performance of battery materials.*

Dr Gaylord Kabongo Booto *is a postdoctoral researcher at IFE assessing the environmental impacts of Heavy Transport Vehicles – with a defined zero emission technology – by means of Life Cycle Analysis. The environmental benefits at full scale deployment are quantified in order to inform decision makers and enable strategic environmental management.*

MSc. Hamid Reza Zamanizadeh*'s PhD project focuses on Ni-based bipolar plates for alkaline water electrolysis cells. The work covers surface engineering, corrosion investigation and electro-catalytic activity evaluation for both the oxygen- and hydrogen evolution reactions. He started his studies at NTNU in 2018 under the supervision of Profs. Frode Seland and Svein Sunde.*

MSc. Xinwei Sun *started her PhD studies on hydrogen technology in 2018. The objective of her project is to develop low cost, high performance composite membranes for PEM fuel cells, which can be operated under higher temperatures (> 80˚C) and low relative humidities (RH < 20%). Her studies are carried out at UiO under the supervision of prof. Truls Norby.*

MSc. Halvor Høen Hval *started his PhD studies at UiO in 2018, working on batteries. He aims at developing new, as well as improving existing, high-voltage cathode materials with supervision from prof. Helmer Fjellvåg and prof. Ola Nilsen. Parts of the work will also be conducted in collaboration with FFI.*

MSc. Vegard Østli *started his PhD studies at NTNU in 2018, with prof. Fredrik Carlsen as supervisor. The project focuses on developing behavioral models for travelers and firms in order to predict the market impact of introducing new technologies in the transport sector. Another key aspect is to evaluate how public policy can contribute to the uptake of new technological solutions.*

MSc. Agnieszka Lach's *PhD studies are undertaken at USN under the supervision of Prof. Knut Vågsæther and Assoc. Prof. Andre Vagner Gaathaug . The project focuses on hydrogen release in confined spaces such as parking garages and tunnels, and experimental studies will investigate hazards related to formation of combustible clouds and their combustion phenomena.*

MSc. Eivind Hugaas*' project at NTNU focuses on hydrogen storage tanks, and he is studying fatigue data via experimental testing and modelling, in close collaboration with the Norwegian industrial partner Hexagon. Eivind's supervisor is prof. Andreas Echtermeyer.*

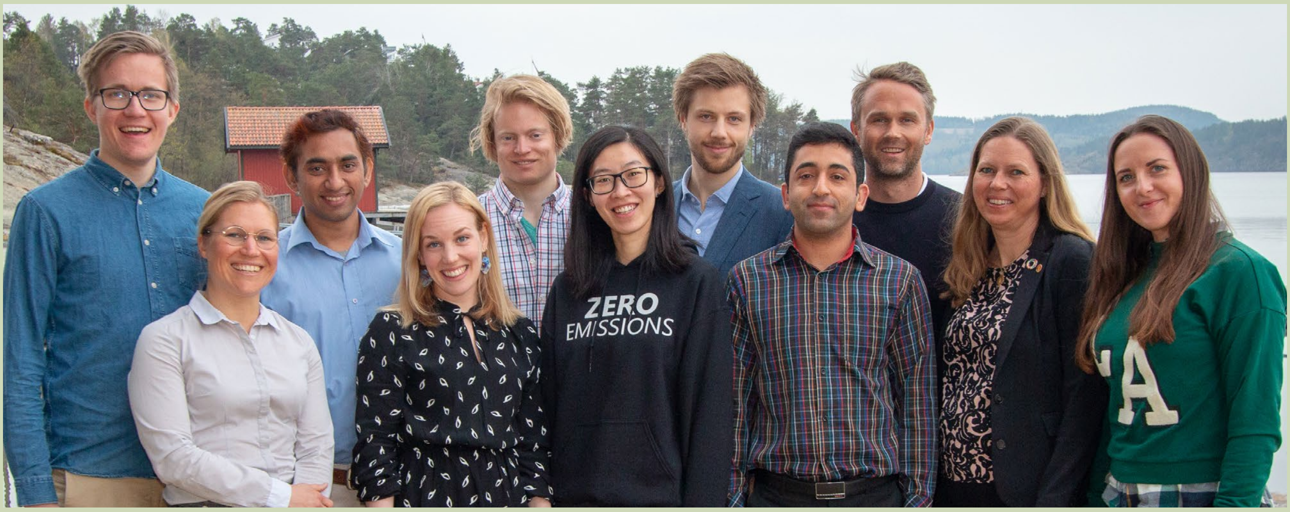
MSc. Daniel Tevik Rogstad *embarked on his PhD studies at NTNU the fall 2017, with prof. Ann Mari Svensson as his supervisor. Daniel is investigating Silicon anodes and ionic liquids in Lithium-ion batteries.*

MSc. Elise Ramleth Østli *started her PhD studies at NTNU in 2017, with RA1 manager Prof. Fride Vullum Bruer as supervisor. She aims at the development of water-based manufacturing routes for electrodes in an effort to stabilize the electrode/electrolyte interface.*

MSc. Ika Dewi Wijayanti *joined MoZEES as a PhD student at NTNU and IFE from 1 January 2017 and is working on Nickel metal hydride batteries. The studywas undertaken in collaboration with our international industrial partner BASF-Ovonic, aiming to develop high voltage and high power non-aqueous metal hydride batteries.*

MSc. Mathias Henriksen *embarked on his PhD studies at USN in 2017, and focuses on hazards – such as explosions – related to accidents with Li-ion batteries in transportation. The work is supervised by prof. Dag Bjerketvedt and conducted in close collaboration with FFI.*

The Participants of the PhD seminar gathered on the pier during the MoZEES Annual Meeting 2019 (Photo: J.A. Wilhelmsen)



Statkraft and Hydro New Partners in MoZEES

In 2019 Hydro and Statkraft joined the MoZEES team as new partners. Statkraft is the largest renewable power supplier in Europe with interests in both batteries and hydrogen technology. Hydro Energy AS is a power company fully owned by Norsk Hydro ASA, a major producer of aluminium, now also a company with interests in batteries. Both these partners will provide invaluable input to our research on batteries and hydrogen for the heavy-duty transport sector.

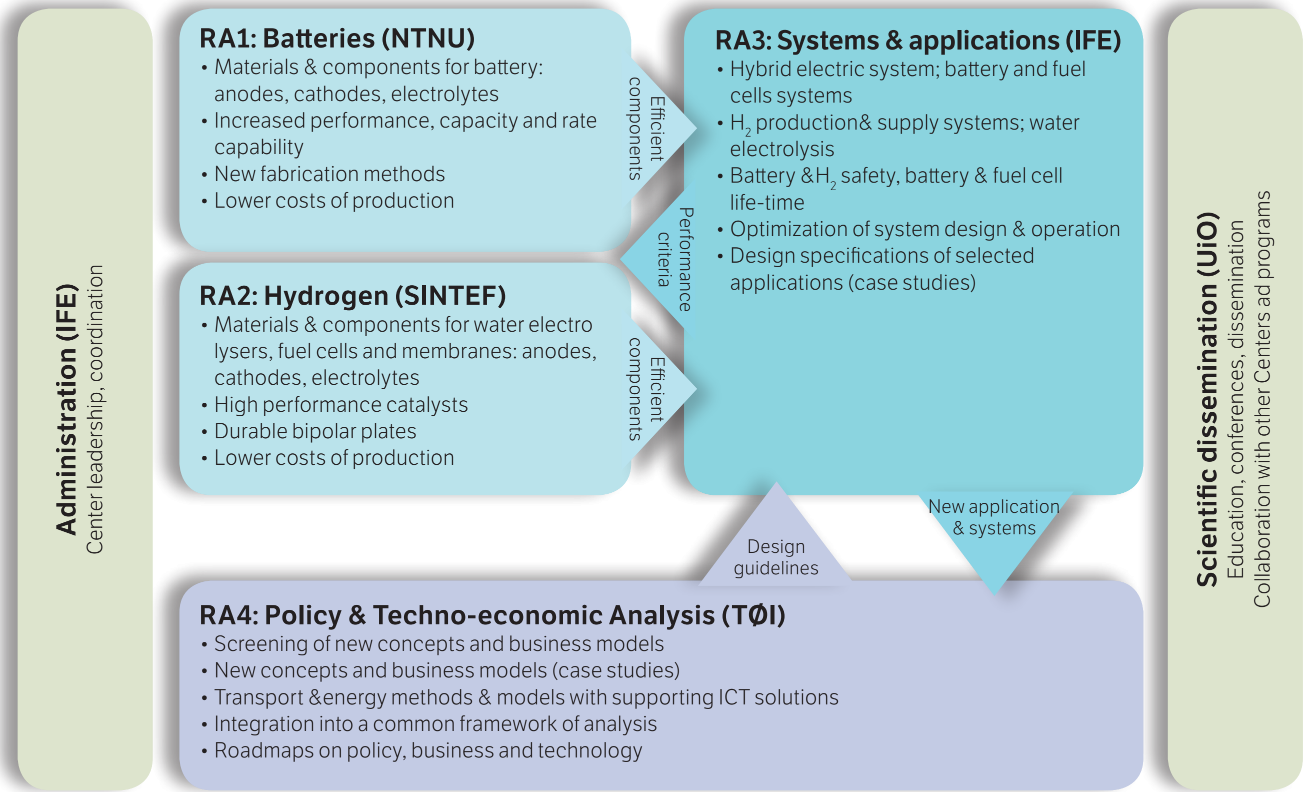
A MoZEES contract signing ceremony with representatives from our two new partners took place during the Board Meeting on Friday 8 November. Presentations were held by Ulf Eriksen (Head of Hydrogen Unit in Statkraft), Eeva Kantanen (Head of Business Development, New Technologies in Hydro) and Nils Morten Huseby (President, IFE).

MoZEES contract signing ceremony with Eeva Kantanen (Hydro), Ulf Eriksen (Statkraft) and Nils Morten Huseby (IFE). Photo: Øystein Ulleberg/IFE

From left: Øystein Ulleberg (IFE), Eeva Kantanen (Hydro), Nils Morten Huseby (IFE) and Ulf Eriksen (Statkraft). Photo: Gry Slotterøy/IFE.

Research Areas

An overview of the four main Research Areas (RAs) of the Center is provided in the figure below. RA1 and RA2 focus on research that can lead to breakthrough development in materials and key components for batteries and hydrogen technologies. The focus will be on building strong research teams to take advantages of multi-disciplinary expertise and cross sectorial capabilities. RA3 focuses on the design and operation of battery and hydrogen systems for specific applications. Detailed technical studies on safety, reliability, and energy efficiency will be performed, and used to develop system specifications and guidelines. In RA4 the focus is to establish a common framework of analysis, allowing new transportation concepts to be analyzed comprehensively under varying assumptions on technology, policies, incentives and governance measures.



RA1 Battery Materials and Components

The research area devoted to battery materials focuses mainly on the development of next generation high energy Li-ion batteries based on anodes with a high silicon (Si) content, and a spinel cathode $LiNi_{2-x}Mn_xO_4$ (LNMO). Two possible Si materials have been investigated. Several MoZEES industry partners are contributing to the research. Si from Elkem represents a material readily available at low cost and with low environmental impact. The second option is supplied by Cenate, which aims to develop nano-Si as anode material for Li-ion batteries. The LNMO material was obtained from commercial sources (Haldor Topsøe), synthesized by the research partners, or supplied by CerPoTech.

The NAFUMA group at UiO has explored how to achieve maximum charge storage out of laboratory synthesized spinel cathode $LiMn_{2-x}Ni_xO_4$ where x = 0.3-0.6 (LNMO) and of silicon anodes provided by Cenate. The work focuses on the material modifications and operando studies to understand the cause of capacitive losses in these electrode materials. For LNMO, different stoichiometries of nickel were introduced at manganese sites of the $LiMn_2O_4$ spinel material for achieving longer cycling stability and higher energy density. Having more Ni is good for the energy density while Mn is good for structural stability. Four compositions were synthesized and tested for charge storage performance in half-cells against Li/Li+ at C/5 current rate in the potential window of 3.0-5.0 V, as shown in Figure 1a). LNMO with x = 0.6, 0.5 and 0.4 show huge initial losses during the initial ~25 cycles and lower capacity retention in further cycles. However, LNMO with x = 0.3 performed well with, and showed a stable charge storage capacity of ~115 mAh g^{-1} up to 200 cycles with minimal losses in the initial 25 cycles, while x= 0.4, 0.5 and 0.6 have capacities below ~100 mAh g^{-1} after 100 cycles. Stability of interface, crystallographic phase and structural stability of spinel during lithium ion movement is important for the long-term performance of spinel cathodes.

Photo: Geir Mogen

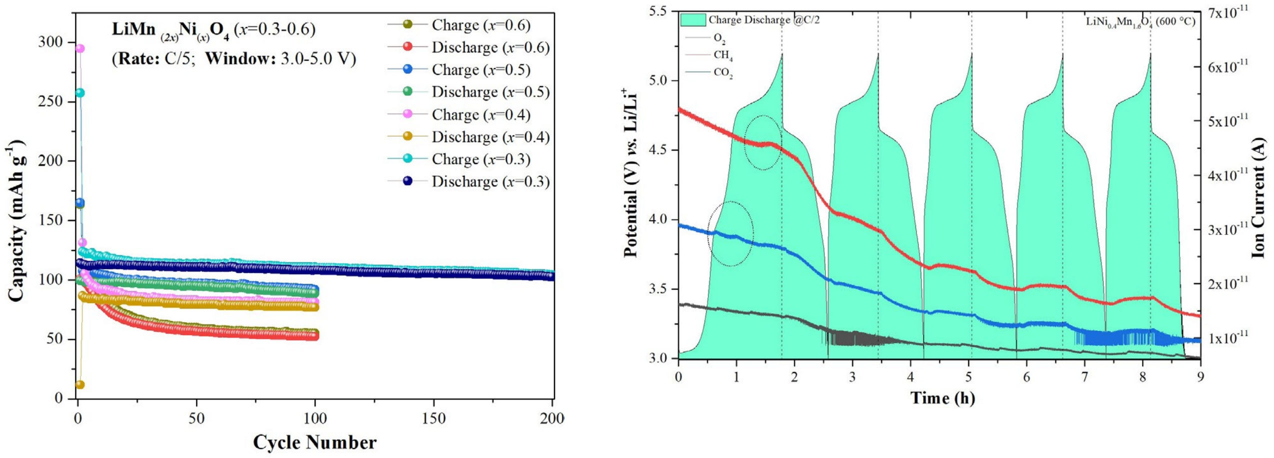


Figure 1: $LiMn_{(2-x)}Ni_xO_4$ (x = 0.3-0.6) half cell a) Charge-discharge at C/5 current rate in potential window of 3.0-5.0V and, b) Operando-Mass Spectrometry of $LiMn_{1.6}Ni_{0.4}O_4$ (ordered phase) cathode charge-discharge at C/2 against to Li/Li^+ in potential window of 3.0-5.2V.

To check the cause for instability, the x=0.4 composition of LNMO was tested by in operando mass spectrometry to analyze gas evolution. The conventional battery electrolyte 1M $LiPF_6$/(EC:DMC) is unstable in the working potential window of the LNMO cathode, but due to interface formation in the initial charge cycle, an electrode-electrolyte interface is formed which provides basis for reversible charge storage activity. During this formation, components break, and solid mass is deposited on electrodes and gases evolve are indirect signatures of the interface formation. The ordered variant of the $LiMn_{1.6}Ni_{0.4}O_4$ cathode was tested for gas evolution by means of in operando mass spectrometry, Figure 1b). The two plateaus in the electrochemical curves at 3.9 V and 4.8 V represent Mn and Ni activity, respectively, and result in two different gas evolutions during the first charging cycle. During Mn activity only CO_2 has evolved, while at Ni activity both CO_2 and CH_4 are evolved, as encircled in Figure 1b) in the first charge cycle. This is directly showing the peculiar roles of Ni and Mn in the interface formation at the LNMO cathode. A detailed study on these phenomena is on its way and will give new understanding on the LMNO electrode stability. Furthermore, synchrotron operando data are being analyzed for LMNO materials (including Co-substituted variants).

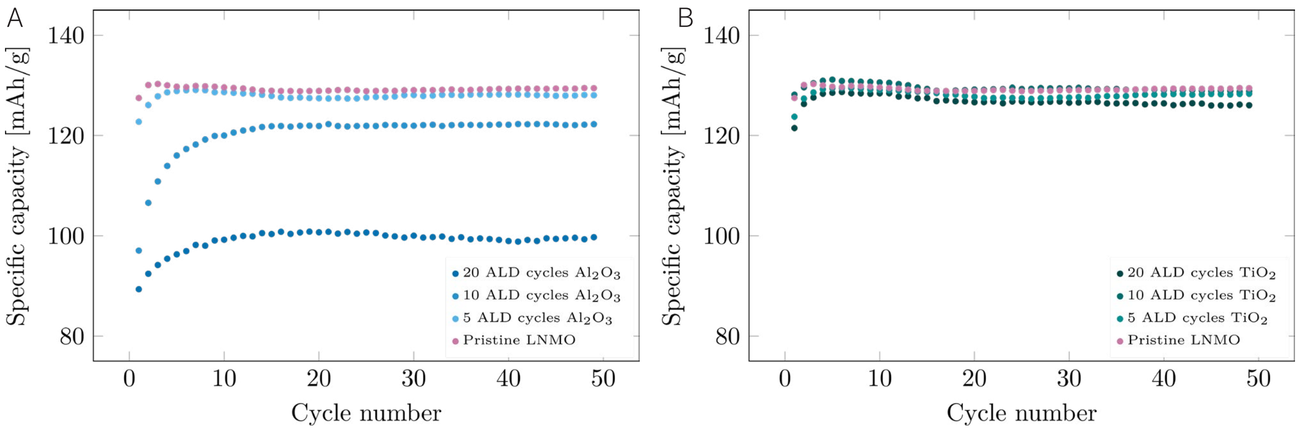


Figure 2: Discharge capacity for a) LNMO coated with Al_2O_3 b) LNMO coated with TiO_2.

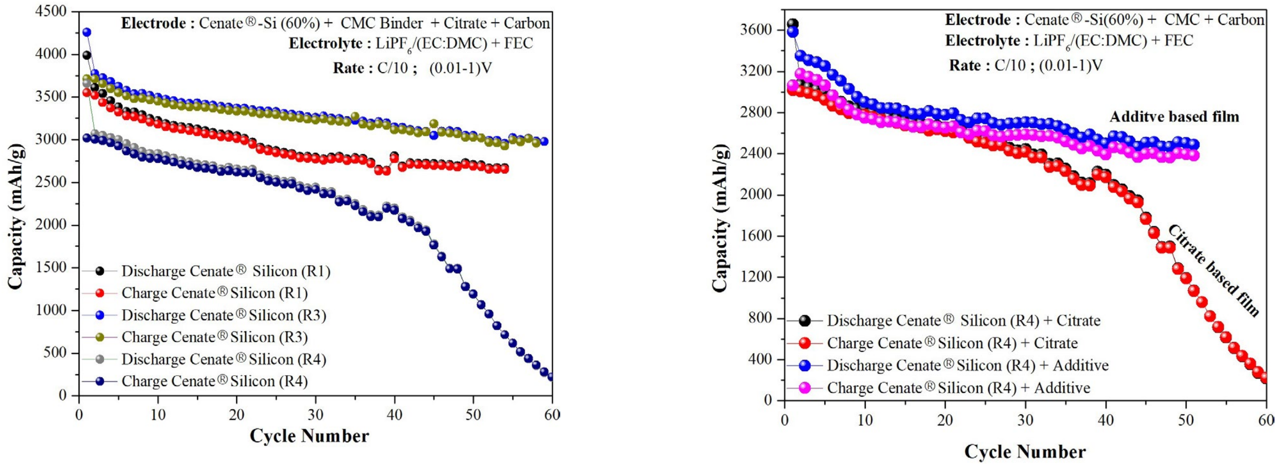


Figure 3: Electrochemical charge storage performance of Cenate® silicon in half cell assembly at C/10 in potential window of 0.01-1.0V against to Li/Li^+ a) Different size and crystallinity of silicon electrodes with citrate buffer b) Cenate® silicon R4 with newly developed additive without citrate buffer.

In collaboration with the University of Uppsala, NTNU has coated the commercial LNMO ($LiNi_{0.43}Mn_{1.57}O_4$) material with thin layers of TiO_2 or Al_2O_3 to evaluate the effect of coating on the cyclability. Several thicknesses of coating have been tested (5, 10, and 20 ALD cycles). Figure 2 shows the discharge capacity for half-cells containing Al_2O_3-coated and TiO_2-coated LNMO compared to the pristine LNMO material. The cells were tested using C/10 rate for all cycles. There is a clear trend of decreasing capacity with increasing coating thickness for the Al_2O_3 coated samples, while for the TiO_2-coated samples there is no such clear trend.

At SINTEF, in collaboration with NTNU, the focus of the cathode research has been on Ni-rich NMC materials (such as $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$), and modification of these, either by coating with silica, or doping with Al (such as $LiNi_{0.83}Mn_{0.07}Co_{0.09}Al_{0.01}O_2$). The best results were obtained for Al-doped NMC with respect to cycling stability. Furthermore, aqueous processing of electrodes from Ni-rich NMC active materials has been attempted, and a promising route involving additions of phosphoric acid has been demonstrated, although the cycling stability of the processed electrodes still need to be improved. Successful aqueous processing is very important for improving the environmental footprint of battery fabrication.

At UiO, three variants of silicon provided by Cenate has been explored; R1 is amorphous with particle size 200-500 nm; R3 of 80-120 nm size is slightly crystalline; R4 of 50 nm size is crystalline. Their electrochemical charge storage performance has been tested against to Li/Li^+ at C/10 rate in an electrolyte of $LiPF_6$/(EC:DMC) with FEC as additive in the window of 0.01-1.0 V. The R1 and R3 sample performed better, whereas the fully crystalline nanoparticles of R4 silicon started losing capacity from the initial cycles and gradually lost capacity after the 30th cycle, Figure 3a). As the degree of crystallinity is increasing, irrespective of particle size distribution, the capacity appears to fade faster. The tests used electrodes made in a citrate buffer, well-known to tune properties of the CMC binder and in turn stabilize the silicon anode during cycling. The citrate buffer is not effective for crystalline nanoparticles, R4.

UiO has furthermore developed an electrochemically inactive additive that is introduced to the anode film. The newly developed additive stabilizes the electrode without using a citrate buffer. Various crystalline R4 samples are compared for electrochemical performance in Figure 3b). The R4 silicon that showed a huge capacity fade after 30 cycles for the citrate buffer electrodes at C/10 rate, get stabilized with the newly developed additive. Capacities of ~2500 mAh/g were noted after 50 cycles at C/10 rate, Figure 3b). A detailed study of the structural aspects of the additive and the impact of additive on electrode kinetics is underway.

On-going research within RA1 at NTNU focus on electrolytes based on ionic liquids in combination with anodes made from silicon provided by Elkem, with high content of Si (73 wt%). A wide range of ionic liquids have been tested in the project, and their excellent thermal stability have been verified by differential scanning calorimetry, implying that they have a potential for significantly improving the safety of battery packs. Most of the work has been conducted with addition of the LiFSI salt. EMIMFSI and $Pyr_{13}FSI$ have been identified as the most promising ionic liquid electrolytes and have been selected for further studies. For EMIMFSI, addition of LiFSI salt was compared to LiTFSI salt, and high content silicon anodes were found to cycle with a slightly improved stability compared to the LiFSI. However, the viscosity of these electrolytes is high, and the transport properties of Li^+ ions need to be further improved. The attempts to improve the transport properties have so far included the addition of small amounts of carbonate solvents, as well as operating the cells at higher temperatures. The addition of small amounts of carbonates did not compromise the thermal stability of the electrolyte. The operation of the cells at elevated temperatures is potentially appealing as it may reduce the need for cooling of battery packs.

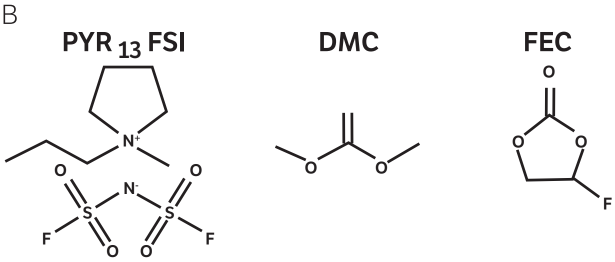
Cycling performance obtained with $Pyr_{13}FSI$ mixed with carbonate solvents, are shown in Figure 4 below. While the pure ionic liquid shows excellent cycling stability, the rate performance is significantly improved upon addition of both FEC and DMC carbonates.

A

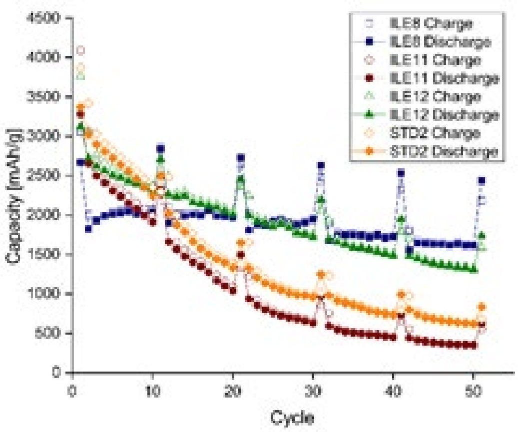
Electrolytes, mixture of Pyr13FSI and carbonates

Name	Composition
ILE8	LiFSI:$PYR_{13}FSI$
ILE11	LiFSI:$PYR_{13}FSI$:DMC
ILE12	LiFSI:$PYR_{13}FSI$:DMC:FEC
STD 2	1 M LiFSI in EC:DMC:FEC:VC

B



C



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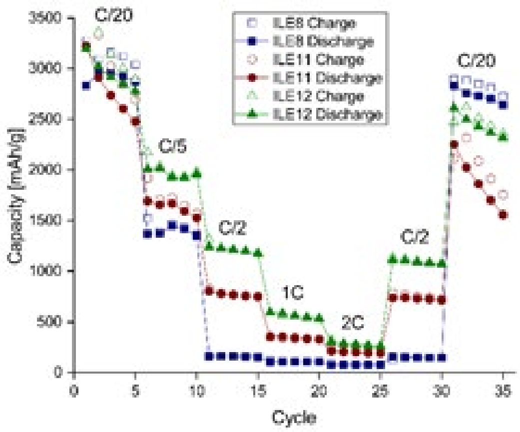


Figure 4: a) Electrolyte compositions studied b) Structure of the electrolyte components c) Cycling performance of anodes made from Elkem´s silicon (73 wt% Si) with the electrolytes, obtained at C/5 d) Rate capability of the same electrodes and electrolytes.

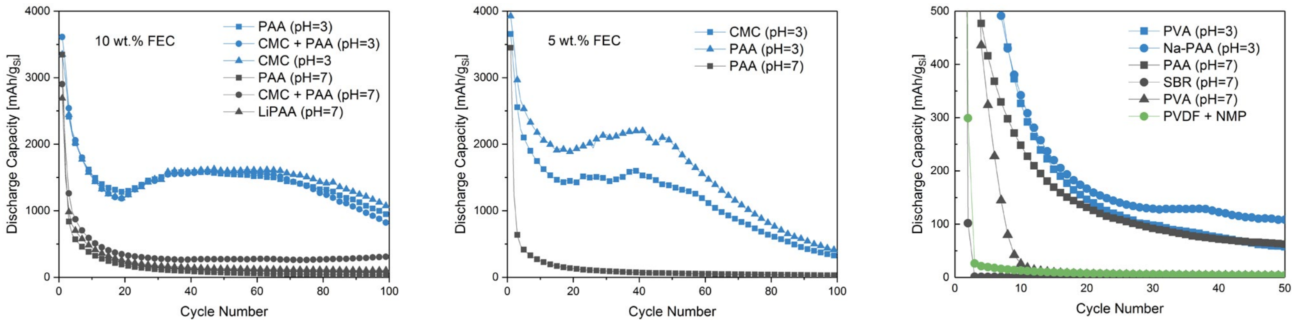


Figure 5: Influence of pH for electrode slurry processing on the lifetime for Si-based anodes: left – cycling performance with high FEC content in the electrolyte; middle – cycling performance with moderate FEC content in the electrolyte; right – a collection of binder combinations that were not found practical for the electrodes with high Si content (cycled using moderate FEC content; included for reference and will not be included in the publication).

Pre-lithiation of Si-anodes has been studied at IFE, as well as the effect of different binder systems on the Si-based electrodes. The latter include studies of the fabrication of the electrodes with high Si content, using Si particles obtained from Elkem (part of SiBEC-project). The results obtained with different polymeric binders and electrolytes in this work are shown in Figure 5. The influence of the pH of the binder-solvent system was shown to have a tremendous effect on the stability of the electrodes. A paper summarizing the results is currently in the final stage of preparation.

International Collaboration

UNIVERSITY OF UPPSALA

Within the Battery Materials Research area, there has been an active collaboration with University of Uppsala, involving visit by PhD student Elise Ramleth Østli, starting from 1st of August 2019. The aim of her stay was to apply coatings (by ALD) to commercial LNMO materials, and thereby demonstrate improved stability of these cathodes. Professor Ann Mari Svensson was a guest professor at University of Uppsala in the period August 2018 to June 2019, funded by the KPN project SiBEC, affiliated to MoZEES. Professor Kristina Edström (Uppsala University) gave a presentation (High Precision and Post Mortem Studies of Li-ion Batteries) at MoZEES Battery Days 2019.

SAFT

In 2019, an active collaboration has been initiated with the industrial partner SAFT (French battery producer). Together with SAFT, partners in MoZEES have designed a Round Robin test for electrochemical characterization of commercial electrodes supplied by SAFT. The activity will later be extended to include a larger variety of materials, i.e. from MoZEES partners. All battery materials research partners are participating in the activity (IFE, NTNU, UiO, SINTEF), as well Elkem. On the 5th of December 2019, a MoZEES workshop was organized at the premises of SAFT in Bordeaux, with all MoZEES research partners represented.

Figure 6: Participants in the workshop in Bordeaux.

RA2 Hydrogen Components and Technologies

The main objective of RA2 is to enable the production of fuel cells, electrolysers and hydrogen storage tanks with lower cost and higher efficiency, and thereby contributing to reaching the 2025 targets (DOE & EU) for transportation fuel cells, hydrogen production from renewable energy sources and hydrogen storage. The work is prioritized within development of high performance electrocatalysts, low-cost bipolar plates and membranes and improvement of testing protocols for high pressure composite hydrogen pressure vessels.

Collaboration with user partners and international collaboration

In RA2 the collaboration with user partners in 2019 has been through discussions, transfer of knowledge and on-site training. Johnson Matthey visited the Norwegian Fuel Cell and Hydrogen Centre in Trondheim to perform tests on PEM electrolysis in collaboration with SINTEF researchers and have actively participated in several discussions on materials selection and testing of components. NEL Hydrogen has given valuable input to materials and relevant experimental conditions for investigation of alkaline bipolar plates.

Task 2.1 – High performance catalysts

Ruthenium pyrochlores have lately been reported to have high catalytic activity for oxygen evolution and higher stability than ordinary ruthenium oxides in acidic environments. We have in MoZEES started an activity to also investigate this class of materials under operating conditions in single PEM electrolyser cells. In 2019, $Ru_2Y_2O_{7-d}$ electrocatalyst powder were produced and characterized ex situ to ensure proper microstructure and composition for catalyst layer manufacture and *in situ* testing in PEM electrolyser single cells will be performed in 2020.

Task 2.2 – Low cost bipolar plates

Alkaline electrolysers

Various stainless steels, particularly 316 SSL, have been studied for the use as the electroactive material for oxygen evolution in alkaline water electrolysis. Stainless steels offer cheaper electrode materials than the current solutions but needs certain surface modifications in order to reach necessary performance. In this task, stainless steel material is activated through electro-oxidation

Figure 1: SEM micrograph of $Ru_2Y_2O_{7-d}$ catalyst powders.

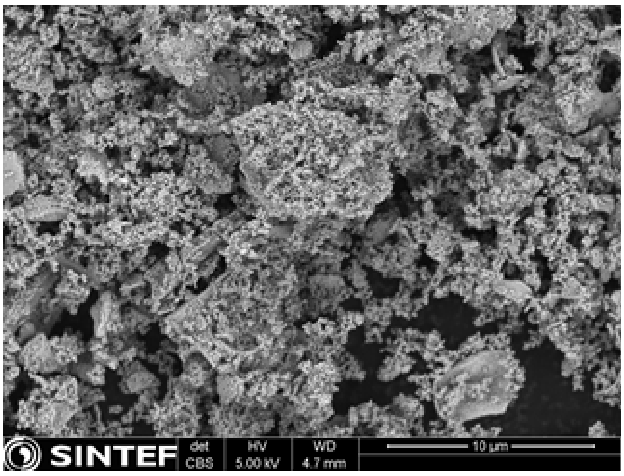
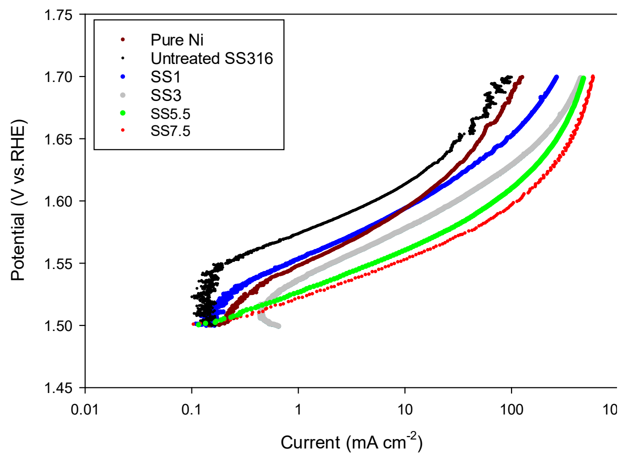


Figure 2: Polarization curve of the various stainless steel samples and nickel in 1M KOH and at ambient condition. The numbers (1, 3, 5.5 and 7.5) represents the pretreatment solution's molarity.



at high pH. Durability and activity of the samples were analysed by polarization curves (Figure 1) and potential step measurements. A correlation between surface properties and pre-treatment solution's pH has been established by using surface characterization techniques such as XPS, GD-OES, GI-XRD, Raman spectroscopy and SEM. These correlations will be further used as a starting point for selecting the optimum pretreatment procedure for other electrode materials such as Incoloy 800 and Inconel 718.

PEM fuel cells

SINTEF has been working with Teer Coatings LTD (TCL), based in Birmingham, UK. Coated stainless steel bipolar plates (BPPs) of two varieties, one with a proprietary carbon-based coating and a second with a standard gold coating, have been provided by TCL for testing at the Norwegian Fuel Cell and Hydrogen infrastructure, in Trondheim, Norway.

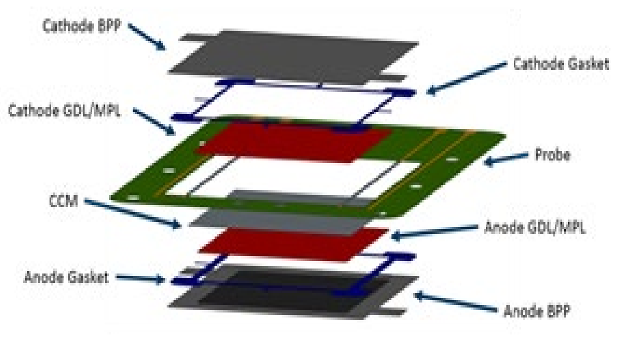


Figure 3: The in-situ ICR setup, whereby probes are placed between the MEA and cathode side GDL, to measure the contact resistance of the BPP/GDL interface over the lifetime of the fuel cell.

These two types of bipolar plate are currently being tested by performing a series of fuel cell load cycles, designed to simulate a fuel cell vehicle being driven on European roads. Full characterisation of the fuel cells was performed to determine the long-term performance of the bipolar plate over time. Techniques including electrochemical impedance spectroscopy, polarisation curves, cell voltage monitoring, and a novel *in situ* interfacial contact resistance (ICR) measurement (Figure 2) were performed while the cell was operating.

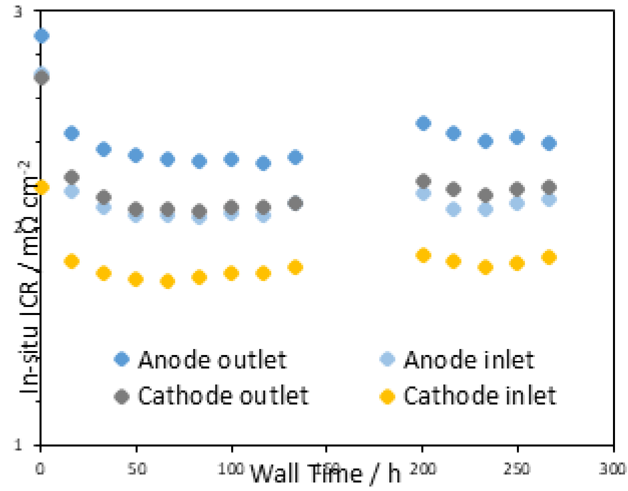


Figure 4: The in-situ ICR at the inlet and outlet of each BPP can be monitored over time, and shows a stable performance over 250 hours

Both sets of bipolar plated have so far undergone cycling for over 250 hours, and it is was observed that the gold coated BPPs showed better initial performance with a higher cell potential than the carbon coated BPPs. However, the results also showed that there was a much smaller performance recovery after shutdown at 170 hours. The subsequent performance of both bipolar plates was similar and will be further probed over the next 2000 hours.

Successful measurement of the *in-situ* contact resistance for the carbon coated BPP (Figure 3) shows that the ICR decreases in the first 50 hours of operation, due to gas diffusion layer saturation enhancing the contact, followed by a small increase in ICR afterwards, possibly due to some coating degradation or passivation. It is also observed that the anode side ICR is higher than the cathode, presumably due to the water production and therefore better conduction on the cathode side.

Task 2.3 – Improved membranes

In this task we investigate high temperature proton conductive polymers PBI and PEEK with various porosities, acid doping, and oxide fillers to identify the roles of surface and interfacial water and concentration and mobility of protons on long-term proton conductivity at temperatures above 100°C. The work has comprised synthesis, fabrication, and proton conductivity measurements of

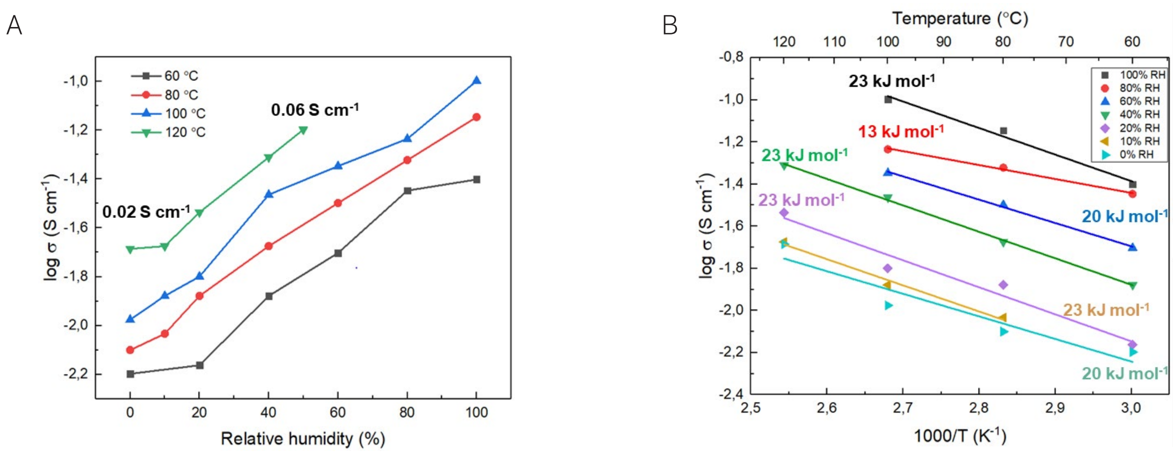


Figure 5: a) Conductivity of H_3PO_4-PBI as a function of RH measured at different temperatures with the commercial 4-probe testing compartment, b) the corresponding Arrhenius plot at fixed RHs.

H_3PO_4-PBI membranes under controlled relative humidity (5%<RH<100%) and temperature (RT<T<120 °C), as shown in Figure 1. Besides, H_3PO_4-PBI-TiO2 composite membranes with controlled filler contents and acid-doping were synthesised, the conductivity measurements will be conducted. PEEK pellets were fabricated, and are now ready to be measured.

Commercialization is cultivated in the Group for Electrochemistry at UiO, and a prototype 4-probe PEEK sample holder for conductivity measurements of polymer membranes in a ProboStat® was designed and constructed (Figure 2 a). This allows measurements under higher temperatures and steam pressures than what is reachable in previous commercial systems. The PEM sample holder has been tested with selected standard PEM materials incl. Nafion® N-115 (activated), undoped PBI membrane and gold contacts. One example with results to 160 °C is shown in Figure 2 b.

There was also published a review article on "Composite membranes for high temperature PEM fuel cells and electrolysers by PhD-student Xinwei Sun *et al*.

Task 2.4 – Lifetime, durability and performance

In 2019 the main focus was on processing and analysis of the neutron image recordings of a PEM water electrolysis cell in operando performedand writing up of a report describing the experimental and methodological aspects of these experiments. This activity has been part of an

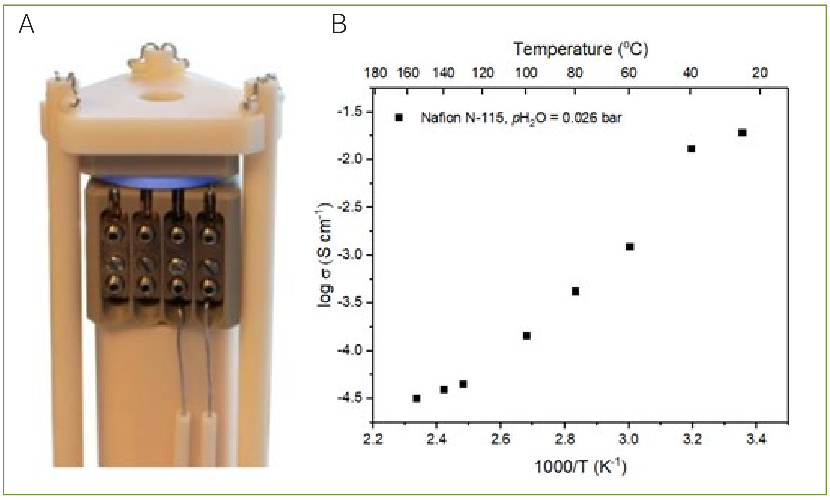


Figure 6:

a) PEEK 4-probe sample holder for conductivity measurements of polymer membranes in a ProboStat®,

b) temperature-dependence of the conductivity of Nafion® N-115 membrane investigated between room temperature and 160 °C in a 4-electrode configuration at pH_2O = 0.026 bar.

effort to investigate the applicability and usefulness of neutron imaging for characterization of PEM WE cells, as well as to develop expertise on the methodology in order to be able to utilize the planned Norwegian beam line NIMRA to its full potential. NIMRA was supposed to be commissioned in 2019/2020 as a part of the national research infrastructure NcNeutron, but after the shut-down of the nuclear reactor JEEP II at IFE in 2019, the activity has been put on hold until a replacement beam line has been identified.

Task 2.5 – Hydrogen storage tanks

Traditional testing methods of composites often come short of capturing the underlying mechanisms of fatigue and fracture. They typically measure global properties from test specimen with simple geometries that cannot characterize the local effects governing fatigue, particularly around damaged areas. This lack of understanding has become critical when evaluating and modelling the effect of damage to large and expensive composite pressure vessels for hydrogen transport or storage. Good models are needed for providing the basis to make decisions whether a damaged composite pressure vessel can remain in service, needs to be repaired or discarded.

In this research task the cutouts from damaged pressure vessels were fatigue tested using a split disk setup monitored using high frequency digital image correlation (DIC). It was found that micro failure of the epoxy may be beneficial for the structural integrity over time and that the fiber can locally withstand very high strains over long time. The experimental results were used to develop a numerical method to predict fatigue failure and damage spread in pressure vessels and composite components. Figure 5 outlines the numerical method's principle and shows structural response for a load-controlled fatigue test of a damaged split disk specimen. Figure 6 shows damage evolution in a split disk test of a damaged specimen (hole) and in the numerical model at the same stage in fatigue life. As can be seen, the split disk test has a very uneven spread of damage but averaged over all four sides it resembles the model reasonably well. By applying a data-based approach using the DIC data for damage calculation as in the numerical model, a good comparative background emerges that has served both the understanding and the numerical development well.

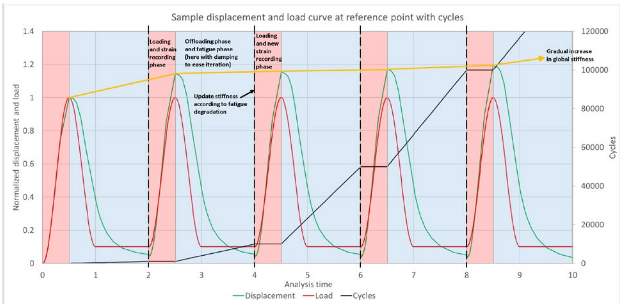
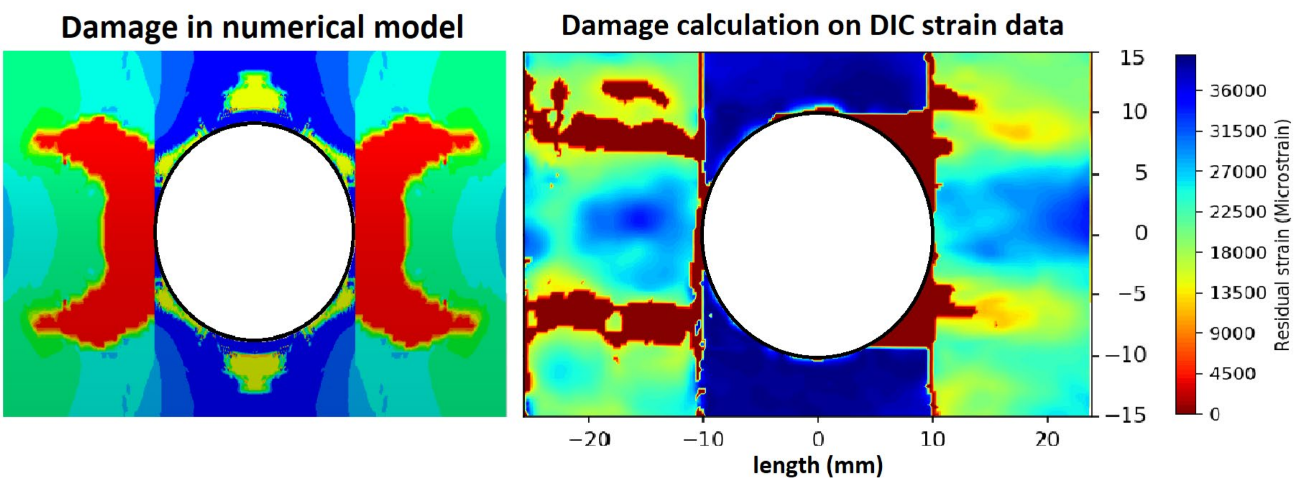


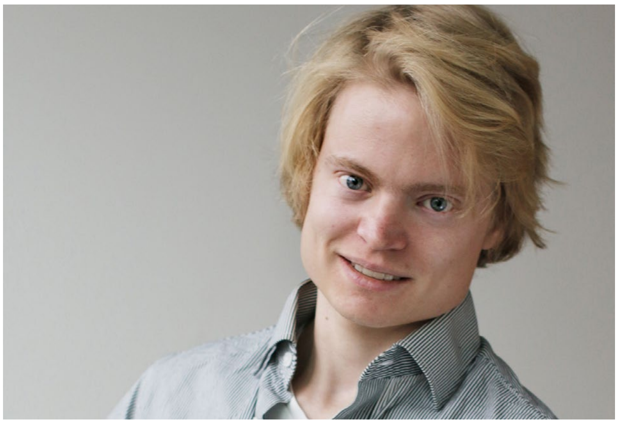
Figure 7: Schematic showing the structural response of a fatigued split disk specimen with damage in a numerical analysis.

Figure 8: Damage calculated on the DIC strain data compared to the numerical models damage prediction on a split disk specimen with damage (hole) with the global response as seen in Figure 1.



RA2 PhD Blog: Skis, Composites and Hydrogen

Isn't it fascinating how much deformation your skis can handle, and yet they suddenly break without warning? In this blog post PhD student Eivind Hugaas describes the properties of composite materials used in hydrogen storage tanks and his experience with testing them in the lab.



Composites are fairly complex materials. The testing of them is no exception.
First of all, carbon and particularly glass fibre reinforced epoxy (in popular terms just "glass fibre") is a lot softer material than steel. Though "soft" is maybe not what people associate with their windows (made of glass), the opposite is true in relative terms when compared to most standard steel types. This makes for some interesting scenes in the lab. It can be a bit unnerving to see your sample stretched like a spaghetti compared to the metal rod that's barely doing anything on the neighbouring test rig while actually being close to breaking. Very likely your sample got a lot more residual strength, so no need to worry.

Looking at ski sports such as ski jumping or downhill in slow motion is a very good exercise to understand just how much deformation glass or carbon fibre can take before breaking. The skis often consist of glass or carbon fibre in areas that are subjected to large deformations. The skis sometimes bend ninety degrees or more but if you try to bend them that much by hand you would need superhuman force. Though the softness

Photo by David Becker on Unsplash

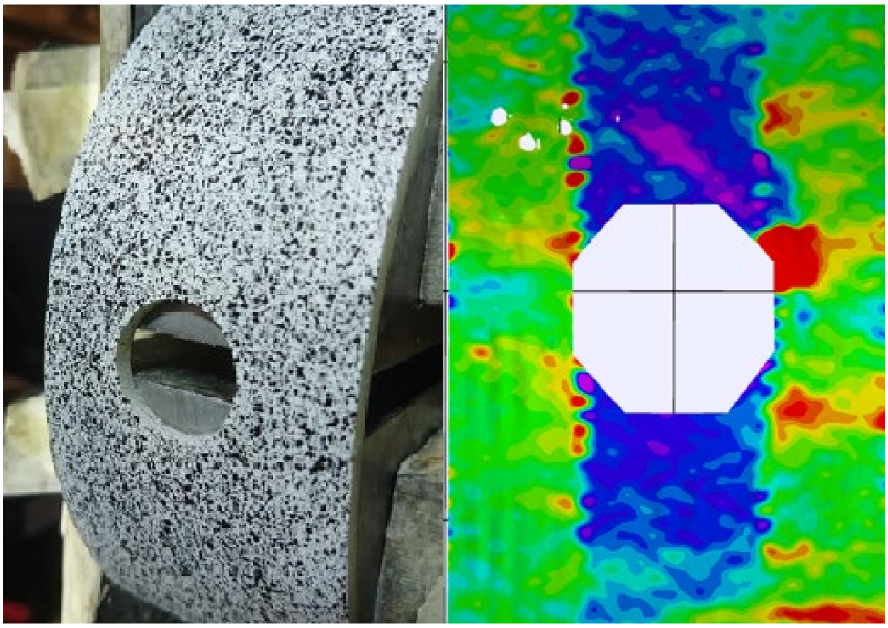
obviously contributes to the fact that the glass fibre can handle so much deformation, it does not get any softer as it deforms, such as most metals; it just suddenly brakes. Through the years, countless ski enthusiasts have encountered this quality as their skis break without warning.

The skis sometimes bend ninety degrees or more but if you try to bend them that much by hand you would need superhuman force.

From a testing perspective, dealing with large deformations is nice as it's very visually obvious what's going on in the material. To monitor the deformations, Digital Image Correlation (DIC) is a good and robust solution employed in my research. DIC uses images to recognize patterns on the sample, usually in the form of a black and white speckle pattern that is sprayed onto the sample. When the sample deforms, clever software calculates how much the speckles have moved and then gives you the deformation in the different areas of the sample. Figure 1 shows a raw image from a sample during testing and how it is processed by the software to show degree of deformation. As can be seen, the sample deforms a lot around the hole, as would be expected.

The big question is what happens to the material when it is subjected to large deformations over longer periods of time such as a ski used over many years? Does the ski have the same feel after say, two years? This question is my main topic of interest.

Based on what is known, quite a lot happens to the ski over time. Firstly, the epoxy will crack. This happens early on and for most skis has likely happened already after the first trip. Though the epoxy cracks, it keeps the structure together, and keeps an even distance between the glass or carbon fibres, which are the actual loadbearing parts of the material. After the epoxy has cracked, the material loses a tiny bit of stiffness and reaches a "steady state" stiffness. Further load cycling will gradually make the bonding between the epoxy and the fibre shear and as a result deformations will in most cases be distributed more evenly, which is beneficial for the strength. Exactly what mechanisms are in play and how they interact is a hot topic for research and something I'm trying to solve. It is likely to assume that an expensive ski with high quality carbon and epoxy will be less prone to fatigue problems and will perform consistently over many years.



The glass fibre specimen with speckles and the resulting degree of deformation plot

RA3 Battery and Hydrogen Systems and Applications

The main objective with RA3 is to develop, test, validate, and study the performance of battery and fuel cell technologies and systems, and to optimize the design and controls of systems suitable for heavy duty road, rail, and maritime applications. There is a specific focus on heavy duty hybrid battery/fuel cell systems, battery and hydrogen safety issues, and maritime applications. The main research questions in RA3 are related to:

- Design and control of battery and fuel cell systems (with the goal to maximize lifetime)
- Safety and risk management associated with heavy-duty battery and FCH-systems
- Design of RE-based water electrolysis and hydrogen supply systems (with the goal to reduce costs)

Task 3.1 – Advanced Fuel Cell Control Systems
In this task PEMFC-systems are designed, validated, and optimized for use in heavy-duty transport applications, with a special focus on systems suitable for integration into ships.

One of the major accomplishments in this task has been the finalization of a MATLAB Simulink PEM fuel cell and Li-ion battery model. In this model the FC and Li-ion battery are connected through DC/DC converters to a DC bus that provides power to the load. The FC converter controls the FC current (boost converter) and the battery converter controls the DC grid voltage (bidirectional converter). Upon changes in the FC output power, the battery absorbs/inject power to keep the DC bus stable. Fig. 1 depicts the battery state of charge (SoC) and current for a simulation where the reference fuel cell power is increased as a ramp signal from 400 W at time t = 12s until it reaches 800 W at t = 50s. Then, at time t = 220s, the power decreases as a ramp signal until it reaches 600 W. The simulation shows that when the fuel cell is

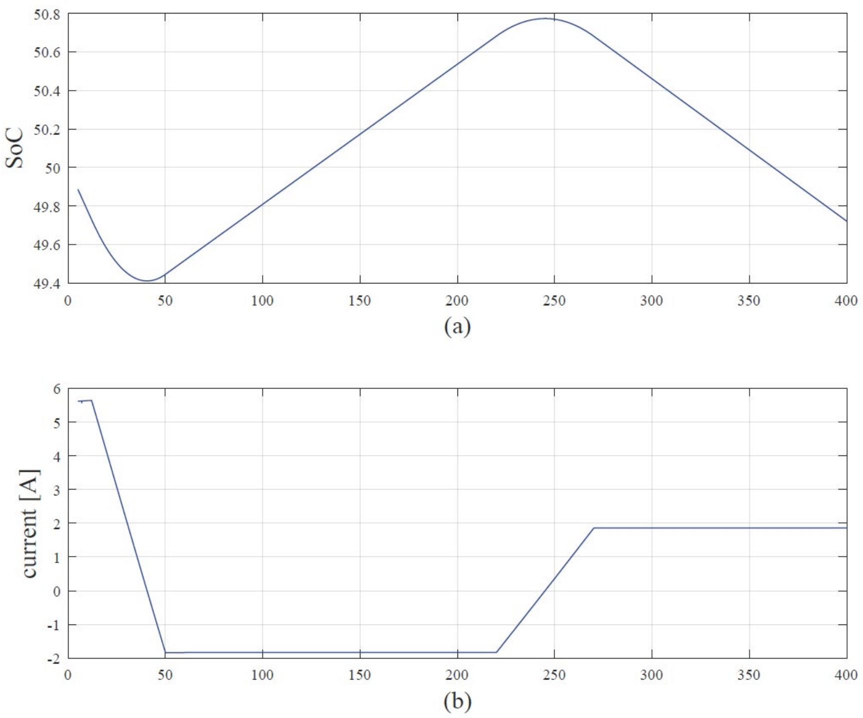


Figure 1: battery state of charge and current during simulation of a PEMFC, Li-ion battery and two DC-DC converters

producing 800 W, the excess energy is absorbed by the battery (notice the negative current), and the SoC starts to increase. This MATLAB Simulink model will be further refined within MoZEES by implementing a realistic FC load duty cycle relevant for MoZEES transport applications (ref Task 3.5). Furthermore, by adding battery- and fuel cell lifetime models, an energy management system maximizing the component lifetime and minimizing the fuel consumption may be developed.

Task 3.2 – Battery cell lifetime, durability, and safety

Battery cell design and operation is crucial for battery cell performance and safety, and so is the development of different methods to study degradation occurring in the batteries as result of cycling. The procedure developed for non-destructive battery cell characterization in 2018 were applied to cycled 18650 Li-ion cells with an NMC-graphite chemistry in 2019. The post-mortem analysis of a cell with 76% of original capacity clearly showed a physical change in form of buckling of the electrode roll into the core void of the battery cell. The results also showed that the microstructure of the electrodes had been changed; silicon particles in the anode became porous, and a fine nano-structuring was formed on the surface of these. On the cathode side, intergranular cracks in the NMC granulate particles were observed. The analysis of the electrolyte demonstrated a significant effect of cycling on the electrolyte composition.

In order to be able to collaborate and share information about battery cell degradation and lifetime openly between all partners, as well as to publish results without restrictions, it was decided to acquire a common battery reference cell with a known cell chemistry. In 2019 such a MoZEES Li-ion reference cell was selected: 50 small (142 x 125 mm) tailor-made pouch cells with graphite anode, NMC cathode (6:2:2) and electrolyte with all known additives and solvents were procured from the company Customcells. In 2020 these cells will be characterized with respect to lifetime and degradation by IFE, FFI, SINTEF and NTNU.

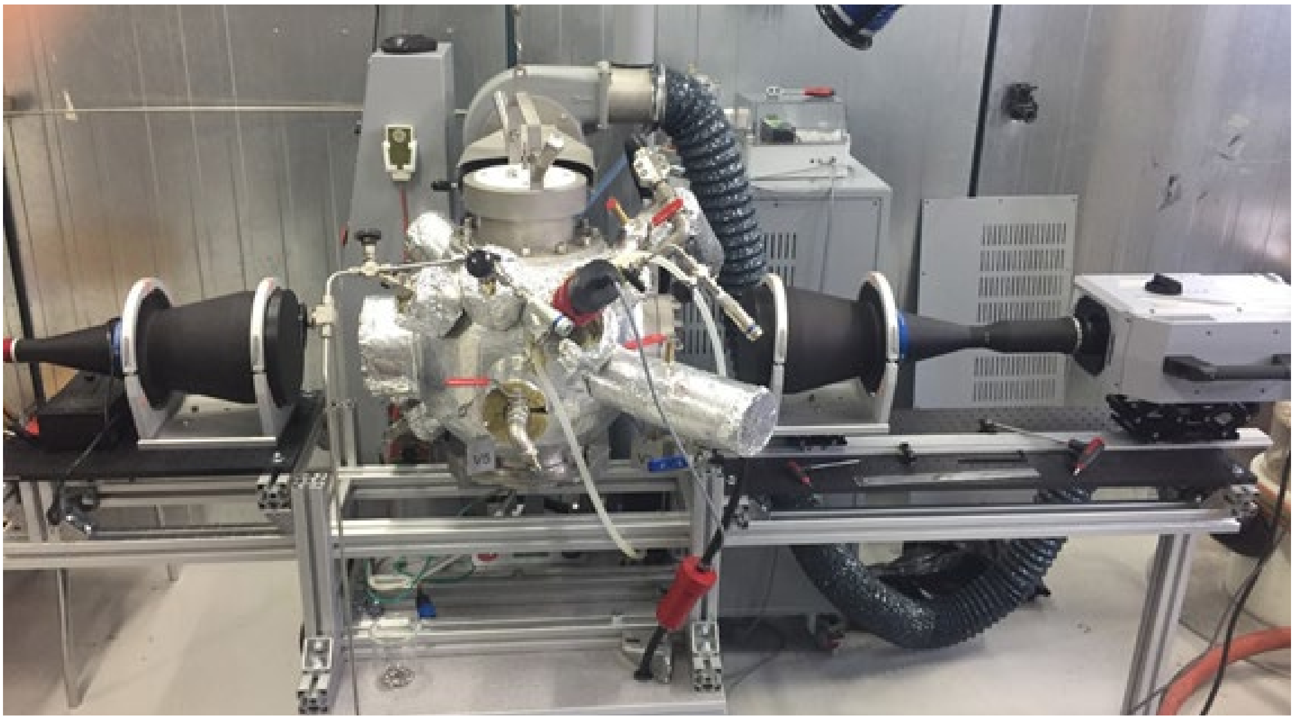
Finally, in 2019 a battery cycle life model was finalized at IFE based on an Artificial Neural Network on two sets of battery ageing data. A paper on the state of health prediction of Li-ion batteries was published in the proceeding of the IEEE PowerTech 2019. A popular scientific summary of this work is provided below.

Task 3.3 – Battery and Hydrogen Safety

Battery Safety

In 2019 an explosion rig for Li-ion battery electrolytes was commissioned at USN to produce validation data for CFD-models. The rig is a semi-closed small container with obstacles of 18 mm diameter for flame acceleration and is pictured in Fig. 2. The explosion sphere was used to determine the explosion pressure, the rate

Figure 2: The 20-liter explosion test rig at USN



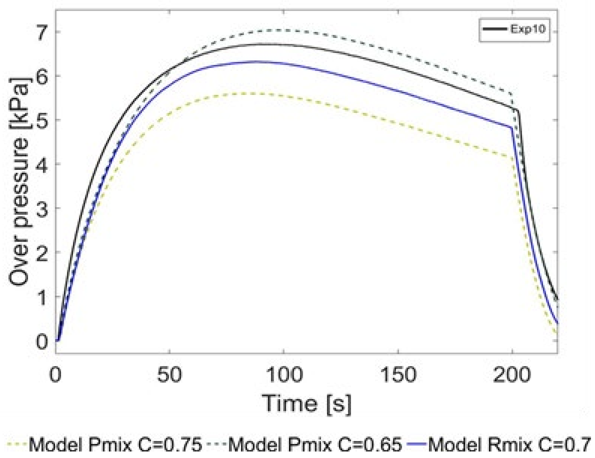
of explosion pressure rise, and the lower and upper explosive limit for dimethyl carbonate, diethyl carbonate, and ethylmethyl carbonate (representative of gasses vented from Li-ion batteries during thermal events) at different concentrations. The carbonates analysed where shown to have very similar explosion pressures and rate of explosion pressure rise as propane. The explosion characteristics found for the three carbonates can be used in future consequence and risk assessments for Li-ion battery installations. This work was summarized in apaper on “Explosion characteristics for Li-ion battery electrolytes at elevated temperatures“ the Journal of Hazardous Materials.

Hydrogen Safety

A PhD student working with hydrogen safety started at USN in 2019. The focus of her project is hydrogen release, dispersion and jet fires in semi-closed spaces. This research is also is part of the European HyTunnel-CS project.

The rapid discharge of hydrogen from a storage tank in a vented enclosure may lead to a transient overpressure with a characteristic peak, which may cause life and property damages. This is a so called pressure peaking phenomenon (PPP) and occurs when the released hydrogen mass flow rate is relatively high, and the vent area is relatively small. In 2019 USN investigated the PPP for unignited and ignited hydrogen releases in a 15 m^3 enclosure. Ten tests were performed for unignited H_2 releases with mass flow rate in the range 1.9-10.2 g/s, and approximately thirty tests were performed for ignited tests with hydrogen mass flow rate in the range 1.4 g/s to 11.5 g/s. For both unignited and ignited releases, the venting area was varied to assess the combinations of H_2 flow rate and venting area leading to damaging overpressure. The second stage of the experimental campaign will be the investigation of releases from a 700 bar tank, a tank which will be supplied by MoZEES industry partner Hexagon.

Figure 3: Transient overpressure for unignited hydrogen release. Experimental data compared to models with various loss coefficients (C).



Task 3.4 – Water Electrolysis processes

The main objective with this task is to study novel efficient low temperature water electrolysis (WE) processes, with a special focus on design of PEMWE systems suitable for dynamic operation.

In 2019 a detailed PEMWE model was developed. This includes thermodynamic-, electrochemical and fluid-dynamic sub-models and returns the voltage- and faradaic efficiency of the cell and stack under various operating conditions. A preliminary version of a system model which includes the auxiliary equipment was also implemented. In 2020 the modelling tool will be further developed to study how PEM water electrolyzer systems exposed to dynamic operation from variable renewable energy sources (e.g. solar PV and wind) can be optimized with respect to energy efficiency and costs. The models will further be combined with cost models and applied in techno-economic studies of renewable energy based hydrogen refuelling systems (ref. Task 3.5).

User partner Nel Hydrogen provided operational data for one of their PEMWE systems (C Series hydrogen generators) performing under different conditions. Data representing a cold start, a warm restart and different load cycle tests were provided, and these were used to validate the models.

In 2019 the containerized high-pressure (350 bar) PEMWE system laboratory set-up constructed at IFE's workshop in Halden was installed at IFE Hynor Hydrogen Technology Center at Kjeller, and the low-pressure H_2O/O_2 loop was commissioned. A detailed description of the design of the test rig was published in a paper in

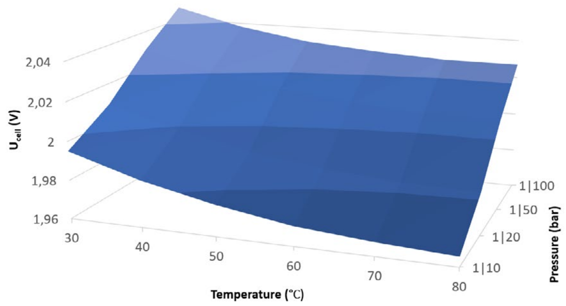


Figure 4: Modelled cell voltage as a function of temperature and cathodic pressure

the proceedings of the European Fuel Cell Forum 2019. The final commissioning of the high-pressure PEMWE test rigis planned for 2020.

Task 3.5 – Design specifications for specific applications
The main objective of this task is to derive design specifications of the fuel cell and battery hybrid systems on a selection of specific heavy-duty applications. Initially (2017-2019) there was a special focus on maritime applications. There exists today very limited knowledge on how to design and operate hydrogen and fuel cell driven energy systems for maritime applications in a safe and cost-efficient manner. The research performed in the maritime case studies provides public and private stakeholders in MoZEES with more detailed knowledge on technical and techno-economic risks and barriers related to the introduction of battery and hydrogen technology into the maritime.

The result from the first part of the Maritime Case Study dealing with hydrogen safety was published in the International Journal of Hydrogen Energy by Aarskog *et al*. This work was carried out according to the IGF. code and focuses on fatality risk related to the hydrogen systems on the vessel, both during operation and while moored in harbour. Based on this assessment, a new hydrogen ignition probability model and vulnerability thresholds were proposed, and recommendations on vessel design and risk reducing measures were given. The conclusion of the study is that risks associated with the hydrogen systems on the ferry are well within expected tolerance criteria.

In 2019 IFE also developed a new method on how to calculate energy/hydrogen consumption for a ship based on its power-speed-characteristics and positional data from AIS-data. The new method was then applied to a a case study on a high-speed passenger vessel route in Florø. The study included an analysis of the duty cycling of the fuel cell system, and a techno-economic analysis comparing the TCO of operating the ship with diesel, bio diesel and hydrogen. A manuscript from this work has been submitted to International Shipbuilding Progress. The methods and modelling tools developed by IFE were shared with TØI for further RA4-based MoZEES maritime case studies in 2020.

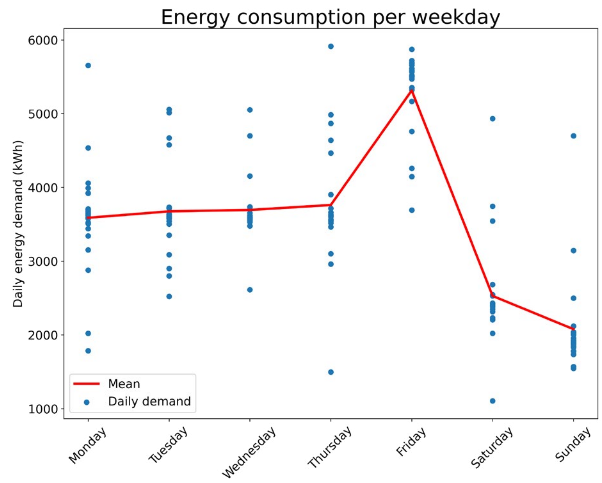


Figure 5: Estimated energy consumption per weekday for the reference route.

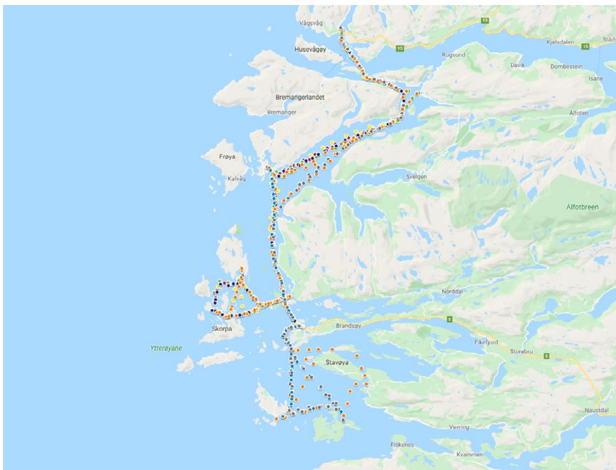


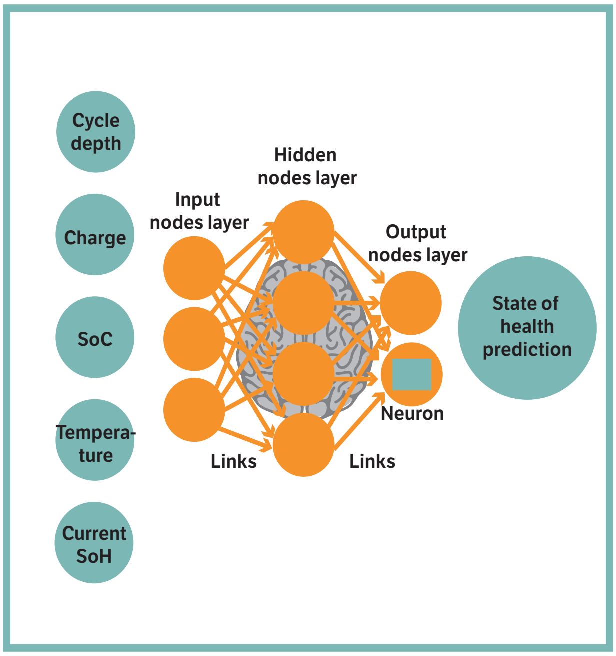
Figure 6: Historical positional data (AIS) for the high-speed vessel reference route.

RA3 Lifetime prediction of batteries by imitating the human brain

Self-learning models based on artificial neural networks can be used to analyze the state of health of Li-ion batteries and predict their lifetime.

Lithium-ion (Li-ion) batteries have become the most promising solution for energy storage in various applications, from laptops and smartphones to electric vehicles and grid storages. However, the cost of Li-ion batteries is still significant, making the battery lifetime critical for reaching profitability in many applications.

Due to the complexity of these electrochemical devices there is currently a lack of knowledge on the aging processes in the Li-ion battery, which again restricts the development of accurate lifetime prediction models. To overcome this challenge, accelerated aging tests in combination with data-driven models –extrapolating the aging test results to real life conditions – are needed to provide a lifetime model that can be used to develop operational strategies.



In 2019 post doc Mohsen Vatani (IFE) developed a mathematical and data-driven aging models for Li-ion batteries in MoZEES. Artificial neural network (ANN) was used as basis for the calculations. ANN is a mathematical tool with the adaptability and self-learning ability to represent complex nonlinear models of systems that often lack scientific background knowledge. The main idea behind the ANN concept is to imitate the neural network of the human brain. Each ANN is made up of some neuron sets which learn through examples and generalizes without any prior knowledge about the data nature and interactions.

The data used to validate the model was based on experiments performed on two different commercially available types of Li-ion battery cells (NCA and LFP chemistry), which were cycled under different conditions (temperature, starting state of charge, depth of discharge, and discharge current rate). The capacity loss of the cells were measured with respect to the amount of the charge that has passed through the cells (total Ampere hours). The data from these accelerated cycling tests were then used to develop the ANN-based model for each cell chemistry, which then can predict one-step ahead state of health of the cells cycled under different conditions.

The ability of the ANN-based model to predict lifetime and analyze the state of health of Li-ion batteries was validated and presented in a conference paper. The model confirms that Li-ion battery cells have the highest degradation rate when they are charged at low ambient temperatures.

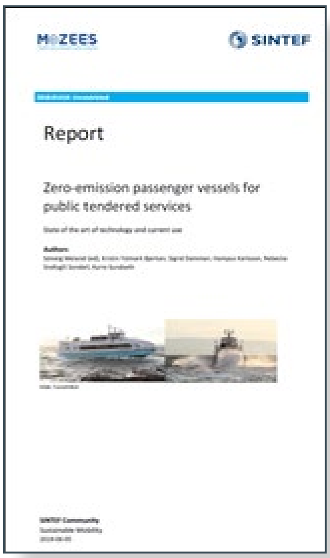
RA4 Policy and Techno-Economic analysis

Research Area 4 identifies the market potential, business cases, and policy prerequisites for innovative and energy efficient transport concepts, based on electricity or hydrogen. There is here a specific focus on markets that are supported by demanding national climate and transport policy goals, and applications where Norwegian industries and technology companies can assume a leading position.

MoZEES aims to support decision makers in different governance levels and businesses with a common framework of analysis, allowing new transportation concepts to be analyzed comprehensively under varying assumptions on technology, policies, incentives and governance measures. This comprehensive interdisciplinary approach will on one hand increase the reliability and quality of predictions on technology uptake and the need for (and dosage of) policies and incentives, and on the other hand decrease the uncertainty related to different business models. The overall result will be better planning and management of public transport infrastructures and assets and more reliable business decision support tools for the private sector.

Key questions in RA4 are how and when new technoogy can become competitive in the market and how public and corporate stakeholders can avoid the lock-in effects typical of current technologies and end user habits. Predicting the market for an entirely new mode of transportation is difficult, but not impossible. Analysis of international technology development road maps, policy options, incentives, and other governance measures will be required to produce national road maps for how the international and Norwegian value chains for the trans-port, energy and ICT sectors may undergo stepwise transformation towards 2030.

Specific case studies of new concepts and business models are made based on the needs of user partners within four prioritized transportation subsystems: (1) Urban mobility and logistics, (2) Coastal line vessels and ferries, (3) Long-haul freight and passenger transport, and (4) Transportation terminals. In order to be able to define relevant concepts, business models, and values chains, RA4 collaborates closely with system experts in RA3 battery and hydrogen technology experts in RA1 and RA2 and other experts among our MoZEES industry partners.



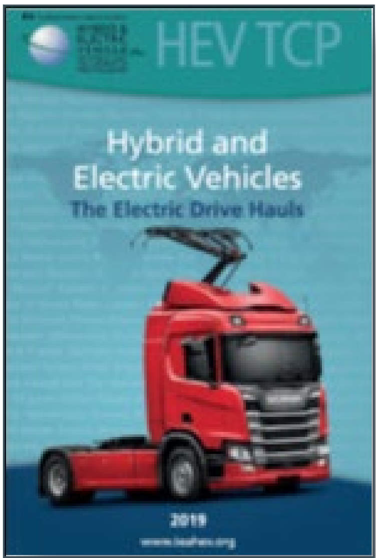
During 2019, RA4 carried out case studies for Heavy duty trucks,buses and passenger vessels in tendered services. The work was documented in three reports, one by TØI and two by SINTEF.

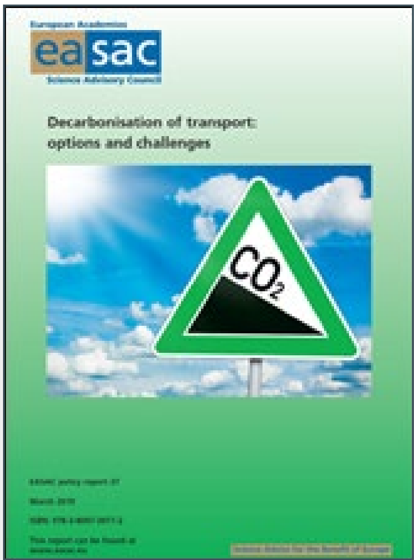
Three research papers from the work were presented at the Electric Vehicle Symposium in Lyon in May 2019. A fourth paper from TØI on fast charging usage was also presented under the MoZEES logo, as the results on temperature variation of fast charging also is relevant for fast charging of light commercial vehicle and heavy-duty vehicles. Furthermore, two papers were published as articles in the World Electric Vehicle Journal, while two others are in a review process. Results from this work was also presented at the MoZEES annual meeting and at a conference about Heavy Duty Vehicles arranged by RA4 in October 2019 in Oslo.

The case study on Heavy Duty Vehicles and Buses contributes to a better understanding of the potential and prerequisite for reaching Norwegian goals of selling only zero-emission city buses and small Light Commercial Vehicles from 2025, and that 50% of trucks and 75% of long distance buses sold in 2030 should be zero-emission. The results also contribute to the international research agenda on zero-emission HDVs and buses through the analysis of early user experiences with battery electric trucks and buses gained in Norway's harsh winter conditions and demanding topography.

In summary, experiences from the few pilots in Norway have been promising and there might be a growing potential for electrification of commercial vehicles in Norway. The main obstacles are related to limitations with respect to range, loss of payload because of lower energy-density in batteries compared to operation with diesel engines, and high investment costs. Battery electric operation using current technology levels will require considerable route tailoring and daytime charging. Analyses on the cost of ownership show that reductions in investment premiums of electric vehicles, through cheaper series and mass production, go a long way to improving the cost-competitiveness of zero-emission solutions compared to diesel-trucks. In the years to come, incentive schemes, charging solutions, policy facilitation, and technological developments will therefore remain important aspects for zero-emission adoptions.

The case study on tendered maritime passenger services contributes to a better understanding of how authorities can directly influence developments in maritime transport through green public procurement, as well as an overview of domestic public maritime passenger





services and their respective operational characteristics, thus forming a basis for considerations about potential and bearings for zero-emission operation. AIS data sets provided by the Norwegian Coastal Administration has formed the basis for analysis with a systemic view, as well as in-depth analyses on speed profiles. Initial analyses provided an overview of domestic public maritime passenger transport service operations, of which conventional Ro-Ro ferries and high-speed passenger vessels are the main categories. The considerations of the potential for zero-emission operation is based on fleet profile and operational characteristics such as sailing distances, and estimates of fuel consumption and CO2 emissions. Document studies and stakeholder interviews has provided insights into practices of green public procurement and the perspectives of procuring authorities and operators on the efficiency of green public procurement in accelerating sustainability transitions. The case study contributes to the international research agenda by identifying critical issues for green public procurement to accelerate maritime passenger transport toward sustainability. Procedural issues include timelines of multiple calls coinciding in time and diverging views on the ideal duration of contracts. Service delivery issues include provision of infrastructure for charging and energy capacity in remote areas. In the fall of 2019, further work on AIS data-analysis of the speed profile of high-speed ferries was initiated as a co-operation between RA3 and RA4, and TØI, IFE, SINTEF, DNV-GL and the Norwegian Coastal Administration. This work continues into 2020.

A status report on the market for and availability of battery electric and hydrogen solutions for trains was published in TØIs report series in 2019. It is being revised for re-release in Spring 2020 to account for new studies published by The Norwegian Railway Directorate as part of their NULLFIB-project ("NULLutslippsløsninger For Ikke-elektrifiserte Baner")

RA4 also has had an activity on Life-Cycle Analysis of heavy-duty battery electric and hydrogen fuel cell trucks, with the aim to include LCA data into energy system models to gain a better understanding of the global impact potential of different options to reduce transport emissions. The transport corridor between Oslo and Trondheim was used as a basis for an article of the work, which is under review.

Each year RA4 contributes to the IEA HEV collaboration framework by writing a chapter reporting on the development of Electromobility and hydrogen in the transportation sector in Norway. This chapter is part of the IEA HEVs annual report on the global status for battery-electric, hybrid, plug-in hybrid and hydrogen transportation solutions and markets. RA4 also contributed to a report on decarbonization of transport published by EASAC in co-operation with the MoZEES center director. MoZEES RA4 co-operated with the FME CenSES on an input about hydrogen to the work on a national plan for the roll out of hydrogen in the transportation sector.

Presentations where made at various workshops and meetings arranged by IEA, ECTRI, UC Davis and TØI, and conferences such as the Nordic EV summit, the Sustainable Energy and Environmental Development conference (SEED2019), the Nordic Baltic 8 in Ireland, and meetings with politicians and researchers such as a German delegation from Rheinland-Pfalz.

MoZEES Innovation Activities

Zero Emission High-Speed Passenger Ferries
In 2017 the MoZEES partners decided to investigate the possibility to develop zero emission high-speed passenger ferries based on fuel cells and hydrogen, in a so-called MoZEES maritime case study. The background and motivation for this was (and still is) that there in Norway (and MoZEES) exist several private and public stakeholders with an interest to develop new and innovative solutions for zero emission maritime transport. Several industry partners in MoZEES are contributing to this work.

Selfa Arctic has promoted the development of zero emission high speed vessels for many years. A deep dive in the archives show that already more than 15 years ago Selfa submitted a R&D project proposal to the Research Council of Norway on a hydrogen and fuel cell driven vessel, but it was not until couple of years ago this activity started to take more shape and form. In 2017 Selfa was awarded a contract by the Norwegian NOx-fund (NOx-fondet) to produce a report on zero emission high speed vessels, which demonstrated the feasibility of hydrogen.

Another very important driving force on this topic has been the Maritime Association for Sogn and Fjordane, recently renamed to Hub for Ocean. In the county of Sogn of Fjordane, now part of Vestland, there was in 2019 established an ARENA Ocean Hyway Cluster network to further promote and coordinate activities, demonstrations, and innovation projects on hydrogen in the maritime. Several MoZEES-partners are participating in this Ocean Hyway Cluster.

In Selfa's report for the NOx-fund two high high-speed passenger ferry routes in the Trøndelag County were analyzed in some detail. One of the finding was that 6 of the high-speed vessels consume the same amount of fossil fuel as 600 buses. Statistics from Trøndelag County Municipality (MoZEES Partner) shows that the high-speed ferries account for nearly 30% of all the greenhouse gas (GHG) emissions in the county. In comparison, the high-speed ferries account for nearly 50% of the total GHG-emissions in the area of Sogn og Fjordane.

Further calculations performed by the NOx-fund show that all of the high-speed ferries (ca. 100 in operation) in Norway consume 86 000 tonnes of diesel per year, which accounts for 1% of Norway's total consumption of petroleum products and a total emission of 233 000 tonnes of CO_2. This demonstrates the need to act on a national level. Hence, the question for MoZEES has been to investigate possible technical and economically viable solutions. There has also been a specific focus on hydrogen safety on high-speed passenger vessels.

MoZEES partners have contributed with research and knowledge on zero emission high-speed passenger vessels. This has eventually led to the development two new innovative concepts in the first phase of a tender process by Trøndelag County Municipality: Aero 42 concept by Brødrene Aa (top figure) and the ZeFF concept by Selfa (lower figure).

Since the start-up of MoZEES in 2017 there has been research activities in the center that has contributed, directly or indirectly, with new knowledge on hydrogen driven high-speed passenger ferries. In parallel, Trøndelag County Municipality has completed a pre-project to prepare for a tender for zero emission routes from 2024. These activities have strongly contributed to the development of several new and highly innovative concepts for high-speed passenger ferries, where several MoZEES partners have been involved (e.g. Hub for Ocean and Selfa).

MoZEES continues to support these innovation activities through R&D activities that can support the ongoing pilot projects and pre-commercial activities on high-speed passenger vessels. The Ocean Hyway Cluster in Vestland and the Renewable Energy Cluster (Fornybarklyngen) in Trøndelag are two important networks where MoZEES partners can participate and contribute to the further development of new solutions and innovations in the maritime industry.

Zero Emission Solutions for Heavy Duty Road Transport

MoZEES is supporting the development of zero emission solutions for heavy duty road transport. In 2019 the partners in MoZEES began to study the potential applications and investigate the possibility to establish a large national project on zero emission heavy duty trucks, activities that will continue with full force in 2020. Several MoZEES partners have large ambitions in this area and are already actively involved in relevant demonstration projects.

In 2017 ASKO established a hydrogen refueling station together with Nel that will serve hydrogen trucks in the Trøndelag region. In 2019 four fuel cell driven 26 tonne trucks from Scania where completed and made ready for operation [official launch on 20 January 2020]. The 2026-goal for ASKO is that all their grocery distribution trucks will be zero emission vehicles using battery- or hydrogen electric technology.

In the Oslo region there are also plans by Nel and partners to establish a large hydrogen production plant and supply system that can serve large fleets of hydrogen trucks and buses; Nel is now developing technology systems for similar projects in the USA and Europe.

MoZEES partners are involved in the development of zero emission solutions for heavy-duty road transport, such as in the hydrogen and fuel cell truck project by ASKO in Trøndelag.

Statkraft (new MoZEES Partner in 2019) is now looking into different markets in Scandinavia and Europe where they can produce green hydrogen from renewable energy and water electrolysis to supply fleets of heavy-duty trucks. Public partners in MoZEES, such as Viken County Council and Oslo Port Authority, are also interested in finding zero emission solutions for transport and distribution of goods in the Oslo region.

MoZEES is trying to coordinate the different activities on zero emission heavy duty transport. In October 2019 we hosted a workshop on Heavy Duty Transport Solutions, where MoZEES partners and external stakeholders where invited to discuss this topic further. In 2020 there are plans to organize several more open and innovation-oriented meetings and events, to facilitate the development of good common solutions for the introduction of zero emission trucks. The Lillestrøm Centre of Expertise (Kunnskapsbyen Lillestrøm) plays an important role in the build-up of a national Hydrogen Cluster, where heavy-duty transport has been defined as key focus area.

The overall goal in Norway (ref. National Transport Plan) is that 50 % of all new trucks in 2025 are to be zero emission. MoZEES will continue to provide research and support innovation activities for zero emission heavy duty transport for the next years, with the goal to develop commercially sustainable solutions by 2025. In 2020 the MoZEES partners will intensify the work on making roadmaps for zero emission heavy duty transport and ensure that all existing and new research and demonstration projects are coordinated in a coherent manner.

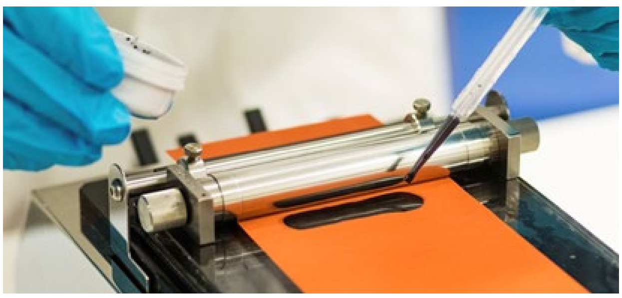
Production of key materials for Li-ion Batteries

One of the main objectives with MoZEES is to perform research and develop new knowledge in the area of Li-ion batteries. Elkem, the main partner in MoZEES on battery material manufacturing, has worked in a dedicated manner over several years to establish themselves in Li-ion battery markets and global battery value chains. The focus for Elkem and their research partners in Norway has been on the development of silicon and silicon composites, but lately Elkem has also started production of anode graphite materials for Li-ion batteries.

The development of materials for Li-ion batteries is a highly multifaceted exercise that requires a wide knowledge base. MoZEES has facilitated meetings and workshops on batteries ever since the start-up of the research center in 2017. At the annual MoZEES Battery Days key personnel from Elkem has participated in battery laboratory courses and learned how to synthesize and test battery materials. These MoZEES battery activities have contributed to new battery developments within Elkem, and the company has now launched optimized graphite for Li-ion electrodes for their customers.

An important competitive edge for Elkem and other potential battery producers is that production of raw materials and further processing in Norway is based on clean hydro-electric power, which gives a much lower CO_2-footprint compared to production in other countries. MoZEES will continue to support new initiatives for battery material and cell production in Norway in the coming years.

MoZEES partners are involved in the Li-ion battery manufacturing for the world marked: From small-scale battery material synthesis (top photo) to prototype manufacturing of anode graphite electrode materials (bottom photo) to supply to real-world customers.



Seminars and Outreach

MoZEES Battery Days 2019
The MoZEES Battery Days were organized for the second time on 13-14 February 2019. About 40 participants attended the Battery Seminar on Day 1 during which topics encompassing battery applications and safety, modelling, testing, and materials synthesis and characterizations where addressed by speakers from both academia and industry. We were very pleased that Kristina Edström, Professor at the University of Uppsala and a member of the MoZEES Scientific Advisory Board, had the opportunity to attend the seminar and hold a presentation on High Precision and Post Mortem Studies of Li-ion Batteries. The MoZEES Battery Laboratory Course on Day 2, held at IFEs laboratory facilities, had more than 20 participants and consisted of some introductory theory followed by several hands-on laboratory stations allowing the participants to practice the different steps of battery cell fabrication and electrochemical testing.

MoZEES Annual Meeting 2019
The second annual meeting for MoZEES was successfully completed on 24-25 April 2019, with more than 80 participants. The first day was an open event, and included several newcomers to MoZEES. There is clearly an increased interest for zero emission transport and MoZEES.

On the first day there were 14 presentations made on a wide range of topics, from policy and systems to technology and materials. The presentations gave a good mix of results of MoZEES research performed over the past year. In addition, there were a couple of very relevant presentations made by our new International Research Partners at UC Davis and RWTH Aachen University. The first day ended with lots of excellent networking and a conference dinner.

Participants at the MoZEES Battery Laboratory Course at IFE

On the second day there was a PhD and Post.doc. seminar in the morning, which was run in parallel with another couple of sessions. New of this year was a session on Markets and Innovations where 4 key Industry Partners in MoZEES presented the status and outlook on battery and fuel cell material technology, hydrogen storage and application of hydrogen in the maritime sector. This was very inspiring. The second day ended with presentations of Research Highlights and Results produced by some our PhD students and young researchers, and clearly showed that we are on track with our research.

In summary, the MoZEES Annual Meeting 2019 was a great success. The Annual Meeting is likely to continue to grow further in 2020, as we plan to invite more external partners for the open first day of the meeting. However, we do not want to expand the event beyond the capacity of the Son Spa hotel, which provides a wonderful platform for informal discussions.

Erik Ianssen (Selfa) presented new high-speed hydrogen ferry concept on Day 2 (photo: J.A. Wilhelmsen)

Snapshots from MoZEES Annual Meeting 2019

Ole Kristian Sollie (Statens vegvesen) and Center Director Øystein Ulleberg (IFE) leads a united MoZEES General Assembly (Photo: J. A. Wilhelmsen)

MoZEES Heavy-Duty Transport Workshop

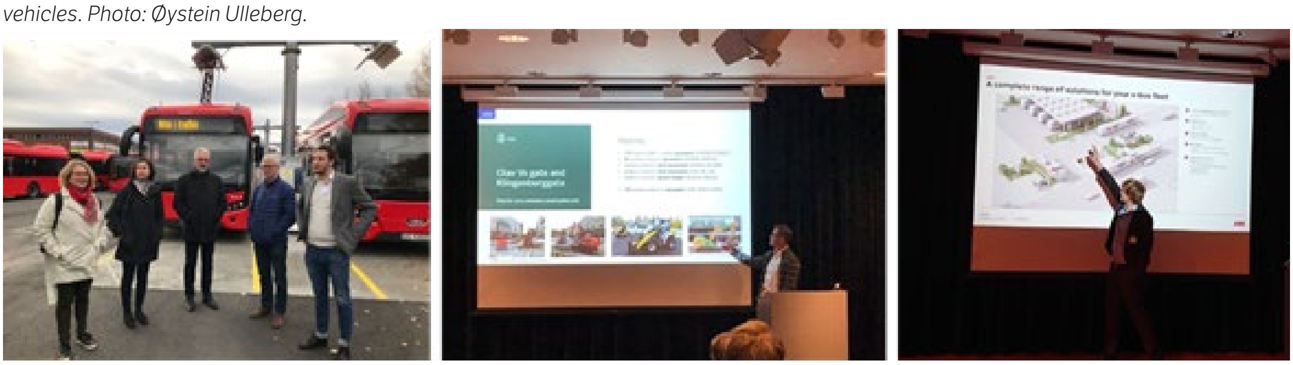
Cross industry stakeholders and researchers from MoZEES met at the Oslo Centre for Interdisciplinary Environmental and Social Research (CIENS) on 22-23 October to discuss developments in zero emission heavy-duty vehicles and machinery, with the goal to provide input to RA4 on heavy-duty transport roadmaps and policy. Andreas Hedum from the Ministry of Transport kicked off the meeting and spoke about the government's plan for a 40 % greenhouse gas emission reduction by 2030. Since road transport is the source of over half of these emissions, zero emission solutions can be a large part of the solution; the roadmaps that RA4 will produce can thus potentially be of great use to enabling this transition.

The program for the two days was divided into sessions on 1) policy direction for each segment (rail, bus, construction vehicles and heavy duty trucks), 2) technology outlooks for battery and fuel cells, 3) case study work in Norway, 4) value chain components and 5) practical implementation across Europe. The presentations were complemented by a site visit to SINTEF laboratories and the Unibuss bus depot at Alnabru, where participants were treated to a tour of Unibuss's electric bus facilities. The site visit to Alnabru made the participants appreciate the scale of Unibuss' electric bus operations. The cold weather also gave everyone a wake-up-call after the warm and dark lecture theatre!

The two days provided many learnings, discussions, and networking opportunities. In the case of Norway, we heard about plans for zero emission trains on non-electrified lines such as the (challenging) Nordland line from Jernbanedirektoratet as part of their NULLFIB project, Ruter's experiences and plans for zero emission buses across Oslo, a joint initiative to promote zero-emission construction vehicles (Fellesinitiativet) and various zero emission truck initiatives, to name but a few examples. We also learned of other exciting experiences in Europe, such as the German Coradia iLint (by Alstom) – the world's first passenger train powered by a hydrogen fuel cell. One key take-home message was that it is crucial to have in place supporting infrastructure to make these developments a reality, which includes good planning, policy support and favorable and stable framework conditions.

The lessons learned from the workshop will be used as a starting point for the work to be conducted in 2020 on the developments of MoZEES roadmaps . For example, a repeating issue at the workshop was that companies that are keen to buy zero emission vehicles or equipment currently feel too small alone to utilize zero emission solutions, due to the relative risk they entail. Perspectives such as these, which cannot be solved from technical discussion alone, are a valuable outcomes from the discussion. Thanks to all participants who made the workshop a great success!

Left: Glenn-Ivar Gaalaas gave the participants a tour of Unibuss' charging station at Alnabru. Middle: Jon Eriksen (Kunnskapsbyen) presenting the world's first zero emission construction site in Oslo. Right: Øystein Hahre describing ABB's components and solutions for heavy duty vehicles. Photo: Øystein Ulleberg.



Appendix 1: Personnel

Postdoctoral Researchers with financial support from the Center Budget					
Institution	Name	Sex M/F	Nationality	End date	Topic
UiO	Alok Mani Tripathi	M	India	31.03.2021	Advanced characterization of Li-ion batteries
UiO	Athanasios Chatzitakis	M	Greece	14.07.2019	Photo electrochemistry and solid state ionics
IFE/UiO	Gaylord Kabongo Booto	M	Kongo	05.09.2020	Life Cycle Analysis

PhD students with financial support from the Center Budget					
Institution	Name	Sex M/F	Nationality	End date	Topic
NTNU	Daniel Tevik Rogstad	M	Norway	31.08.2020	Silicon anodes and ionic liquids
NTNU	Elise Ramleth Østli	F	Norway	20.08.2020	Water-based manufaturing routes for electrodes
NTNU	Eivind Hugaas	M	Norway	31.08.2020	Fatigue mechanisms of hydrogen sto-rage tanks
NTNU	Hamid Reza Zamanizadeh	M	Iran	19.09.2021	Bipolar plates for alkaline water electrolysis
USN	Mathias Henriksen	M	Norway	15.08.2021	Explosion hazards of Lithium ion batteries
UiO	Halvor Høen Hval	M	Norway	31.12.2021	High voltage cathode materials for Li-ion batteries
UiO	Xinwei Sun	F	China	31.08.2021	Composite Proton conducting membranes

Key researchers		
Institution	Name	Main research area
NTNU	Ann Mari Svensson	Battery materials and components
NTNU	Sverre Magnus Selbach	Battery materials and components
NTNU	Frode Seland	Battery and electrolysis components and technology
NTNU	Andreas Echtermeyer	Hydrogen components, testing and modelling
NTNU	Asgeir Tomasgard	Policy and techno-economic analysis
UiO	Helmer Fjellvåg	Battery materials and components
UiO	Truls Norby	Fuel cell and electrolyzer materials and component
UiO	Katinka Elisabeth Grønli	Energi, miljø og klima
USN	Dag Bjerketvedt	Hydrogen and Battery safety
USN	Joachim Lundberg	Hydrogen and Battery safety
USN	André Vagner Gaathaug	Hydrogen and Battery safety
USN	Knut Vågsæther	Hydrogen and Battery safety
FFI	Helge Weydahl	Battery safety, fuel cell systems
FFI	Martin Gilljam	Chemical characterization of lithium ion batteries
FFI	Toreif Lian	Thermal stability of lithium ion batteries
FFI	Sissel Forseth	Battery safety
SINTEF	Alejandro Oyarce Barnett	PEMFC and PEMWE testing, BPP, membranes, catalysts and AST protocols
SINTEF	Kristin Ystmark Bjerkan	Social scientific transport research
SINTEF	Rune Bredesen	Functional oxides, solid state diffusion/kinetics, membranes, fuel cells and electrolysers
SINTEF	Paul Inge Dahl	Materials synthesis and processing for batteries
SINTEF	Halvor Dalaker	Batteries, Si-anodes
SINTEF	Sigrid Damman	Governance, institutional drivers and barriers
SINTEF	Truls Flatberg	

SINTEF	Johansen Ulf	Operations research, economic analysis
SINTEF	Michal Kaut	
SINTEF	Karlsson Hampus	Social Scientific Transport research
SINTEF	Thulile Khoze	PEMFE and PEMWE
SINTEF	Solveig Meland	Social scientific transport research
SINTEF	Edel Sheridan	Batteries, RA1 SINTEF PL
SINTEF	Vibeke Stærkebye Nørs-tebø	Operations research, economic analysis
SINTEF	Anders Ødegård	PEMFC Bipolar plates and PEMFC systems
SINTEF	Magnus Skinlo Thomassen	RA coordination. PEMWE/PEMFC materials and systems
SINTEF	Julian Richard Tolchard	Functional oxide materials, structural characterisation
SINTEF	Werner Adrian Tobias	Operations research and mathematical programming, economics
SINTEF	Zenith Federico	Fuel cell control, techno-economic analyses
SINTEF	Bjerkan Kristin Ystmark	Social scientific transport research
SINTEF	Ulf Johansen	Operations research, economic analysis
SINTEF	Gerardo A Perez-Valdes	Operations research, economic analysis
SINTEF	Anita Hamar Reksten	PEMWE catalysts
SINTEF	Graham Thomas Smith	PEMFC Bipolar plates and PEMFC systems
SINTEF	Artur Tron	Batteries Development
SINTEF	Kyrre Sundseth	Techno-economic analyses
SINTEF	Kristin Tolstad Uggen	
SINTEF	Per Erik Vullum	Battery materials characterization
SINTEF	Nils Peter Wagner	Li ion batterier utvikling av katoder og anoder
SINTEF	Tor Olav Sunde	Catalyst development
SINTEF	Graff Joachim Seland	Sample characterisation by SEM and EDS
IFE	Jan Petter Mæhlen	Silicon anodes for Li-ion batteries
IFE	Volodymyr Yartys	Ni-metal hydride batteries
IFE	Preben Joakim Svela Vie	Battery lifetime and characterization
IFE	Øystein Ulleberg	Hydrogen systems - fuel cells and electrolyzers
IFE	Fredrik Aarskog	Hydrogen systems - fuel cells
IFE	Ragnhild Hancke	Hydrogen systems - electrolyzers
IFE	Asbjørn Ulvestad	Silicon anodes for Li-ion batteries
IFE	Hanne Flåten Andersen	Silicon anodes for Li-ion batteries
IFE	Carl Erik Lie Foss	Silicon anodes for Li-ion batteries
IFE	Morten Tjelta	Corrosion in alkaline media
IFE	Jon Kvarekvål	Corrosion in alkaline media
IFE	Kari Aa Espegren	Energy system modelling
IFE	Ida Hugem Lereng	Energy System Modelling
IFE	Janis Danebergs	Energy System Modelling
IFE	Sedsel Thomassen	Energy System Modelling
TØI	Erik Figenbaum	Electric vehicles, environmental characteristics of vehicles, technology diffusion
TØI	Inger Beate Hovi	Vehicle and demand modelling, SCGE-modelling, cost functions, economic incentives, user needs and obstacles
TØI	Rebecca Thorne	Environment, Energy, Technology
TØI	Ingrid Sundvor	Environment, Energy, Technology
TØI	Lasse Fridstrøm	Vehicle fleet forecasting, vehicle and demand modelling, economic incentives
IFE	Morten Tjelta	Corrosion in alkaline media
IFE	Jon Kvarekvål	Corrosion in alkaline media
IFE	Kari Aa Espegren	Energy system modelling
IFE	Stefano Deledda	Neutron radiography
IFE	Pernille M. S. Seljom	Energy system modelling
IFE	Ida Hugem Lereng	Energy system modelling
TØI	Erik Figenbaum	Electric vehicles, environmental characteristics of vehicles, technology diffusion
TØI	Inger Beate Hovi	Vehicle and demand modelling, SCGE-modelling, cost functions, economic incentives, user needs and obstacles
TØI	Rebecca Thorne	Environment, Energy, Technology
TØI	Lasse Fridstrøm	Vehicle fleet forecasting, vehicle and demand modelling, economic incentives

PhD students working on projects in the Center with financial support from other sources					
Institution	Name	Nationality	Period	Sex M/F	Topic
UiO	Rasmus Vester Thøgersen	Norway	2018-2022	M	High-end catamaterials
UiO	Frida Hempel	Norway	2018-2021	F	Solid electrolytes
UiO	Xinyu Li	China	2018-2019	F	Solid electrolytes
UiO	Anders Brennhagen	Norway	2019-2022	M	Anodes
USN	Agnieszka Lach	Norway	2019-2022	F	Hydrogen release in confined spaces
NTNU/TØI	Vegard Østli	Norway	2018-2022	M	Vehicle and demand modelling
NTNU/IFE	Ika Dewi Wijayanti	Indonesia	2017-2019	F	Ni-metal hydride batteries

Postdoctoral researchers working on projects in the center with financial support from other sources					
Institution	Name	Nationality	Period	Sex M/F	Topic
UiO	Julia Wind	Austria	2018-2020	F	Solid electrolytes

Master degrees			
Institution	Name	Sex M/F	Topic
NTNU	Steinar Åsmund Fagervold	M	NMC katodematerialer
NTNU	Silje Nordnes Bryntesen	F	NMC katodematerialer
NTNU	Philip Keck	M	Solid state electrolytes
NTNU	Live Mølmen	F	Metallhydrid batterier
UiO	Stian Simonsen	M	Composite Polymer Membranes
USN	Jonathan Johnsplass	M	Battery Safety
USN	Erik Nygaard	M	Hydrogen Safety, ATEX

Appendix 2: Statement of Accounts

Funding	Amount
The Research Council	16 561
The Host Institution (IFE)	1 640
Research Partners	9 809
Industry partners	5 561
Public partners	3 259
Total funding	**36 830**

Costs	Amount
The Host Institution (IFE)	7 593
Research Partners	23 403
Industry partners	4 387
Public partners	759
Equipment	688
Total costs	**36 830**

(All figures are given in kNOK)

Appendix 3: Publications

PUBLICATIONS IN REFEREED JOURNALS

Aarskog, Fredrik Gundersen; Hansen, Olav R.; Strømgren, Trond; Ulleberg, Øystein.
Concept risk assessment of a hydrogen driven high speed passenger ferry. International journal of hydrogen energy 2019 s. 1-14

Bjerkan, Kristin Ystmark; Karlsson, Hampus; Sondell, Rebecka Snefuglli; Damman, Sigrid; Meland, Solveig.
Governance in Maritime Passenger Transport: Green Public Procurement of Ferry Services. World Electric Vehicle Journal 2019 ;Volum 10.(4) s. 1-15

Chatzitakis, Athanasios Eleftherios; Sartori, Sabrina.
Recent Advances in the Use of Black TiO_2 for Production of Hydrogen and Other Solar Fuels. ChemPhysChem 2019 ;Volum 20.(10) s. 1272-1281

Henriksen, Mathias; Vågsæther, Knut; Lundberg, Joachim; Forseth, Sissel; Bjerketvedt, Dag.
Explosion characteristics for Li-ion battery electrolytes at elevated temperatures. Journal of Hazardous Materials 2019 ;Volum 371. s. 1-7

Hovi, Inger Beate; Pinchasik, Daniel Ruben; Figenbaum, Erik; Thorne, Rebecca Jayne.
Experiences from Battery-Electric Truck Users in Norway. World Electric Vehicle Journal 2019 ;Volum 11.(5)

Lian, Torleif; Vie, Preben Joakim Svela; Gilljam, Martin; Forseth, Sissel.
Changes in Thermal Stability of Cyclic Aged Commercial Lithium-Ion Cells. ECS Transactions 2019 ;Volum 89.(1) s. 73-81

Sun, Xinwei; Simonsen, Stian Christopher; Norby, Truls Eivind; Chatzitakis, Athanasios Eleftherios.
Composite Membranes for High Temperature PEM Fuel Cells and Electrolysers: A Critical Review. Membranes 2019 ;Volum 9.(7)

Ulleberg, Øystein; Hancke, Ragnhild.
Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway. International journal of hydrogen energy 2019 ;Volum 45.(2) s. 1201-1211

Vatani, Mohsen; Szerepko, Mariusz; Vie, Preben Joakim Svela.
State of Health Prediction of Li-ion Batteries using Incremental Capacity Analysis and Support Vector Regression. I: 2019 IEEE Milan PowerTech. IEEE 2019 ISBN 978-1-5386-4722-6.

Volodin, Alexei A.; Denys, Roman Volodymyrovich; Wan, ChuBin; Wijayanti, Ika Dewi; Suwarno, Suwarno; Tarasov, Boris P.; Antonov, Vladimir E.; Yartys, Volodymyr.
Study of hydrogen storage and electrochemical properties of AB2-type $Ti_{0.15}Zr_{0.85}La_{0.03}Ni_{1.2}Mn_{0.7}V_{0.12}Fe_{0.12}$alloy. Journal of Alloys and Compounds 2019 ;Volum 793. s. 564-575

Wan, ChuBin; Denys, Roman Volodymyrovich; Lelis, M.; Milcius, D; Yartys, Volodymyr.
Electrochemical studies and phase-structural characterization of a high-capacity La-doped AB(2) Laves type alloy and its hydride. Journal of Power Sources 2019 ;Volum 418. s. 193-201

Wijayanti, Ika Dewi; Mølmen, Live; Denys, Roman Volodymyrovich; Nei, Jean; Gorsse, Stéphane; Guzik, Matylda N.; Young, Kwo;Yartys, Volodymyr.
Studies of Zr-based C15 type metal hydride battery anode alloys prepared by rapid solidification. Journal of Alloys and Compounds 2019; Volum 804. s.527-537

Wijayanti, Ika Dewi; Mølmen, Live; Denys, Roman Volodymyrovich; Nei, Jean; Gorsse, Stéphane; Young, Kwo; Guzik, Matylda N.;Yartys, Volodymyr.
The electrochemical performance of melt-spun C14-Laves type TiZr-based alloy. International journal of hydrogen energy 2019 ;Volum 45.(2) s.1297-1303

Zenith, Federico; Isaac, Raphael; Hoffrichter, Andreas; Thomassen, Magnus; Møller-Holst, Steffen.
Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries: Case studies in Norway and USA. Proceedings of the Institution of mechanical engineers. Part F, journal of rail and rapid transit 2019

PUBLISHED REPORTS AND MONOGRAPHS

Bettzüge, Marc Oliver; Blok, Kornelius; Bradshaw, Alex; Bruce, Peter; Duic, Neven; Frank, Harry; Georges, Gil; Giannopoulos, George; Hamacher, Thomas; Johnsson, Filip; Kretzschmar, Jan; La Poutré, Han; Laurikko, Juhani; Oswald, Kirsten; Schmidt, Thomas Justus; Sturm, Peter-Johann; Ulleberg, Øystein; Gillett, William; Boulouchos, Konstantinos.
Decarbonisation of transport: Options and challenges. Germany: European Academies' Science Advisory Council (EASAC Secretariat) 2019 (ISBN 978-3-8047-3977-2) 58 s.

Bjerkan, Kristin Ystmark; Sondell, Rebecka Snefuglli; Karlsson, Hampus; Damman, Sigrid; Meland, Solveig.
Public tendered maritime passenger services. Opportunities and barriers for zero-emission operation. SINTEF Community 2019 46 s.

Danebergs, Janis.
Techno-economic Study of Hydrogen as a Heavy-duty Truck Fuel, A Case Study on the Transport Corridor Oslo – Trondheim. Digitala Vetenskapliga Arkivet 2019 101 s.

Hovi, Inger Beate; Pinchasik, Daniel Ruben; Thorne, Rebecca Jayne; Figenbaum, Erik.
User experiences from the early adopters of heavyduty zero-emission vehicles in Norway. Barriers and opportunities. Oslo, Norway: Transportøkonomisk institutt 2019 (ISBN 978-82-480-2282-4) 130 s. TØI-rapport (1734/2019)

Tomasgard, Asgeir; Berstad, David Olsson; Burheim, Odne Stokke; Blekkan, Edd Anders; Dawson, James; Espegren, Kari Aamodt; Karstad, Per Ivar; Løvås, Terese; Meyer, Julien; Møller-Holst, Steffen; Nekså, Petter; Pollet, Bruno G.; Størset, Sigmund Østtveit; Sundseth, Kyrre; Thomassen, Magnus; Ulleberg, Øystein.
Hydrogen i fremtidens lavkarbonsamfunn. Trondheim: Center for Sustainable Energy Research (CenSES), NTNU 2019 (ISBN 978-82-93198-31-4) 40 s.

Zenith, Federico; Møller-Holst, Steffen; Myklebust, Thor; Thomassen, Magnus; Tolchard, Julian R; Hovland, Jon; Thomassen, Tonje Warholm; Wittgens, Bernd; Bustad, Joakim; Landmark, Andreas D.; Tschentscher, Roman; Hansen, Olav R.
Analyse av alternative driftsformer for ikke-elektrifiserte baner 2. utgave. Trondheim: SINTEF Digital 2019 (ISBN 978-82-14-06371-4) 119 s.

Mobility Zero Emission Energy Systems

FORSKNINGS-
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