MOZEES
Mobility Zero Emission Energy Systems

FME
FORSKNINGS-
SENTER FOR
MILJØVENNLIG
ENERGI
Norges forskningsråd

Annual Report 2022

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Message from the Chair of the Board

The role of the MoZEES Center is to support the use of zero-emission energy systems in heavy-duty transport with focus on battery and hydrogen technologies has become more evident in 2022. The recent roadmap "Grønt Industriløft" from the Government has ambition to develop Norway as a green industry and energy giant. Hydrogen, batteries, and maritime industry are 3 of the 7 focused areas of this roadmap. Also, the Government's battery strategy was launched in 2022, following up the hydrogen strategy of 2021, with 10 action-oriented priorities. This strategy states that the Government will build strong communities of education, research, and competence in parallel to the industrial battery efforts. These and many other news and actions justify my strong believe in the increasing relevance of FME MoZEES, both in a Norwegian and European context.

MoZEES has passed half its operation period and will continue with increasing focus on innovation built on research results from the Center. The first initiative to generate MoZEES innovation spin-off projects was successfully carried out by the MoZEES Innovation Committee and the Director in 2022. It is my hope that the 4 selected pre-projects, out of 10 proposals, presented at the MoZEES Annual Meeting will lead to spin-off activities, and that similar stimulation of innovation could be continued in the next years. In line with these ambitions, it is also encouraging to observe the industrial uptake of research results and recruitment of PhDs by MoZEES Partners.

It is important that MoZEES continues to focus on dissemination and international cooperation as shown through several events in 2022. In this respect I would like to mention the co-operation with RWTH Aachen to organize a battery seminar at the Center for Ageing and Lifetime with participation of 7 MoZEES partners, the 2nd MoZEES PhD Summer School with international lectures organized together with the FME Norwegian Centre for Energy Transition Strategies (NTRANS), the 2-days Annual Meeting that included among many presentations 4 Keynotes from distinguished international experts, and the MoZEES Battery Days 2022 with 21 participating Partners. Many efforts lie behind these and other successful events in 2022, and I would like to express my gratulations to the Centre Management and staff for these excellent meetings.

It is a significant challenge to reduce the large greenhouse gas emissions from the transportation sector in Norway. In MoZEES we are committed to an overall ambitious goal: to contribute to the design and operation of safe, reliable, and cost competitive zero emission transport solutions. During the last years of the period for the Center, I believe that MoZEES' footprint towards development and deployment of zero-emission mobility will continue to grow along with the many results emerging from the ongoing activities, including research and innovation, education and training, spin-off activities and international collaboration.

On behalf of the Board, I would like to thank the Research Council for the support to the Center, and all MoZEES partners, our students and researchers for their continuous strong commitment and significant contributions. I also thank the MoZEES Director Øystein Ulleberg, his leader group, and the administrative staff for their large efforts in leading a successful Center.

Rune Bredesen

Letter from the Center Director

In 2022 we got back to normal operation again after a long period with travel and meeting restrictions due to the COVID-19 pandemic. It was therefore very nice to observe that the strong relationships built up between the Research and Industry Partners in MoZEES over the past few years continued to strive as soon as we had the chance to meet again. In the fall there was even a "ketchup" effect with several large and important MoZEES meetings organized right after each other. First, there was the MoZEES Battery Meeting and Technical Visit to CARL in Aachen in October, then came the MoZEES Annual Meeting 2022 in Asker in the beginning of November, and finally the MoZEES Innovation Forum 2022 in Oslo in the middle of November. It was very impressive and encouraging to see the great interest and high attendance at these events despite the short time between the meetings. There is a lot of capacity in MoZEES!

Education and research collaborations around our PhD-students is an important "glue" in our relationships in MoZEES. A big thanks to UiO for organizing the MoZEES Research Training Network, which includes taking care of the MoZEES Mobility Program for young researchers, facilitation of meetings and workshops between researchers and students, and the organization of the MoZEES Digital Lunch Talks, including invited talks from some of our Industry Partners. In 2022 there was also organized a very interesting and successful PhD Summer School on Sustainable Transport, again with invited talks from Research and Industry Partners in MoZEES. When I attend these events and meet old and new faces, I feel that we are turning into a "big happy MoZEES family". I hope that more of you feel the same and that you feel welcome to contribute and collaborate in the Center.

MoZEES is continuing to produce very good research results. In 2022 four (4) of our students defended their PhD theses on topics ranging from electrodes for alkaline water electrolysis, material properties of [hydrogen] pressure vessels made of composite materials, hydrogen safety in confined spaces, to high voltage cathode LNMO battery materials. Congratulations to the newly graduated PhDs and their supervisors at NTNU and USN for the completion of these important works. I would also like to congratulate the PhDs in getting relevant jobs in the battery and hydrogen industry. Please note that MoZEES PhD alumni students are always welcome to work with us on new relevant projects. I would also like to acknowledge the hard work of the many researchers at IFE, SINTEF, TØI, and FFI who have continued to produce excellent research results in 2022. Twenty (20) scientific and peer-reviewed publications were recorded last year, and I know that there are still many more on the way. Some highlights from the research conducted in 2022 is provided in this Annual Report.

The MoZEES innovation activities are also taking shape and form, as pointed out in the Message from the Chairman of the Board. Here I would particularly like to thank the MoZEES Innovation Committee for their important contributions in the establishment of the MoZEES pre-projects in 2022. Both the MoZEES Board and the Innovation Committee have been instrumental in the design and writing of the call and evaluation of the pre-projects, which were presented at the MoZEES General Assembly 2022. The quality of the work and results from the MoZEES pre-projects were very interesting and demonstrated that it is worthwhile to set aside this kind of internal seed-funding to create new ideas for future MoZEES spin-off projects. There will therefore be a new round of MoZEES pre-projects in 2023.

I have mentioned this before but believe that it cannot be repeated often enough: The main resource in MoZEES are the people! In 2022 there were more than 100 persons working actively on different research tasks within the Center, including 67 key researchers, 11 PhD candidates, 6 postdoctoral fellows, and more than 25 professionals from public and private sector. We are also a very internationally oriented research center, with 20 different nationalities represented in the consortium.

MoZEES is a large undertaking and there are many people to thank for the progress made in the Center so far. I would especially like to thank the Chairman of the Board Rune Bredesen, the Management Team, and the Coordinator Ragnhild Hancke, who all have made significant contributions to the Center over the past few years. I would also like to thank the Chairman of the MoZEES Innovation Committee Geir Brekke and IFE's battery and hydrogen business developers, Sigmund Kielland and Camilla Røhme, for strengthening the MoZEES Innovation and Outreach activities. I would also like to inform that there will be some small changes in the administration of the Center from 2023. Since Ragnhild is taking a new role as Head of the Hydrogen Technology Department at IFE we will add some more people to assist her with the administration and coordination of MoZEES. For the Partners in MoZEES the small organizational changes should not be too noticeable.

Finally, I would like to thank everyone that has contributed to MoZEES the past year. Your efforts are truly appreciated! We all know that it takes time to change from a fossil fuel-based energy system to a zero-emission energy system. We also know that it will take some time to get the necessary infrastructure and manufacturing capabilities in place so that we can properly convert to zero-emission transport solutions. However, the latest political and commercial developments on battery and hydrogen technology are very encouraging and should give us a strong motivation to continue our important work. MoZEES is an important foundation of knowledge for the future zero emission transport energy systems. I am convinced that our long-term efforts will make a difference in the end.

Keep up the good work!

Øystein Ulleberg (IFE)

About MoZEES

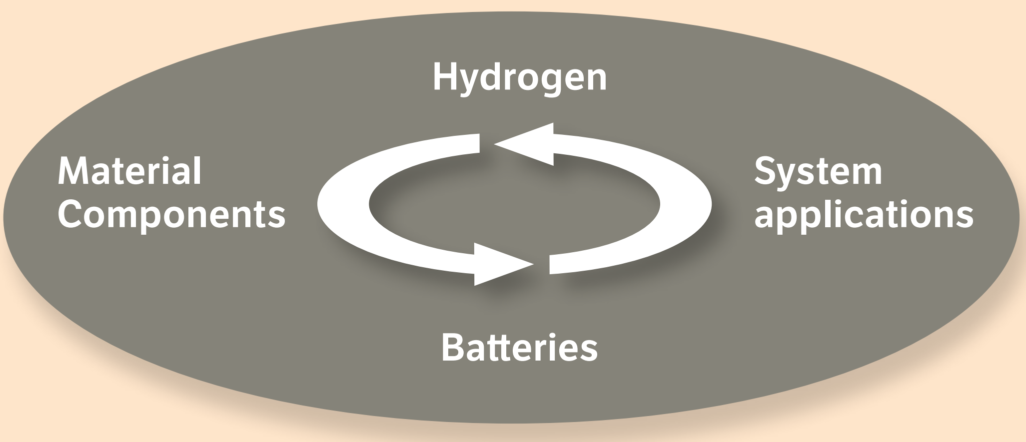
Norway has access to vast amounts of renewable power, some of which can be used to produce electricity and hydrogen for transport. Battery and hydrogen technologies have been demonstrated for use in light-duty zero-emission transport applications. In Norway there are ambitious goals for low- and zero-emission transport, but further developments are needed before new battery and hydrogen technologies can be introduced into heavy-duty transport sectors (road, rail, and sea). This is the motivation to establish a long-term national research effort on zero-emission energy systems for transport.

The main objective of MoZEES is to be a Center for environment-friendly energy research with focus on new battery and hydrogen materials, components, technologies, and systems for existing and future transport applications on road, rail, and sea. The Center contributes to the design and development of safe, reliable, and cost-competitive zero-emission transport solutions. There is also a strong focus on education of PhD-students and post-doctoral fellows in the center.

The specific focus areas for the research activities are:

1. New materials and processes for niche markets in the battery and hydrogen industry
2. Battery and hydrogen components and technologies for export-oriented products
3. Battery and hydrogen systems for application into near-to medium-term transport markets (road, rail, sea), with focus on maritime applications
4. New transport solutions and services, with focus on techno-economic feasible pathways towards zero-emission systems.

MoZEES is a collaboration between 4 research institutes (IFE, SINTEF, TØI, and FFI), 3 universities (UiO, NTNU, and USN), 7 public partners, 2 private interest organizations, and 21 commercial and industrial partners, including key battery and hydrogen materials, components, technology, and systems suppliers. There have also been established formal collaboration agreements (MoUs) with four international universities: RWTH University Aachen (Germany), University of Uppsala (Sweden),



University of California Davis (USA), and University of Genova (Italy). Institute for Energy Technology (IFE) at Kjeller in Norway is the host for FME MoZEES.

In MoZEES there is a special focus on research and development of zero-emission solutions for heavy-duty transport, especially on the use of batteries and hydrogen in maritime applications. There is also a strong focus on battery material research that can assist the development of new Norwegian industrial battery value chains.

In 2022 there were more than 100 persons working actively on different research tasks within MoZEES, including 67 key researchers, 11 PhD candidates, 6 postdoctoral fellows, and more than 25 professionals from thepublic and private sector. In addition, there has been significant activity with external national and international partners. MoZEES is an international research center with participants from 20 different countries.

Photo: Geir Mogen

Partners

Industry and Public Partners

- Kystverket
- Jernbanedirektoratet
- Statens vegvesen – Norwegian Public Roads Administration
- Trøndelag fylkeskommune
- Selfa Arctic
- nel
- Teer coatings
- DNV·GL
- OREEC – Kunnskapsbyen
- ASKO – vi forsyner Norge med mat
- Statkraft
- Johnson Matthey Fuel Cells – the power within
- ABB
- Cerpotech
- hub for ocean
- ENOVA
- Unibuss
- Hexagon Composites
- Saft – a company of Total
- equinor
- CENATE
- Corvus Energy
- Hydro
- Port of Oslo
- Vysus Group
- MORROW
- Viken fylkeskommune
- Elkem
- baldur – Baldur Coatings AS
- ZEM Marine – Zero Emission Energy For the Marine Industry

National Research Partners

Institute of Transport Economics
Norwegian Centre for Transport Research

UiO : University of Oslo

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)


Tor Olav Sunde (SINTEF)


Erik Figenbaum (TØI)


Katinka Elisabeth Grønli (UiO)

Members of the Executive Board


Arve Holt (IFE)


Patrick Bernard (Saft)


Pål Danielsen (Jernbanedir.)


Einar Hjorthol (NTNU)


Bjørne Grimsrud (TØI)


Anders Søreng (NEL Hydrogen)

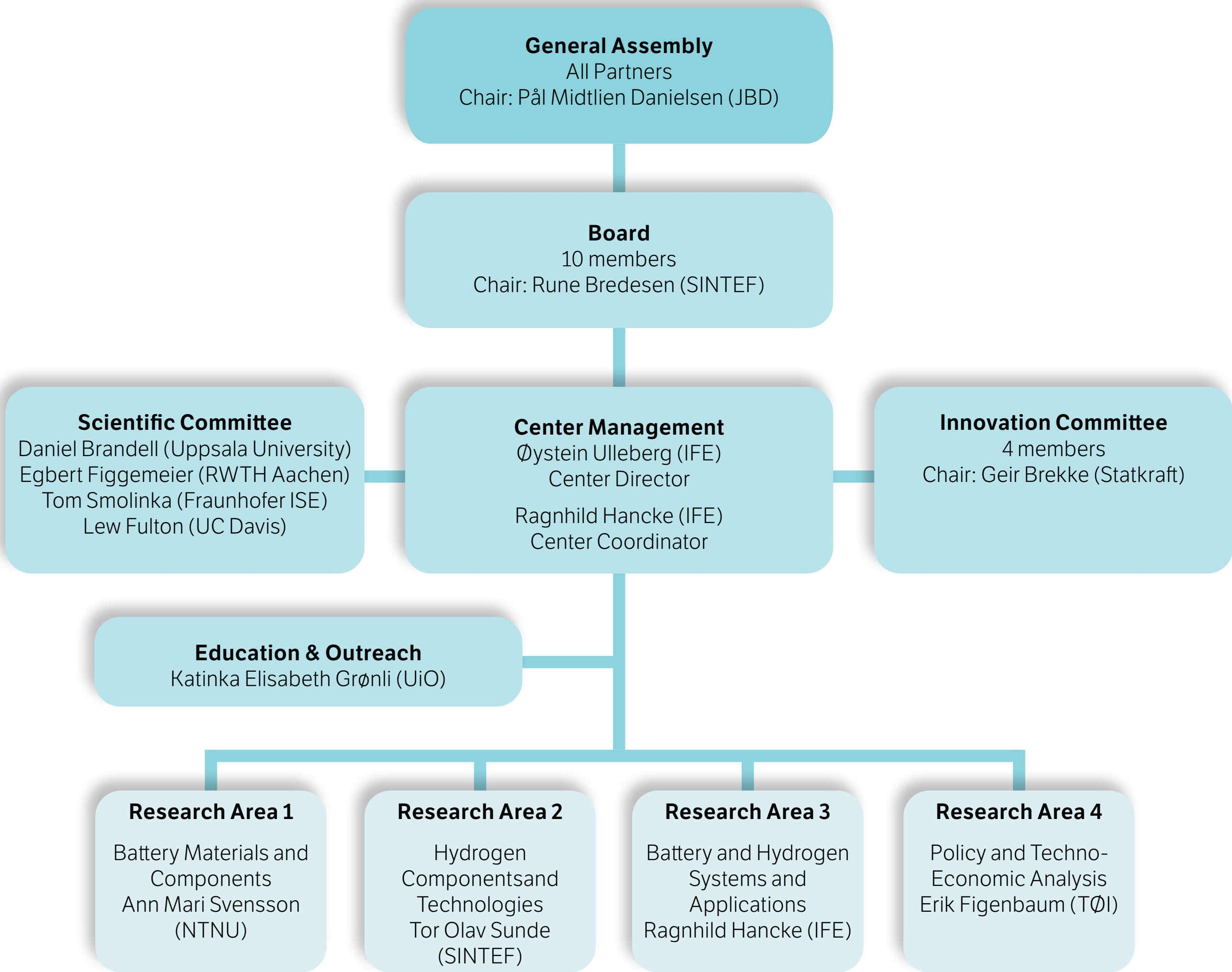

Petter Hersleth (ENOVA)


Marit Dolmen (Elkem)


Rune Bredesen (SINTEF)


Jan Fredrik Hansen (ABB)

Organization



Education

The main objective with the MoZEES Education and Dissemination program is to enhance career developing activities for young researchers in recruitment positions at the Centre and to create synergies between the research areas, partner institutions, and external stakeholders. The dissemination activities are designed to make the MoZEES visible on different arenas, nationally and internationally (more information under Meetings and Seminars). The educational and outreach activities in the MoZEES are jointly administered by the UiO and IFE. The MoZEES Research Training Network (RTN) engages young researchers across all research areas in the Center. An important task for MoZEES RTN is to support the candidates to qualify as scientific researchers within their field of expertise, and at the same time contribute to realizing the goals of the different research areas in the Center. Our goal is to build competence by recruiting and educating new PhD candidates, postdoctoral fellows, and young researchers.

In 2022 there have been 15 PhD-students and 7 postdoctoral fellows directly associated with MoZEES. There is also a trend that more and more PhD and master students, including international students, would like to be associated with different research tasks in the Center. The recruitment of new students to the three university partners UiO, NTNU, and USN has also had a "spill-over effect" to the research institutes SINTEF and IFE. There are several cases where MoZEES students, PhD- and postdoctoral -fellows have migrated from the universities to the research institute. The candidates also migrate to the private industry, particularly to companies with battery research and development.

MoZEES RTN includes the following activities:

- Management of the MoZEES Mobility Program for young researchers; International Academic Mobility Grants have been awarded to five MoZEES PhD students so far and two PhD students have received support for Industry mobility. (More information about the international activities in 2022 are provided below).

- Facilitation of meetings between the Scientific Advisory Committee and researchers, students, and user partners during the MoZEES Annual Meeting, workshops, summer school and internships.

- Organization of special courses and summer schools, including a MoZEES PhD Summer School on Sustainable Transport (2019 and 2022), MoZEES RTN workshops on how to pitch scientific work to the public (2019) and professional scientific writing (2020).

- Extra economic support to PhDs with prolongation related to significant delays caused by the COVID-19 situation. Following the recommendations from the mid-term evaluation, MoZEES have actively supported PhD fellows beyond prolongations provided by their home-institutions. In 2021 five PhD fellows were awarded prolongations corresponding to 40 work weeks and one student was awarded prolongation in 2022.

- Organization of Digital Lunch Talks running monthly as an informal meeting place for all members of MoZEES where current research and new results are presented and discussed. PhDs and young researchers are prioritized as presenters. Both international and industrial partners attend on a regular basis and have also contributed with presentations. The Digital Lunch Talks were established in 2020, in 2022 we hosted 6 talks with a total of 11 presentations.

MoZEES Digital Lunch Talks

January 2022

Glenn-Ivar Gaalaas, Head of Fleet & Infrastructure at Unibuss
Unibuss & Electric buses – From Pilot to Full Scale Operation

Hampus Karlsson, Master of Science at SINTEF Community
Green public procurement for more sustainable urban logistic

February 2022

Thomas Holm, Researcher at Ife
Multi-sine EIS for early detection of PEMFC failure modes.

March 2022

Katie McKay, Research Scientist at SINTEF
Bipolar Plates for PEM Fuel Cells: Current Status and Future Demands

Parnia Navabpour, Research Team Leader at Teer Coatings
Coated aluminium bipolar plates

April 2022

Ruben van Beesten, Postdoctoral fellow at NTNU
Network design modeling for decarbonization of the Norwegian freight transportation system

Øystein Ulleberg, Chief Scientist at IFE and FME MoZEES Director. Highlights from the MoZEES year 2021

September 2022

Inger-Emma Nylund, PhD at NTNU
Stability of LNMO cathodes in ionic liquid electrolytes

Casper Skautvedt, PhD at UiO
An Introduction to myself and my current research interests

October 2022

Wei He, Principal Engineer at Equinor
Accelerating marine battery installations onboard vessels

Heesoo Park, Researcher at UiO
Toward the Understanding of SiNx Anodes' Operation Mechanism in Li-ion Battery.

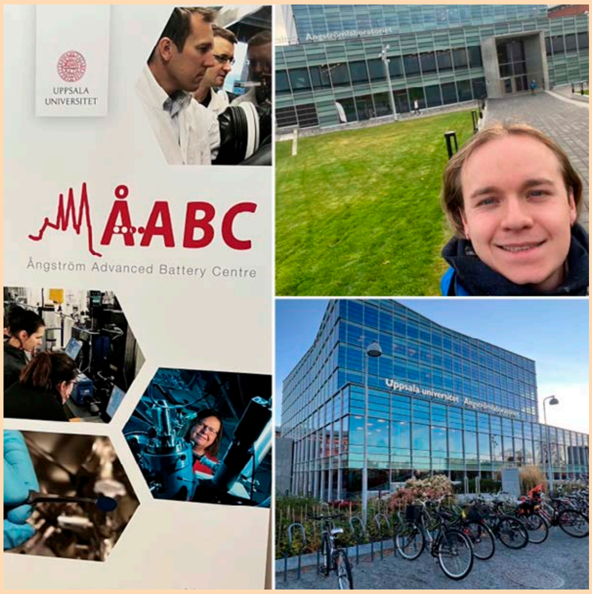
Internationalisation

After a long period with COVID-19 it was in 2022 finally possible to provide the young researchers in MoZEES with international experiences again. Most of the researchers have attended international conferences presenting posters and papers, and our international partners joined the MoZEES Annual Meeting 2022, the MoZEES Battery Days 2022, and the NorRen Summer School 2022. In addition, two PhD fellows have engaged in International Academic Mobility financed by Erasmus and the MoZEES Mobility Program. There have also been visits to ESRF in Grenoble where they could perform different experiments.

Travel letter from Casper Skautvedt (UiO):

I travelled to Uppsala University Ångströmlaboratoriet (Academic partner of MoZEES) in October 2022 and stayed there for two weeks. During my stay there I learned from some of the best in their field within solid state electrolytes. In addition to that I also got to know a lot of other researchers (including PhD students) who contributed to a very nice stay and a broader network.

In November I attended beamtime experiments at ESRF in Grenoble with my colleagues from the battery group at NAFUMA. We were Alexey, Amalie, Anders, Agnieszka, Erlend and I at this experiment. We had two synchrotron experiments at the time, which involved different battery analysis and ex-situ samples.



Travel letter from Halvor Høen Hval (UiO):

In 2022 I was finally able to analyze data from the ESRF, namely from two back-to-back beamtimes at the SNBLs beam lines BM01 and BM31. At BM01 several ex situ and in situ experiments were done to study cation order and rock salt precipitation of $LiMn_{1.5}Ni_{0.5}O_4$ (LNMO), to understand the mechanisms behind these crucial structural traits of the material. At BM31, a range of different LNMO materials with different degree of cation order and rock salt precipitate, were studied operando using XANES and XRD. Lots of data is analyzed, and we expect papers to be submitted from these findings in 2023.

Halvor H Hval mounting a capillary

Halvor H Hval demonstrates the set up where he mounts the operando-cells.

Travel letter from Jonas Martin (NTNU):

In October 2022 I visited the Energy Economics Group at the Technical University of Vienna for a two-month research stay funded by FME MoZEES. This opportunity enriched my Ph.D. project by meeting highly motivated researchers from whom I learned new methods while discussing my ongoing work. A highlight was the opportunity to give a three-hour lecture on "Green Hydrogen and Synthetic Fuels for Heavy Transport" which helped me to further develop my teaching skills. As a result of my stay, I am currently working together with my Austrian colleagues on a scientific paper on minimizing costs when implementing green fuels in heavy transport systems. I met nice and inspiring people, discovered a beautiful city full of culture, and laid the foundation for further research collaborations. Thank you very much!

Jonas Martin with fellow researchers from Technical University of Vienna

MoZEES PhD Graduates in 2022

On 15 February 2022, Eivind Hugaas defended his thesis entitled «Long term material properties of pressure vessels made of composite material». The academic thesis was part of the doctoral work at the Norwegian University of Science and Technology (NTNU), Department of Mechanical and Industrial Engineering. The first opponent at the defense was Professor Christian Berggreen, DTU. Professor Andreas Echtermeyer, Department of Mechanical and Industrial Engineering, was the candidate's main supervisor. Associate Professor Kaspar Lasn, Department of Mechanical and Industrial Engineering, was the candidate's co-supervisor.

On 28 January, Hamid Reza Zamanizadeh defended his thesis entitled "cost effective electrodes for alkaline water electrolysis". The academic thesis was part of the doctoral work at NTNU, Department of Materials Science and Engineering. The first opponent at the defense was Dr Mohamed Mamlouk, Newcastle University, and the second opponent was Dr Egil Rasten, Nel (MoZEES user partner). Professor Frode Seland has been the candidate's main supervisor.

On 13 May 2022 Elise Ramleth Østli defended her thesis entitled "Stabilizing strategies for the high voltage cathode material $LiNi_{0.5 x}Mn_{1.5+x}O_4$ (LNMO)". One of the prioritized research topics in MoZEES is to develop high voltage battery materials in order to increase the energy density of heavy-duty batteries, and the PhD project of Elise was central in these efforts. The doctoral work was carried out at the Department of Materials Science and Engineering, NTNU, where Fride Vullum-Bruer and Sverre Magnus Selbach were the candidate's supervisors. Nils Peter Wagner and Ann Mari Svensson were the candidate's co-supervisors.

On 2 September 2022 Agnieszka Weronika Lach defended her thesis entitled "Hydrogen Safety in confined spaces". This thesis presented large- and real-scale experiments performed to investigate the worst-case scenarios in the case of unwanted hydrogen leakage/release. When hydrogen is released in a confined space like a private garage, carpark, or ship compartment the scenarios are very different from those in an open space. Lack of proper mitigation may lead to enclosure collapse, formation of a flammable cloud, structural damage, and fatalities. The findings presented in the thesis are industry relevant and will be used to shape recommendations, codes, and standards in the EU with the collaboration of 13 other countries. The work was carried out at the University of South-Eastern Norway within HyTunnel-CS project.

MoZEES Battery Days 2022

The MoZEES Battery Days 2022 was organized on 5-6 May 2022 and brought together key national stakeholders from the industry and research. A battery seminar was organized in Lillestrøm on Day 1 while a battery laboratory course was held at IFE on Day 2.

Day 1 – MoZEES Battery Seminar

- **Halvor H. Hval (Morrow)** – The transition between a PhD and working in industry
- **Torleif Lian (FFI)** – The Effect of Internal Pressure on Thermal Runaway Temperature
- **Johan Fridner (Hydro)** – Batteries at Hydro
- **Espen Åkervik (FFI)** – Proposed generic set up for vented Li-ion gases in enclosed spaces within the MoZEES project
- **Andreas Bratland (RCN)** – Funding possibilities for Innovation projects
- **Martin Kirkengen (Cenate)** – What Silicon Nano Robust really is
- **Jinsong Hua (IFE)** – Overview of Battery Modelling Methodology
- **Heesoo Park (UiO)** – Battery Modelling
- **Xavier Raynaud (SINTEF)** – BattMo Demo
- **Azzeddine Bakdi and Kristian Thorbjørnsen (Corvus)** – Parametrized cell models and continuous monitoring of cell degradation
- Panel discussion on battery modelling (Chairs: **Samson Lai and David Wragg**)

Day 2 – MoZEES Battery Laboratory Course

The MoZEES Battery Laboratory course at IFE consisted of some introductory theory and several hands-on laboratory stations allowing the participants to practice the different steps of battery cell fabrication and electrochemical testing. This gave the participants a unique opportunity to practice the different steps of battery cell fabrication and electrochemical testing.

MoZEES Annual Meeting 2022

The MoZEES Annual Meeting 2022 took place at Holmen Fjordhotell in Asker on 1-2 November. The two meeting days were organized according to the program overview below, where the open part of the conference (1 November) included plenary and parallel sessions on battery- and hydrogen technologies and systems from leading experts and industry in the field. Day 2 was a closed meeting dedicated to internal discussions within the MoZEES consortium. The latest research developments in MoZEES were here presented in plenary sessions in the morning and discussed in further detail in parallel RA-sessions in the afternoon.

Plenary Session

- **Lennie Klebanoff (Sandia National Laboratories, Livermore)** – Hydrogen and Fuel Cells for Maritime Applications: From Sandia Feasibility Studies to First Demonstrations
- **Sonia Yeh (Chalmers University of Technology)** – Modeling of future transport systems from different points of views: data, technology, behavior, and policy
- **Deborah Jones (University of Montpellier)** – Membrane and Catalyst Materials and Components Development for Hydrogen Technologies
- **Alexander Blömeke (RWTH Aachen University)** – Battery Electric Systems for Heavy Duty Transport Applications

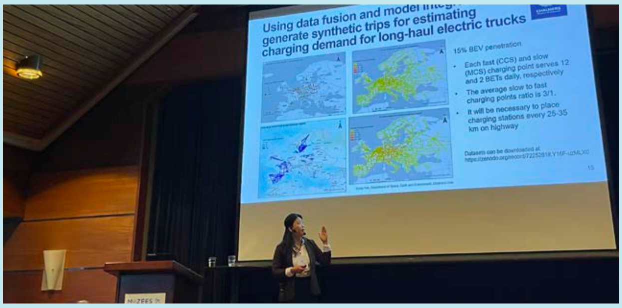
The participants of the MoZEES Annual Meeting (Photo: Gry Slotterøy, IFE)

Battery Session

- **Espen Larsen-Hakkebo (Brim Explorer)** – Learnings from fire on board battery-powered MS Brim
- **Mathias Winther Thorsen (ECO STOR AS)** – Making second life energy storage safe and viable. Status and future outlook
- **Hanne F. Andersen (IFE) and Ingeborg Kaus (SINTEF)**–NABLA: Battery Cell fabrication research infrastructure
- **Martin Kirkengen (Cenate)** – Innovative Silicon-based Anode Materials for High-capacity Li-ion Batteries
- **Andy Naylor (Uppsala University)** – Probing interfacial reactions in sustainable rechargeable batteries
- **Marcus Martinsson (Stena Recycling)** – Industrial recycling of lithium-ion batteries
- **Halvor Høen Hval (Morrow Batteries)** – A sneak peek into Morrow and the technology of tomorrow
- **Johan Fridner (Hydro)** – Hydro Battery Assets and Strategic Direction

Hydrogen Session

- **Eirik Byklum (Equinor)** – Demonstrating green hydrogen solutions for large-scale application
- **Håvard Stave (Hexagon Purus Maritime)** – Compressed hydrogen gas as maritime fuel
- **Svein Johnny Naley (SEAM)** – System Integration of Hydrogen-driven Fuel Cells for Maritime Applications
- **Kai Rune Heggland (NEL Hydrogen)** – The world´s first fully automated electrolyser production facility
- **Kees Van Wingerden (Vysus Group)** – Hydrogen Safety for Maritime Applications – A Liquid Hydrogen Case Study
- **Katie McCay (SINTEF)** – Bipolar Plates for PEM systems: Research Challenges and SINTEF's Contributions
- **Jan-Fredrik Hansen (ABB)** – Experiences with maritime fuel cell systems and prospects for upscaling



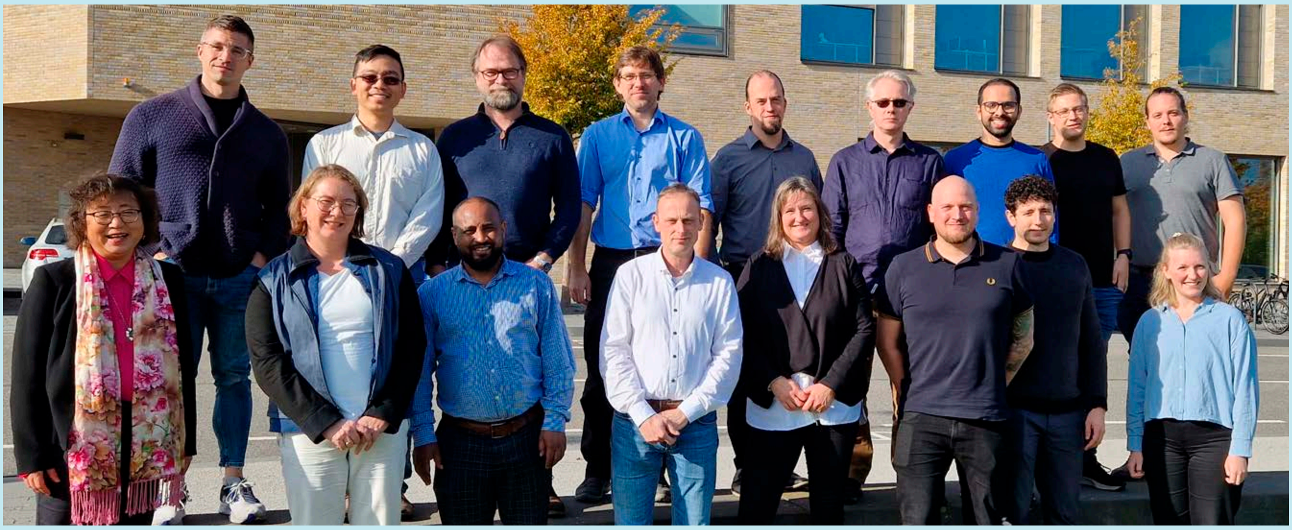
MoZEES Battery Seminar in RWTH Aachen

In October 2022 there was organized a joint MoZEES battery seminar with participants from RWTH Aachen and 7 MoZEES partners (research and industry). The seminar was organized in two main sessions:

1. From Battery Materials to Electrodes and Cells
2. Small Scale Battery Fabrication and Characterization - Cell Making as Joint Headache

There was also organized a special site-visit for a representative from Equinor and the MoZEES Director to a grid-connected 5MW battery installation in Aachen.

MoZEES seminar with RWTH Aachen on October 18. Photo of participants from Norway and Germany in front of the Center for Aging and Lifetime (CARL). (Photo: Ø. Ulleberg, IFE)



NorRen Summer School 2022


Øystein Moen (UiO)


Øystein Moen (UiO)

The 2022 Norwegian Research School in Renewable Energy (NorRen) took place at Holmen Fjordhotell in Asker from 13-17 June. The summer school was organized by UiO:Energy and MoZEES in collaboration with NTNU and FME NTRANS. The program 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.

The school gathered PhD students from UiO, NTNU, Arctic University of Norway, Nord University, and Chalmers for a week-long program. In 2022 the PhD summer school focused on sustainable transport with lectures covering topics such as hydrogen, sustainable batteries, maritime freight, heavy-duty vehicles and geopolitical questions related to sustainable transport. The scientific topics were presented by a mix of lecturers from UiO, NTNU, Technical University of Munich, Uppsala University, SINTEF, and IFE.

Involvement of stakeholders and site visits

The summer school kicked off with a visit to the International Electric Vehicle Symposium Exhibition (EVS35 OSL2022). Both private companies and public organizations were invited to share their views on sustainable transport during the summer school – and to highlight both possibilities and challenges. Wilhelmsen/Massterly and SCANIA gave very interesting and inspiring lectures covering topics related to the transitions to sustainable transport systems within shipping and heavy-duty vehicles. Bærum Municipality and the Norwegian Public Roads Administration gave the participants their view from both local and national perspectives.

In the middle of the week, the students attended several site visits. Unibuss, a public transport operator in Oslo, organized a site visit to their infrastructure facilities at Alnabru, Stubberud, and Furubakken. Unibuss also presented key learnings from the electrification of their bus fleet. Norled, one of Norway's largest ferry and express boat operators invited the participants board on one of the ferries operating between Oslo and Nesodden. Norled shared their key learnings from the electrification of the ferries operating in the Oslo Fjord.

Engaged students

The students themselves played a central role throughout the week. On the first day, each of the students presented their PhD projects with a poster and a short pitch, effectively getting to know all the other participants. The students worked in groups on an interdisciplinary assignment throughout the week and presented their findings on the last day of the school. There were also lots of questions and discussions in conjunction with the various talks, making it a highly interactive experience.

UiO: Energy would like to thank all lecturers and students for making the NorRen summer school of 2022 an interesting and highly enjoyable week!

MoZEES Innovation Activities

In MoZEES there has been established an industry driven Innovation Forum which is steered by an Innovation Committee. The main objective of the MoZEES Innovation Forum is to create a meeting place to coordinate the battery and hydrogen research activities in the Center with national innovation activities and to create MoZEES spin-off projects with partners in relevant industrial clusters in Norway and abroad. Two key innovation activities in 2022 was the establishment of MoZEES pre-projects 2022 and the organizing of the MoZEES Innovation Forum 2022.

MoZEES Pre-Projects 2022

In 2022 it was decided by the MoZEES Board to use some of the non-allocated funds within the Center on pre-projects to develop MoZEES spin-off projects. An internal call for proposals for MoZEES pre-projects was launched end of January and proposals were submitted by mid-March. Out of the ten (10) proposals received the MoZEES Innovation Committee selected and recommended funding for four (4) pre-projects, which were formally approved by the MoZEES Board in May.

The feedback from the MoZEES Partners that were awarded funding and participated in the work with the MoZEES pre-projects 2022 was very positive. The results from the MoZEES pre-projects were presented at the MoZEES Annual Meeting 2022 in November. The general impression of the work performed in the pre-projects was excellent. The MoZEES Partners involved in the pre-projects had done more work than initially anticipated. Hence, a new round of MoZEES Pre-Projects is planned for 2023.

MoZEES Innovation Forum 2022

The MoZEES Innovation Forum 2022 was organized in Oslo on 16 November and gathered about 50 participants. The meeting focused on how Norwegian industry and associated partners can join forces to realize and commercialize new energy technology and services for zero emission heavy duty transport solutions. In the introduction of the meeting the Chairman of the MoZEES Innovation Committee, Geir Brekke from Statkraft, indicated that Norwegian industry seem to be better on innovation than commercialization, which indicates that it is important that we join forces to commercialize our innovations.

List of MoZEES pre-projects that received funding in 2022:

Research Area	Title of Proposal	Applicant	Other User Partners	Research Partners
RA1	Accelerated Rate Calorimetry Towards Ideal Cathodes	Morrow Batteries	Baldur Coatings	UiO, FFI
RA2/RA3	Maritime fuel cell degradation: from single cell to stack	Corvus Energy	Selfa Arctic	SINTEF, IFE
RA3	On the possibility of direct transition to detonation in turbulent hydrogen-air mixtures upon a weak ignition	Vysus Group	Corvus	USN, FFI
RA4	Maritime Zero-emission Infrastructure	Ocean Hyway Cluster	Kystverket	TØI, IFE

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André V. Gaathaug from USN presented results from the EU-project HyTUNNEL-CS (hydrogen in tunnels and confined spaces) and recommendations on how to make hydrogen powered vehicles safer. The project showed that there are some hydrogen safety challenges that need to be solved to reduce the consequences of incidents with heavy duty vehicles in tunnels. Fredrik Aarskog from TECO 2030 asked for more R&D on realistic and representative user cases on heavy duty transport, where the various alternatives are evaluated with the same conditions. There is a need of technology neutral facts, where the total cost must be included for all value chains.

Alexandre Nordvik from Statkraft showed results from calculations made on charging times and energy cost, including the energy losses all the way to the end user. These kinds of cost analyses must reflect capacity, cost, and grid utilization rates. Statkraft sees a considerable advantage of building infrastructure for both electric and hydrogen operated vehicles in parallel. It was also pointed out that zero emission heavy-duty transport analyses carried out for Europe cannot generally be applied to all countries and regions and specific studies should therefore be carried out for Norway and the Nordic region. The discussion at the MoZEES Innovation Forum 2022 showed that there is still significant uncertainty about the range of battery-operated heavy-duty vehicles under various operational and load conditions. The industry asked for more research where all key assumptions and constraints have been factored in, including life cycle analysis (LCA), total cost of ownership (TCO), energy efficiency, social economy, and EU taxonomy. To improve the basis for decision-making there is a need for high-quality models built on best practice, open data sources, and transparent assumptions, including development of cost of the various parts of the infrastructure including uncertainties for the various factors.

As expected, it was not possible to fully answer the main question for the MoZEES Innovation Forum 2022: How can Norwegian industry and associated partners join forces to realize pilot project and commercialize new energy technology and services for zero emission heavy duty transport solutions? However, a conclusion and recommendation from the meeting is that it is important to be open minded and necessary to continue to develop the heavy-duty transport chains for batteries and hydrogen in parallel. In summary, most of us learned something new and we were all reminded that that dialogue and cooperation is key to innovation and commercialization.

Chairman of the MoZEES Innovation Committee, Geir Brekke from Statkraft (left) and an attentive audience (right) at the MoZEES Innovation Forum 2022 in Oslo.

RA1 Battery Materials

This research area is devoted to the development of battery materials with focus on next-generation high energy Li-ion batteries based on anodes with high silicon (Si) content and spinel cathodes $LiNi_{0.5-x}Mn_{1.5+x}O_4$ (LNMO) or Ni-rich NMC layered cathodes. Pre-lithiation of silicon, silicon alloys, as well as alternative electrolytes for cathodes and aqueous processing of cathodes, are examples of research topics that have been pursued in the last period. Industry partners in MoZEES have supplied materials and key components for a joint Round Robin test: Elkem ASA and Cenate® have supplied silicon powders, CerPoTech ceramic materials, while SAFT has supplied electrodes. Other industry partners actively involved in RA1 have been Baldur Coatings (atomic layer deposition of materials), Hydro, and Morrow Batteries.

Cathode activities

Electrolytes based on different ionic liquids have in MoZEES previously been extensively studied in combination with silicon anodes. As these electrolytes also show excellent anodic stability, one of them, namely an electrolyte composed of 1.2 M Lithium bis (fluorosulfonyl) imide (LFSI) salt mixed with the ionic liquid N-Propyl-N-methylpyrrolidinium bis (fluorosulfonyl) imide (PYR13FSI) (ILE) was found to be a suitable electrolyte for the high-voltage cathode material $LiNi_{0.5-x}Mn_{1.5+x}O_4$ (LNMO), supplied from Haldor Topsøe. Improved cycling performance both at 20˚C and 45˚C was found for LNMO||graphite full cells with the ILE electrolyte, which is attributed to a more stable cathode electrolyte interphase (CEI) formed with ILE. The work was performed in a collaboration between NTNU, Uppsala University (UU) and SINTEF, where UU contributed with post-mortem characterization of electrodes by XPS and SINTEF performed post-mortem SEM-EDS analyses.

Figure 1.1 compares the surfaces of LNMO cathode particles cycled at 45 ˚C in a conventional $LiPF_6$ electrolyte and ILE, with a pristine electrode. SEM-EDS element maps for the electrodes cycled at 45˚C are shown in

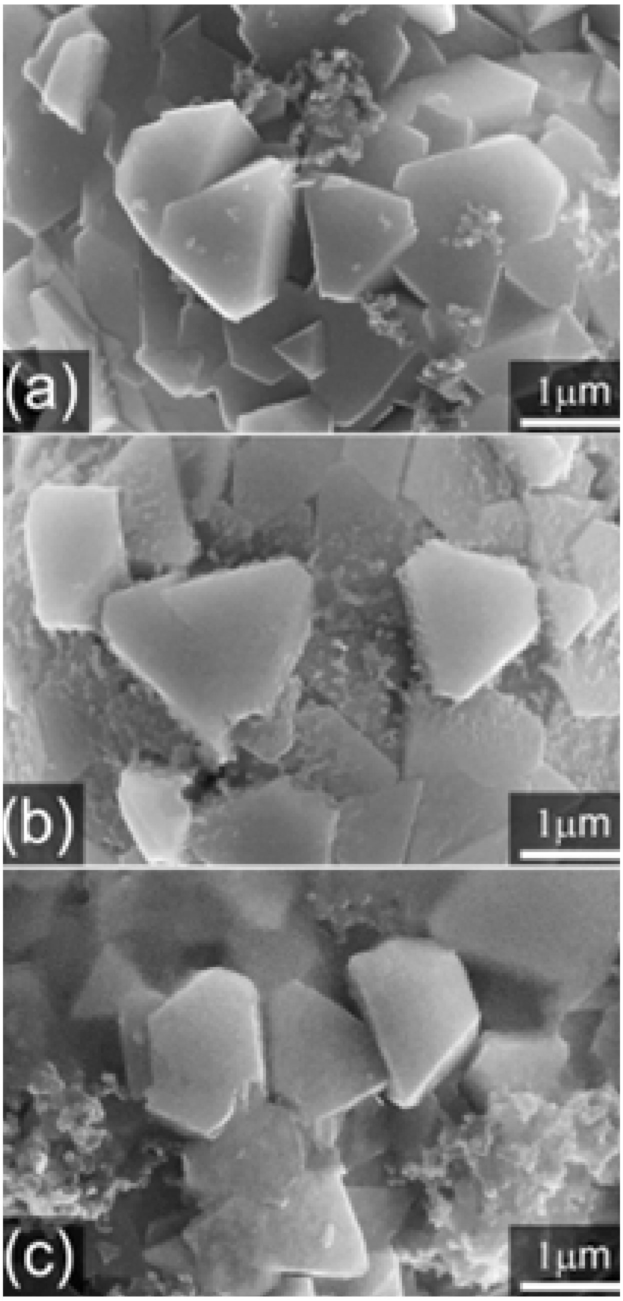


Figure 1.1 Secondary electron images of the surface of LNMO in a) a pristine electrode, b) an electrode after extended cycling at 45 ˚C in $LiPF_6$ electrolyte and c) extended cycling at 45 ˚C in Pyr13FSI

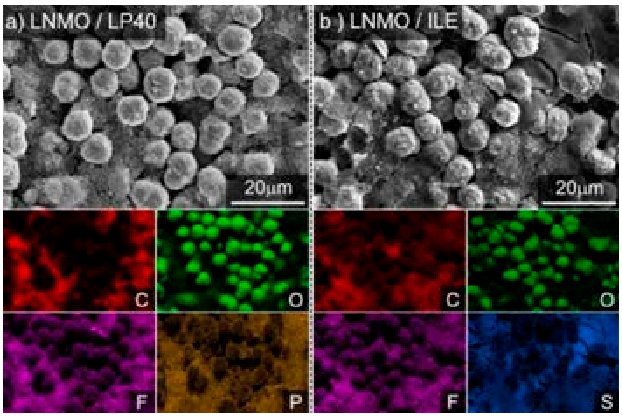


Figure 1.2 Secondary electron image and corresponding EDS maps of the surface of LNMO cathodes after prolonged cycling against a graphite anode at 45 °C in a) $LiPF_6$ and b) ILE electrolyte

Figure 1.2 for cells cycled using the same electrolytes, together with results from a pristine electrode. The CEI visible on the LNMO particles was cycled in both the $LiPF_6$ electrolyte and ILE (Figure 1.1). The conductive carbon/binder phase of the cathode cycled with $LiPF_6$ appears to be enriched in salt decomposition products. The cell cycled in ILE on the other hand shows the appearance of a Sulphur-rich gel/polymeric phase spanning between the active cathode particles while also covering them (Figures 1.1 and 1.2). The improved CEI layer formation of ILE was also confirmed by XPS analysis, which showed a considerably more inorganic CEI layer for ILE.

Anode activities

Molecular dynamics modelling techniques have been applied at UiO to study the atomistic structure transformation of SiNx anodes during the first (de)lithiation cycle at 300 K. The reactive molecular dynamics were coupled with the Pair Distribution Function (PDF) simulation to complement the experimental PDF measurements, which were used for the verification of the modeling results. The approach was used to understand the cycling stability of sub-stoichiometric a-SiNx anode materials by revealing the atomistic features relevant to the changes this material undergoes during lithiation and de-lithiation processes in a LIB.

Advanced characterization

The research on cathode material (high-Ni NMC as well as LNMO) has been supported by advanced techniques such as TEM and FIB-SEM. Furthermore, a methodology has been developed for studies of LNMO cathode material by Atom Probe Tomography (APT), which allows for atomic level resolution of very thin cross-sections of single particles of the active material.

Round Robin

Testing of different techniques for casting Silicon-Graphite composite electrodes was performed with the goal to make sufficiently homogenous electrodes with high loading (target based on the cathode sheets provided by SAFT for the first Round Robin). The method developed included both conventional tape casting and slot die casting, as well as screen printing. Slot die casting was selected as the most appropriate method.

The second version of the Round Robin was planned for 2022 and will be conducted in 2023.

International Activities

RWTH AACHEN

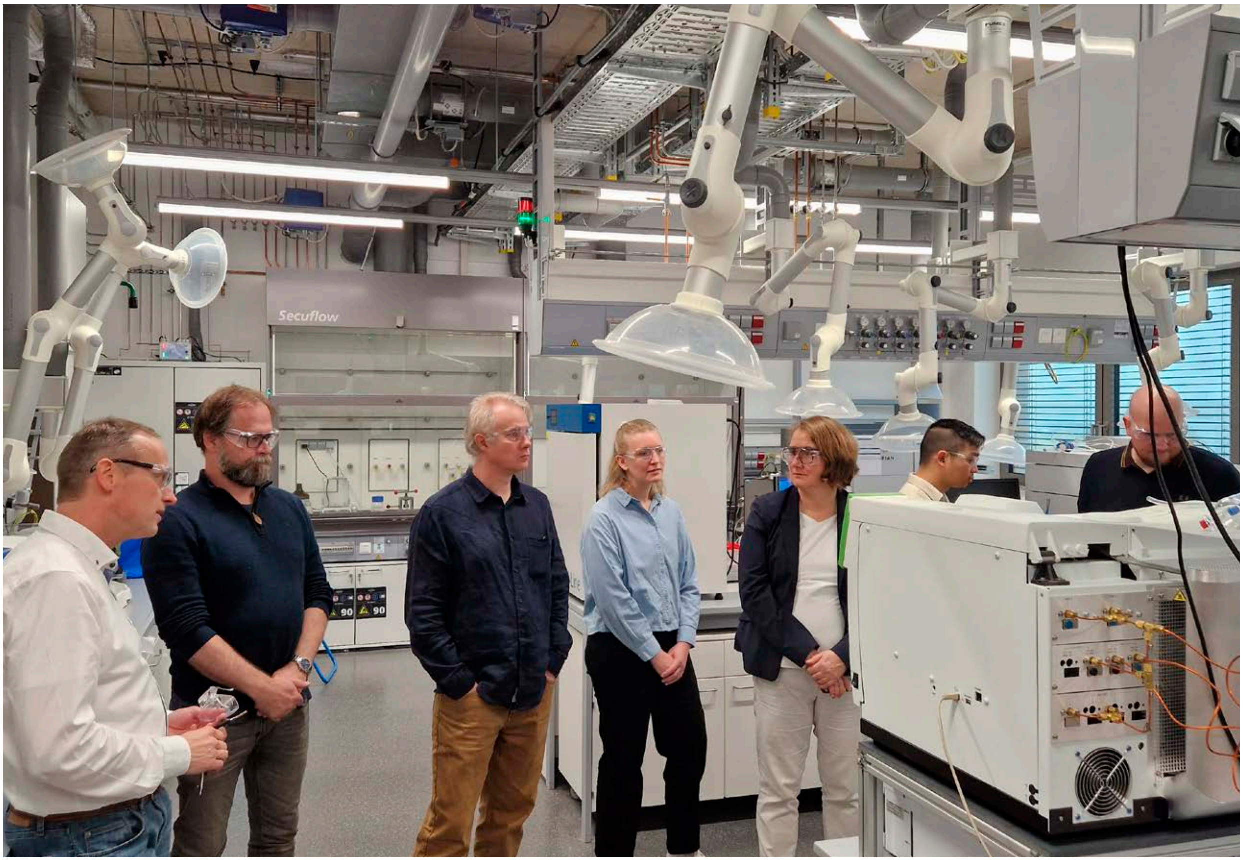
Pre-doping of lithium ions (pre-lithiation) in silicon anodes is a central topic for the research collaboration between IFE and RWTH Aachen, one of the international research partners in MoZEES. During the spring of 2022, a researcher from IFE spent three months as a guest researcher at RWTH Aachen. The purpose of this visit was to investigate various pre-lithiation methods and chemistries for experiments on silicon nitrides; a joint publication from this work is on the way. In October there was organized a MoZEES battery seminar and technical tour at the Center for Aging and Lifetime (CARL) with participation from RWTH Aachen and several MoZEES partners (see Meeting and Seminars for more information).

UNIVERSITY OF UPPSALA

MoZEES has over several years had an active research collaboration with University of Uppsala on LNMO cathodes. In 2022 this international research partner contributed to MoZEES by conducting post-mortem analysis of LNMO cathodes after electrochemical cycling in Pyr13FSI ionic liquid electrolytes. A joint publication has been submitted.

SAFT

SAFT is a key international industry partner in MoZEES and contributed in 2022 to the Round Robin test by supplying industrially relevant NMC cathodes.



MoZEES technical visit to CARL in Aachen, October 2022. (Photo: Ø. Ulleberg, IFE)

RA2 Hydrogen Components and Technologies

The main objective with RA2 is to enable the production of fuel cells, electrolyzers, and hydrogen storage tanks with lower cost, longer durability, and higher efficiency, thereby contributing to reaching the 2025 targets (DoE & EU) for transportation fuel cells, hydrogen production from renewable energy sources and hydrogen storage. The RA2 objectives are also closely linked to the MoZEES Hydrogen Technology Roadmap.

The three most important areas for materials development where MoZEES can contribute to reduce the cost of fuel cells and electrolyzers towards the final targets for mass-market introduction have been selected:

1. High-performance catalysts enabling ultra-low precious metal loading,
2. Lower cost, lighter, corrosion-resistant bipolar plates, and electrodes, and,
3. Low-cost, high-performance membranes

The research in RA2 also includes a task on characterizing and understanding the lifetime, durability, and performance of fuel cells, an activity which is closely linked to RA3. A 4-year research activity on high-pressure composite hydrogen pressure vessels was completed in a PhD in 2022.

Task 2.1 High-performance catalysts

Rare and expensive catalysts are necessary for polymer electrolyte membrane water electrolysis (PEMWE), such as Ir for the oxygen evolution reaction (OER), being state-of-the-art in terms of stability and activity. Ir is a metal with an extremely high risk of supply. Hence, lowering the use of Ir is essential for the large-scale deployment of PEMWE and an important field of research around the world. SINTEF has in MoZEES previously developed a method for depositing nanoparticles of platinum group catalysts on oxide support particles, a promising method

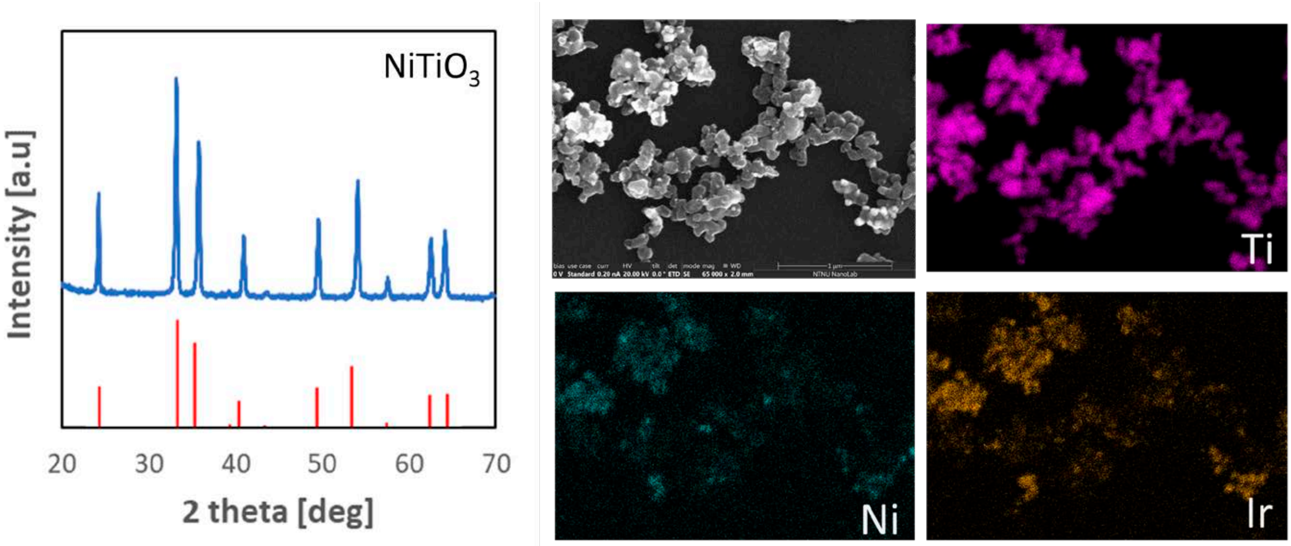


Figure 2.1showing phase-pure $NiTiO_3$ prepared by Cerpotech (right) and SEM images with EDS maps showing Ir deposited on $NiTiO_3$ (left).

for reducing the loading of the catalysts. This has been demonstrated for platinum catalysts for PEM fuel cells. In 2022 we made progress on applying these learnings to develop the concept further for iridium catalysts for PEM water electrolysis. A research collaboration Cerpotech, a MoZEES industry partner, has been established to see if their high-quality oxide powders can be used as catalyst supports for PEMWE. Phase-pure $NiTiO_3$ (Figure 2.1) has been prepared by Cerpotech, which is a good starting point for the further reaction.

Task 2.2 Low-cost bipolar plates and electrodes

Alkaline water electrolysis

A PhD at NTNU on new alkaline water electrolysis materials was completed in 2022. The focus of this study was on the activation of stainless-steel electrodes, as this is a less costly alternative to the commonly used nickel electrodes. In the activation process, the morphology and chemical composition of the electrode is modified, to make the surface of the steel electrode more active toward the hydrogen and oxygen evolution reactions. The research results from this PhD were of high interest to Nel, the main industry partner in MoZEES on water electrolysis.

PEM fuel cells

The overall aim of this activity has been to develop novel low-cost bipolar plates (BPPs) that are durable enough to withstand the harsh dynamic conditions of fuel cells for zero-emission mobility. Stable performance of stainless steel BPPs with coatings from the MoZEES industry partner Teer Coatings has previously been demonstrated. In 2022 the research focus shifted to coated aluminium BPPs, due to their lower weight. The BPP contributes up to 80 % of the weight of the final fuel cell stack, and reducing the weight of the BPPs in the fuel cells is particularly important in applications where weight is of concern (e.g., in MoZEES applications such as trucks, buses, and high-speed passenger ferries). Aluminium has been identified as a lightweight alternative to traditional stainless steel BPPs. It has the additional benefits of being more conductive and cheaper than steel but is notoriously hard to coat due to its electronegativity.

The research in MoZEES shows that the Al-coated BPPs has improved corrosion performance. However, it was also found that pin holes or imperfections in the coatings lead to exposure of the underlying Al substrate, which then corrodes and causes removal of the coating. The next step in the R&D is to prepare and test dense coatings without imperfections. Figure 2.2 shows that the coatings improve the internal contact resistance (ICR) in the PEM fuel cell and that the initial performance of Al-coated materials is equal to that of the stainless-steel (SS) coated materials. However, the Al-coated bi-polar plates degrade faster and the durability targets are not yet reached.

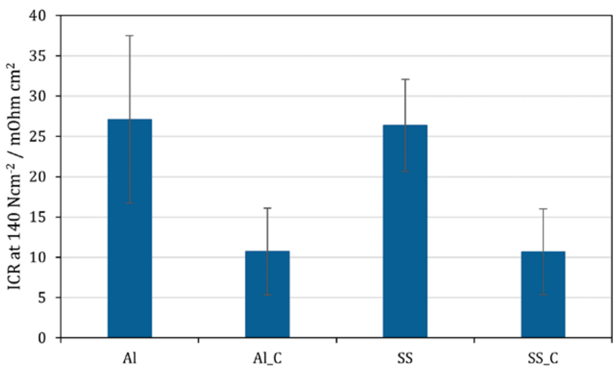


Figure 2.2 - Initial interfacial contact resistance (ICR) of aluminium (Al) and stainless steel (SS) BPPs without and with coating (C) measured ex-situ before in-situ testing.

Task 2.3 Improved high-temperature membranes

The PhD at UiO on high-temperature proton exchange membranes (PEM) is one of the most fundamental studies in MoZEES. The initial focus of the PhD was to develop high-temperature membranes by using composite membranes with ceramic nanoparticles as fillers in polymer membranes. However, detailed studies on the effect of the ceramic fillers revealed that it was necessary with a much deeper understanding of the conductivity of protons on the surface of the ceramics to unlock the potential of the ceramic fillers (Figure 2.3). Hence, the focus of the PhD needed to be shifted to the field of surface protonics. The PhD student has published 3 journal articles on this topic in 2022 and is planning to complete her PhD-thesis in 2023.

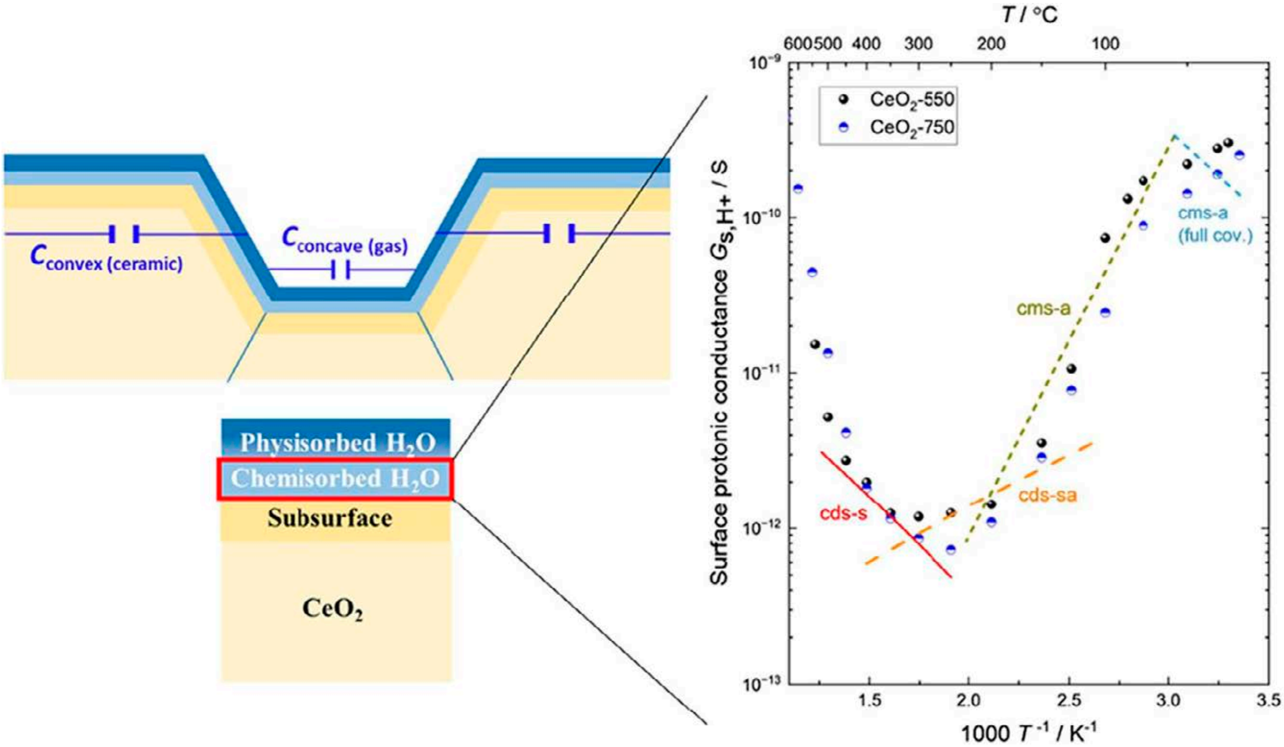


Figure 2.3 – The surface of the ceramic particle is covered by layers of adsorbed water which enable the protons to move and contribute to conductivity. The protons are moving through different mechanisms at varying temperatures and the results show excellent agreement between a brick layer model developed to predict the conductivity and experimentally obtained results.

Task 2.4 – Lifetime, durability, and performance

Fuel cells are gradually becoming a more mature alternative, especially for heavy-duty and marine transport. In these market segments, the lifetime of the fuel cell is particularly important and significant efforts are put into increasing the lifetime from 20 000 to 40 000 hours and beyond. To achieve this, it is important to be able to monitor the performance of the fuel cells during operation and link this to a deep understanding of their degradation mechanisms. Electrochemical impedance spectroscopy (EIS) is a powerful tool that can be used to measure the performance of fuel cells by sending in a weak electrical sine wave at different frequencies and measuring the response. As the various degradation mechanisms take place on different time scales (from seconds and minutes to days, weeks, and months), there will be a different response from EIS depending on which degradation mechanism is taking place. The problem with EIS is that it is difficult and time-consuming to both measure and analyze the results.

IFE and SINTEF have in MoZEES developed a technique based on multi-sine EIS. With this technique, signals are sent at several frequencies simultaneously, which gives more and faster results. The figure below (figure 2.4) shows the changes in the EIS signal from a fuel cell during operation when the relative humidity changes. By capturing these changes and analyzing the data quickly enough, it will be possible to interpret what is happening inside the fuel cell. In 2022, a scientific article about this was published in the journal Frontiers in Energy Research, which shows that multi-sine EIS can be a useful tool for monitoring and diagnosing the condition of the fuel cells *in-situ*, which in the long term is information that can be used to optimize operation for the longest possible lifespan.

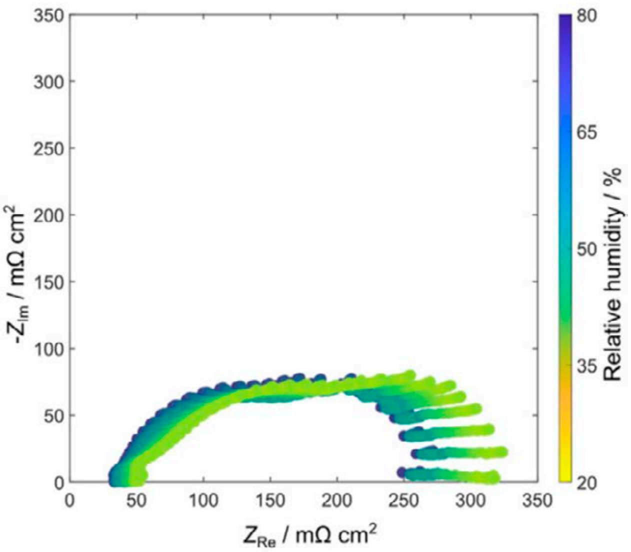


Figure 2.4 – Example of EIS signals (Nyqvist plot) from a PEM fuel cell during operation with varying relative humidity.

Task 2.5 – Hydrogen storage tanks

A PhD on fatigue mechanisms in hydrogen composite cylinders has been performed in MoZEES and was completed in February 2022. The work in this PhD showed that DIC (Digital Image Correlation) monitoring can be used to recognize material strains and early fatigue damage, a result highly interesting and relevant for industry partner Hexagon. The fatigue properties measured locally by DIC can also be used to better predict damage growth under fatigue around a defect. The prediction is done by novel ways to model fatigue damage growth in a finite element program.

RA3 – Battery and Hydrogen Systems and Applications

The main objective of this research area 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. The research area has a special focus on heavy-duty hybrid battery/fuel cell systems, battery and hydrogen safety issues, and maritime applications, including:

- Optimization of operation of maritime fuel cell systems; optimization with respect to lifetime of stacks and systems
- Risk analyses, experiments, and modelling related to battery and hydrogen system safety in heavy-duty vehicle (trucks), maritime, and railway applications
- Optimization of design and operation of water electrolysis processes suitable for renewable energy based dynamic operation

Task 3.1: Advanced fuel cell control systems

The main research activity in this task evolves around PEMFC system modelling and experimentation in a PEM fuel cell system laboratory at IFE Hynor. This experimental setup is designed to validate and optimize PEMFC stacks and key system components on a scale relevant to heavy-duty applications. The final commissioning and first testing of a 20 kW PEMFC stack and its balance of plant (BoP) was completed in 2022 and the first polarization curves for the reference stack were recorded. The data acquisition and control system installed allows for advanced controls and detailed monitoring of the PEMFC and other BoP system components. The experimental setup is now ready to be used to validate different fuel cell system control strategies developed in MoZEES. The industry partners in MoZEES made significant contributions to the work on the PEMFC system in 2022. ABB was consulted in the design and operation of the fuel cell power conditioning system, while Corvus provided a maritime battery system that will be used for hybridization with the fuel cell system in 2023.

In 2022, there was also performed a literature review by SINTEF on the different types of energy management strategies (EMS) that typically can be used in fuel cell systems, namely rule-based, learning-based, or optimization-based strategies (Figure 3.1). The review found that reinforcement learning- and model predictive control-based strategies can be argued to be the most suitable type of EMS, especially if this method can include multiple objectives and be implemented for real-time control. It was also concluded that in future heavy-duty transport and maritime applications there will be a need to take a more holistic approach to optimize the overall energy systems, not just the fuel cell system. This approach is likely to be based on predictive methods and reinforcement learning that utilize tools such as global positioning systems and intelligent transportation systems integration, cameras and computer vision, and Internet-of-Things technology with related sensors. In 2023 new and more advanced energy management strategies (EMS) for hybridized fuel cell/battery systems will be modelled in Matlab Simulink and tested and validated in the PEMFC system laboratory at IFE.

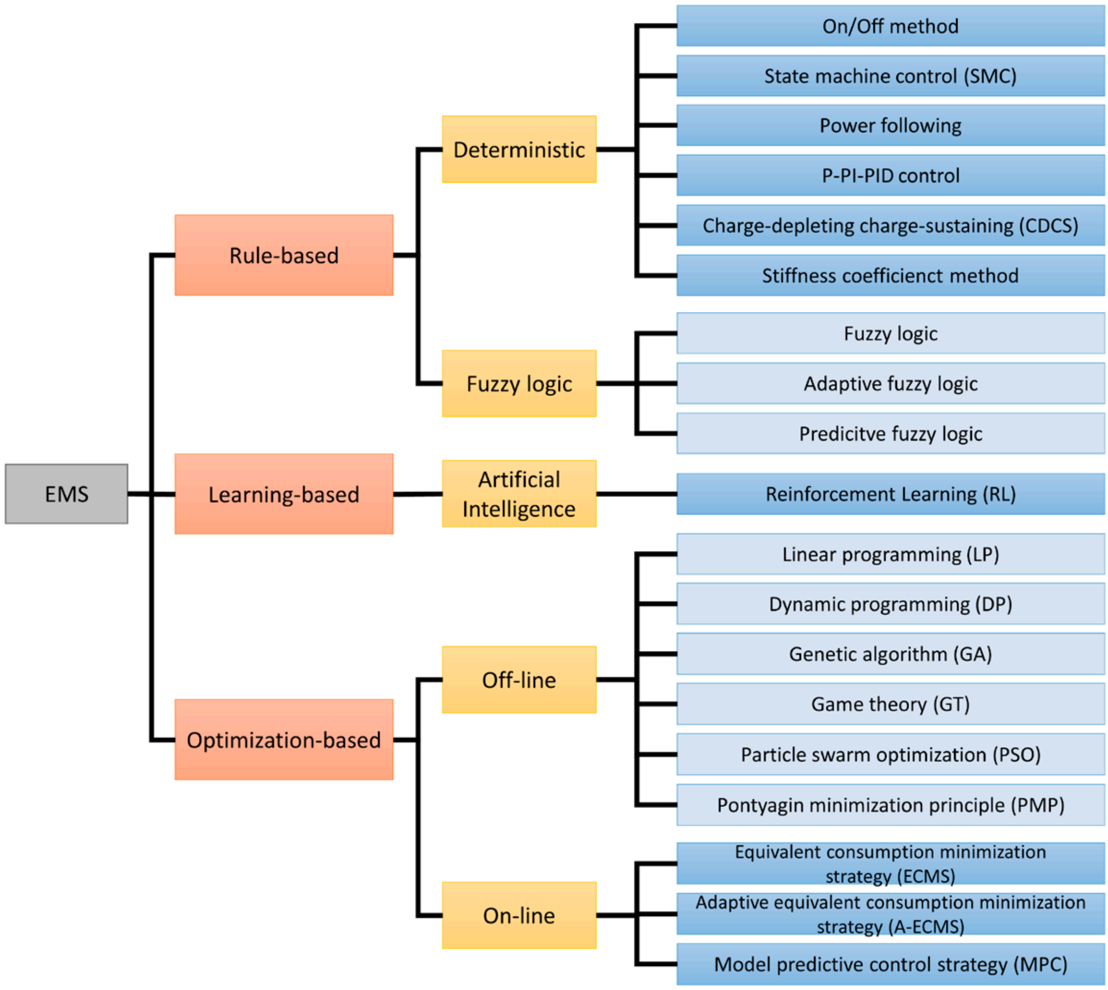


Figure 3.1 - Classification of EMS for control of hybrid fuel cell and battery systems.

Task 3.2 Battery Cell Lifetime, Durability and Safety

The testing of the MoZEES reference cells (tailor-made pouch cells with graphite anode, NMC cathode, and electrolyte with all known additives and solvents) continued in 2021 and 2022, and NTNU joined the cell testing program in 2022. The cycle life of the cells was tested under different ageing conditions. Battery cells that were cycled with similar conditions at IFE and NTNU (Figure 3.2). The cycle life (until reaching 80% remaining capacity) spanned between 50 and 20 cycles depending on the test conditions where high temperature and high State-of-Charge had generally the poorest obtained cycle life. Fresh and cycled cells were then analyzed by non-destructive X-ray computational tomography, revealing cracking within the electrode layers, delamination, and poor alignment of the electrodes in the stack (Figure 3.3). The cells were also dismantled, electrodes removed, cut by an Ar-knife, and investigated by cross-section SEM/EDS analysis revealing an increased fraction of smaller particles and reduced porosity because of the cycling. The aged cells will be safety tested at FFI in 2023.

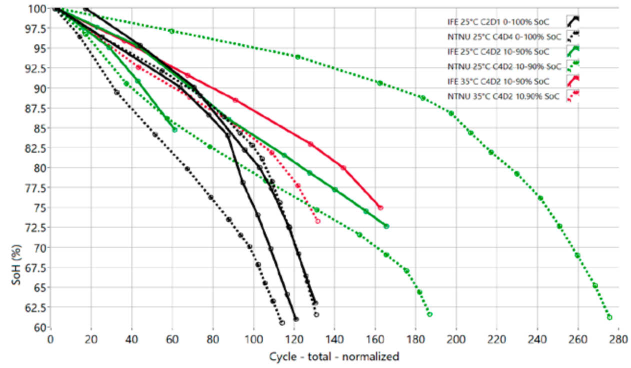


Figure 3.2: Cycle life of MoZEES Li-ion reference cells tested under similar conditions at both NTNU and IFE.

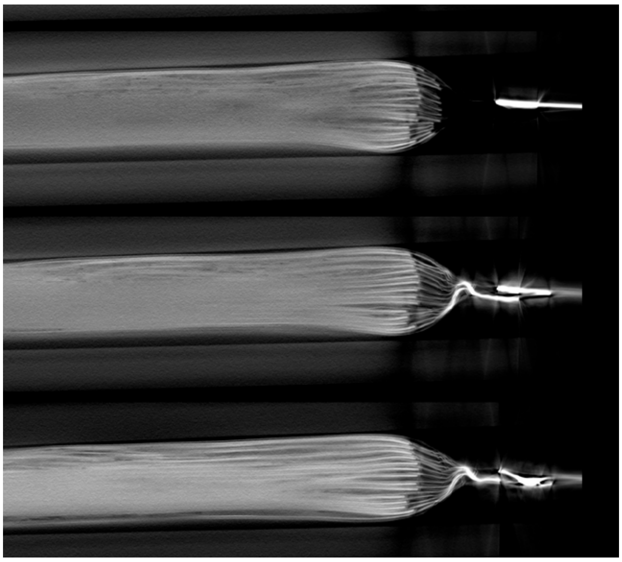


Figure 3.3: X-ray CT scan from one end of a cycled MoZEES reference cell, Stein Rørvik, SINTEF

Task 3.3 Battery and Hydrogen Safety

A PhD on the topic "Hydrogen safety in confined spaces" was completed at USN in 2022. The experimental results form the basis for new recommendations for Regulations, Code and Standards for use of hydrogen vehicles in confined spaces (more details on PhD provided in the section on PhD Dissertations).

Experimental work on hydrogen safety for jet fires in mechanically ventilated compartments for releases from up to 700 bar pressure was also conducted at USN and published in 2022 (in Journal of Loss Prevention in the Process Industries). This work, which also was part of the HyTunnel-CS project (funded by FCHJU in EU H2020 program), compared numerical simulations in XiFoam (open-source CFD combustion model/solver XiFoam in OpenFOAM) with measurements from experiments performed in laboratories at USN. The case analyzed was a 1-meter explosion channel partly filled with 18650 cell-like cylinders, which were filled with premixed fuel and air (Figure 3.4). Two different Li-ion vent gas compositions were used as fuel, which had different combustion properties. In addition, two different channel geometries were tested by moving the 18650 cylinders in the channel. The prediction accuracy was determined by calculating the mean geometric (MG) bias and variance (VG) for the temporal pressure evolution, maximum pressure peak, positive impulse, and spatial flame front velocity for two different channel geometries, in addition to two gas compositions at several fuel-air equivalence ratios.

Based on the calculated overall average MG and VG values, the XiFoam CFD solver had an overall acceptable model performance. XiFoam had the highest prediction accuracy for the center channel geometry High LBV Li-ion gas cases and the lowest prediction accuracy for the center channel geometry Simplified Li-ion gas cases. The lower prediction accuracy was mainly due to an over-predicted flame acceleration in the initial laminar flame propagation stage. Adjusting model parameters and numerical schemes in post-analysis for each simulation case can significantly increase the prediction accuracy. However, predicting with high precision the maximum pressure peak and positive impulse in the same simulation is difficult with the XiFoam combustion model. A recommendation for future research is to validate the

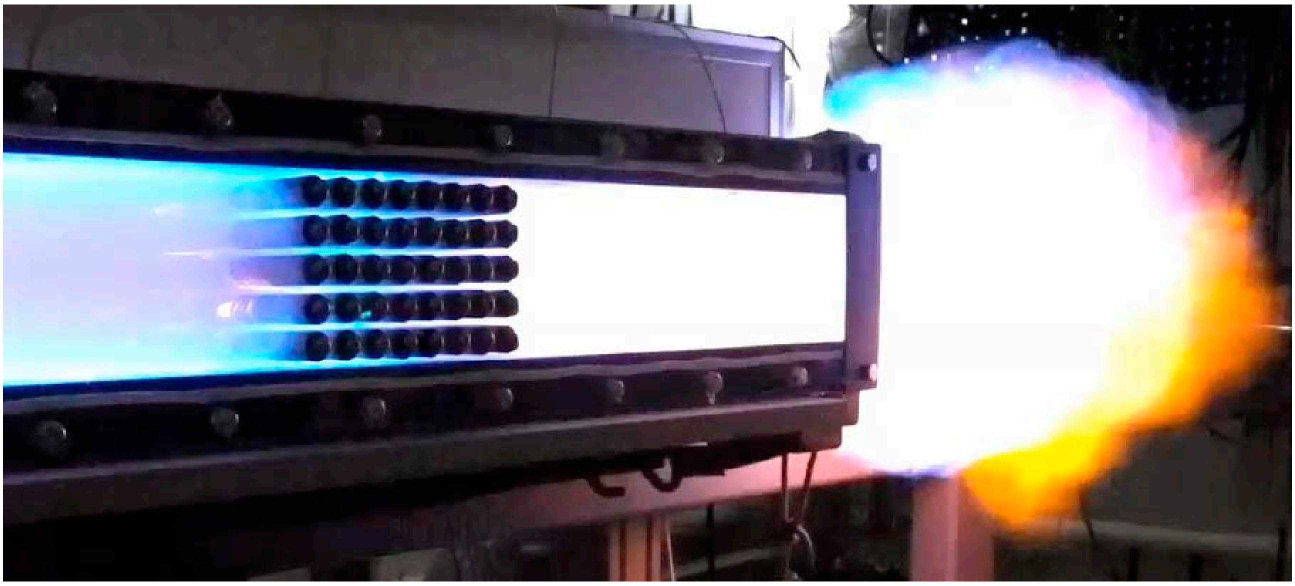


Figure 3.4: Picture from flame propagation experiment in 1 m explosion channel with obstructions at USN.

XiFoam model with results from large-scale experiments of battery incidents.

The safety of a cylindrical Li-ion battery cell with iron phosphate-based chemistry was in 2022 investigated by FFI. The study showed that using different initiation methods for thermal runaway significantly affects the results of the propagation tests. FFI has now built a 6 m long container that is to be used in more thermal runaway and flame propagation experiments. The work will continue in 2023 where the results in a 1 m explosion channel from USN and the results from the rig at FFI will be compared. These tests are highly relevant for several of the MoZEES industry partners, particularly those working with safety related to maritime battery modules and installations.

In 2022 the was also performed a "CFD study to assess safety aspects of TPRD releases from heavy-duty hydrogen vehicles and trains in tunnels" (publication in Chemical Engineering Transaction) by the MoZEES industry partner Vysus and collaborator HYEX. Safety aspects related to the design of a hydrogen tank (size and dimensions) for heavy-duty and train application was studied, with a special focus on the design of the thermal pressure release devices (TPRD) to ensure appropriate depressurization of the hydrogen tanks in case of a fire.

The results showed that for the heavy-duty vehicle case, the TPRD release rates should be kept below 200 g/s while for the train case, slightly higher release rates can be tolerated. The results from this study can be used as the basis for recommendations for Regulations, Code and Standards for use of hydrogen vehicles and trains in tunnels.

Task 3.4 Efficient low temperature water electrolysis processes

Research on a flexible PEM water electrolyser (PEMWE) system platform for testing high-pressure stacks up to 200 barH2 continued at IFE in 2022. Further tests up to 180 bar were conducted and showed an expected trend of increased performance with increasing temperature and a decreased performance due to increasing pressure (Figure 3.5). The numerous temperature sensors in the test rig, together with accurate measurements (e.g., temperature, pressures, flow rates, and water levels) make the experimental setup ideal for validating detailed PEMWE process models developed within MoZEES. This work was presented at the 241st ECS Meeting in May 2022 and the 3rd International Conference on Electrolysis in June 2022.

A detailed techno-economic analysis of high-pressure PEM water electrolysis was also published by IFE in 2022 (Journal of Energy Conversion and Management). A full hydrogen system process model was here developed and various applications at pressures between 5 and 700 bar were studied. The losses related to pressurized operation and safety aspects due to hydrogen crossover were analysed (Figure 3.6). The main conclusions were that high-pressure operation is promising for delivery pressures up to 200 bar where for example e-fuel production, feed into natural gas pipelines, and ammonia production were relevant cases.

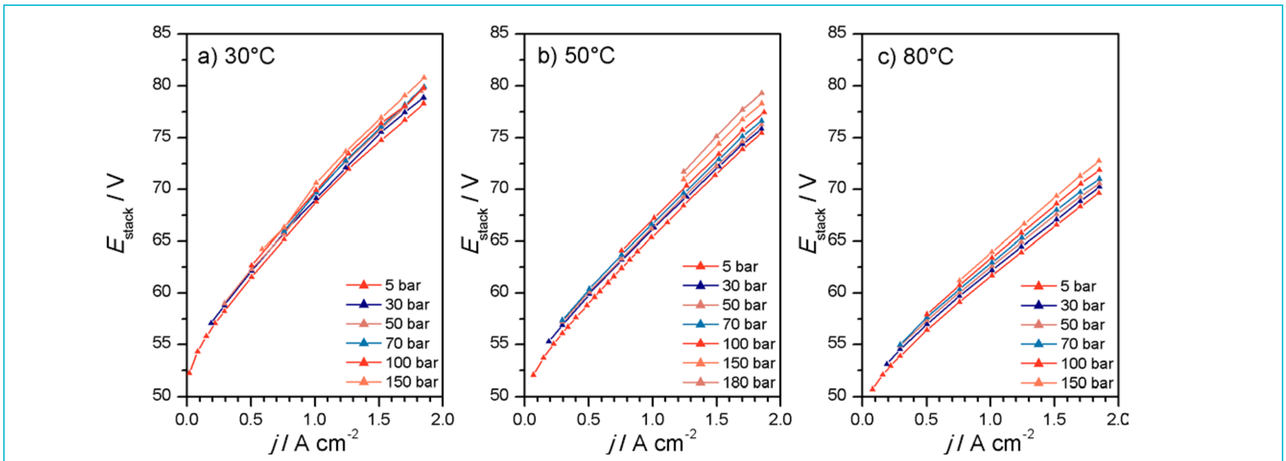


Figure 3.5: Polarization curve at different temperatures and pressures for the PEMWE rig at IFE.

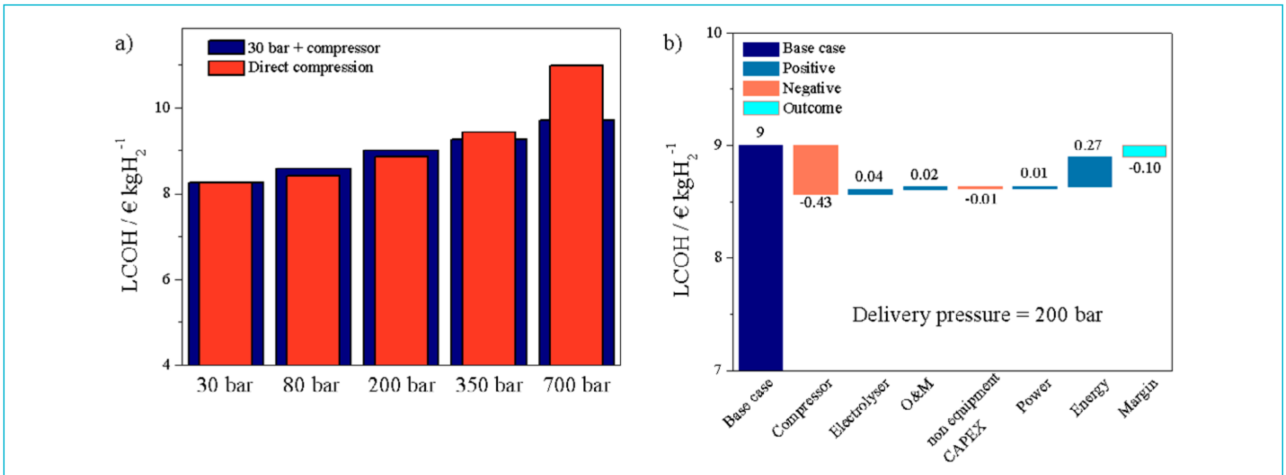


Figure 3.6: Comparison of cost of direct compression and 30 bar + H2-compressor for different delivery pressures. The right plot shows the savings and losses when comparing the two cases at 200 bar.

RA4 Policy and Techno-Economic analysis

The main goal with this research area is to identify the market potential, business cases, and policy prerequisites for innovative and energy-efficient transport concepts, based on electricity or hydrogen. The specific focus is on markets 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, allowing new transportation concepts to be analyzed comprehensively under varying assumptions on technology, policies, incentives, and governance measures. This interdisciplinary approach increases the reliability and quality of predictions on technology uptake and the need for (and dosage of) policies and incentives, and decreases the uncertainty related to different business models. Key research questions here are:

- How and when can new technology become competitive?
- How can public and corporate stakeholders avoid the lock-in effects typical of current technologies and end-user habits?

Analysis of international technology development road maps, policy options, incentives, and other governance measures is in MoZEES performed to produce national road maps for how the international and Norwegian transport and energy value chains may be transformed towards 2030. Specific case studies of new concepts and business models are made based on the needs of user partners' 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

In MoZEES there is a close collaboration among all the research and industry partners. In practice, this means that the societal and techno-economic studies (RA4) are closely linked to the system level and applied oriented research (RA3), which in turn is linked to the more basic research on key battery and hydrogen technologies (RA1 and RA2). Several key publications and presentations have been made in 2022.

A comprehensive analysis on "A pathway to zero emission road freight" was in 2022 published by TØI and IFE together with the NTRANS FME and the ITEM project and presented at the Norwegian Mobilitet 2022 conference. In this roadmap[1)], it was found that "Zero-emission technologies for heavy-duty freight vehicles can become competitive as a result of increasing returns to scale coupled with high carbon taxes on fossil fuel". Through integration of models covering, respectively, transportation demand, the vehicle fleet, and the energy system, the pathway toward zero-emission road transportation in Norway was drawn up. Using assumptions underlying this pathway as checkpoints, an assessment can be made of whether we are behind or ahead of schedule toward 2030 and 2050 GHG abatement targets.

In 2022 researchers in MoZEES also contributed to four scientific papers at the 2022 World Electric Vehicle Symposium (EVS35) in Oslo. The first EVS35 paper was written by SINTEF researchers and later published as an article in the World Electric Vehicle Journals special issue from the EVS 35, which showed that "green public procurement (GPP) can be used to push the market in an environmentally sustainable direction". This study was based on interviews with both public authorities and freight service providers. GPP is in the article found to be a useful tool for public authorities to both boost the uptake of zero-emission vehicles and to share the investment costs with freight service providers, but there are differences between small and large municipalities. To succeed with GPP, public authorities must prioritize such tasks in their

1) A pathway to zero emission road freight. Joint report TØI (Report nr. 1880/2022), MoZEES FME, NTRANS FME, ITEM project. https://www.toi.no/publications/a-pathway-to-zero-emission-road-freight-article37512-29.html

daily routines through political decisions and strategies. The second EVS35 paper was later published as a joint TØI/MoZEES report. The last EVS35 paper, "Empirical Analysis of the User Needs and the Business Models in the Norwegian Charging Infrastructure" was published in the World Electric Vehicle Journal with a MoZEES contribution in the section about HDV charging. A conclusion in this paper was that HDV charging needs to be better organized than the conundrum in the current fast charge market where users encounters 20-30 Apps and 14 payment systems to be able to access all charging infrastructure.

In MoZEES there has also over the few years been developed a method for estimating the energy needs for different types of vessels by analyzing ship movement data (AIS). In 2022 this method was further improved in a MoZEES pre-project entitled "Maritime Zero-emission Infrastructure" led by Ocean Hyway Cluster with participation from TØI, IFE, and the Norwegian Coastal administration. There has also significant RA4 releated research output from two PhD students and a Post.doc at NTNU.

Life Cycle Assessment of Battery Electric Buses

(Highlights from article by Ellingsen et al., 2022)

Compared to conventional diesel buses, battery electric buses (BEBs) offer advantages such as zero tailpipe emissions, high efficiency, reduced noise, and good acceleration. The performance with respect to driving range, charging time, and lifetime varies with use of different Li-ion battery technology. Previous life cycle assessment (LCA) studies on the environmental performance of BEBs have mainly focused on comparisons between diesel buses and the generic use of batteries, while more detailed knowledge on how various Li-ion battery technologies affect the environmental performance of BEBs is lacking. Hence, a study was undertaken to provide a better understanding of how differences in battery technology and sizing alternatives affect the environmental performance of BEBs.

An updated and detailed battery inventory for the bus reflecting the real-world BEB use across a full lifetime was used as the basis for the study. For this purpose, cradle-to-grave life cycle inventories were used to assess the environmental impacts over an extended BEB life with use phase considerations beyond the typical length of a bus tender or contract. The study examined how choice in battery size, charging solution, and resulting range affect the environmental impact potentials of battery electric 12-meter city buses. The LCA was conducted as a hypothetical case study considering seven alternative buses with different battery technologies, battery sizes, and charging solutions. The first two alternatives were similar in that they both considered a 100 kWh battery using wireless opportunity charging. The main difference here was the choice of the battery technology, where one utilized an LTO battery and the other an NMC battery. Both Li-ion batteries had an NMC-622 cathode, while the LTO battery was assumed to have an LTO anode and the NMC battery a conventional graphitic anode. LFP was considered inappropriate for this application due to its poor charging power capability. The next three alternatives consider a 200 kWh LTO, LFP, and NMC battery using a pantograph for charging at end-stations. Finally, the last two alternatives consider a 400 kWh LFP and NMC battery using a plug-in charging in the depot overnight. LTO was considered inappropriate for 400 kWh battery packs due to its low specific capacity.

Differences in technological properties and performances (e.g., lifetime, specific capacity, efficiency) were considered and incorporated into the analysis together with primary use phase data for battery electric and diesel buses operated by Unibuss in the Oslo area. Since Unibuss usually sell their used buses to Eastern Europe, where they have a second use phase after Norway, this study considered both a Norwegian cradle-to-grave life cycle with 10 years of use in Norway and an additional 10 years of operation in Hungary. The functional unit of the study was "the use of one bus over one kilometer". This means that the functional unit includes the reporting of emissions per kilometer, either for a life cycle of 10 years and a driving range of 600 000 km (first use in Norway) or 20 years and 1 200 000 km (including second-hand use in Hungary). A process-based attributional and comparative approach was used to estimate the cradle-to-grave environmental impact potentials of the seven buses. To assess the overall environmental performance of the seven bus alternatives six mid-point impact category potentials were studied: global warming potential (GWP), photochemical oxidant formation potential (POFP), ozone layer depletion potential (ODP), acidification potential (AP), freshwater ecotoxicity potential (FETP), and mineral/metal resource depletion potential (RDP).

It is important to note that since the two life cycle considerations (10 years and 20 years) are based on two different premises, the results are complementary and not comparative. While the relative GHG emission performance of the various buses is similar in both life cycle considerations, the contribution shares differ significantly between the shorter life cycle (Norway) and the extended life cycle (including Hungary). One of the main differences comes from the use of different electricity mixes in the two countries. The first LCA assumes a Norwegian electricity mix (25 g CO2-eq/kWh) for its entire usage over 600 000 km, while the second LCA assumes a Hungarian electricity mix (456 g CO2-eq/kWh) including an additional 600 000 km. The differences in WTW emissions can simply be explained by different electricity mixes, while the differences in equipment life cycle emissions are caused by multiple (and sometimes counteracting) factors. When it comes to the initial production emissions it is particularly beneficial to extend the life cycle since these emissions are then distributed over twice as many kilometers. On the other hand, since extending the lifetime increases the need for battery replacements, emissions associated with battery replacement are similar or higher when going from the Norwegian to the extended life cycle scenario. The relative increase in battery replacement emissions is particularly large for the 200 kWh LTO and 400 kWh LFP buses, as their battery modules have the highest production emissions.

The relative environmental performance across the five impact categories follows that of GHG emissions closely, with some minor differences. The most significant difference is that the wirelessly charged 100 kWh LTO bus offers the lowest environmental impact across all impact categories for the Norwegian life cycle as well as for AP, FETP, and RDP over the extended life cycle. In addition to battery lifetime, the results also reflect other differences in battery properties. LTO batteries offer the

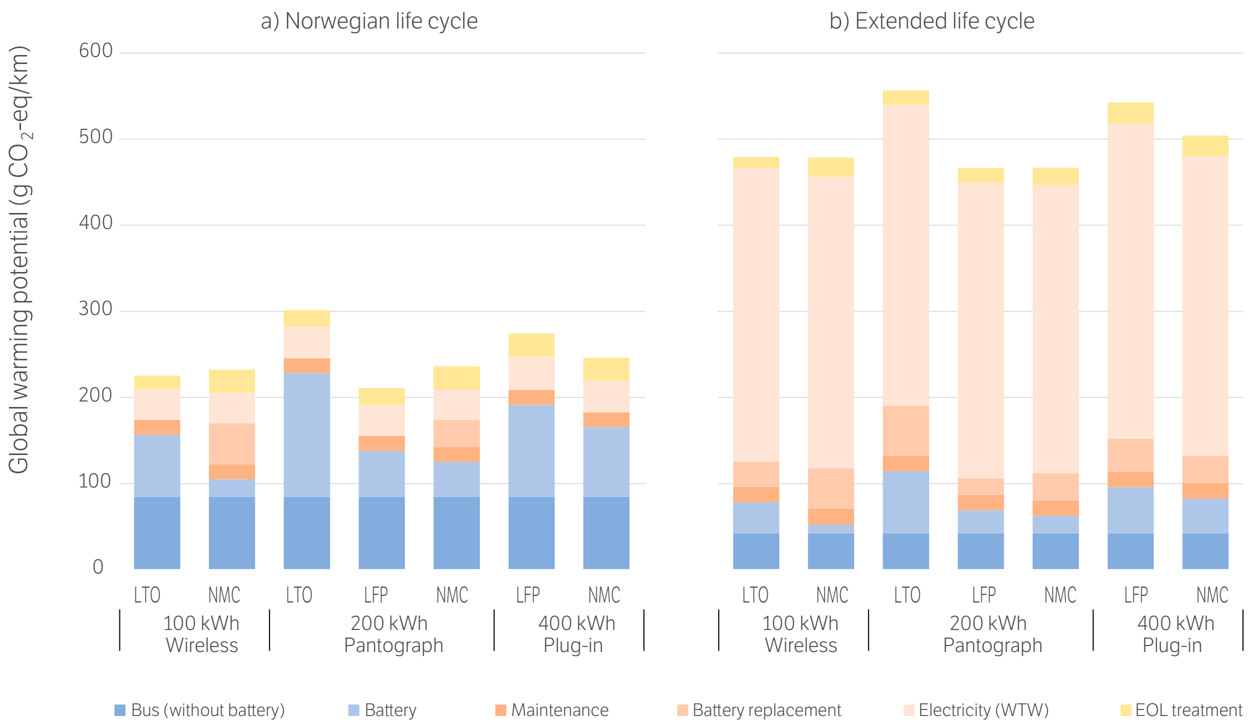


Figure 4.1 - Cradle-to-grave GHG emissions per kilometer both for the Norwegian life cycle (left) and the following extended life cycle in Hungary (right).

highest cycling efficiency while NMC batteries offer the highest specific capacity.

Both properties affect electricity use during operation. It was found that the higher cycling efficiency of the LTO batteries is less beneficial than the higher specific capacity of the NMC batteries. Consequently, the NMC buses have lower electricity use compared to the LTO buses for the same capacity. This benefit increases with mileage and electricity carbon intensity.

In conclusion, based on the six environmental impact categories it was found that the size and range effect depends to a large extent on the performance of the battery technology and that a smaller battery size of the same technology is not necessarily environmentally preferable. LTO batteries offer a good solution for a smaller battery packs where frequent fast charging can compensate for limited driving range, while NMC batteries are more appropriate where higher capacity and extended driving range are a priority. The study shows that decision makers such as bus operators may optimize environmental performance by considering different battery technologies and pack sizes as well as charging solutions appropriate for their specific areas or routes.

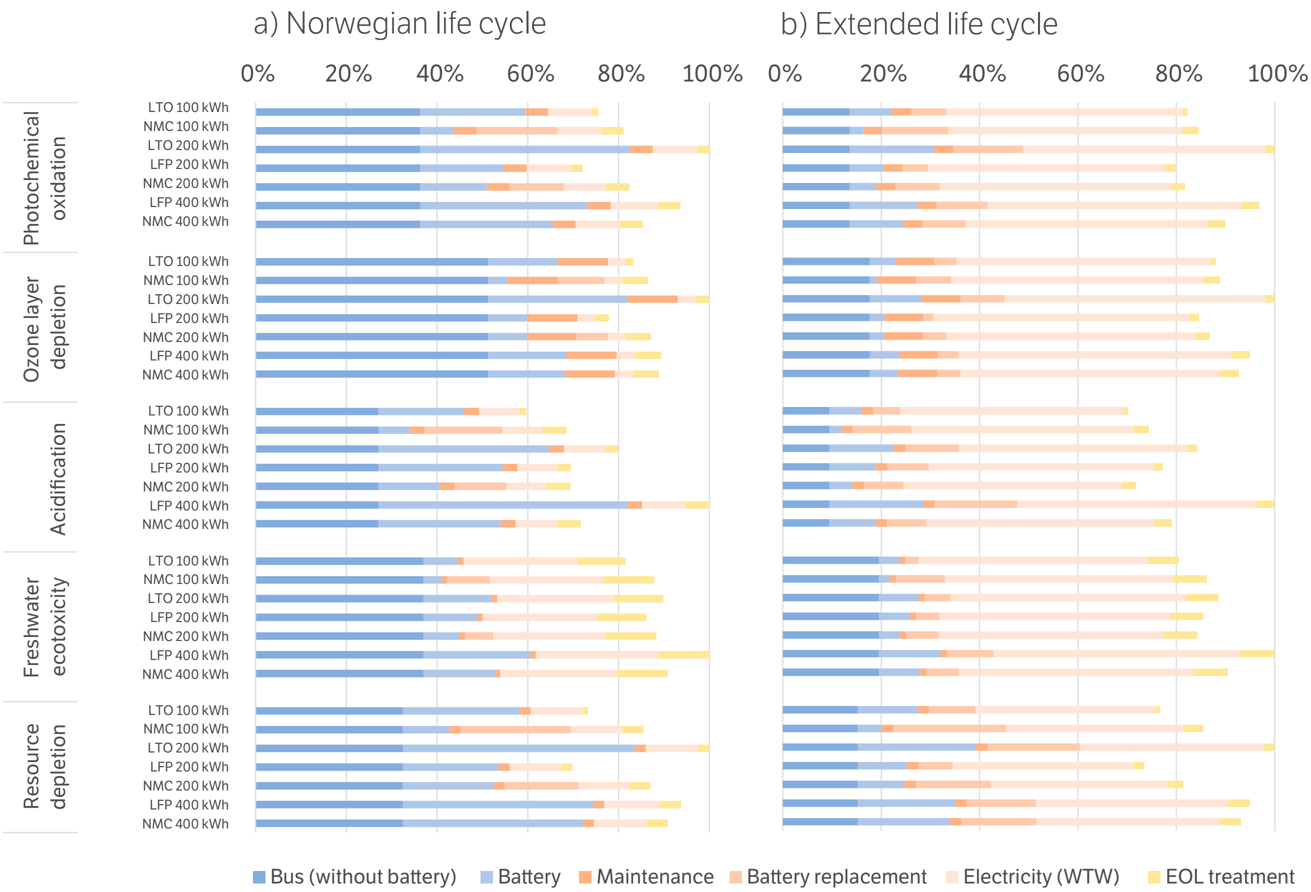
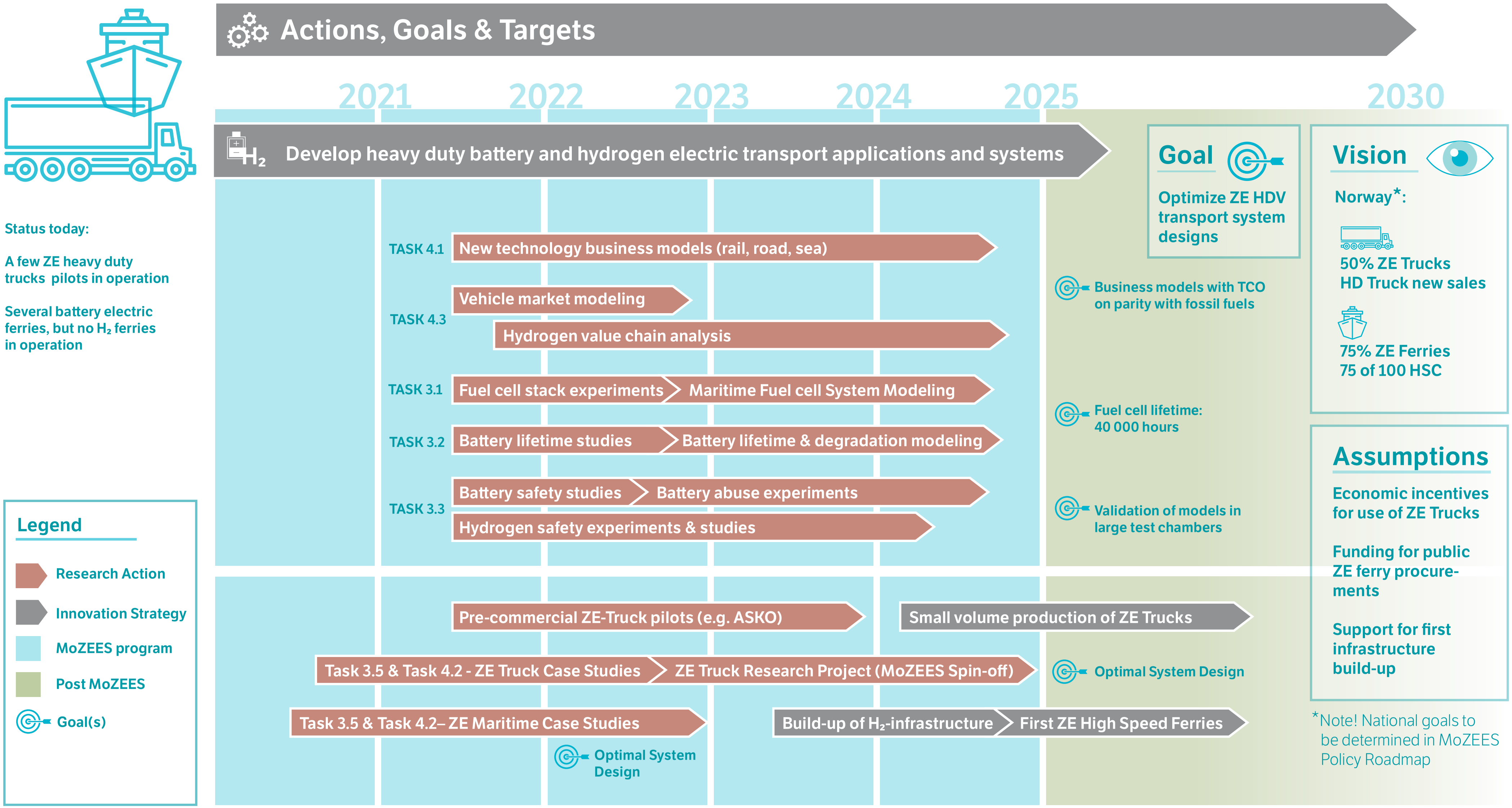
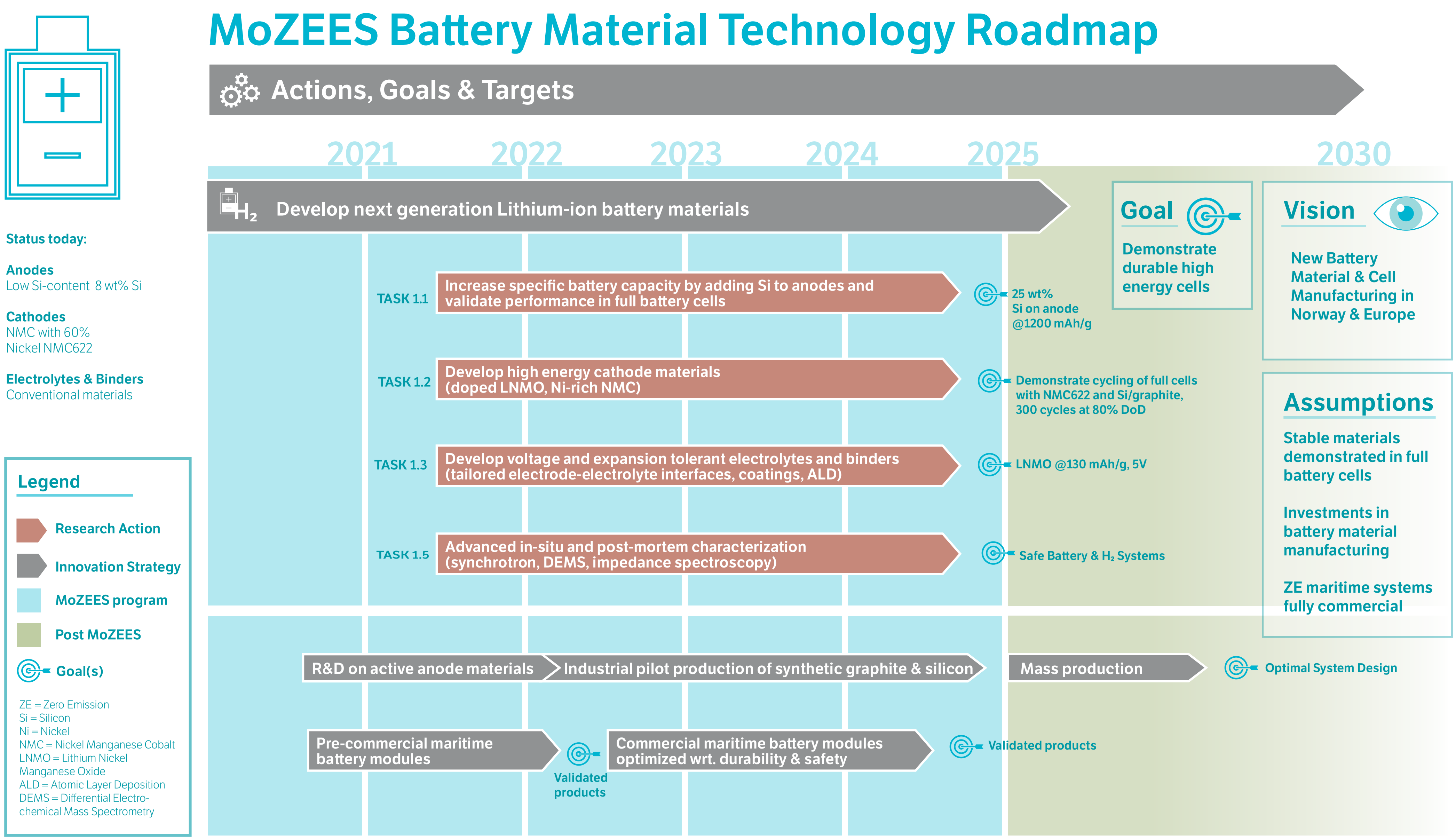


Figure 4.2 - Relative environmental performance of the seven BEB alternatives for the Norwegian life cycle (left) and the extended life cycle (right), relative to the LFP 400 kWh BEB, which has the highest impact in all categories.

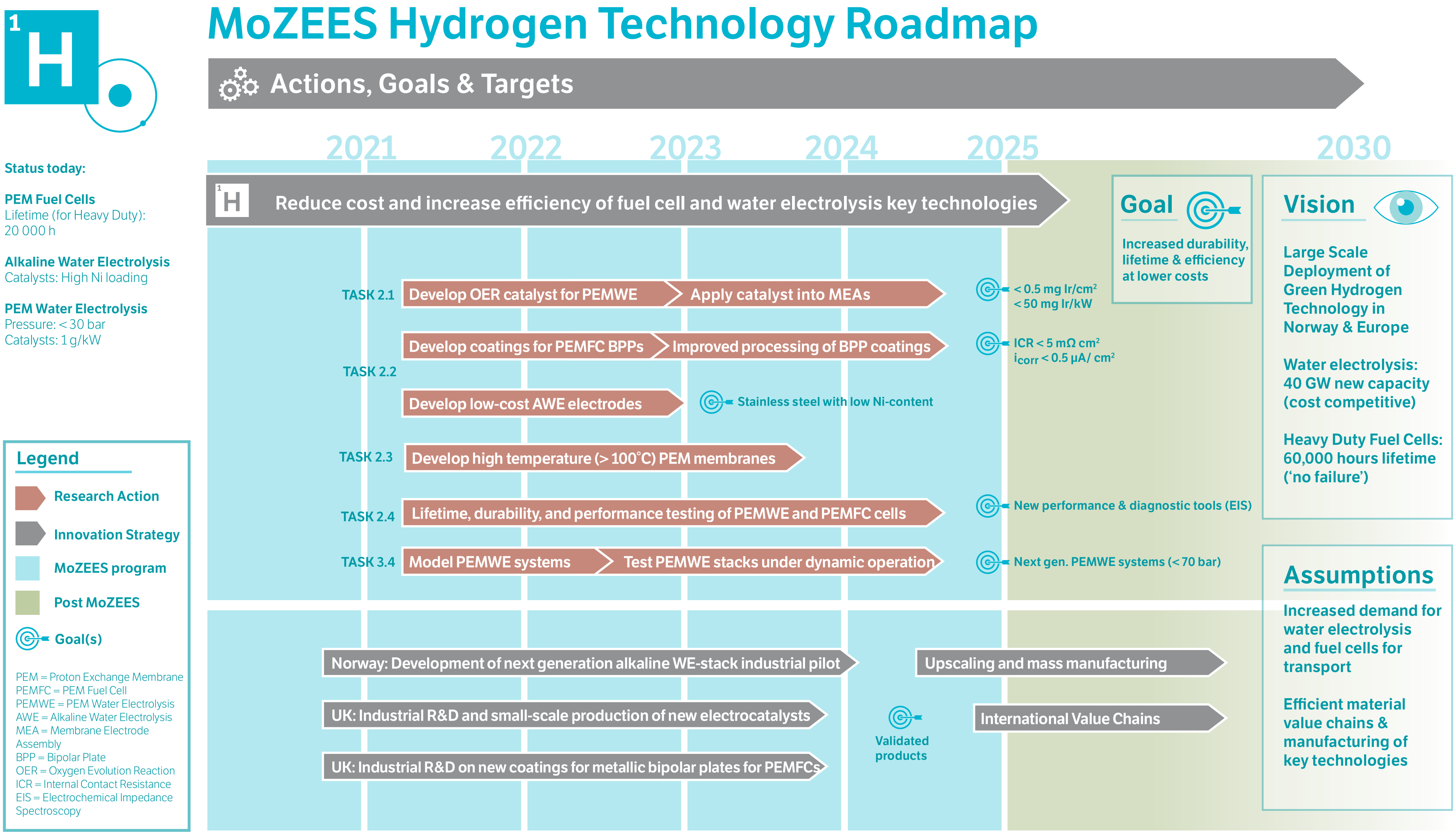
MoZEES Zero Emission Heavy Duty Transport Roadmap



(Figure 1).


MoZEES Battery Material Technology Roadmap
Actions, Goals & Targets
2021
2022
2023
2024
2025
2030
Status today:
Anodes
Low Si-content 8 wt% Si
Cathodes
NMC with 60%
Nickel NMC622
Electrolytes & Binders
Conventional materials
Develop next generation Lithium-ion battery materials
TASK 1.1
Increase specific battery capacity by adding Si to anodes and validate performance in full battery cells
25 wt% Si on anode @1200 mAh/g
TASK 1.2
Develop high energy cathode materials (doped LNMO, Ni-rich NMC)
Demonstrate cycling of full cells with NMC622 and Si/graphite, 300 cycles at 80% DoD
TASK 1.3
Develop voltage and expansion tolerant electrolytes and binders (tailored electrode-electrolyte interfaces, coatings, ALD)
LNMO @130 mAh/g, 5V
TASK 1.5
Advanced in-situ and post-mortem characterization (synchrotron, DEMS, impedance spectroscopy)
Safe Battery & H₂ Systems
Goal
Demonstrate durable high energy cells
Vision
New Battery Material & Cell Manufacturing in Norway & Europe
Assumptions
Stable materials demonstrated in full battery cells
Investments in battery material manufacturing
ZE maritime systems fully commercial
R&D on active anode materials
Industrial pilot production of synthetic graphite & silicon
Mass production
Optimal System Design
Pre-commercial maritime battery modules
Validated products
Commercial maritime battery modules optimized wrt. durability & safety
Validated products
Legend
Research Action
Innovation Strategy
MoZEES program
Post MoZEES
Goal(s)
ZE = Zero Emission
Si = Silicon
Ni = Nickel
NMC = Nickel Manganese Cobalt
LNMO = Lithium Nickel Manganese Oxide
ALD = Atomic Layer Deposition
DEMS = Differential Electro-chemical Mass Spectrometry

(Figure 2).


MoZEES Hydrogen Technology Roadmap
Actions, Goals & Targets
Status today:
PEM Fuel Cells
Lifetime (for Heavy Duty): 20 000 h
Alkaline Water Electrolysis
Catalysts: High Ni loading
PEM Water Electrolysis
Pressure: < 30 bar
Catalysts: 1 g/kW
2021
2022
2023
2024
2025
2030
Reduce cost and increase efficiency of fuel cell and water electrolysis key technologies
TASK 2.1
Develop OER catalyst for PEMWE
Apply catalyst into MEAs
< 0.5 mg Ir/cm²
< 50 mg Ir/kW
Develop coatings for PEMFC BPPs
Improved processing of BPP coatings
ICR < 5 mΩ cm²
icorr < 0.5 μA/ cm²
TASK 2.2
Develop low-cost AWE electrodes
Stainless steel with low Ni-content
TASK 2.3
Develop high temperature (> 100˚C) PEM membranes
TASK 2.4
Lifetime, durability, and performance testing of PEMWE and PEMFC cells
New performance & diagnostic tools (EIS)
TASK 3.4
Model PEMWE systems
Test PEMWE stacks under dynamic operation
Next gen. PEMWE systems (< 70 bar)
Norway: Development of next generation alkaline WE-stack industrial pilot
Upscaling and mass manufacturing
UK: Industrial R&D and small-scale production of new electrocatalysts
International Value Chains
UK: Industrial R&D on new coatings for metallic bipolar plates for PEMFCs
Validated products
Goal
Increased durability, lifetime & efficiency at lower costs
Vision
Large Scale Deployment of Green Hydrogen Technology in Norway & Europe
Water electrolysis: 40 GW new capacity (cost competitive)
Heavy Duty Fuel Cells: 60,000 hours lifetime ('no failure')
Assumptions
Increased demand for water electrolysis and fuel cells for transport
Efficient material value chains & manufacturing of key technologies
Legend
Research Action
Innovation Strategy
MoZEES program
Post MoZEES
Goal(s)
PEM = Proton Exchange Membrane
PEMFC = PEM Fuel Cell
PEMWE = PEM Water Electrolysis
AWE = Alkaline Water Electrolysis
MEA = Membrane Electrode Assembly
BPP = Bipolar Plate
OER = Oxygen Evolution Reaction
ICR = Internal Contact Resistance
EIS = Electrochemical Impedance Spectroscopy

(Figure 3).

Appendix 1: Personnel

Postdoctoral Researchers with financial support from the Center Budget						
Institution	Name	Sex M/F	Nationality	Start date	End date	Topic
NTNU	Inger-Emma Nylund	F	Norway	01.05.2022	30.04.2024	Stable HF free electrolytes for Li-ion batterie
NTNU	Egbert Ruben van Beesten	M	Netherland	01.02.2022	31.01.2024	Value chain optimization in ZE transport network
UiO	Heesoo Park	M	South Korea	14.10.2021	15.10.2023	Materials design for battery electrodes
UiO	Asbjørn Slagtern Fjellvåg	M	Norway	01.07.2022	06.12.2022	Accelerated rate calorimetry of cathodes
USN	Mathias Henriksen	M	Norway	01.04.2022	01.10.2022	Hydrogen detonation

PhD students with financial support from the Centre Budget						
	Name	Sex M/F	Nationality	Start date	End date	Topic
NTNU	Elise Ramleth Østli	F	Norway	21.08.2017	27.03.2022	Water-based manufacturing routes for electrodes
NTNU	Jonas Martin	M	Germany	01.08.2020	31.07.2023	Policy and techno-economic analysis
NTNU	Manuel Lenti	M	Italy	01.09.2021	30.04.2022	Optimization of maritime fuel cell systems
UiO	Halvor Høen Hval	M	Norway	01.01.2018	07.02.2023	High voltage cathode materials for Li-ion batteries
UiO	Carina Geiss	F	Germany	21.09.2020	31.03.2022	In-operando studies of Silicon anodes
UiO	Casper Skautvedt	M	Norway	15.08.2022	15.02.2026	Si as anode material for Li-ion batteries

Key researchers		
Institution	Name	Main research area
NTNU	Ann Mari Svensson	Battery materials and components
NTNU	Sverre M. Selbach	Battery materials and components
NTNU	Asgeir Tomasgard	Policy and techno-economic analysis
NTNU	Anne Neumann	Policy and techno-economic analysis
NTNU	Peter Schutz	Policy and techno-economic analysis
NTNU	Ingrid Schjølberg	Battery and hydrogen systems for marine applications
UiO	Helmer Fjellvåg	Battery materials and components
UiO	Alexey Koposov	Battery materials and components
UiO	Truls Norby	Fuel cell and electrolyzer materials and component
UiO	Katinka E. Grønli	Energy, Environment, Climate
UiO	Øystein Moen	Energy, Environment, Climate
USN	Dag Bjerketvedt	Hydrogen and Battery safety
USN	Joachim Lundberg	Hydrogen and Battery safety
USN	André V. Gaathaug	Hydrogen and Battery safety
USN	Knut Vågsæther	Hydrogen and Battery safety
FFI	Helge Weydahl	Battery safety, fuel cell systems
FFI	Kjetil Valset	Chemical characterization of lithium ion batteries
FFI	Torleif Lian	Thermal stability of lithium ion batteries
FFI	Sissel Forseth	Battery safety
FFI	Espen Åkervik	Battery safety

PhD students working on projects in the Center with financial support from other sources					
Institution	Name	Nationality	Period	Sex M/F	Topic
UiO	Rasmus V. Thøgersen	Norway	2018-2022	M	High-end catamaterials
UiO	Anders Brennhagen	Norway	2019-2023	M	Anodes
USN	Agnieszka Lach	Norway	2019-2022	F	Hydrogen release in confined spaces
NTNU/TØI	Vegard Østli	Norway	2018-2023	M	Vehicle and demand modelling
NTNU	Šárka Štádlerová	Czech Rep.	2020-2023	F	Optimization of ZE transport systems in maritime applications

Postdoctoral researchers working on projects in the center with financial support from other sources					
Institution	Name	Nationality	Period	Sex M/F	Topic
NTNU	Masha Ebadi	Iran	2020-2022	M	Interfaces in Li-batteries

Master degrees			
Institution	Name	Sex M/F	Topic
NTNU/IFE	Nora Kvalvik	F	Coating of LNMO cathodes
NTNU	Helene L. Langli	F	Stability of current collectors
NTNU	Mika Serna Malmer	M	LNMO cathodes
NTNU	Martin Raaen	M	Silicon nanowire anode materials
NTNU	Marthe Nybrodahl	F	MgO addition to LLZO
NTNU	Hanna Kvam Herskedal	F	Solid state electrolytes
NTNU	Vegard Vesterdal Viki	M	Modelling of solid state electrolytes
UiO	Amund Raniseth	M	Al-substituted LMNO
UiO	Casper Skautvedt	M	Bi-based anode conversion materials
UiO	Mats Aspeseter Rødne	M	Titanium (di)oxide coating of electrodes in Lithium Capacitors

Appendix 2: Statement of Accounts

Funding	Amount
The Research Council	15 392
The Host Institution (IFE)	939
Research Partners	6960
Industry partners	5776
Public partners	2 160
Total funding	**31 233**

Costs	Amount
The Host Institution (IFE)	7 386
Research Partners	19 165
Industry partners	4 066
Public partners	616
Total costs	**31 233**

(All figures are given in kNOK)

Appendix 3: Peer-reviewed publications in 2022

1
Asheim, Karina; Vullum, Per Erik; Wagner, Nils Peter; Andersen, Hanne Flåten; Mæhlen, Jan Petter; Svensson, Ann Mari.
Improved electrochemical performance and solid electrolyte interphase properties of electrolytes based on lithium bis(fluorosulfonyl) imide for high content silicon anodes. RSC Advances 2022, Volume 12 (20), pp. 12517-12530
SINTEF, NTNU and IFE

2
Ellingsen, Linda Ager-Wick; Thorne, Rebecca Jayne; Wind, Julia; Figenbaum, Erik; Romare, Mia; Nordelöf, Anders.
Life cycle assessment of battery electric buses. Transportation Research Part D: Transport and Environment 2022, Volume 112 (November), pp. 1-13
TØI and IFE

3
Figenbaum, Erik; Wangsness, Paal Brevik; Amundsen, Astrid Helene; Milch, Vibeke.
Empirical Analysis of the User Needs and the Business Models in the Norwegian Charging Infrastructure Ecosystem. World Electric Vehicle Journal 2022, Volume 13 (10)
TØI

4
Fortin, Patrick; Gerhardt, Michael Robert; Ulleberg, Øystein; Zenith, Federico; Holm, Thomas.
Multi-Sine EIS for Early Detection of PEMFC Failure Modes. Frontiers in Energy Research 2022, Volum 10
SINTEF and IFE

5
Hancke, Ragnhild; Holm, Thomas; Ulleberg, Øystein.
The case for high-pressure PEM water electrolysis. Energy Conversion and Management 2022, Volume 261.
IFE

6
Henriksen, Mathias; Vågsæther, Knut; Bjerketvedt, Dag.
Deflagration to Detonation Transition of Hydrogen-Air Mixture in a Highly Congested, Open-ended Channel. I: Proceedings of the Tenth International Seminar on Fire and Explosion Hazards: 22-27 May 2022, Oslo, Norway. Universitetet i Sørøst-Norge 2022 ISBN 978-82-7206-721-1. pp. 107-115
USN

7
Henriksen, Mathias; Vågsæther, Knut; Lundberg, Joachim; Forseth, Sissel; Bjerketvedt, Dag.
Numerical study of premixed gas explosion in a 1-m channel partly filled with 18650 cell-like cylinders with experiments. Journal of Loss Prevention in the Process Industries 2022. Volume 77.
USN and FFI

8
Karlsson, Hampus; Meland, Solveig; Bjerkan, Kristin Ystmark; Bjørgen, Astrid; Bjørge, Nina Møllerstuen; Babri, Sahar.
Green Public Procurement for Accelerating the Transition towards Sustainable Freight Transport. World Electric Vehicle Journal 2022, Volume 13.(9)
SINTEF

9
Martin, Jonas; Dimanchev, Emil; Neumann, Anne.
Carbon Abatement Costs for Hydrogen Fuels in Hard-to-Abate Transport Sectors and Potential Climate Policy Mixes. Working Paper Series 2022
NTNU

10
Martin, Jonas; Neumann, Anne; Ødegård, Anders.
Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model. Working Paper Series 2022
NTNU and SINTEF

11
Medina, Johanne; Ziaullah, Abdul Wahab; Park, Heesoo; Castelli, Ivano E.; Shaon, Arif; Bensmail, Halima; El-Mellouhi, Fedwa.
Accelerating the adoption of research data management strategies. Matter 2022, Volum 5 (11) pp. 3614-3642
UiO

12
Pinchasik, Daniel Ruben; Figenbaum, Erik; Hovi, Inger Beate.
User experiences from the first series produced battery-electric trucks. Interviews in 2021 with the first Norwegian users. Oslo: Transportøkonomisk Institutt 2022 (ISBN 978-82-480-1964-0) 48
TØI

13
Rogstad, Daniel Tevik; Einarsrud, Mari-Ann; Svensson, Ann Mari.
High-Temperature Performance of Selected Ionic Liquids as Electrolytes for Silicon Anodes in Li-ion Batteries. Journal of the Electrochemical Society 2022, Volum 169
NTNU

14
Skurtveit, Amalie; Brennhagen, Anders; Park, Heesoo; Cavallo, Carmen; Koposov, Alexey.
Benefits and Development Challenges for Conversion-Alloying Anode Materials in Na-Ion Batteries. Frontiers in Energy Research 2022, Volum 10.
IFE UiO

15
Stadlerova, Sarka; Aglen, Trygve Magnus; Hofstad, Andreas; Schütz, Peter.
Locating Hydrogen Production in Norway Under Uncertainty. Lecture Notes in Computer Science (LNCS) 2022, Volum 13557, pp. 306-321
NTNU

16
Sun, Xinwei; Gu, Jie; Han, Donglin; Norby, Truls.
Quantifiable models for surface protonic conductivity in porous oxides - case of monoclinic ZrO2. Physical Chemistry, Chemical Physics - PCCP 2022, Volume 24 (19) pp. 11856-11871
UiO

17
Sun, Xinwei; Vøllestad, Einar; Rørvik, Per Martin; Prodinger, Sebastian; Kalantzopoulos, Georgios; Chatzitakis, Athanasios; Norby, Truls.
Surface protonic conductivity in chemisorbed water in porous nanoscopic CeO2. Applied Surface Science 2022, Volum 611, pp. 1-12
UiO and SINTEF

18
Thøgersen, Annett; Sun, Xinwei; Jensen, Ingvild Julie Thue; Prytz, Øystein; Norby, Truls.
In-situ electron loss spectroscopy reveals surface dehydrogenation of hydrated ceria nanoparticles at elevated temperatures. Journal of Physics and Chemistry of Solids 2022, Volume 170, pp. 1-7
SINTEF and UiO

19
Zamanizadeh, Hamid Reza; Sunde, Svein; Pollet, Bruno; Seland, Frode.
Tailoring the oxide surface composition of stainless steel for improved OER performance in alkaline water electrolysis. Electrochimica Acta 2022, Volume 424.
NTNU

20
Østli, Elise Ramleth; Ebadi, Mahsa; Tesfamhret, Yonas; Mahmoodinia, Mehdi; Lacey, Matthew; Brandell, Daniel; Svensson, Ann Mari; Selbach, Sverre Magnus; Wagner, Nils Peter.
On the Durability of Protective Titania Coatings on High-Voltage Spinel Cathodes. ChemSusChem 2022, Volume 15 (12)
NTNU

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Mobility Zero Emission Energy Systems

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