MoZEES
Mobility Zero Emission Energy Systems

FME
FORSKNINGS-
SENTER FOR
MILJØVENNLIG
ENERGI
Norges forskningsråd

Annual Report 2017

Message from the Chair of the Board

The starting year of the MoZEES Center has been a very exciting one. The large enthusiasm at the Center kick-off has been turned into an operating organisation with the partners working in research groups bonded together across technologies and activities. Also outside the Center the importance of zero emission mobility is increasingly recognised. Promoted by political incentives and technological developments currently one of every four new vehicle purchased in Norway is battery electric. Hydrogen powered fuel cell cars are also introduced in the market as well as heavy duty trucks. In the maritime sector, following the first battery powered ferry MF AMPERE, Norway has taken the role as a forefront developer for both battery and hydrogen powered vessels. The trend is clear, zero emission mobility is now turning from a political wish to combat climate changes to a market driven business. In these times of fast changes, the MoZEES Center with its scientific and industrial competence will be an important instrument in the development of technology and sustainable solutions supporting a broader implementation of zero emission mobility in the transportation sector. I look forward to taking part in this journey into a greener future.

At this stage I would like to congratulate all partners, and the Director Øystein Ulleberg and his staff for a successful first year of MoZEES, and express my strong belief in an even more exciting future for the Center.

Rune Bredesen
Chairman of the Board

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Letter from the Center Director

It is now nearly two years since the Research Council of Norway announced the award of eight new national centers on environment-friendly energy research, including one with focus on zero emission transport. MoZEES confirms that there is a need in society to couple research on new energy technologies and systems with research on future transport systems and applications, and that this research needs to be conducted over several years. MoZEES has a long-term research focus on battery and hydrogen technologies for zero-emission energy systems for transport.

It has taken us about a year to establish the Center, after the contract was signed. The Minister of Transport Ketil Solvik-Olsen conducted the official opening at IFE Kjeller on 20 March 2018. In his speech he highlighted the strength of the MoZEES consortium, with key stakeholders from research, industry, and public sector. As a matter of fact, we are 40 partners in all: 4 research institutes, 3 universities, 26 industry partners, and 7 public organizations. The large number of members in the consortium can be a challenge from an organizational point of view. It is therefore important to focus on how to align the research tasks in the Center with our partner's ongoing and planned developments and innovation activities. The goal is to make a real contribution in the area of zero emission transport.

The main strength with MoZEES is the knowledge among the partners and their willingness to work together over time in a complimentary and collective manner. It is therefore wonderful to observe that people within the consortium are already beginning to find each other and are starting to work together in different settings than before. One excellent example of this can be found among our PhD students and post.docs that started up during the fall of 2017. They are being co-supervised by researchers and industry members in MoZEES, in addition to receiving world-class supervision from professors at our host universities. The PhD kick-off seminar at Lysebu in Oslo on 8 December 2017 marked a very successful start for a close collaboration with and among our students. We plan to organize many similar events in the years to come, where the goal is to facilitate scientific and technical discussions in the area of zero emission transport.

The organization of the Center has also come together in 2017. The MoZEES Board, Management Team, and Research Area (RA) groups have organized several meetings where we have discussed everything from strategy, to long-term goals, milestones, and detailed plans on how to organize our research activities in the years to come. MoZEES covers a wide range of research, from battery and hydrogen material and components research (RA1 and RA2) to battery and hydrogen systems, applications, and techno-economics (RA3 and RA4) in the area of zero emission transport. I would like to express my thanks to everyone who have contributed to the important start-up phase of the Center. A special thanks goes to colleagues at IFE and the MoZEES Management Team. The establishment of the Center is true Team Work.

The time has come for renewable energy and zero-emission transport, and the timing of MoZEES is perfect. I hope this motivates for a strong engagement and long-term commitment to our research.

Øystein Ulleberg
Center Director

About MoZEES

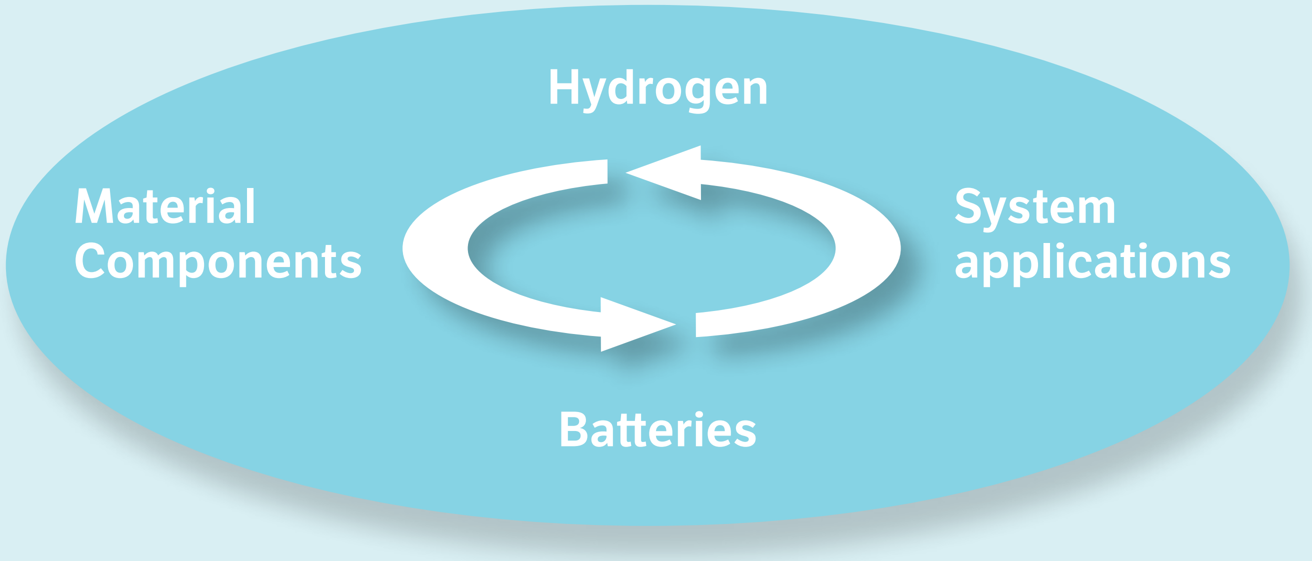
MoZEES is a Center for environment-friendly energy research with focus on battery and hydrogen technologies for zero-emission transport on road, rail, and sea.

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

KYSTVERKET

Jernbane-direktoratet

Statens vegvesen
Norwegian Public Roads Administration

Trøndelag fylkeskommune

GrapheneBatteries

AKERSHUS County Council

DYNATEC ENGINEERING

Innovation in Motion Miba

DNV·GL

Selfa Arctic

OREEC
KUNNSKAPSBYEN

ASKO
-vi forsyner Norge med mat

MARITIM FORENING SOGN OG FJORDANE

JM Johnson Matthey Fuel Cells
the power within

ABB

Cerpotech

nel

ENOVA

UNIBUSS

HEXAGON COMPOSITES

saft

A Member of The Linde Group AGA

ZEG Power

BASF
The Chemical Company

PORT OF OSLO

Lloyd's Register

GRENLAND ENERGY

BELLONA

Elkem

baldur
BALDUR COATINGS AS

ZEM Marine

TØI Institute of Transport Economics
Norwegian Centre for Transport Research

FFI Forsvarets forskningsinstitutt
Norwegian Defence Research Establishment

IFE Institute for Energy Technology

HSN University College of Southeast Norway

NTNU
Norwegian University of Science and Technology

SINTEF

UiO : University of Oslo

Organisation

General Assembly
All Partners and EB Chairman

Executive Board
Chair: Rune Bredesen (SINTEF)

Center Management
Øystein Ulleberg (IFE)
Center Director

Ragnhild Hancke (IFE)
Center Coordinator

Education
Katinka Elisabeth Grønli (UiO)

RA1
Battery Materials and Components

Fride Vullum Bruer (NTNU)

RA2
Hydrogen Components and Technologies

Magnus Thomassen (SINTEF)

RA3
Battery and Hydrogen Systems and Applications

Øystein Ulleberg (IFE)

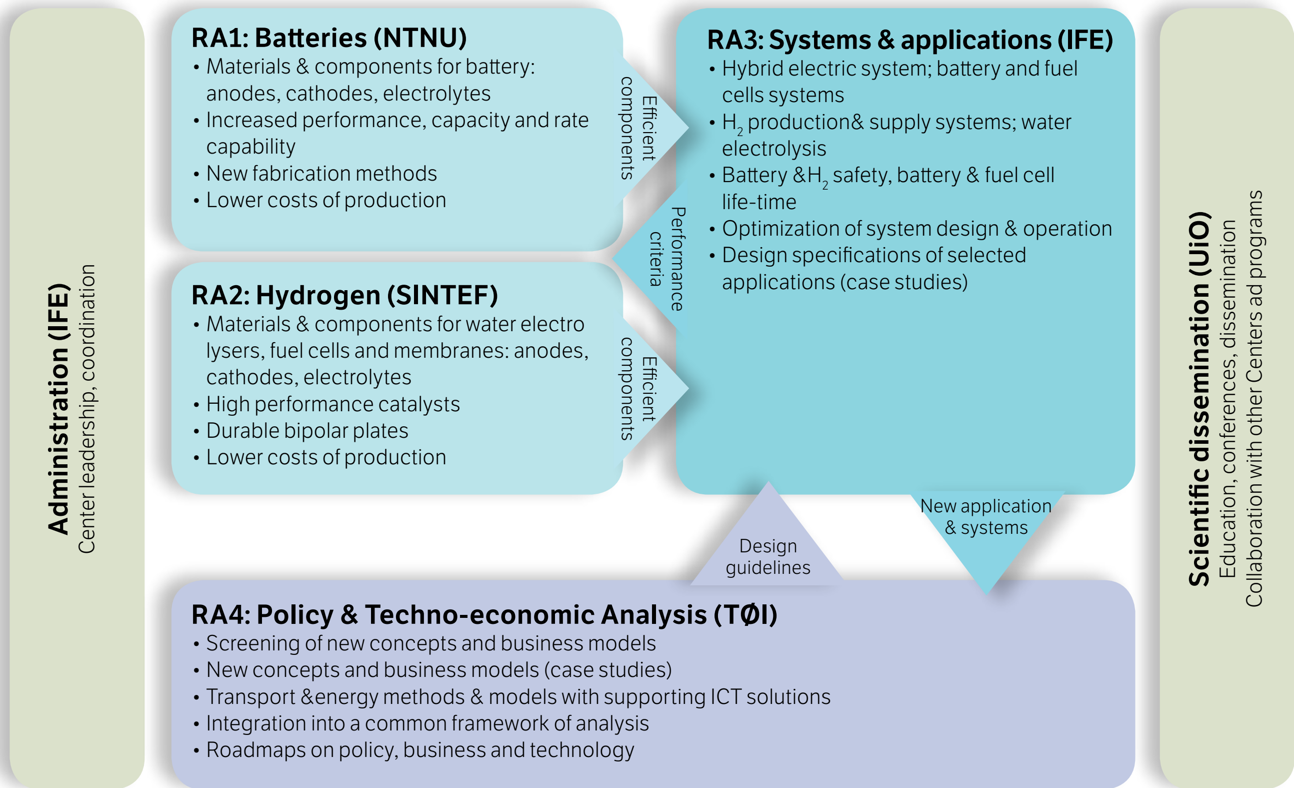
RA4
Policy and Techno-Economic Analysis

Erik Figenbaum (TØI)

Members of the Executive Board and the Center Management Team gathered at IFE in September for a Board meeting.

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 multidisciplinary 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.

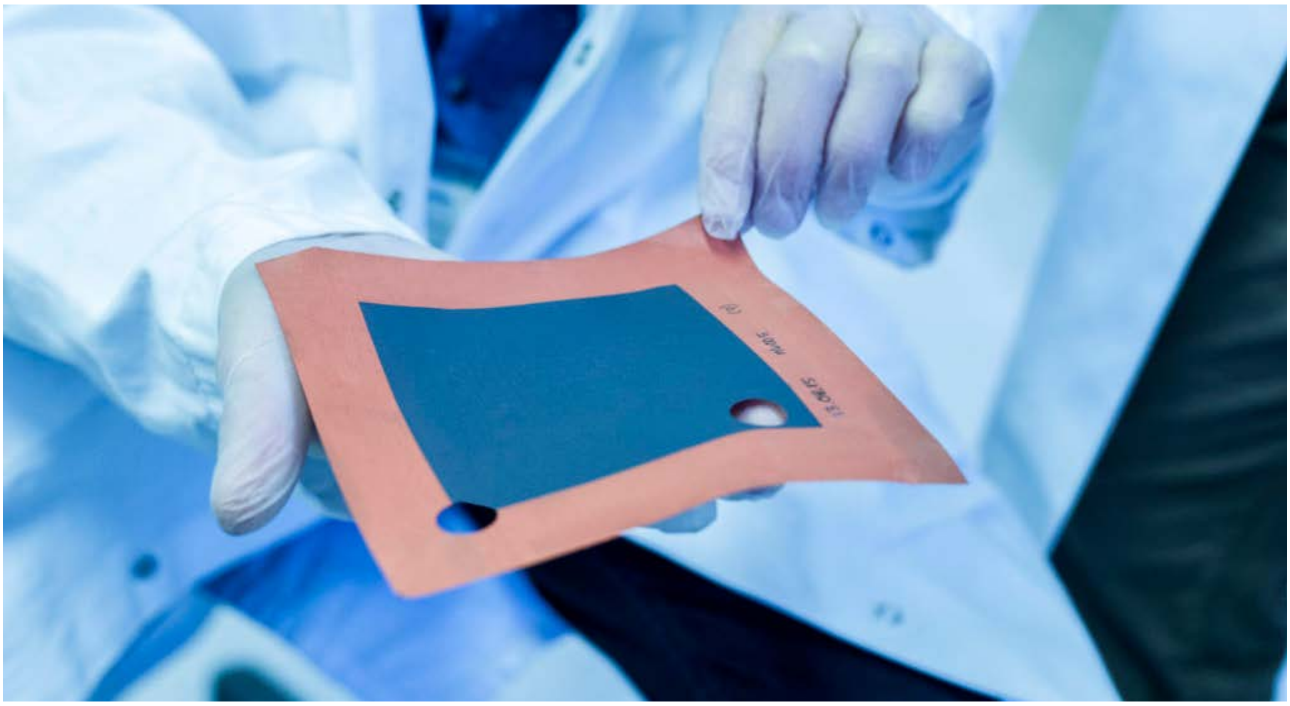


RA1 – Battery Materials and Components

The main objective of RA1 is to develop new battery materials and components that lead to significant improvements in battery performance and reduced production cost. The work will support existing Norwegian and international industry partners to access and/or strengthen their share of the international battery market. The Center will focus on improving the overall characteristics of batteries, and hereby provide meaningful and reliable information on performance. The Research and Industry Partners have complementary competencies and access to extensive infrastructures for manufacturing, characterization, and testing, all of which will be used to develop and study battery materials, components, as well as interactions between new materials and components.

Both "energy batteries" and "power batteries" are investigated. The energy density is of major importance in electric vehicles, and lithium ion batteries (LIBs) with NMC ($Li(Ni/Mn/Co)O_2$), or NCA ($Li(Ni/Co/Al)O_2$) cathodes are therefore generally preferred for this application. LMNO-spinel ($LiMn_{1-x}Ni_xO_4$) battery types are also interesting due to their high operating voltage, which gives a high energy density. In hybrid power system configurations it is important to use batteries with high power density and stable chemistries, e.g., LTO ($Li_4Ti_5O_{12}$)/LFP ($LiFePO_4$) and NiMH batteries.

In order to achieve significant improvements in the energy density of conventional LIBs, a three-fold approach is taken to improve the anode, cathode, and electrolyte (approach in accordance with the EU SET-plan). This is also the focus of the first three research tasks in RA1. The first task focuses on improving and understanding the behavior of Si anodes in addition to developing new electrolytes, while the second task

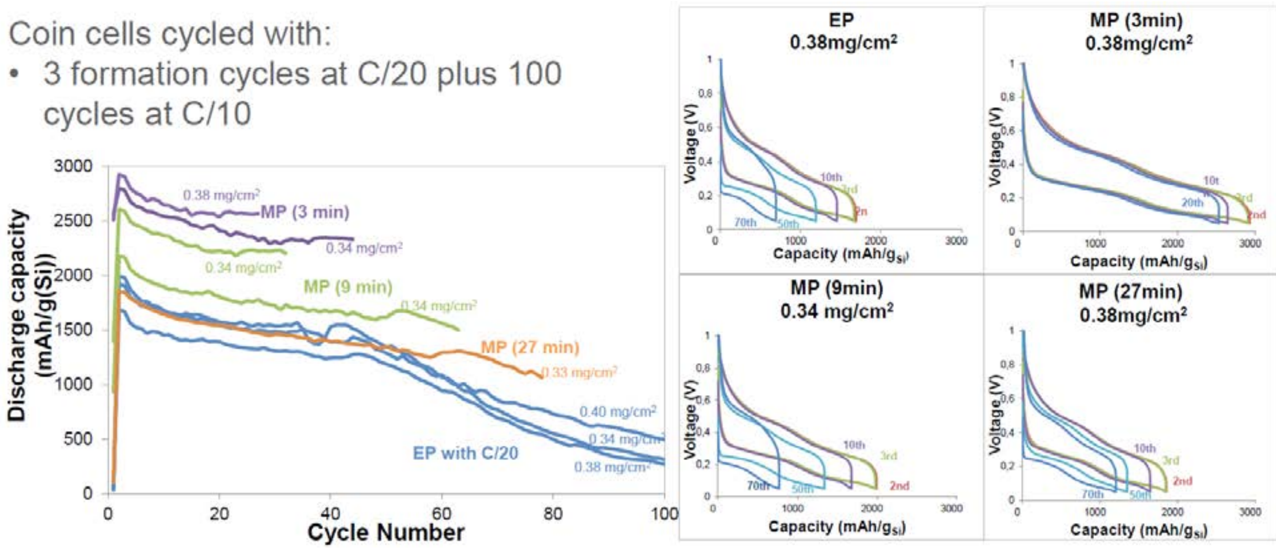


focuses on high voltage/high energy cathodes, and in particular thermal stability. In the third task the electrode/electrolyte interface of these cathodes are investigated, where the focus is on stabilizing the materials at high voltages. The main focus in MoZEES has initially been on NMC and LMNO cathodes. However, since NiMH-batteries (nickel metal hydrides) are the preferred option in many hybrid electric vehichles (e.g. Toyota Prius and Mirai), and also is a suitable option for heavy duty applications with very demanding charging behavior (e.g. regenerative braking in trains), one of the tasks in RA1 focuses on the development of new alloys for NiMH-batteries. The last task in RA1 focuses on advanced characterization methods, development of new methods, as well as implementation of existing methods to gain a better understanding of the battery charge/discharge mechanisms and degradation behavior.

The user partners in RA1 have been involved in many aspects of the activities during the first year of the center. All user partners were represented during the kick-off meeting in March, and many of them also participated in the RA1 workshop held in Trondheim in October 2017. In addition to participating during workshops and meetings, Elkem provides Si-powders for the work on anodes. SAFT has also provided the research partners with cathode materials in addition to valuable information and advice on materials selection and cycling protocols. Both Elkem and SAFT are closely involved in the planning of further research in MoZEES. The collaboration with BASF on NiMH-batteries has also started up in a good way. One of the PhD students from NTNU (co-supervisor from IFE) has visited BASF in the USA to learn more about their battery material production processes, and the BASF representative in MoZEES has also officially been appointed as co-supervisor for the PhD candidate. There has also been some collaboration with international institutions, which are not partners in MoZEES. One master student working on the metal hydrides in collaboration with IFE/NTNU and the PhD student have spent some time at the University of Bordeaux/CNRS in the fall of 2017.

In the work on Si anodes several approaches have already been implemented in the 2017. Investigation of various water soluble binders is in progress, a literature study on electrolytes has been completed. These results have been made available to the consortium as internal documents. Based on the literature studies, four promising ionic liquid electrolytes based on FSI anions have been selected. Investigations of these in combination with Si anodes supplied by Elkem have been initiated. Initial results on pre-lithiation of Si-anodes was published at the 3rd Nordic Battery Conference in Finland,

Electrochemical cycling behaviour of pre-lithiated Si electrodes. MP = mechanical pre-lithiation, EP = electrochemical prelithiation

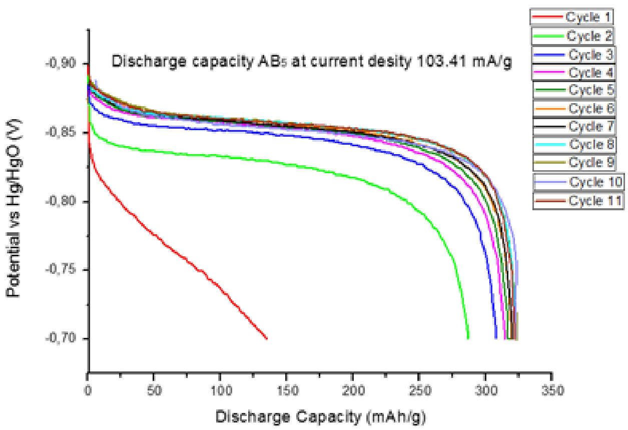


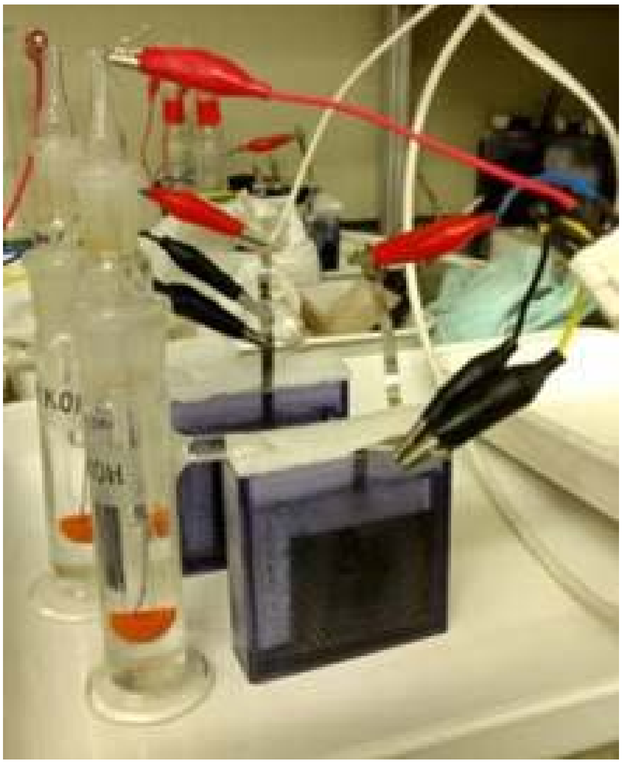
and some of the results are summarized in the figure above. Here, both mechanical and electrochemical methods were investigated as possible options for pre-lithiation. It was found that the mechanical methods worked equally well and in some cases even better than the electrochemical method.

For the Li-ion battery (LiB) cathode materials, work has been initiated with post treatment of cathode powders using spray drying. In further work, these powders will be characterized in half-cell configuration and compared to commercially available cathode materials. In addition to the experimental work on cathodes, a literature review is being performed on suitable cathode materials for high energy/high power LiBs. This literature review will be made available to the consortium in the first quarter of 2018. The work here will involve materials produced by CerPoTech in addition to in-house made materials. Baldur Coatings will also be involved in this work through coating of cathode powders to produce core-shell structures.

The work on NiMH-batteries started by testing commercially available Co-containing AB_5 alloys, which will be used as base line for further investigations. The initial results from the cycling of this AB_5 alloys is shown in Figure below, and agree well with results in literature. A literature review on Laves type intermetallics of Ti and Zr for battery electrodes was also conducted. Based on this literature review, novel high capacity alloys belonging to a group of Laves type compounds were synthesized. The alloys of Ti and Zr with V, Mn and Ni were prepared by arc melting. These new materials have been characterized with regards to phase purity and crystal structure. A study on rapid solidification (RS) of a group of alloys showed significant changes in morphology, grain size and phase abundances compared to other synthesis methods. Electrochemical characterisation of these RS alloys is currently in progress.

First 11 discharge cycles for AB_5 commercial alloy, showing capacities around 320 mAh/g and activation behaviour requiring around 5 charge/discharge cycles to reach maximum electrode performance (left). NiMH cell setup (right).





RA1 Batteries – Travelogue from Kokkola

From the 1st to the 3rd of November the Nordic Battery Conference 2017 (NordBatt 2017) was held in Kokkola, Finland. In this travel letter, MoZEES PhD students Elise and Daniel describes their experience of the conference, which was their first!

-After a quite long journey both by train, bus and airplane, we arrived in Kokkola the evening before the conference started, as part of a large delegation from NTNU. «Where and what is Kokkola?», you might be wondering. Well, Kokkola is a city of approximately 50 000 people situated along the west coast of Finland. Historically the city has been a major exporter of tar. This, along with its large shipbuilding industry has led to the city having a large shipping port, one of the busiest in Finland. The port is now the location of several companies in the chemical industry, such as Boliden, Freeport Cobalt and Yara. In fact, the chemical industry is one of the major employers in the region!

The broad spectrum of research presented at the conference opened our minds to the importance of thinking about the whole lifecycle of a battery

Since the conference would not start until 2 p.m. the next day, we had time for both some sightseeing and some social activities, including the tasting of tar-flavoured local food and beverages, and a beautiful walk to the local harbour.

The conference was opened by Professor Ulla Lassi from the University of Oulu and Stina Mattila who is the Mayor of Kokkola City. The following days were filled with talks and poster presentations where the topics ranged from the extraction and production of raw materials for the battery industry, through the manufacturing of batteries both in cell and battery pack systems, to post mortem analysis and recycling of used batteries. Several groups from all of the Nordic countries presented their current research covering several different battery technologies, including Li-ion, Li-S, Li-O_2, Mg, NiMH, and Zn-O_2 to mention a few. Some recurring themes were the shortage of Co on a global basis, and the ethical aspect of the extraction of Co in Congo.

The COO of Northvolt, Paolo Cerruti, held a convincing presentation about the planned battery factory that will be built in Skellefteå, Sweden, and how important this is in order to strengthen the competence of the battery technology community in the Nordic countries. The availability of cheap green energy, the close vicinity of raw materials and the importance of european battery production for self-reliance were highlighted as reasons for choosing this location. The broad spectrum of research presented at the conference opened our minds to the importance of thinking about the whole lifecycle of a battery, and how it is important to remember the economic, ethical, and environmental cost that comes with the materials and processes one chooses to work with. To sum up; it is safe to say that a lot of exciting things are happening within battery technology in the Nordic countries. The next Nordbatt conference will be held in Denmark in 2019, and we hope to be able to attend it with exciting research of our own!

Part of the NTNU delegation on sightseeing in Kokkola. From the front left: Daniel Tevik Rogstad, Karina Asheim, Ingeborg Røe, and Elise Ramleth Østli. From the back left: Jacob Hadler-Jacobsen, Matthias Augustin, and Henning Kaland. Photo: Daniel Tevik Rogstad.

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. 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.

The collaboration with user partners in 2017 has been through discussions and transfer of knowledge. Johnson Matthey has participated in several teleconferences with UiO and SINTEF on the discussions on materials selection, testing and preparation of hybrid membranes. Discussions with Cerpotech on manufacturing of the inorganic filler materials have been performed. Plans for training of MoZEES scientists on new catalyst evaluation techniques established at Johnson Matthey in 2018 has also been established. NEL Hydrogen has given valuable input to materials and relevant experimental conditions for investigation of alkaline bipolar plates.

A PhD student from University of Cape Town in South Africa has visited SINTEF for 3 months as part of a strategic collaboration. During the stay the PhD student has worked closely with SINTEF researchers on synthesis and characterization of novel electrocatalysts for PEM electrolysers.

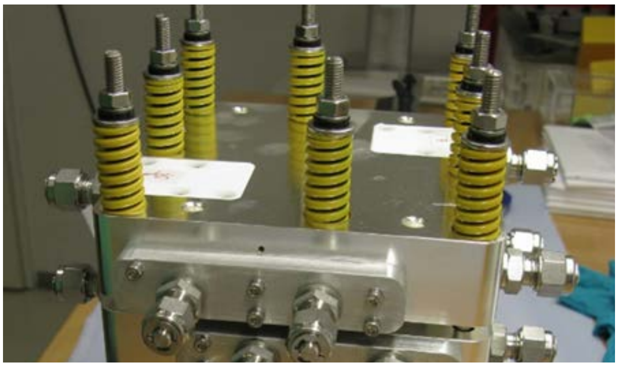
Development of a novel methodology for synthesis of oxide supported noble metal catalysts for PEM fuel cells and electrolysers have been a central activity during 2017. To have good control of the final electrocatalyst powder, it is essential to have a reproducible and well-established synthesis route. Proof of concept of the method has been successful and catalyst particles with nanometer sized Pt can be prepared. During 2018, the method will be further optimized to increase the loading of noble metal and to improve the powder morphology and size.

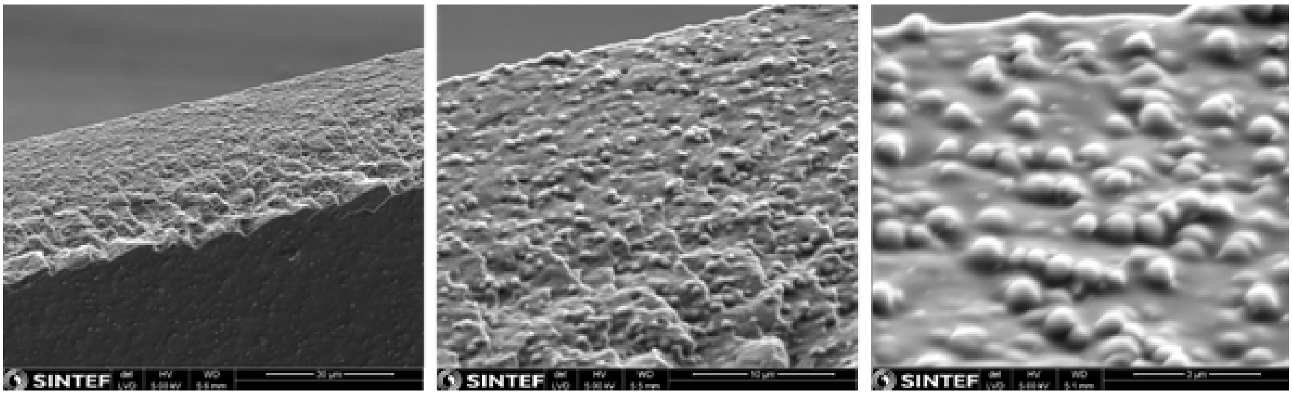
For the work on low cost bipolar plates, SINTEF has modified a PEM singe cell and test-station to enable in-situ contact resistance measurement. The work has been related to improving the measurement technique and transfer to more industrial relevant single cells. The technique is now able to measure the development of contact resistance between the bipolar plate and the porous transport layer in operating laboratory fuel cells and can be used to evaluate coatings and the effect of operating conditions.

A literature review on materials and methodology for evaluation of bipolar plates for alkaline electrolysers is ongoing at NTNU and plans for experimental

Oxide powders ready for noble metal deposition.

Industry relevant single cell test hardware for PEM electrolyzers.





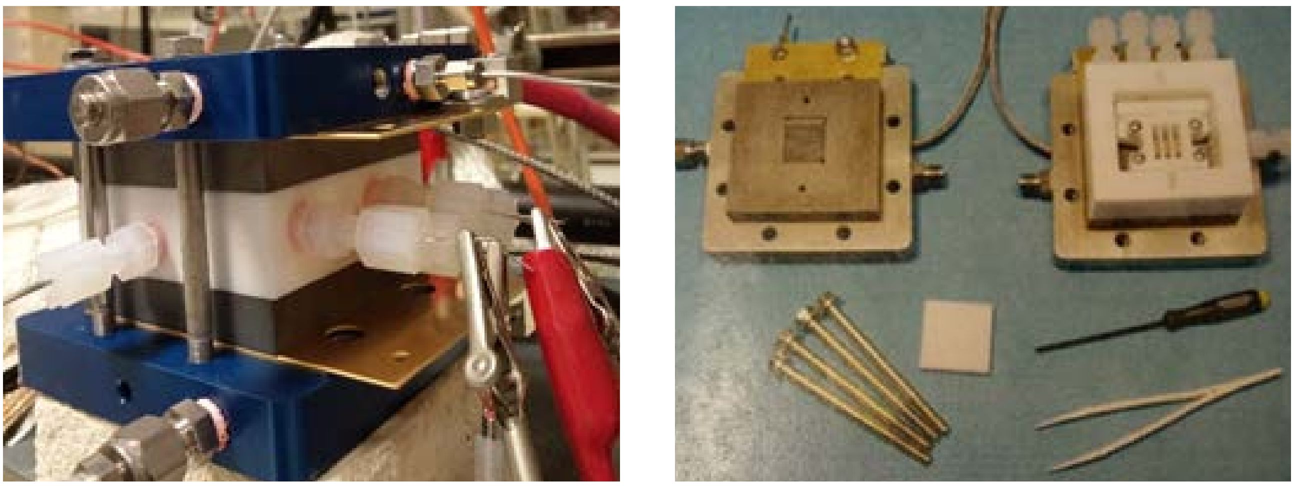
SEM micrographs with different magnifications in cross-section view of Nafion membrane embedding SiO_2 mesoporous fillers.

investigation has been made. In-situ characterization of ohmic resistance and electrolyzer performance development are not as straight forward as PEMFCs. In MoZEES the initial focus will be on ex-situ techniques such as surface characterization (SEM/EDS, XPS, XRD) and electrochemical measurements in a 2 and 3-electrode set-up. The corrosion group at IFE has key instruments that are of disposal to the collaborating partners in MoZEES. Currently IFE is performing corrosion and materials testing in alkaline environment for existing partners in MoZEES, operating high-pressurized alkaline electrolyzers producing oxygen at 30 bars with 20-35% KOH at 60-80 °C.

Another task in RA2 is to develop polymer proton conducting membranes (PPCM) with improved performance under high operating temperatures (>80 °C) and low relative humidities (e.g.20%). This will be investigated by incorporating inorganic fillers, which can act as a desiccant in the PPCM and take up and retain the water content in the membrane even at low RH.

During 2017 a protocol for tape-casting composite inorganic-filler /polymer membranes was developed at SINTEF making use of ball milling and tape-casting. A series of Nafion membranes blended with varying amounts of mesoporous and nanoporous SiO_2 were

Assembled (left) and the dismounted 4-probe conductivity measurements cell.



Instrumentation of GFRP laminate before and after vacuum infusion. As can be seen, the optical fibers are embedded inside the laminate and the picture to the left is from ply number two out of four, meaning the fibers are located in the middle of the laminate.

prepared by SINTEF and supplied to UiO. The produced membranes were characterized by SEM and TEM to study the interface between the polymeric phase and the inorganic particle. In UiO an apparatus for proton conductivities measurements under controlled temperature and relative humidity conditions was set up, including water bath, gas lines connected to wet and dry stages and flowmeters. A standard and commercially available PEM fuel cell with an additional accessory for conductivity screening (4-probe conductivity measurements) were obtained by sai:Scribner Associates. The conductivity cell was connected to a frequency response analyzer to obtain the impedance measurements.

The PhD position at NTNU allocated to work with hydrogen storage tanks was manned in September 2017. A thorough literature review was conducted to establish the research frontier regarding pressure vessels for hydrogen made of composite materials and to get acquainted with different composite material failure criteria currently made available through finite element programs to model the structural integrity of the vessels. A test program has also been made and initiated.

Test sample geometry and instrumentation has been decided on and samples have been produced. Testing is expected to commence in late March 2018. The figure above shows how optical fibers are embedded in the glass fiber plies to measure the strain inside composite laminates. Using optical fiber allows for near continuous strain field measurements, giving very good control of the strain in the samples and very convenient for comparison with numerical methods. In this stage, glass fiber reinforced epoxy is used instead of carbon fiber as it has the same damage mechanisms but is more convenient to work with due to its translucency and HMS requirements.

RA3 Battery and Hydrogen Systems and Applications

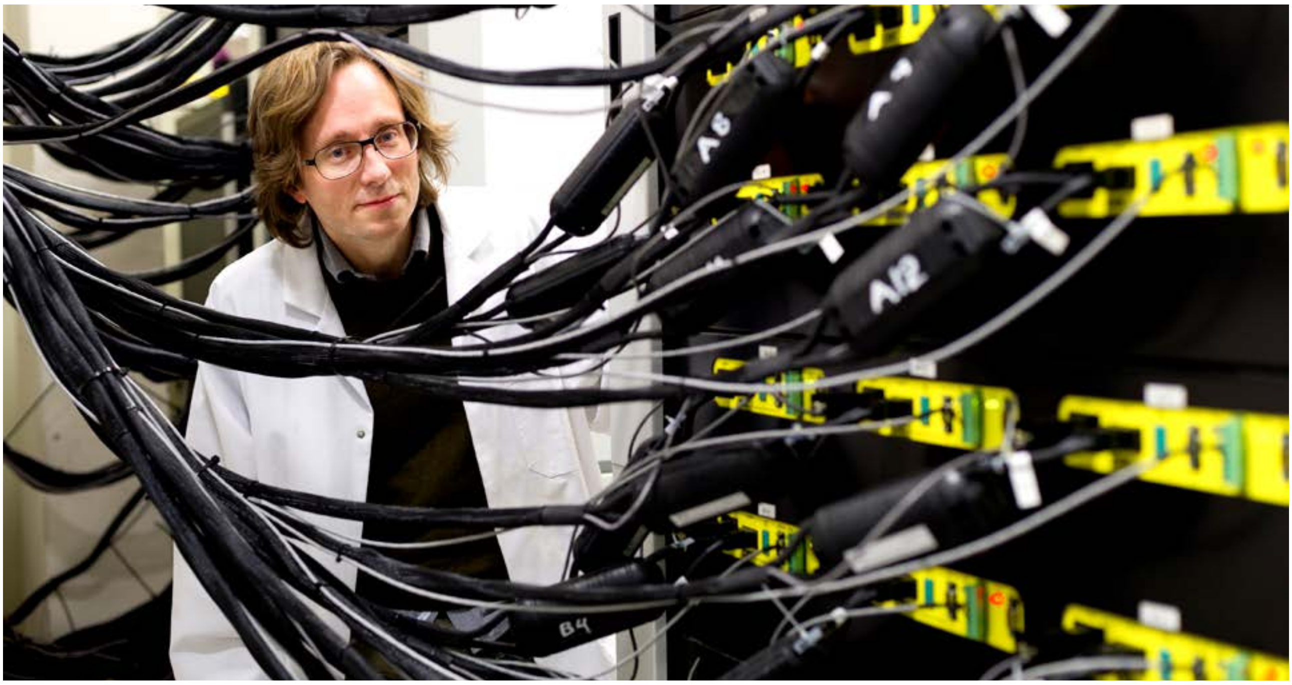
The main objective with RA3 is to develop, test, validate, and study the performance of battery and fuel cell technologies and systems, and to optimize the design and controls of systems suitable for heavy duty road, rail, and maritime applications. There is in RA3 a special focus on lifetime of key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

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 H2-supply systems (with the goal to reduce costs)

The research related to the design and control of hybrid battery/fuel cell systems focuses on maximizing the lifetime of the key components, namely the battery and fuel cells. The long-term goal of this research activity is to develop detailed technical models, including battery and fuel cell degradation models, for simulation of the performance of hybrid battery/fuel cell systems for use in heavy duty transport applications. The fuel cell and hydrogen laboratories at IFE, SINTEF, and NTNU will be used to test and validate new stacks and prototype systems. The construction of a fuel cell system laboratory was initiated at the IFE Hynor Hydrogen Technology Center in 2017, and will be completed in 2018. Investigations on duty cycles for different heavy duty transport applications have been initiated in 2017. NTNU and IFE have started to collect operational data from a high speed passenger ferry (ref. maritime case study), while SINTEF started to look into load profiles for non-electrified railroads in Norway. Literature studies on prognostics and diagnostics of fuel cells were also initiated in 2017.

Battery cell experiments at IFE

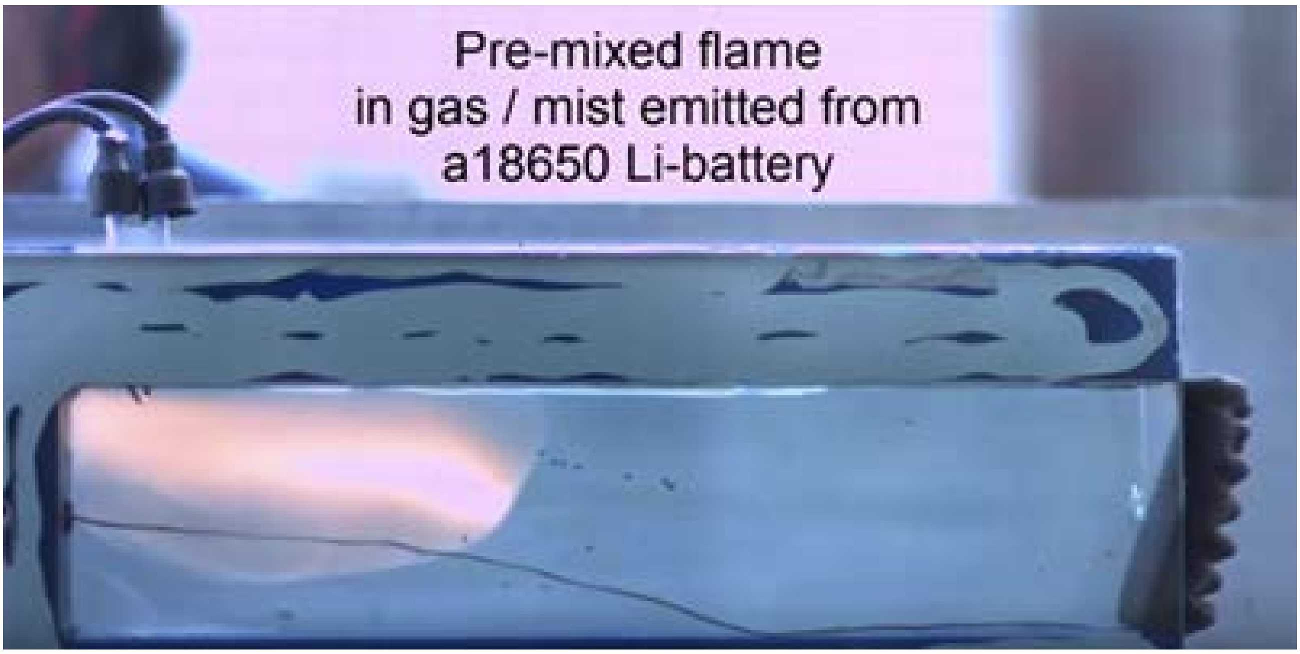


Another key research area in RA3 is to develop tools and methods to evaluate battery lifetime, durability, and safety in a holistic manner. Battery testing facilities at IFE, FFI, and SINTEF will be used to perform in-depth battery lifetime and degradation tests. New theoretical models for simulation of battery degradation will be developed in collaboration with industrial partners (ABB, SAFT, DNV GL, ZEM, Grenland Energy) and international research partners, and validated using experimental data. A Li-ion lifetime battery model developed by RWTH University Aachen was reviewed in 2017, and further modeling developments (in Matlab) are underway in a post. doc. at IFE. This battery lifetime model will be validated using experimental data from long-term testing for Li-ion batteries in IFEs battery testing laboratory. Alternative modeling approaches using actual data from the operation of similar batteries in maritime applications are also being investigated. Degradation mechanisms and potential failure modes for batteries cells will also be investigated using different characterization techniques (SEM, TEM, ICP, XRD etc.) available in laboratories at SINTEF.

Battery system safety is closely related to the design and operation of the battery cells. A PhD-study on battery safety was started up at USN in 2017. This work is supported by abuse tests and experiments performed at FFI, which also has co-supervised. Physical abuse or internal short-circuit of Li-ion batteries can cause fires and explosion. An experimental study on Li-ion battery safety was performed as part of master thesis at USN in 2017. The experiment showed that the vented gas and mist from thermally abused batteries burned fast and represent fire and explosion hazard. This research activity is now being followed up in the PhD-study. The main objective with the PhD study is to find the combustion properties of the materials vented from abused Li-ion batteries, and to use the experimental results to develop a CFD tool in OpenFOAM for simulation of explosions. Application related battery safety studies will also be conducted in close collaboration with DNV GL and other industry partners with particular interest for battery safety (SAFT, PBES, ZEM, Grenland Energy). The first activities in MoZEES on hydrogen also started up in 2017 (ref. maritime case study described below).

In 2017 there was a special focus on maritime applications. Data for a case study of a high speed passenger ferry was provided by the Maritime Association of Sogn og Fjordane (MFSF) and the ship builder Brødrene Aa.

Li-ion battery explosion experiments at USN



A case study project kick-off workshop was conducted in Florø in August 2017. A preliminary design of a hydrogen and fuel cell system for the high-speed passenger ferry was analyzed in a pre-HAZID workshop facilitated by Lloyds' Register and IFE in October 2017. The pre-HAZID identified main hazards related to installing compressed hydrogen and fuel cells on the high speed passenger ferry, and some initial recommendations were made. The work on the case study continues in 2018; the final report will include data (load profile and duty cycle) for a high speed passenger ship in normal route production (IFE, NTNU, MFSF /Brødrene Aa), preliminary design of the the fuel cell and battery energy system (IFE), economic evaluation (SINTEF), and a risk assessment of the preliminary hydrogen system design (Lloyds' Register). NTNU contributed in 2017 with a post.doc. on hydrogen in the maritime.

Research leading to development of zero emission solutions based on battery and hydrogen technology is key innovation area identified in MoZEES. The battery technology and system oriented research performed in RA3 is closely linked to the material and component characterization and testing of batteries activities in RA1. Common activities battery testing/cycling protocols were initiated in 2017. A collaboration between RA3 and RA2 on hydrogen safety related to high pressure composite storage tanks (Type IV) was also initiated in 2017. Finally, the RA3 research work described above will form the basis for more high-level techno-economic analysis performed in RA4, which eventually will lead to the development of roadmaps for technology, business, and policy. MFSF has established a national maritime network, while NTNU has established an international network on Hydrogen in Maritime Transport within the IEA. Both of these networks have been used extensively by several of the MoZEES partners in 2017.

Hydrogen system laboratories at the IFE Hynor Hydrogen Technology Center are available for use in MoZEES RA3 research activities.

A new concept for a hydrogen driven high speed passenger ferry is being investigated in a RA3 case study.

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 a particular 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 will 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 technology 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 transport, energy and ICT sectors may undergo stepwise transformation towards 2030.

Specific case studies of new concepts and business models will be 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
4. Transportation terminals

RA4 will cooperate closely with RA3, and utilize the technology expertise in RA1 and 2 as well as the user partner expertise within RA4 to define relevant concepts and refine business models and values chains.

In 2017 the work focused on establishing the RA and the cooperation between partners. The RA used resources and time to establish the formal organizational solutions for a PhD position at TØI and a Post-doc position at IFE/UiO. The PhD position at TØI was planned to be in co-operation with UiO but was moved to NTNU. The Post-doc position was turned into a temporary research position at IFE/UiO. The PhD at TØI will start up from January 2018 whereas the recruitment process for the temporary researcher is under way, leading to a potential start up in Q2 2018. The start-up of both these positions is thus delayed 6-12 months compared to the original plan.

In 2017 RA4 also collaborated with the FME CENSES on a position paper for hydrogen and electricity in the transportation sector and IEA on the Nordic EV Outlook published in Q1 2018. RA4 also contributes to a policy report on Decarbonisation of Transport through the MoZEES Director's participation in a working group within the European Academies Science Advisory Council (EASAC).

Further work in RA4 established a list of interesting case studies, of which two have been selected with start-up from January 2018. These are; (1) Electric and hydrogen solutions for heavy duty trucks and buses, and (2) Electric and hydrogen solutions for tendered ferry services. These are broad case studies, studying user needs versus technology characteristics and costs and related policies and impacts.

The fuel cell powered trucks of ASKO Midt-Norge will be part of the case study on zero emission heavy-duty freight vehicles. From left: Jørn Endresen (ASKO), Anders Ødegaard and Steffen Møller Holst (both SINTEF).

Education

MoZEES aspires to integrate our educational activities with the scientific development of the Center. Our three academic partners (UiO, NTNU and HSN) 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. 2017 has been a kick-off year for both recruitment, organizational- and scientific educational activities. The Center has recruited 5 PhD fellows and 2 post docs and researchers. They have been integrated in local research environments, and have been introduced to their closest collaborative partners in their respective Research Areas. Several of the PhD students have an industrial specialist as a co-supervisor.

A few participated at the official opening seminar for the Center in March, where they met most of the consortium and relevant interest groups. We aim to develop an interactive arena for all the participants at the Center where students and young researchers will have a dedicated session at our annual conference. In particular, we will develop a scheme for fruitful interactions between international renowned mentors and our younger scientists.

MoZEES Research Training Network (RTN)

The Center is developing 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. The MoZEES RTN had its own kick-off seminar in November 2017. Here the MoZEES students and researchers joined the Center management and selected industry partners in fruitful discussions, see separate box for more details.

In MoZEES, we are looking forward to develop the MoZEES RTN. During 2018 we will develop principles and a funding scheme for International and Industry Exchange for PhDs and young researchers. This is to foster increased interactions and mobility of candidates.

PhD kick-off seminar

On December 5th the MoZEES PhD students and postdoctoral researchers gathered at Lysebu, Oslo for a day of scientific discussions and networking. The purpose of this kick-off seminar was to consolidate the MoZEES training network by bringing the students within different research areas and disciplines together to discuss their projects in the broader context of Zero Emission Transport, and to reach a common understanding of the challenges the Center is set to solve and our strategy to meet them.

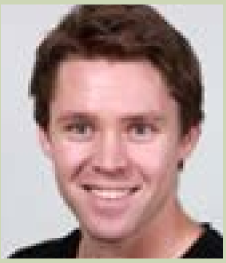
The day started with site visits to ceramic processing and electrochemistry labs at SINTEF and UiO, before the group was transported to Lysebu for lunch and an afternoon filled with interesting discussions, inspiring presentations and an engaging session of interactive group work. Both students, the Center management, supervisors and some user partners held presentations and contributed to the common reflections and discussions. The wide range of scientific activities in MoZEES – all linked together by the common goal of decarbonizing the Norwegian heavy duty transport sector – was also reflected by the wide range of topics covered in the student presentations: Ionic liquids for Li-ion batteries, Fatigue of composite pressure vessels, Next generation proton conductive membranes for PEM applications, Combustion properties of vented materials from Li-ion batteries, and The influence of technological development and economic incentives on the demand of zero emission vehicles – Something for every taste!

The wide range of scientific activities in MoZEES – all linked together by the common goal of decarbonizing the Norwegian heavy duty transport sector – is well illustrated by the titles of the student presentations Via the presentations of Elkem and Lloyd's Register – held by Jorunn Voje and Olav Roald Hansen, respectively – the students were also granted insight into the user partners' perspective on the objectives of MoZEES and learned about their activities and interests in the field. The students find that the large industry- and user partner network in MoZEES represents a unique opportunity and advantage for them in their scientific work in the years to come.

Both students, the Center management, supervisors and some user partners contributed to the common reflections and discussions during the seminar

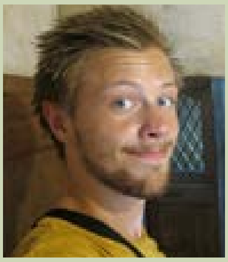
Recruitment

Dr Einar Vøllestad is a researcher at the University of Oslo. In collaboration with prof. Truls Norby Einar has been exploring the properties of non-porous, protonic conducting composite membranes for use in PEM fuel cells and electrolyzers. Einar is starting a new job in SINTEF in 2018, and the work on this topic will be continued by Athanasios Eleftherios Chatzitakis.



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.

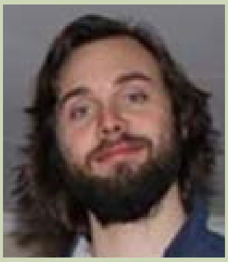
MSc. Daniel Tevik Rogstad embarked on his PhD studies at NTNU in the fall 2017, with Prof. Ann Mari Svensson as his supervisor. Daniel is investigating Silicon anodes and ionic liquids in Lithium-ion batteries.



MSc. Elise Ramleth Østli started her PhD studies at NTNU in August, with RA1 manager Prof. Fride Vullum Bruer as supervisor. She is aiming 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 study is 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 is embarked on his PhD studies at USN in September, 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.



Dissemination

A central part of MoZEES is to set the agenda on zero emission transport, and make our vision more known in the public domain and among key stakeholders. In order to achieve this, MoZEES and participants in the Center have been involved in arranging several open seminars and workshops in 2017.

- FME MoZEES was officially opened by Minister of Transport and Communications Ketil Solvik-Olsen on 20 March in connection with a two-day kick-off seminar held at IFE, Kjeller. More than 100 participants witnessed inspiring presentations by partners from both public government agencies and industry; each of them sharing their perspectives on zero-emission transport as well as their stakes in and ambitions for MoZEES. Solvik-Olsen highlighted the strength of MoZEES in having such a wide range of partners, with central actors from both research, academia, industry and public government agencies.

- This isn't something individual players can solve by themselves. In order to succeed with emission cuts in the transport sector we have to work together, both on the national and international level, Solvik-Olsen emphasized in his opening speech.

- As a part of the workshop series Clean Tuesday & Bellonaforum –OREEC, Bellona and IFE/MoZEES invited to a workshop on Zero emission transport solutions 14 March.

From left: IFE's Director Nils Morten Huseby, Minister of Transport Ketil Solvik-Olsen and MoZEES Center Director Øystein Ulleberg at the kick-off seminar.

- A seminar on Zero emission in transport was hosted at NTNU 26 April with Norges Tekniske Vitenskapsakademi as main organizer.
- MoZEES organized a workshop about Green transformation in transport and energy as a part of the CIENS conference 6 December at UiO. A report of the workshop and the presentations can be accessed here: http://mozees.no/workshop-gronn-transformasjon-i-transport/

In addition, the Center Director, research leaders, and other MoZEES-partners have attended several national and international conferences and open meetings with presentations and poster sessions:

- HFC 2017 - Hydrogen and Fuel Cell Conference, 5-6 June, Vancouver
- ICE 2017 - International Conference on Electrolysis, 12-14 June, Copenhagen
- ICHS 2017– International Conf. on Hydrogen Safety, 11-13 September, 2017, Hamburg
- Marine Energy Conference 2017, 13-14 September, Florø
- EVS30 - Electric Vehicle Symposium & Exhibition, 9-11 October, Stuttgart
- UN Capacity Development Seminar on Sustainable Transport, 16-17 October, Trondheim
- EERA seminar - PEM fuel cell lifetime for maritime applications, 30 October, Oslo
- NordBatt 2017 – Nordic Battery Conference, 1-3 November, Kokkola, Finland

MoZEES has published six articles in 2017: two on the topic of lifetime and aging of Li-ion batteries (UiO, IFE), two on Nickel-metal hydride batteries (IFE, BASF), one on hydrogen safety (USN) and, finally, one on battery safety (HSN). The Center Director was furthermore interviewed about MoZEES in an article in Teknisk Ukeblad, and a senior research scientist in MoZEES debated Li-ion batteries in the radio program NRK Ekko.

Mali Hole Skogen (OREEC), Ola Elvestuen (V, Minister of Climate and Environment) and Martin Kirkengen (Cenate) discussing the future energy carriers of the transport sector at the Clean Tuesday & Bellonaforum workshop.

Appendix 1: Personnel

Postdoctoral Researchers with financial support from the Center Budget						
Institution	Name	Sex M/F	Nationality	Start date	End date	Topic
UiO	Einar Vøllestad	M	Norwegian	07.08.2017	28.02.2018	Proton conducting composite membranes
NTNU	Julia Wind	F	Norwegian	01.10.2017	31.03.2018	Advanced characterization techniques

PhD students with financial support from the Center Budget						
Institution	Name	Sex M/F	Nationality	Start date	End date	Topic
NTNU	Daniel Tevik Rogstad	M	Norwegian	01.09.2017	31.08.2020	Silicon anodes and ionic liquids in Lithium-ion batteries
NTNU	Elise Ramleth Østli	F	Norwegian	21.08.2017	20.08.2020	Water-based manufaturing routes for electrodes
NTNU	Eivind Hugaas	M	Norwegian	01.09.2017	31.08.2020	Fatigue mechanisms of hydrogen storage tanks
HSN	Mathias Henriksen	M	Norwegian	15.08.2017	15.08.2021	Explosion hazards of Lithium ion batteries
IFE	Ika Dewi Wijayanti	F	Indonesian	28.04.2017	31.08.2019	Nickel metal hydride batteries

Key researchers		
Institution	Name	Main research area
FFI	Helge Weydahl	battery safey, 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 safey
HSN	Dag Bjerketvedt	Hydrogen and Battery safety
HSN	Joachim Lundberg	Hydrogen and Battery safety
HSN	André Vagner Gaathaug	Hydrogen and Battery safety
HSN	Knut Vågsæther	Hydrogen and Battery safety
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 - elektrolyzers
IFE	Samson Lai	Silicon nano particles for Li-ion batteries
IFE	Asbjørn Ulvestad	Silicon anodes for Li-ion batteries
IFE	Hanne Flåten Andersen	Silicon anodes for Li-ion batteries
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	Eva Rosenberg	Energy system modelling
NTNU	Fride Vullum-Bruer	Battery materials and components
NTNU	Ann Mari Svensson	Battery materials and components
NTNU	Frode Seland	Battery and electrolysis components and technology
NTNU	Andreas Echtermeyer	Hydrogen components, testing and modelling
NTNU	Ingrid Schjølberg	Battery and hydrogen systems for marine applications

Key researchers		
NTNU	Asgeir Tomasgard	Policy and techno-economic analysis
SINTEF	Bredesen Rune	Funtional oxides, solid state diffusion/kinetics, membranes, fuel cells and electrolysers
SINTEF	Dahl Paul Inge	Materials synthesis and processing for batteries
SINTEF	Dalaker Halvor	Batteries, Si-anodes
SINTEF	Damman Sigrid	Governance, institutional drivers and barriers
SINTEF	Denonville Christelle	Composite membranes for PEMFC
SINTEF	Fontaine Marie-Laure	Composite membranes for PEMFC
SINTEF	Kaus Ingeborg	Functional oxide materials
SINTEF	Kongstein Ole Edvard	PEMFC Bipolar plates and PEMFC systems
SINTEF	Midthun Kjetil Trovik	Operations research, economic analysis
SINTEF	Mokkelbost Tommy	Batteries, RA1 SINTEF PL
SINTEF	Møller-Holst Steffen	H2-technologies, feasibility studies, policy, strategy (EU)
SINTEF	Norvik Roar	Social scientific transport research
SINTEF	Ødegård Anders	PEMFC Bipolar plates and PEMFC systems
SINTEF	Stange Marit Sæverud	High-temperature/ceramic FC/EC; Catalysts for PEMFC/EC
SINTEF	Thomassen Magnus Skinlo	RA coordination. PEMWE/PEMFC materials and systems
SINTEF	Tolchard Julian Richard	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	Barnett Alejandro Oyarce	PEMFC and PEMWE testing, BPP, membranes, catalysts and AST protocols
SINTEF	Bjerkan Kristin Ystmark	Social scientific transport research
SINTEF	Hanetho Sidsel Meli	Li-ion batteries development of cathodes and anodes
SINTEF	Rørvik Per Martin	High-temperature/ceramic FC/EC; Catalysts for PEMFC/EC
SINTEF	Smith Graham Thomas	PEMFC Bipolar plates and PEMFC systems
SINTEF	Sunding Martin Fleissner	Material characterisation by microscopical and spectroscopical techniques
SINTEF	Sundseth Kyrre	Techno-economic analyses
SINTEF	Wagner Nils Peter	Li-ion batteries development of cathodes and anodes
SINTEF	Wang Lu	Batteries, electrode manufacturering, assembly and evaluation
SINTEF	Graff Joachim Seland	Sample characterisation by SEM and EDS
SINTEF	Kvello Jannicke Hatlø	Electrode manufacturering and assembly
SINTEF	Lein John Erik	Electrode manufacturering and assembly
SINTEF	Abdillah Maulid Yussuf	Fabrication of ceramic materials
TØI	Erik Figenbaum	Energy, technology and environment - Electric vehicles, environmental characteristics of vehicles.
TØI	Inger Beate Hovi	Vehicle and demand modelling, SCGE-modelling, cost functions, economic incentives, user needs and obstacles
TØI	Lasse Fridstrøm	Vehicle fleet forecasting, vehicle and demand modelling, economic incentives
UiO	Helmer Fjellvåg	Battery materials and components
UiO	Truls Norby	Fuel cell and electrolyzer materials and component
UiO	Katinka Elisabeth Grønli	Energy, environment and climate
UiO	Øystein Moen	Coordinates multidisciplinary energy education

PhD students working on projects in the Center with financial support from other sources					
Institution	Name	Nationality	Period	Sex M/F	Topic
NTNU	Katie McCay	UK	2016-2019	F	Bipolar plates for fuel cells

Postdoctoral Researchers working on projects in the Center with financial support from other sources					
Institution	Name	Nationality	Period	Sex M/F	Topic
NTNU	Sepideh Jafarzadeh		2016-2018	F	Battery and hydrogen systems for marine applications

Master degrees						
Institution	Name	Sex M/F	Topic			
HSN	Jonathan Johnsplass	M	Battery safety	Spring 2017		
HSN	Erik Nygaard	M	Hydrogen safety, ATEX	Spring 2017		

Appendix 2: Statement of Accounts

Funding	Amount
The Research Council	8 944
The Host Institution (IFE)	2 664
Research Partners	5 526
Industry partners	4 537
Public partners	2 358
Total funding	**24 029**

Costs	Amount
The Host Institution (IFE)	8 066
Research Partners	11 283
Industry partners	3 703
Public partners	557
Equipment	420
Total costs	**24 029**

(All figures are given in kNOK)

Appendix 3: Publications

The activities in the Center have resulted in the following publications in refereed journals in 2017

1 Gaathaug, A.V., K. Vågsæther, J. Lundberg, and D. Bjerketvedt, *Detonation Propagation in Stratified Reactant Layers*. Proceedings of the 58th Conference on Simulation and Modelling, 2017(138): p. 162-167.

2 Johnsplass, J.S., M. Henriksen, K. Vågsæther, J. Lundberg, and D. Bjerketvedt, *Simulation of burning velocities in gases vented from thermal run-a-way lithium ion batteries*. Proceedings of the 58th Conference on Simulation and Modelling, 2017(138): p. 157-161.

3 Richter, F., P.J.S. Vie, S.H. Kjelstrup, and O.S. Burheim, *Measurements of ageing and thermal conductivity in a secondary NMC-hard carbon Li-ion battery and the impact on internal temperature profiles*. Electrochimica Acta, 2017. 250: p. 228-237.

4 Ulvestad, A., H.F. Andersen, J.P. Mæhlen, Ø. Prytz, and M. Kirkengen, *Long-term cyclability of substoichiometric silicon nitride thin film anodes for Li-ion batteries*. Scientific Reports, 2017. 7(1).

5 Young, K.-H., J.M. Koch, C. Wan, R.V. Denys, and V. Yartys, *Cell Performance Comparison between C14- and C15-Predomiated AB2 Metal Hydride Alloys*. Batteries, 2017. 3(4): p. 15.

6 Young, K.-H., J. Nei, C. Wan, R.V. Denys, and V. Yartys, *Comparison of C14- and C15-Predomiated AB2 Metal Hydride Alloys for Electrochemical Applications*. Batteries, 2017. 3(3): p. 19.

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MoZEES
Mobility Zero Emission Energy Systems

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