Annual Report 2023

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Message from the Chair of the Board

During my reflections on this message, my thoughts have circulated around the fact that MoZEES is ending in 2024. The final results and evaluation of the centre should wait until later, but still, I would like to give some personal reflections about MoZEES' relevance and impact.

Since the kick-off of MoZEES, as a Centre for Environment-friendly Energy Research (FME) on 20 March 2017, much has changed within the fields of battery and hydrogen technologies and the deployment in mobility. In what we may call the first wave of electrification of the transport sector, the current Li-ion battery technology has demonstrated its potential in replacing fossil fuels. This battery technology has conquered scepticism towards range, cold climate, and performance decay. It is fair to state that a combination of politics and our broadly electrified society has enabled Norway becoming the optimal test bed for battery electric vehicles and contributed to the battery success in zero-emission mobility. But, on the other hand, the success of the technology has also lifted more challenging issues related to raw materials, recycling, and geopolitics. By way of comparison, the hydrogen fuel cell technology at the start of MoZEES was at a less developed stage and market uptake has also been much slower. There are many reasons for this difference, and it has become clearer that battery and hydrogen technologies have complementary advantages differentiating the use. Thus, the foreseeable battery technology is not the answer to all types of transportation. This insight was, and still is, the basis for the MoZEES research program. A main challenge related to hydrogen technology is the necessity to build an infrastructure value chain, as reflected in MoZEES through the centre research on hydrogen production, storage, and use.

The importance of building value chains is underlined in Norwegian and European R&D programs for the energy-demanding mobility sectors as maritime, aviation, rail, and heavy-duty road transport. Several research and user partners in MoZEES have contributed to establish two new FME centres (HYDROGENi and HyValue) where research and education along the hydrogen value chain and employment in the maritime sector will continue. Furthermore, many applications for new FME centres and advanced research infrastructures were submitted in November 2023 that will strengthen the continuation of research on battery and hydrogen technologies and their use in mobility. All these new centres, and the large efforts made in these applications, reflect the large growing interest in the industry and public sector in these technologies and their relevance to mobility. As the first centre with a focus on these topics, MoZEES has contributed to the gathering and cooperation in the Norwegian zero-emission mobility community. This, and the knowledge foundation laid in MoZEES, will hopefully support the continuation of groundbreaking research in new centres and many spin-off projects in Norway and Europe. I believe that this illustrates the importance of MoZEES.

Another reason for the success of MoZEES is in my opinion that the MoZEES leadership team has actively reached out to the user partners, and the user partners have actively contributed to defining relevant research and roadmaps towards the goals. I am very pleased to see that in all four MoZEES Research Areas the work is done in cooperation with user partners. This cooperation has strengthened during the centre period, along with the stronger focus on innovation during the last years. Also in 2023, the industry-led Innovation Committee established four new pre-projects well distributed over all Research Areas. The many interesting results from these projects were presented at the nicely organised Annual Meeting 2023 in combination with invited international talks and other MoZEES highlights. International cooperation and national spin-off projects have also further strengthened the MoZEES activities in 2023.

The education and training of Master's students, PhDs, and Post Docs are also important MoZEES activities. While many have already finished their degree and assignment, we can congratulate two new PhDs who graduated in 2023. MoZEES students and Post Docs with their highly relevant background are attractive in the labour market. In total, we expect that 12 PhDs and 11 Post Docs will have finished at the end of 2024, giving valuable impact to society. In due time, I hope the education and experience from MoZEES will be beneficial in their professional careers and that they will look positively back at the time in the centre. I would like to express many thanks to the universities and other partners for following up the work of students and Post Docs in good and supportive ways.

As we all know, 2024 is the final year of MoZEES. This means that our efforts should be directed towards the successful finalization of the planned work. At the end of the centre period, I hope that we as partners and collaborators, as well as the Research Council of Norway and society as a whole, can look back and say, "well done MoZEES!".

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

Rune Bredesen
Chairman of the Board

Letter from the Center Director

Another exciting and productive year in MoZEES has gone by. What did we spend our time on and what did we accomplish in 2023? Are we on track to accomplish our long-term goals and milestones? The answer to the first question is summarized in this MoZEES Annual Report for 2023. The short answer to the second question is yes, while the long answer will require a more detailed review after the final year of operation in 2024.

In 2023 we established detailed two-year research area working plans to make sure that key knowledge and results from MoZEES are properly processed and refined before final documentation in 2024. The strategy and overall goal here is to ensure that the Research and User partners have enough time to discuss the main findings, conclusions, and recommendations before the activities in the Center end. The final two-year work plans for 2023-2024 are designed so that we go in for "soft landing" in several important long-term R&D activities in the Center.

The results from 2023 and the years before show that we have completed most of the planned activities and milestones in the Center and that we have good control of the remaining tasks. The main activities and achievements have been summarized in the Message from the Chairman of the Board, and I will therefore not repeat these here. However, I would like to highlight the extremely high quality of the presentations made by all the speakers at the MoZEES Annual Meeting 2023. Here it became clear to me that the strategic and long-term R&D activities among the Research and User Partners are now really beginning to bear fruit. Two excellent examples from the Annual Meeting are the MoZEES developments on Li-ion battery materials (e.g., new LNMO structures, pre-lithiation of Li-ion batteries, and Si-production for batteries) and proton exchange membrane (PEM) water electrolysis technology (e.g., high-performance catalysts, catalyst-coated membranes, and automation of PEM electrolyzer manufacturing).

I would also like to highlight our collective efforts on the MoZEES Zero Emission Truck Case Study, where we are evaluating the techno-economic and environmental viability of battery and hydrogen fuel cell electric heavy-duty trucks. This topic has been studied and discussed in MoZEES for several years. In 2023 we started the process (i.e., the case study) to wrap up the work so that we can provide some clear conclusions and recommendations in 2024. In mid-August we organized an open mini-seminar on "Decarbonization of Heavy-Duty Transport in Norway" in Arendal, at the largest political gathering in Norway (Arendalsuka). Here we challenged our invited speakers to answer and discuss questions such as "How are we doing in cutting the emissions from heavy duty-transport?" and "Which technologies do we need to reach zero emission?" These and more detailed questions in the same category were then debated in a closed panel discussion on the second day of the MoZEES Annual Meeting 2023 in November. Our conclusions and recommendations will be provided in 2024, as soon as the final peer-reviewed publications are ready and the MoZEES consortium has agreed on the assumptions and results. This MoZEES case study shows how key activities in the Center are organized in an open and transparent manner. It also illustrates how much time it sometimes takes to come to clear conclusions.

Talking about time: Operating an FME Center such as MoZEES can be compared to running a marathon. However, there are some significant differences between running a marathon and operating MoZEES: In a marathon you run by yourself and against other people. In MoZEES we collaborate and have Research and Innovation Teams that run long-term activities; together we run several R&D marathons in parallel. In a marathon, you must stick to a predetermined path to finish. In MoZEES we have road maps, but the best path to reach the goals needs to be adjusted as we build up new scientific and technical knowledge. Finally, in a marathon *you need to stick to the path and spend as little energy as possible along the way. In MoZEES we allow for detours and spin-off projects, and we are not afraid to spend extra energy on new great ideas that pop up along our path.*

MoZEES consists of many Partners: 4 research institutes, 3 universities, 6 public partners, 21 commercial and industrial partners, and 2 private interest organizations. The composition in 2023 is the same as in the last few years, and the Consortium has been remarkably consistent. This has created a very solid foundation for long-term collaboration and trust. In 2023 I also noticed an increased interest among the Industry Partners to make use of this unique partnership to create more spin-off projects and innovation projects, both nationally and internationally. At the MoZEES Battery Innovation Forum 2023 in May, we organized an event with some of our battery industry partners and some battery companies in Germany to identify areas of international collaboration. In 2023 there was also a strong engagement from some of our Industry Partners in the MoZEES Pre-Projects. These events and activities illustrate how several of our Industry Partners now really are using MoZEES as an arena to mature ideas and concepts and to establish new research-based activities and innovation projects.

The significant funding and in-kind contributions made by our Industry and Public Partners to the pre-projects and other R&D activities were clearly reflected in the economic reports for 2023. Both direct funding and in-kind contributions were channeled towards some clear and dedicated common tasks. I am incredibly happy to see that we were able to keep up a high economic activity and at the same time make efficient use of the funding available. Our efforts led to significant spin-off projects in 2023. The budget for 2024 shows that we are on track towards our overall target budget of 255 million NOK for the full MoZEES project period (2027-2024).

Finally, I would like to thank everyone who has contributed to MoZEES over the past year. A recent update of our contact list shows that there are around 200 people on our MoZEES Teams and mailing list and more than 100 people are active in different R&D activities. I am therefore happy that we in 2023 employed a new MoZEES Coordinator, Benedicte Ofstad, to help us keep track of everything going on in the Center. We will need all the help we can get when we go into the final year of operation and start with the final documentation of all the results accumulated over the Center period (2017-2024).

On this note, I would like to end with another comparison with running a marathon, but this time there are some clear similarities. Running MoZEES is like a marathon: It is not over until it is over. You need to get past the finish line to complete the full distance! I am looking forward to a productive and successful final year of MoZEES and hope to see many of you at the Final MoZEES Conference from 5-6 November 2024!

Øystein Ulleberg (IFE)

About MoZEES

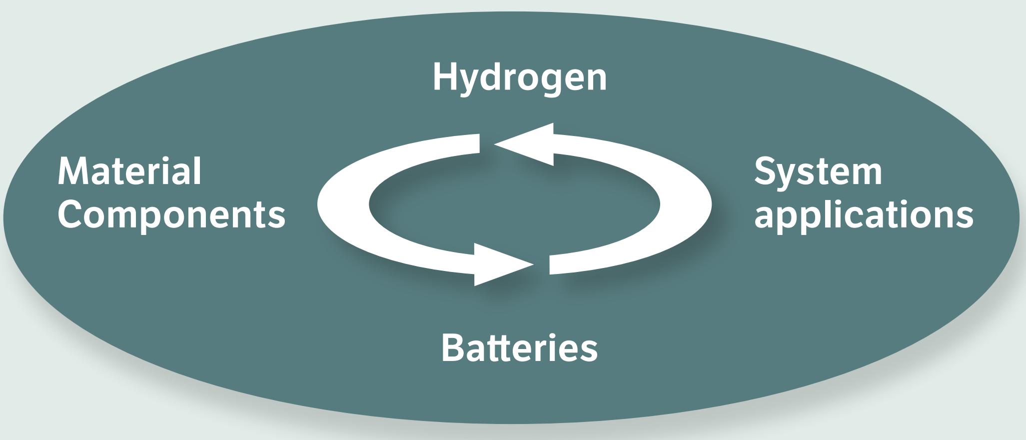
Norway has access to vast amounts of renewable power, some of which can be used to produce electricity and hydrogen for transport. Battery and hydrogen technologies have been demonstrated for use in light-duty zero-emission transport applications. In Norway, there are ambitious goals for low- and zero-emission 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 has been the motivation to establish and operate MoZEES, a long-term national research effort on zero-emission energy systems for transport.

The main objective with MoZEES is to be a Center for environment-friendly energy research (FME) 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 the 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 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 2023, there were more than 100 persons working actively on different research tasks within MoZEES, including 81 key researchers, 5 PhD students, and 3 postdoctoral fellows, in addition to professionals from the public and private sector.

MoZEES proudly involves participants from 25 different countries, underscoring its status as an international research center.

Partners

Industry and Public Partners

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)


Benedicte Ofstad (IFE)


Ann Mari Svensson (NTNU)


Tor Olav Sunde (SINTEF)


Thomas Holm (IFE)


Katinka Elisabeth Grønli (UiO)

Members of the Executive Board


Arshad Saleem (Hydro)


Arve Holt (IFE)


Bjørne Grimsrud (TØI)


Egil Rasten (NEL)


Eva S. Dugstad (UiO)


Geir Brekke (Statkraft)

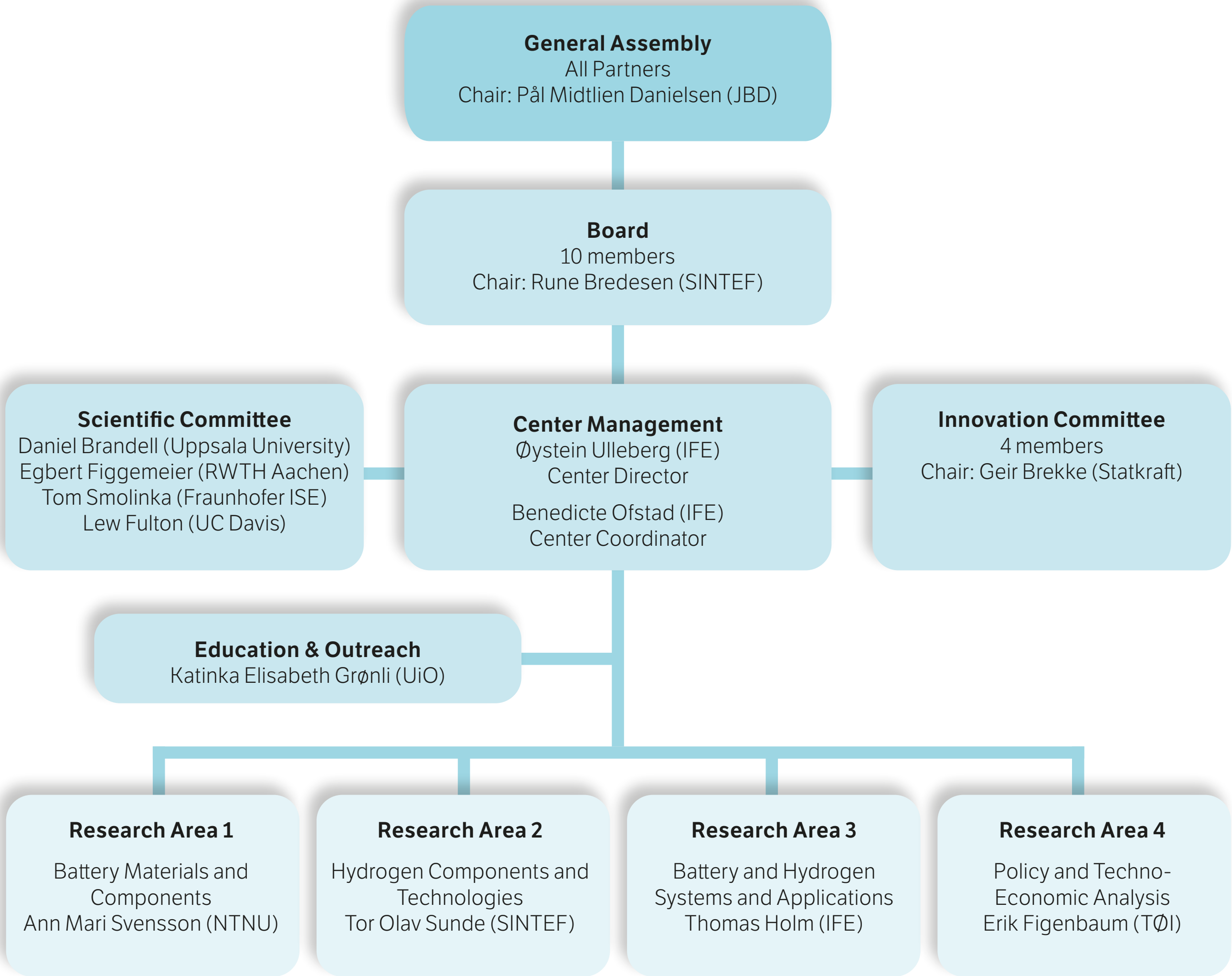

Lars Ole Valøen (Corvus Energy)


Marit Dolmen (Elkem)


Rune Bredesen (SINTEF)


Sigve Aasebø (Statens vegvesen)

Organization



Education

The main objective of MoZEES' Education and Dissemination program is to enhance the career development of young researchers in the Center and to create synergies between the research areas, partner institutions, and external stakeholders. The dissemination activities are designed to increase MoZEES' visibility in different arenas, nationally and internationally. The educational and outreach activities in MoZEES are jointly administered by UiO and IFE.

The MoZEES Research Training Network (RTN) engages young researchers across all of the four Research Areas in the Center. An important task for the MoZEES RTN is to support candidates in qualifying as scientific researchers within their fields of expertise, while simultaneously contributing to realizing the goals of the Centers' research areas. The aim is to build competence by recruiting and educating new PhD candidates, post-doctoral fellows, and young researchers. As MoZEES is coming to an end in 2024, the total number of young researchers involved in the Center is gradually going down. In 2023 there were 7 PhD students and 4 post-doctoral fellows directly associated with the Center.

MoZEES contributes actively to capacity and capability development in zero-emission transport, to strengthen Norway's competitiveness in research, industry, governance as well as to society as a whole. The recruitment of new students and young researchers to the three university partners UiO, NTNU, and USN has also had a "spillover effect" to the research institutes SINTEF and IFE and to relevant actors in industry and government, including MoZEES Partners. Four of the MoZEES RTN alumni now hold permanent associate professor or researcher positions at universities and in several cases MoZEES students, PhD students, and post-doctoral fellows have continued their work at MoZEES research institutes. At least seven RTN alumni have migrated to the industry sector, particularly to companies within battery research and development.

The MoZEES RTN activities include a Mobility Program for the young researchers in the Center; facilitation of meetings between the Scientific Advisory Committee and researchers, students, and User Partners during the MoZEES Annual Meeting, Battery Days, workshops, summer school and internships; organization of international PhD summer schools, workshops, and special courses (e.g., on scientific writing and presentation); organization of Digital Lunch Talks. There has also been provided extra economic support to PhDs in need of prolongation due to significant delays caused by the COVID-19 pandemic.

In 2023 most of the young researchers in MoZEES attended international conferences, presenting posters and papers. There were visits to ESRF in Grenoble to continue relevant experiments and a few other short research visits to relevant international collaborators. Presentations at seminars and conferences were prioritized, and there was therefore only organized one Digital Lunch Talk in June. Here PhD student Jonas Martin presented the final results from his work on renewable electricity, hydrogen and synthetic electro-fuels for trucking, shipping, and aviation. Finally, two PhD students defended their thesis in 2023: Xinwei Sun (UiO) on hydrogen technology, and Šárka Štádlerová (NTNU) on policy & techno-economic analysis.

NorRen Summer School 2023

The Norwegian Research School in Renewable Energy (NorRen 2023) took place from 21 - 25 August in the serene surroundings of Langesund Bad. The event was coordinated by UiO:Energy and Environment, in collaboration with NTNU, the University of Bergen (UiB), FME MoZEES, and FME NTRANS.

Enlightening lectures

The interdisciplinary and interactive program included a mix of expert talks, lectures, and collaborative group activities. It convened a multidisciplinary group of PhD students from NTNU, University of Stavanger (UiS), Norwegian School of Economics (NHH), UiO, Western Norway Research institute and Eidgenössische Technische Hochschule Zürich (ETH). Many of the students had international backgrounds.
At the NorRen 2023 summer school the PhD-students had the opportunity to interact with experts from various fields and gain fresh perspectives on industrial transition issues. Lectures were delivered by a diverse group of experts from University of Agder (UiA), Norwegian University of Life Sciences (NMBU), UiB, and UiO.

The program featured state of the art analyses of the role of the energy system in decarbonization, hydropower, wind and sustainable battery value chains, questions of work and labour in a green economy, corporate greenwashing, CO_2-pricing mechanisms, and many other topics.

Industrial site visits

NorRen 2023 also showcased relevant activities among key Industry Partners, who shared insights into their ongoing transitions. The first stop, with transportation a courtesy of Unibuss, was Herøya Industry Park (HIP); one of Norway's largest industrial parks. The students received a comprehensive lecture on HIPs history and current transition initiatives highlighting projects along the hydrogen value chain, followed by a guided tour of the park and a closer look at of some of Yara's production facilities. The visit concluded with a series of lectures at the companies' technology centre, discussing a selection of ongoing initiatives for achieving climate neutrality by 2050.

The second stop was the cement plant at Heidelberg Materials in Brevik. Personnel at Heidelberg Materials and Aker Carbon Capture presented the Brevik CCS project, one of the most advanced projects in industrial carbon capture and storage (CCS) in the world. Brevik CCS is part of the Norwegian Longship project, which reflects the Norwegian government's ambition to develop a full-scale CCS value chain in Norway by 2024.

MoZEES PhD Graduates in 2023

On 19 April 2023, Xin Wei Sun defended her thesis entitled "Quantification of surface protonic conduction in porous oxides". The research has been part of MoZEES RA2: Hydrogen Components and Technology. The thesis describes a study of adsorption and dissociation of water and resulting protonic surface conduction in porous ceramic oxides. New nomenclature and models developed in this work enable quantitative interpretation of and a predictable role for protonic surface conduction in electrochemical and photoelectrochemical cells, humidity sensors, and heterogeneous catalysis. The work has been carried out at the Department of Chemistry at the University of Oslo and was supervised by Professor Truls Norby (UiO), Researcher Athanasios Chatzitakis (UiO), and Researcher Marie-Laure Fontaine (SINTEF).

Summary:

Xin Wei Sun's work provides a fundamental and methodological framework for parameterization of the thermodynamics and kinetics involved in surface protonic conduction of porous ionic oxides. A novel nomenclature for defect surface species is introduced. The surface protonic conductance has been estimated and various proton migration routes have been considered. A brick layer model that connects surface conductance with macroscopic sample conductivity via microstructural parameters has been developed. This allows quantitative discrimination between types of adsorption and surface transport in the different water layers on oxide surfaces, supported by water vapor partial pressure dependencies and enthalpies of adsorption and conductivity. The enthalpies for protonic surface mobility for oxides decrease systematically with lower temperatures (higher relative humidity) as the water layers grow in coverage and thickness and protons go from jumping between surface oxide ions to jumping between loosely bonded adsorbed hydroxide ions and water molecules. The findings and models developed in this work contribute to the understanding and control of surface protonics in porous oxides, which is believed to play an important role in electrochemical and photoelectrochemical cells, humidity sensors, and heterogeneous catalysis.

On 27 October 2023 Šárka Štádlerová defended her thesis entitled ”Multi-period facility location problems with capacity expansion: Locating hydrogen production in Norway”. Šárka Štádlerová's project is associated with MoZEES RA4: Policy & techno-economic analysis. This thesis formulates optimization models and develops efficient solution methods to solve the problem of designing hydrogen production infrastructure in Norway. The papers in this thesis contribute to the state-of-the-art on deterministic and stochastic multi-period facility location problems with capacity expansion. The work has been carried out at the department of industrial economics and technology management at the Norwegian University of Science and Technology (NTNU) and supervised by Professor Peter Schütz and Professor Asgeir Tomasgard.

Summary:
According to the Paris Agreement on climate change the CO_2-emissions must be decreased by 40% towards 2030. Decarbonization of the transportation sector is a crucial step to meet the emission reduction targets in the Paris Agreement. Hydrogen is considered a promising low-emission fuel alternative in the transportation sector. However, low experience with hydrogen and limited availability are the main challenges when introducing hydrogen as a low-emission fuel in the transportation sector. Hence, designing the hydrogen production infrastructure and providing a reliable hydrogen supply is essential to encourage potential customers to switch from fossil fuels to hydrogen.

This thesis formulates optimization models and develops efficient solution methods to solve the problem of designing hydrogen production infrastructure in Norway. The papers in this thesis contribute to the state-of-the-art on deterministic and stochastic multi-period facility location problems with capacity expansion. To accurately represent the costs of hydrogen production specific aspects of hydrogen production technologies have been studied in mathematical models. These aspects include economies of scale in investment, capacity-dependent short-term production costs, and considerations of minimum production requirements. Solution methods for deterministic and stochastic formulations based on Lagrangian relaxation has also been developed. The results from this PhD work has provided managerial insight into the cost analysis of hydrogen production in Norway.

Seminars and Outreach

MoZEES Battery Days 2023

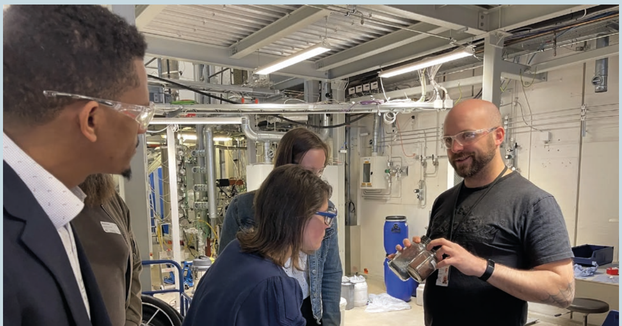
The MoZEES Battery Days from 11-12 May 2023 marked another successful year of this annual event, bringing together nearly 50 participants from across the battery value chain. Designed as a dynamic platform for industry and research collaboration, this year's event showcased an impressive assembly of expertise and insights.

The seminar at Kunnskapsbyen Lillestrøm on 11 May featured a diverse lineup of speakers, including MoZEES research partners, national and international industry stakeholders, and members of the MoZEES Scientific Committee. Discussions spanned a wide range of topics, from the latest advancements in anode and cathode material development, updates from cell manufacturers, to innovative battery systems for maritime applications, and sustainable strategies for car battery recycling.

On the second day of the seminar participants were welcomed to a hands-on laboratory course at IFE. Participation here was extended beyond MoZEES partners and included industry professionals, representatives from the Research Council, students, and members of Kunnskapsbyen Lillestrøm. MoZEES Battery Days 2023 not only highlighted the cutting-edge research and developments within the battery sector but also underscored the importance of cross-sector collaboration in driving forward the future of energy storage solutions.

MoZEES Battery Days 2023 Presentations:

- Nils Wagner (SINTEF) – High voltage cathodes
- Benoit Mortemard de Boisse (SAFT) – Towards high energy advanced lithium-ion batteries
- Inger Emma-Nylund (NTNU) – Stabilizing $LiNi_{0.5-x}Mn_{1.5+x}O_4$ by using a phosphonium-based ionic liquid as electrolyte
- Hannibal Fossum & Espen Åkervik (FFI) – Poof or KABOOM? Experiments on ethane-hydrogen vapour clouds in a rectangular duct
- Jonas Sottman (Hydro) – Hydro Batteries' new technology activities
- Abirdu Nemaga (IFE) – SiN_x developments
- Egbert Figgemeier (FZ Jülich) – Prelithiation as enabler for Si-based electrodes and on the verge of industrialization
- Leif Olav Jøsang (Cerpotech) – LLZO
- Casper Skautvedt (UiO) – Operando characterization of Si-based anodes
- Lars Ole Valøen (Corvus) – Maritime batteries now and the way forward
- Violette Ervioli (Equinor) – Equinor Battery Journey
- Panel discussion on Round Robin (Chair: Zbigniew Rozynek, IFE)



Arendalsuka 2023

Members of FME MoZEES were heavily represented at the Arendalsuka event on the topic of a zero-emission future in Norway's heavy-duty transport. The event, titled "Slik knekker Norge koden for nullutslipp i transport" (How Norway Deciphers the Zero-Emission Code in Transport), underscored the complexities of transitioning heavy-duty vehicles to zero emissions through presentations and a panel debate.

Participating at the panel were (left to right) Tine Uberg Nærland (IFE), Ulf Eriksen (Statkraft), Sigve Jarl Aasebø (Statens vegvesen), Jørn Arvid Endresen (ASKO), Mari Sundli Tveit (NFR), Bjørne Grimsrud (TØI), Astrid Margrethe Hilde (Glire Nett), Liv Kari Eskeland (H), Tom Kalsås (Ap), and Torkil Vederhus (MDG).

Both battery and hydrogen technologies were discussed as potential paths forward for the transport sector. The need for better infrastructure and continued research in this field was emphasized. Key contributions were made by the following MoZEES members:

- Tine Uberg Nærland, Research Director at IFE guided the discussions.
- Kari Aamodt Espegren, from IFE, provided insight into the current status of emissions in the transport sector and showcased the technologies that need to come into play to achieve zero emissions.
- Ulf Eriksen, from Statkraft, drew attention to the energy mix, both electric and biofuel, that will power Norway's zero-emission transition.
- Bjørne Grimsrud, from TØI, offered his perspective during the panel debate, addressing economic implications and strategic alignments.

Statens Vegvesen, Glitre Nett, ASKO, and some representatives from government also provided valuable contributions to the panel discussion. The event was concluded with a summary by the MoZEES Director, who synthesized the discussions, providing a clear trajectory for Norway's sustainable transportation ambitions.

Visit from the Research Council of Norway

The new Executive Director for Sustainable Development at the Research Council of Norway, Eva Falleth, visited IFE on 8 September. The purpose of the visit was to provide an overview of the FME centers at IFE: FME MoZEES with focus on zero emission transport, FME SuSoltech with focus on solar technology advancements, and the proposed new FME Battery with focus on battery research. The visit was an excellent opportunity to showcase the ongoing research and collaborative efforts in MoZEES.

During the visit the MoZEES Director emphasized the vital role of knowledge exchange and sustainable energy research in shaping Norway's future. Hanne Andersen, the department head of Battery Technology at IFE, provided an insightful tour of IFE's state-of-the-art battery development laboratory. A key highlight was a presentation made by post-doctoral researcher Mustapha Jamma, who presented MoZEES research on hybrid power systems for maritime transportation and the development of new energy management strategies for maritime PEM fuel cell/battery systems.

We extend our heartfelt thanks to the Norwegian Research Council for their visit and eagerly anticipate further collaboration in the pursuit of sustainable development solutions.

Present during the visit were (left to right) Mustapha Jamma, Lars Erik Walle, Åse Slagtern, Tine Uberg Nærland, Erik Marstein, Eva Falleth, Hanne Andersen, Martin Smedstad Foss, Rune Volla, Benedicte Ofstad, and Marija Vukovic.

MoZEES Annual Meeting 2023

Group photo captured in Hollendersalen at Son Spa (Photo:Gry Slotterøy, IFE)

The MoZEES Annual Meeting 2023 was held at Son Spa on 29-30 November, as a closed meeting for MoZEES Partners only. The meeting was the last in a series of annual meetings since 2018. (The MoZEES Final Conference 2024 will be held from 5-6 November in Oslo, and will be organized as an open meeting.) The 2023 Annual Meeting commenced with the MoZEES Director's insights and thoughts on the Center's achievements to date. The completion of the MoZEES Zero Emission Truck Case Study and the MoZEES Railway Case Study were highlighted as important collective activities in the final two years (2023-2024) of the Center.

At the Annual Meeting the MoZEES Partners engaged in in-depth discussions about the latest R&D results from the four key research areas in the Center. The two-day agenda featured presentations from experts across various fields, delving into topics such as advanced low-temperature water electrolysis technology, marine battery applications, fuel cell manufacturing, zero-emission solutions for Norwegian Heavy-Duty Road Transport, and advancements in battery and electrolyzer technologies. The diverse attendance included 72 participants: 18 from research institutes, 32 representing the industrial sector, 15 from universities (including 5 PhD students), 6 from the public sector, and one each from the Research Council of Norway and the MoZEES Scientific Board.

Day 1
- *Tom Smolinka (Fraunhofer ISE) – Latest developments on advanced low-temperature water electrolysis technology*
- *Jan-Fredrik Hansen (ABB) – Marine Battery and Fuel Cell Applications; Experiences and Challenges*
- *Ingo Machenbach (Statkraft) – The road to zero emission on Norwegian Heavy-Duty Road Transport*
- *Halvor Hval (UiO) – Unravelling the LMNO structure*
- *Kenneth Friestad & Alberto Olivo (Elkem) – Si for Batteries*
- *Mar Maller Roig (Morrow Batteries) – Increasing Technology Readiness*
- *Samson Lai (IFE) – Pre-Lithiation of Li-Ion Batteries: A Meta-Review on Methodologies*
- *Kathy Ayers (Nel) – Advancements in Automation for PEM Electrolyzer Manufacturing*
- *Tor Olav Sunde (SINTEF) – Development of High-Performance Catalysts,*
- *James Stevens (Johnsen Matthey) – Catalyst Coated Membranes for Electrolysis*

Day 2
- *Andre Wilhelms (KIT) & Usman Saleem (NTNU) – Utilizing Industrial Wastes for Low-Cost Battery Cathode Production*
- *Tor Olav Sunde (SINTEF) – Advanced Porous Transport Layers for PEM Water Electrolysers*
- *Knut Vågsæther (USN) – Safety of Large Marine Energy Storage Systems*
- *Ann Mari Svensson (NTNU) – New Potential Battery Chemistries for Marine Energy Storage Systems*
- *Michal Mielniczek (Corvus) – Fuel Cell and ESS: Perfect Partnership from Corvus Energy*
- *Mathias Henriksen (USN) – Large-Scale Study of Dispersion and Explosions of Hydrogen & Li-Ion Battery Gases*
- *Mustapha Jamma (IFE) – Modeling and Controls of Maritime Fuel Cell / Battery Hybrid Power Systems*
- *Sigrid Lædre (SINTEF) – Experiences from the Zerokyst-project*
- *Jonas Martin (NTNU) – Renewable Hydrogen and Synthetic Fuels versus Fossil Fuels for Trucking, Shipping, and Aviation*
- *Sigve Aasebø (Statens vegvesen) – Results from the Work on Fast Charging of Heavy-Duty Vehicles*

The meeting ended with a panel discussion on How to Speed up Zero Emission in Heavy-Duty Transport. The following panelists were invited up on stage: Geir Brekke (Statkraft), Sigve Aasebø (Statens Vegvesen), Bjørn Bryne (NRD), Bjørne Grimsrud (TØI), and Glenn-Ivar Gaalaas (Unibuss). RA4 leader Erik Figenbaum (TØI) and the MoZEES Director co-chaired this MoZEES internal discussion, which was a follow-up from an open panel discussion at Arendalsuka 2023.

The MoZEES Annual Meeting 2023 showcased the collaborative effort and progress in research and innovation, underscoring the Center's role as a hub for interdisciplinary discourse on advancing zero-emission technologies.

MoZEES Innovation Activities

Facilitating innovation is a cornerstone of the MoZEES center. For this purpose, an industry driven Innovation Forum has been established, steered by the MoZEES Innovation Committee. The main objective of the MoZEES Innovation Forum is to create a meeting place to coordinate the MoZEES research activities with national innovation activities and to create new battery and hydrogen activities (MoZEES spin-off projects) with partners in relevant industrial clusters in Norway and abroad. Two key innovation activities in 2023 have been the MoZEES Pre-Projects and the organization of the MoZEES Innovation Forum 2023.

MoZEES Pre-Projects 2023

The MoZEES Innovation Committee completed their evaluation and recommendation for four MoZEES Pre-Projects 2023 in April, before these were formally approved for funding (from non-allocated funds) by the MoZEES Board in May. Presentations of the results from the Pre-Projects were made at the MoZEES Annual Meeting 2023 in November. Below a brief description of the Pre-Projects.

Utilizing Industrial Wastes for Low-Cost Battery Cathode Production

Research Area: RA 1 Battery materials. Partners: Hydro (applicant), NTNU, Equinor.

Projected to significantly increase by 2030, lithium (Li) demand underscores the importance of recycling from secondary sources, especially given Li's uneven global distribution. Current recycling rates are alarmingly at 0%, prompting the EU to legislate recycling targets of 50% by 2027 and 80% by 2031 for batteries. This research advocates for leveraging Direct Lithium Extraction (DLE) processes, typically used in primary Li production, for recycling lithium-ion batteries (LIBs) from electric vehicles (EVs) to mitigate primary Li supply pressures. The purpose of this pre-project was to evaluate the pretreatment options for EV LIB recycling, compare wet and dry crushing methods, and froth flotation for anode and cathode material separation. The study identified pyrolyzing entire cells or modules, followed by dry crushing and flotation, as the optimal pretreatment route to minimize Li losses, facilitating easier Li leaching. Further analysis covered the downstream hydrometallurgical process's stream concentrations, compositions, and volumes, identifying Li-containing streams with Na^+ as a major impurity. An extensive review of available DLE technologies (e.g., solvent extraction, sorption, membranes, and electrochemical separation) rated them on technical parameters and recommended specific DLE types for certain Li concentrations in the feed stream. This highlights the potential of DLE to minimize Li losses during recycling, although it suggests experimental validation for various DLE methods tailored to different recycling process stages.

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APOSTLE: Advanced Porous Transport Layers for PEM Water Electrolysers

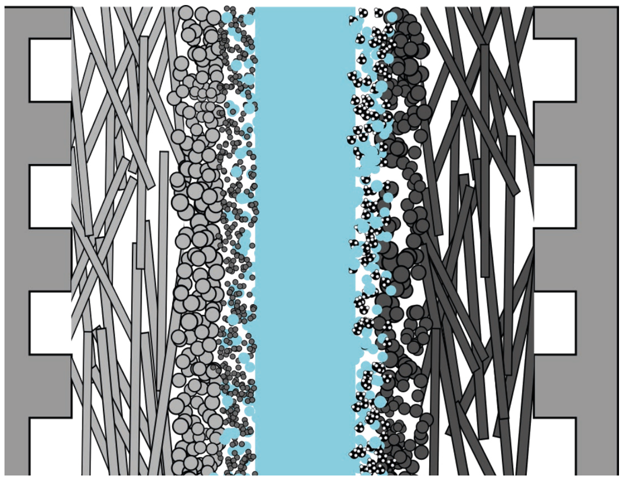
Research Area: RA2 Hydrogen components and technologies. Partners: Johnson Matthey (applicant), Teer Coatings, NTNU, SINTEF.

A significant increase in the implementation of water electrolysis to produce hydrogen is expected in the coming years. The necessary use of the scarce and precious element iridium as a catalyst in polymer electrolyte membrane (PEM) electrolysers is a critical bottleneck for the implementation of this technology in the anticipated scale. To utilize the iridium in the most efficient manner, all the components in the PEM electrolyser cell, including the catalyst coated membrane (CCM) and the porous transport layer (PTL), must be considered together in a holistic manner. The main objective with the Apostle pre-project was to study how the PTL affects the performance obtained from various CCMs. The long-term goal is to develop a series of guidelines for choice of an optimal PTL, with a specific porosity, pore size etc, depending on the properties of the CCM (material, thickness, conductivity). In Apostle there was developed a simple multiphysics model to investigate these relationships. There were also studies made on PTLs produced by different methods by X-ray mictotomography, to quantify its physical parameters (porosity, pore size), which are used as input into the modelling. Additionally, coating experiments were performed to gain insight into how the PTL can best be coated. The goal with this pre-project was to lay the foundation for a proposal for a larger research project with MoZEES partners as key members of the consortium.

Safety of Large Marine Energy Storage Systems

Research Area: RA3 Battery and Hydrogen Systems and Applications. Partners: Hydro (applicant), Corvus, USN.

Ensuring the operational integrity and environmental safety of expanding marine energy storage solutions is vital, making research in this area indispensable. A primary focus is thermal runaway propagation, a phenomenon where an overheated cell can induce failure in adjacent cells, precipitating a hazardous chain reaction. This risk is of particular concern due to its potential to cause fires, explosions, and the release of toxic gases. To understand the mechanisms behind cell-to-cell thermal runaway, the process has been modelled, examining the roles of gas-solid heat transfer, heat conductance through busbars and holders, and air gap heat transfer. The fundamental work carried out in this Pre-Project will hopefully lead to a full project proposal aimed at dissecting the distinct mechanisms controlling thermal runaway propagation. The study will strive to experimentally isolate these effects, supported by modeling efforts.

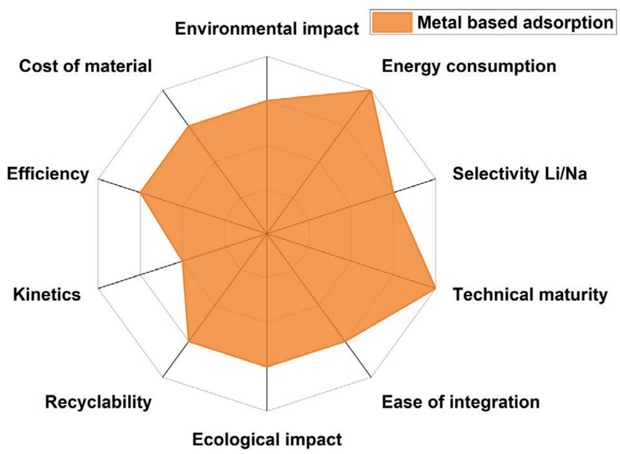


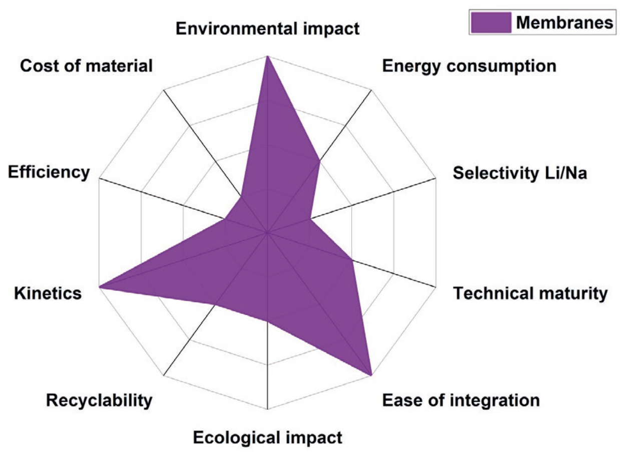
Schematic illustration of a 2D cross-section of a PEM water electrolysis cell used as a model and studied in COMSOL in APOSTLE.

New Potential Battery Chemistries for Marine Energy Storage Systems

Research Area: RA1 Battery materials and components.
Partners: Corvus (applicant), Hydro, NTNU.

The marine energy storage segment is characterized by a diversity of key performance indicators (KPIs) with respect to energy storage technologies. In general safety and lifetime is considered more important, and gravimetric energy density less important, compared to road transport. Norwegian industrial actors have positioned themselves as world leading with respect to integration of batteries in ships, and up to now Li-ion chemistries have been dominating. However, the high demand of Li-ion batteries is set to outnumber supply in just a few years and several of the key materials are becoming a concern with respect to conflicts, abundancy, and global polarization. This has caused a renewed interest in alternative battery chemistries. Hence, within the framework of this MoZEES pre-project, a literature review was performed in order to collect comparable data and identify the most promising chemistries. The main focus was on Na-ion, Li-sulphur, and the more abundant Li-ion chemistries, such as the emerging cathode material $Li(Fe,Mn)PO_4$ (LMFP). The status of these technologies, including some analysis and comparisons of published data, were summarized in a report. In addition, major players with respect to industrialization were identified. The review can serve as a guideline for new research project proposals.





MoZEES Innovation Forum 2023

On the second day of the MoZEES Battery Days 2023 there was organized a MoZEES Innovation Forum on batteries with the objective to explore potential industrial R&D collaborations between Norway and Germany. The meeting was hosted at IFE Kjeller on 12 May and brought together 16 invited participants. Introductions and overviews of the Norwegian and German perspectives on battery technology were presented by Hanne Andersen (IFE) and Prof. Egbert Figgemeier (RWTH Aachen), respectively. This was then followed by round table discussions with focus on cell manufacturing and battery applications and possible areas for future industrial collaborations.

MoZEES Innovation Forum 2023 organization committee

Name	Company	Role
Kenneth Friestad	Elkem	Member of MoZEES Innovation Committee
Arshad Saleem	Hydro	Member of MoZEES Board
Lars Ole Valøen	Corvus	Member of MoZEES Board
Egbert Figgemeier	RWTH Aachen	Member of MoZEES Scientific Committee
Øystein Ulleberg	IFE	MoZEES Director

Research Areas

The research in the Center is organized into four primary Research Areas. RA1 and RA2 are dedicated to pioneering advances in materials and key components for batteries and hydrogen technologies. These areas prioritize the assembly of robust research teams, leveraging multidisciplinary expertise and cross-sectoral capabilities. RA3 focuses on the design and operational dynamics of battery and hydrogen systems tailored for specific applications. It encompasses detailed technical investigations into safety, reliability, and energy efficiency, forming the basis for the development of system specifications and guideline. RA4 aims at crafting a unified framework for analysis, enabling a holistic evaluation of new transportation concepts under various scenarios influenced by technological advances, policy frameworks, incentives, and governance measures. Together, these RAs form a comprehensive research ecosystem, designed to push the boundaries of energy technology and application.

RA1 Battery Materials and Components

This research area is devoted to the development of battery materials and components, focusing on next-generation high-energy lithium-ion batteries based on anodes with a high silicon content, and either $LiNi_{0.5-x}Mn_{1.5+x}O_4$ (LNMO) spinel cathodes or nickel-rich $LiNi_xMn_yCo_zO_2$ (NMC) layered cathodes. $LiNi_{0.5}Mn_{1.5}O_4$ is a promising cobalt-free cathode material for application in lithium-ion batteries, owing to a high operating voltage of approximately 4.7 V vs. Li/Li^+. The overall aim of the research area is to demonstrate a high-energy lithium-ion cell based on silicon-graphite composite anodes, and NMC cathodes. In 2023, the research primarily concentrated on two key areas: (1) Exploring alternative electrolytes for LNMO cathodes and the aqueous processing of cathodes and (2) Fundamental studies of the lithiation processes in silicon and graphite anodes.

Cathode activities

NTNU has focused on detailed studies of degradation mechanisms of LNMO cathodes upon long term cycling. This material faces stability issues when used with common battery electrolytes, usually composed of LiPF6 salt dissolved in a mixture of carbonate solvents, like diethyl carbonate (DEC) and ethylene carbonate (EC). One cause of degradation is related to the presence of hydrofluoric acid, resulting from reactions between $LiPF_6$ and traces of water, which leads to the dissolution of the transition metals and damages the integrity of the LNMO. Another issue is the instability of EC at high voltages. Ionic liquid electrolytes are interesting alternatives, and a topic of research in MoZEES. Based on previous results with silicon anodes, the ionic liquid P_{111i4}FSI (ILE) was shown to possess excellent high temperature performance. A systematic comparison of degradation of LNMO cathodes cycled in an LP40 ($LiPF_6$ in EC:DEC) electrolyte and an electrolyte composed of LiFSI in P_{111i4}FSI at 25˚C and 45˚C revealed significant differences with respect to degradation (Figure 1.1). Results from long term cycling (200 cycles) show improved performance of the ionic liquid electrolyte with respect to capacity and capacity retention (Figure 1.2). However, the coulombic efficiency drops for the ionic liquid electrolyte at 45˚C. Postmortem Transmission Electron Microscopy analysis (Figure 1.3) clearly shows that the surface of the LNMO is covered with pits extending below the upper atomic layers after cycling in LP40, while the surface remains intact after cycling with the ionic liquid.

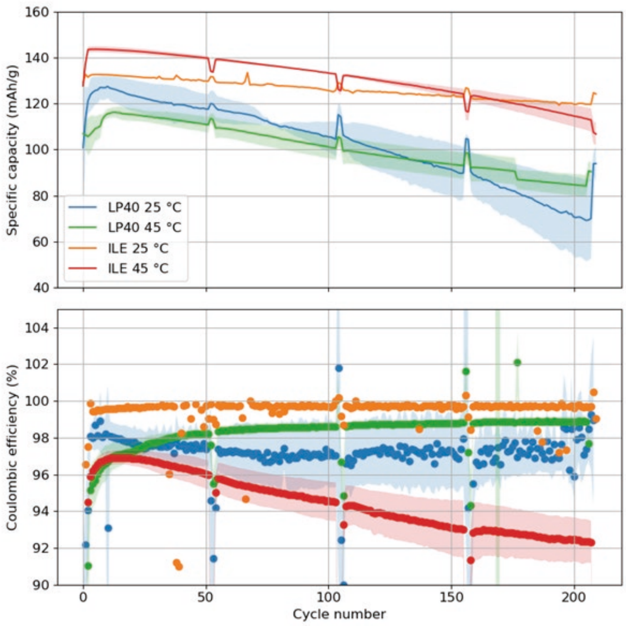


Figure 1.1. Upper: Results from galvanostatic cycling at 1C for the LP40 electrolyte, and the ionic liquid electrolyte (ILE) at 25°C and 40°C. Lower: The corresponding coulombic efficiencies

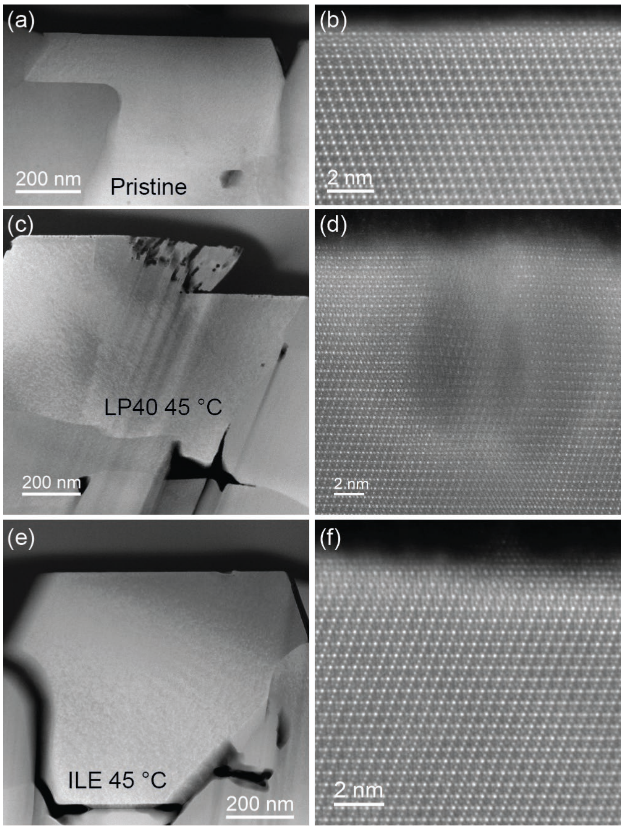


Figure 1.2. High-Angle Annular Dark-Field Scanning Transmission Electron Microscopy images of LNMO before cycling (a,b) and after cycling in LP40 at 45°C (c, d), and after cycling in ILE at 45°C (e,f).

A shift to aqueous processing of cathode materials is highly desirable from an environmental perspective but has proven to be challenging for nickel-rich NMC-type materials. The difficulty comes from the material's tendency to leach both lithium and transition metals, which raises the slurry pH beyond the stability window of the current collector aluminium foil and results in corrosion, pitting and unwanted secondary phases. A possible solution to this (as proposed in literature) is to add orthophosphoric acid to the slurry to both buffer the pH and precipitate transition metals at the NMC surface.

Studies performed at SINTEF investigated this route from a more industry-relevant rapid-processing perspective. Using NMC622 as the cathode active material, it was found that with shorter "wet" times than those previously reported (approximately 45 minutes, compared to the previously reported durations of more than 3 hours) the addition of orthophosphoric acid still greatly aids casting, but also leaves an unwanted phosphorous-rich residue on the electrode due to incomplete reaction of the orthophosphoric acid. On cycling this results in excessive cathode electrolyte interphase build-up and sudden-onset cell failure. However, this can be removed by washing with ethanol to yield an aqueously processed cathode with excellent capacity retention (78% over 400 cycles).

From this it can be concluded that industrial implementation of an aqueous NMC processing route using phosphoric acid additive should be possible, but attention must be paid to the mixing and drying processes to ensure that no unreacted residues remain in the electrode at cell assembly.

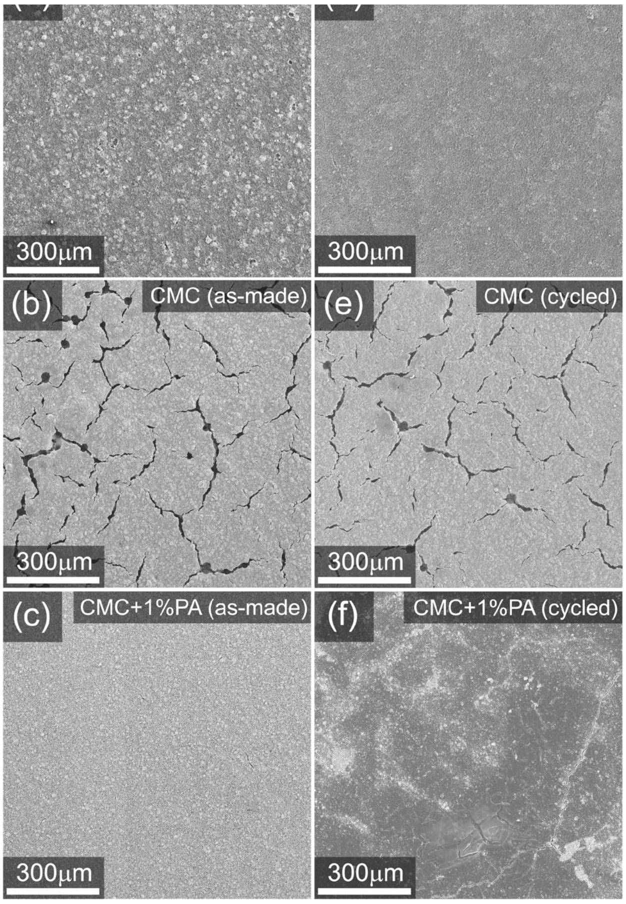


Figure 1.3. Secondary electron images of electrodes using binders of Polyvinylidene fluoride (PVDF), Carboxymethyl cellulose binder (CMC) and CMC with phosphoric acid additive. As made electrodes shown to the left, and cycled electrodes shown to the right.

Silicon anode activites

Detailed studies of the lithation mechanisms of silicon was conducted as a collaborative effort between UiO and IFE, using amorphous silicon materials fabricated from silane in a reactor at IFE. The study was based on total scattering computed tomography and experiments conducted at the European Synchrotron Radiation Facility (ESRF). Total scattering computed tomography enables the visualization of chemical changes occurring in the electrodes during lithiation. Additionally, it facilitates the creation of a 3D-map of the electrode components, including both amorphous active and inactive materials (Figure 1.4). The mapping was used to select a region of interest in the electrode from which the best possible operando pair distribution function (PDF) of the active material could be obtained. By use of differential analysis, the small but systematic changes in the PDF during lithiation could be revealed, including the subtle structural transformations at the atomic scale.

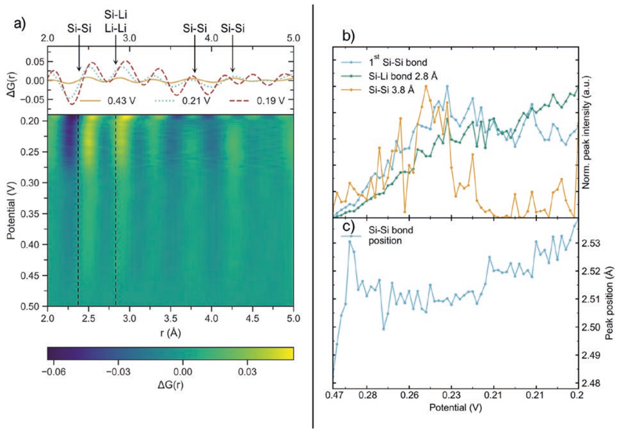
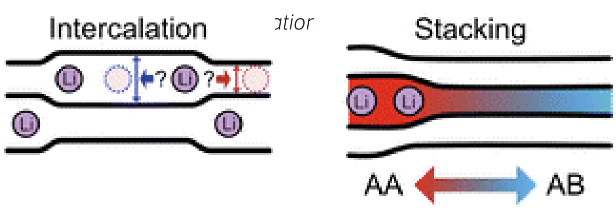


Figure 1.4. Evolution of the difference PDF pattern for the middle slice of Si-based electrode measured at 150 mA g^{-1} as a function of the applied electrochemical potential. The PDF patterns at the top are the difference PDFs for selected potentials to highlight the changes over time. The contour pattern below is the series of operando dPDFs, b) normalized dPDF peak intensities vs potential, c) Position of the dPDF signal from extension of the 1st Si-Si bond vs potential.

Advanced Characterization and Modelling

A theoretical study of lithium intercalation in graphite was undertaken at UiO, based on replica-exchange molecular dynamics in combination with the ReaxFF force field. In this manner, limitations of conventional molecular dynamics simulations could be overcome, given the typical diffusion coefficients of lithium in graphite (10^{-5} nm^2/ns). In this way, the behavior of lithium-intercalated graphite from any starting arrangement of lithium at any value of x in Li_xC_6 could be studied. The focus was on analyzing the energetic favorability differences between the relaxed structures. One outcome of the study is to show the tendency for clustering of lithium, which could lead to dynamic local structures that approximate the staging models used to explain intercalation into graphite (Figure 1.5).

This approach enabled the researchers to surpass the limitations typically associated with conventional molecular dynamics simulations, especially considering the diffusion coefficients of lithium in graphite, which are around 10^{-5} nm^2/ns. By employing this method, it became possible to analyze the behavior of lithium-intercalated graphite starting from any lithium arrangement and for any stoichiometry represented by x in Li_xC_6. The study primarily aimed to examine the differences in energetic favorability among various relaxed structures. A key finding is the observed tendency of lithium to cluster, potentially leading to dynamic local structures. These structures closely resemble the staging models traditionally invoked to describe the process of lithium intercalation into graphite.



The Li atom diffuses toward the vacant site (following the blue arrow) with increased gallery height due to a neighboring Li atom, rather than following the red arrow into the area with standard graphitic spacing.

RA2 Hydrogen Components and Technologies

The main objective of 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 international targets for these key hydrogen technologies. The main objectives are clearly linked with the MoZEES Hydrogen Technology Roadmap. The materials and components that have been selected for R&D within MoZEES with the goal to reduce the cost and increase the lifetime of fuel cells and electrolyzers are: (1) High-performance catalysts enabling ultra-low precious metal loading, (2) Lower cost, lighter, and corrosion-resistant bipolar plates and electrodes, and (3) Low-cost high-performance membranes. RA2 also includes a task on characterizing and understanding the lifetime, durability, and performance of fuel cells, which is closely linked to RA3.

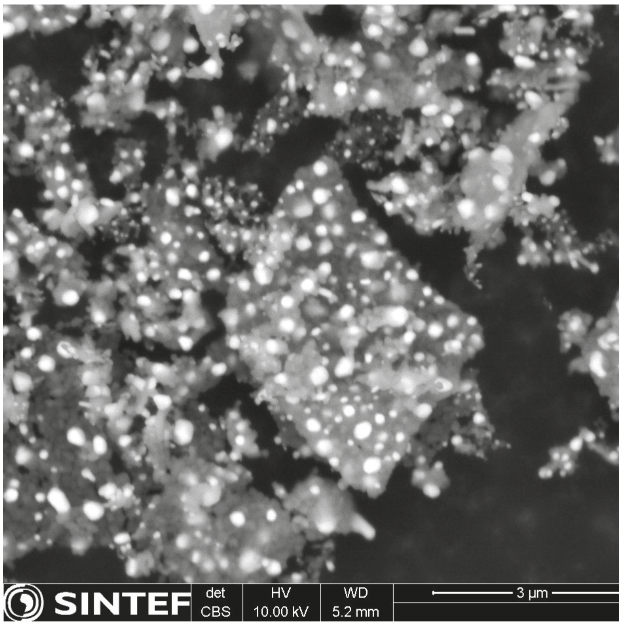


Fig 2.1: Scanning electron microscopy image of powder from Cerpotech after heat treatment in reducing atmosphere. The larger particles are TiO_2 and the small bright particles are metallic nickel which will be replaced with iridium catalyst.

High-performance catalysts

Proton-exchange membrane water electrolysis (PEMWE) requires the use of rare and expensive catalysts, often from the platinum group metals (PGMs). Iridium, favored for its exceptional catalytic activity and stability, is utilized in the oxygen evolution reaction at the anode, where conditions are notably harsh. One strategy to minimize iridium usage involves decreasing particle size to increase the active surface area. However, achieving the necessary homogeneity and thickness in the catalyst layers is challenging with nano-sized particles. An alternative approach to deposit the catalyst nanoparticles on larger particles of a support oxide material. SINTEF has adapted a technique previously used for platinum to now apply to iridium, in collaboration with industrial partner Cerpotech. The objective here is to find out if Cerpotech's high-quality oxide powders can serve as effective catalyst supports for PEMWE. A $NiTiO_3$-powder prepared by Cerpotech is heated in a reducing atmosphere to produce TiO_2 and metallic nickel (Figure 2.1). Here the prior acts as the support oxide, while the latter is used as a sacrificial metal when depositing the iridium in the next step in the process.

Low-cost bipolar plates

In fuel cells, bipolar plates are typically made from coated titanium, contributing to roughly 25% of the cost and 50-80% of the weight of the fuel cell stack. Reducing this expense and weight by using more affordable materials is a critical objective. Promising results with stainless steel bipolar plates coated by industrial partner, Teer Coatings, has previously been achieved in MoZEES. Given the stringent weight and space constraints in the aviation sector, an increasingly important market for fuel cells, aluminum emerges as a potential alternative for bipolar plate material due to its lighter weight. However, challenges related to coating processes and lifespan remain. To thoroughly evaluate bipolar plates performance, in-situ testing is essential but time-intensive, necessitating the development of accelerated stress tests (AST). Currently, there is a lack of AST protocols in the literature that specifically address bipolar plates degradation. Hence, this is the research focus in MoZEES for the last two years (2023-2024).

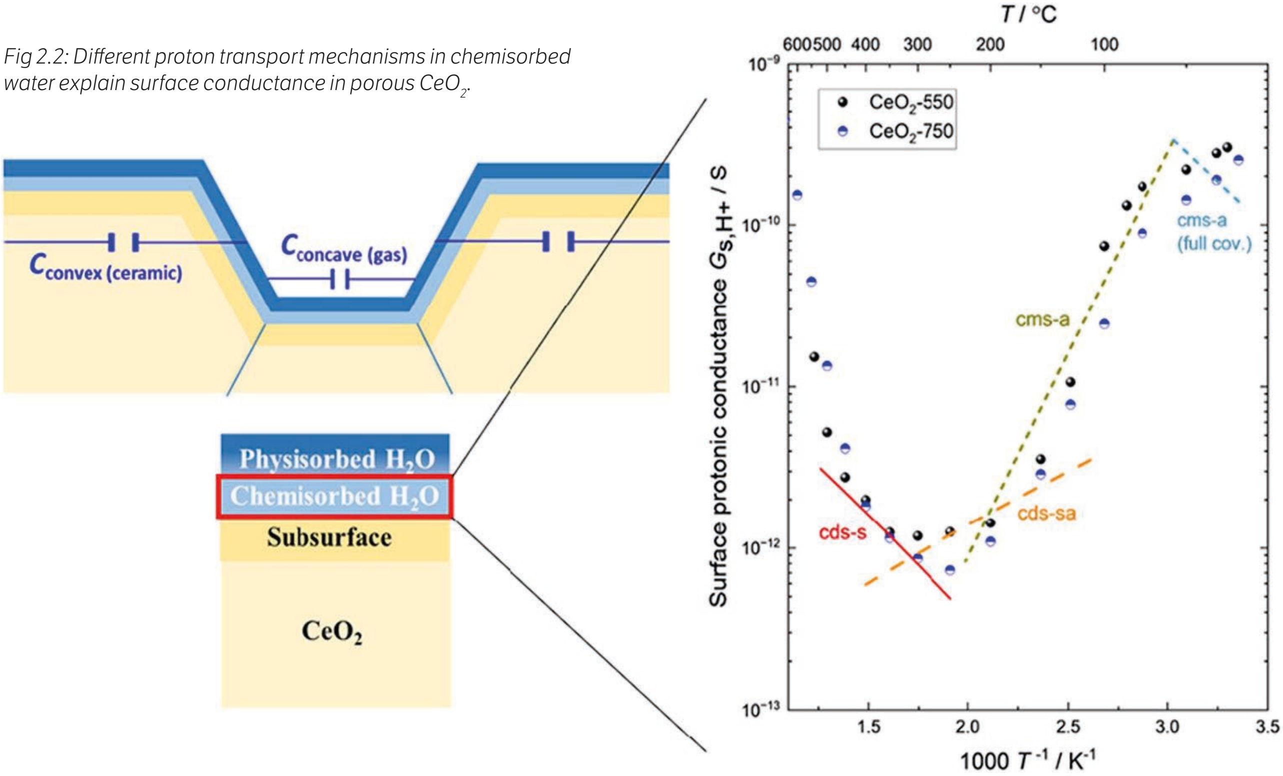
Low-cost electrodes for alkaline electrolyzers

A PhD by Hamid Reza Zamanizadeh at NTNU on low-cost electrodes for alkaline water electrolyzers was completed in 2022. The final results from this research was published in 2023 under the title “Performance of Activated Stainless Steel and Nickel-Based Anodes in Alkaline Water Electrolyzer”. The main objective with this work was to explore the use of stainless steel as a cost-effective alternative to conventional nickel electrodes in alkaline electrolyzers. This study was of particular interest to the industry partner Nel, as it demonstrated the potential for significant cost reductions in electrolyzer manufacture.

Improved high-temperature membranes

This task is one of the more fundamental studies in RA2. Xinwei Sun defended her thesis at UiO, entitled ” Quantification of surface protonic conduction in porous oxides” in 2023. The motivation for studying proton conduction on the surface of oxides was to enable high-temperature membranes by using composite membranes with ceramic nanoparticles as fillers in polymer membranes (Figure 2.2). Xinwei Sun published two papers in 2023.

Fig 2.2: Different proton transport mechanisms in chemisorbed water explain surface conductance in porous CeO_2.

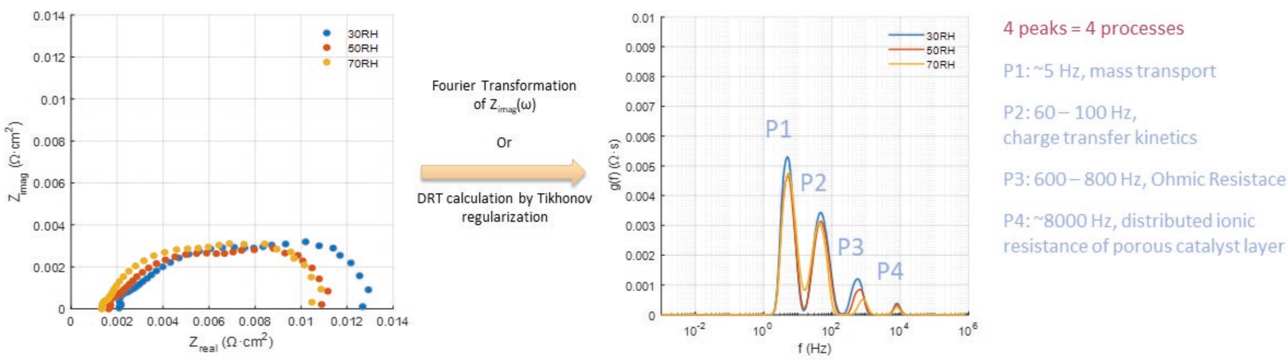


Lifetime, durability, and performance

Fuel cells are increasingly emerging as a mature alternative, particularly within heavy-duty transport and maritime applications. In these areas, the longevity of the fuel cell system is of great importance. Consequently, considerable efforts are being dedicated to extending the lifetime of these cells 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 its degradation mechanisms.

Electrochemical Impedance Spectroscopy (EIS) serves as a potent tool in this regard. By applying a weak electrical sine wave across various frequencies and measuring the response, EIS can effectively gauge the performance of fuel cells. Since the degradation mechanisms of fuel cells occur across different time scales (from seconds and minutes to days, weeks, and even months) the response captured by EIS can provide insights into the specific degradation mechanism at play. In 2023, the research in this MoZEES task has focused on the analysis of Fourier-transformed EIS signals through the distribution of relaxation times analysis method (Figure 2.3). This approach makes it possible to distinguish more easily between the various degradation mechanisms in the fuel cell, each characterized by different relaxation times.

Figure 2.3: Signal from electrochemical impedance spectroscopy before (left) and after a Fourier transformation to more readily be able to distinguish between different physical processes with different time constants (right).



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. Central to this research is heavy-duty hybrid battery/fuel cell systems, battery and hydrogen safety issues, and maritime applications. Key focus areas include:

- 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.

Advanced fuel cell control systems

Research on the modeling, control, and simulation of a proton-exchange membrane fuel cell/lithium-ion battery-based hybrid power system for maritime applications was conducted at IFE in 2023. A detailed dynamic model of a zero-emission hybrid-power system for a double-ended ferry has been developed and simulated using the MATLAB/Simulink software (Figure 3.1). Additionally, an energy management strategy (EMS) has been developed, incorporating a fuzzy logic approach and a rule-based technique. This EMS is designed to stabilize the DC bus voltage at the necessary constant value, efficiently manage the power distribution between the fuel cells and batteries to meet the load power demand, and minimize fuel cell degradation, while taking into account the state of charge of the battery.

To enhance the performance of the designed hybrid zero-emission system, an intelligent energy management strategy (EMS) was developed. Utilizing a neural network algorithm this optimal EMS intelligently controls the energy flow by determining the optimal operating point for each system component (Figure 3.2a). The primary objectives were to maximize system efficiency, ensure fuel economy, and minimize degradation. The suitability of the hybrid system was then evaluated based on a real driving profile and the power required by the fuel cell under various operating conditions of the vessel and different battery states-of-charge were calculated (Figure 3.2b). The main finding was that the proposed intelligent EMS outperforms traditional rule-based techniques, maintaining the battery charging/discharging rates at less than 0.3C, thus achieving higher efficiency. This research work was presented at the 2023 IEEE International Conference on Energy Technologies for Future Grids in Australia.

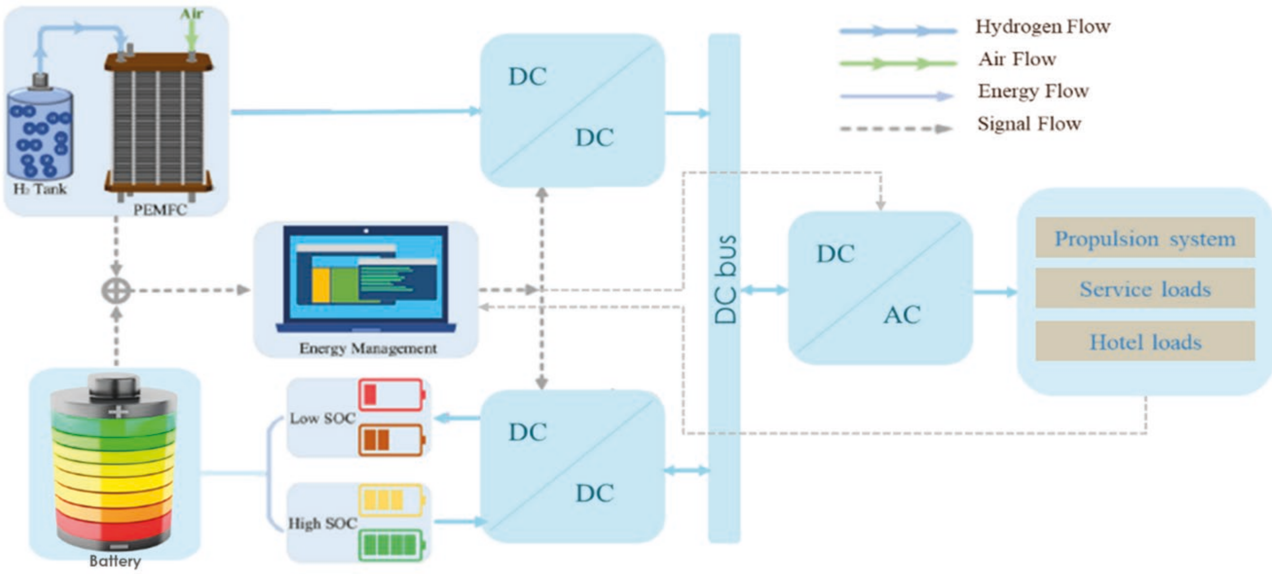


Figure 3.1: Simplified configuration of the developed PEMFC/battery-based hybrid power system.

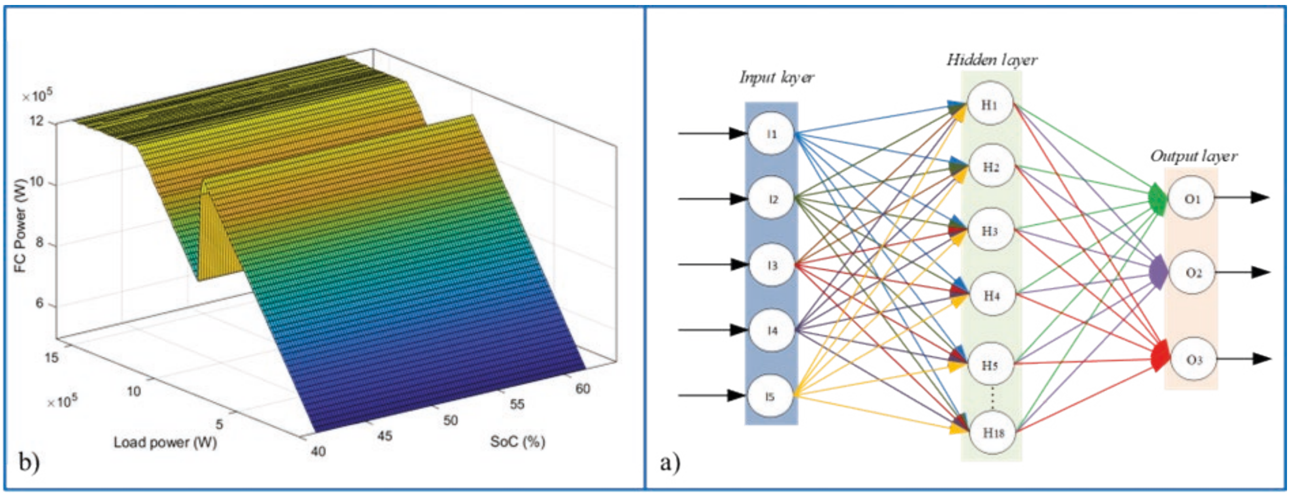


Figure 3.2: a) Configuration of the designed neural networks model, (b) Power map of fuel cell system.

Battery and Hydrogen Safety

FFI and USN conducted dispersion and deflagration experiments in April 2023. Pure hydrogen, hydrogen-air, and hydrogen-ethane mixtures were released continuously from the ceiling in the rear part of a 6 m long duct which was open in the opposite end. The channel volume was approximately 6 m^3, and one of its side walls was made of polycarbonate windows to allow visual inspection (Figure 3.3). In some of the experiments, geometrical obstructions were inserted into the channel.

To determine the dispersion pattern, hydrogen concentrations were measured by 29 sensors in the channel for a range of injected mass flows (Figure 3.4). Then, similar injected mixtures were ignited at the back end of the channel. The resulting vapor cloud explosions were recorded by a high-speed camera, and the pressure levels along the channel ceiling were measured.

Numerical simulations (with the open-source OpenFOAM code) of the gas dispersion in the channel were carried out, and subsequent deflagration simulations (with XiFoam, a part of OpenFOAM) are planned for 2024. The prediction accuracy of the CFD dispersion simulations were satisfactory for pure-hydrogen mass flows ranging from 0.08 to 1.25 g/s. Results from both the experiments and the simulations will be published in 2024 in the form of at least two academic papers.

Figure 3.3: Deflagration of an ethane-hydrogen mixture in the 6 meter channel.

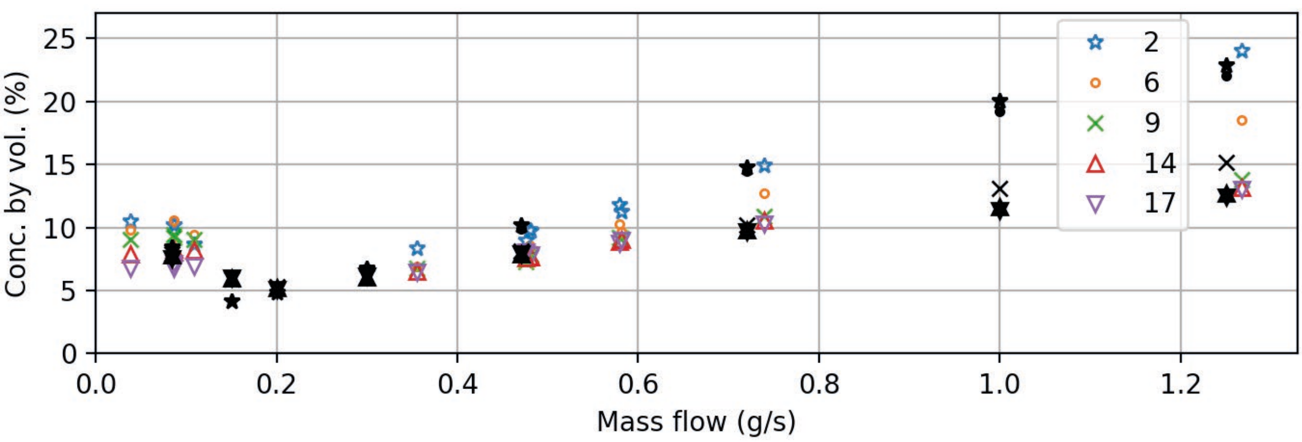


Figure 3.4: Measured (colored symbols) and simulated (black symbols) hydrogen concentrations at selected locations in the channel for different injected mass flows.

Efficient Low Temperature Water Electrolysis Processes

Direct production of high pressure hydrogen from water electrolysis can potentially curtail energy and cost intensive downstream mechanical compression processes. Experimental work on a 12 kW high-pressure PEM water electrolysis (PEMWE) prototype stack from Nel was carried out at IFE in 2021 and 2022. In 2023 this work was presented at the European Fuel Cell Forum (EFCF 2023) in Luzern in July and the International Conference on Electrolysis (ICE2023) in August and properly documented in an article submitted to the Journal of Power Sources [approved in March 2024].

The performance of the high-pressure PEMWE stack was characterized with respect to electrochemical performance, net hydrogen production rate, and water crossover (Figure 3.1). The PEMWE system (national experimental test rig at IFE) was also tested for its operability and performance of the thermal and gas management systems (Figure 3.2). The test campaigns showed that the voltage increase with pressurization from 5 to 30 bar is 30% smaller than expected, but further pressurization reduces performance. The study confirmed that high-pressure PEMWE system has higher energy consumption than state-of-the-art electrolyser systems with mechanical compressors. However, there can be a business case for high-pressure PEMWE if the trade-off between stack efficiency and system efficiency is balanced.

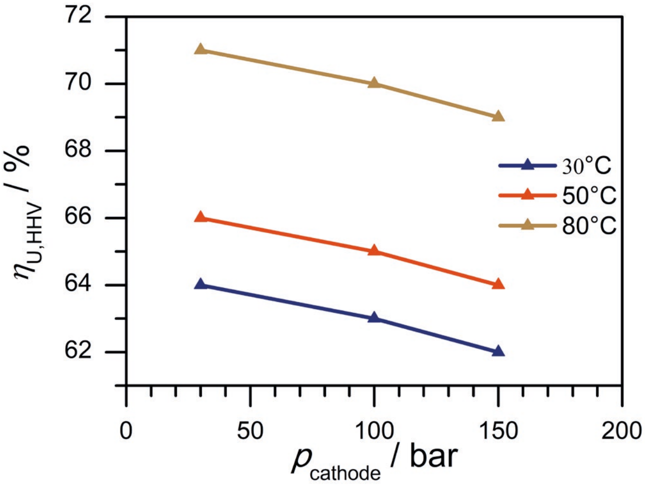


Figure 3.5 Voltage efficiency as a function of temperature and pressure at 1.86 A/cm²

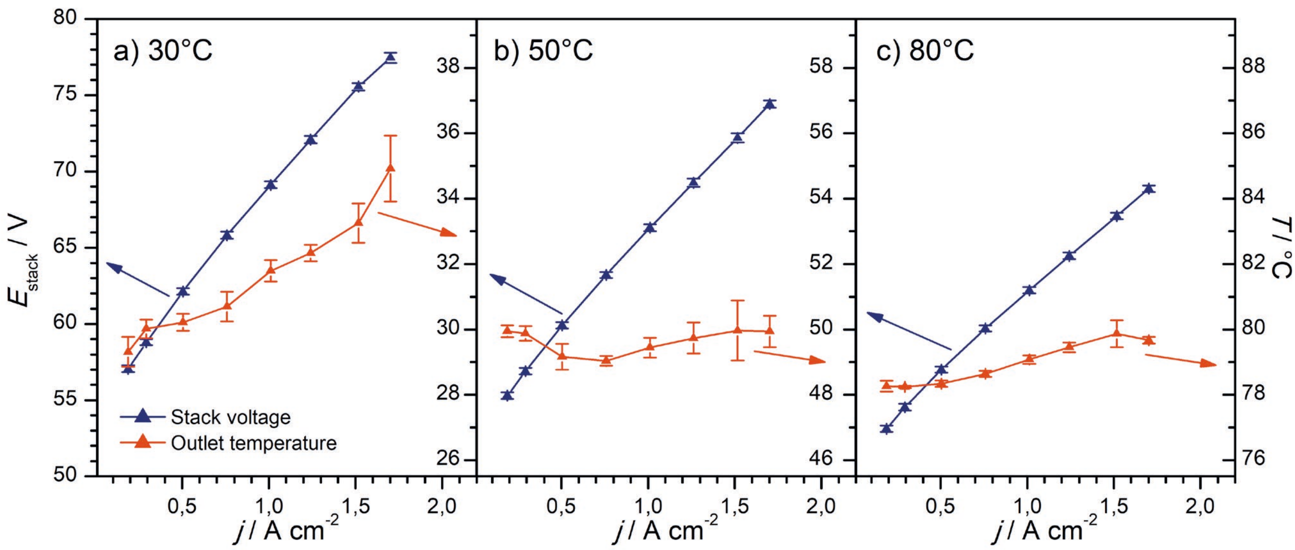


Figure 3.6 Stack voltage and outlet temperature as a function of current density at 30 bar.

RA4 Policy and Techno-Economic analysis

The aim of 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.

RA4 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 questions in RA4 are how and when new technology can become competitive and how public and corporate stakeholders can 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 are performed in order 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 within four prioritized transportation subsystems: (1) Urban mobility and logistics, (2) coastal line vessels and ferries, (3) long-haul freight and passenger transport, and (4) transportation terminals. To define relevant concepts, business models, and values chains, RA4 collaborates closely with system experts in RA3 battery and hydrogen experts in RA1 and RA2 and the MoZEES Industry Partners.

Case Study Heavy Duty Trucks

The RA4 work in 2023 focused on a zero-emission heavy-duty truck study which will continue in 2024. The overall aim of the study is to provide transparent information about the cost and environmental impacts of replacing diesel trucks (DTs) with Battery Electric Trucks (BETS) or Hydrogen Fuel Cell Electric Trucks (HFCETs). Biogas Trucks and Hydrogen Internal Combustion Engine Trucks are also investigated. To this end, the MoZEES-ZET (Zero Emission Truck) Integrated Business and Societal Costs model has been under development and will be finalized in 2024. An overview of the model is shown in Figure 4.1. The MoZEES-ZET model estimates business cost, i.e., Total Cost of Ownership (TCO) with current taxes, costs without taxes, societal costs that includes external costs, i.e., environmental, queues, accidents, and road wear costs, and the environmental impacts through LCA (Life Cycle Assessment) from 2024.

The calculations are carried out for BETs, HFCETs, HICETs, BGTs and DTs. The costs data is based on literature and own data (from MoZEES Partners) whereas the LCA part also include data from LCA data bases and relevant literature. Truck user profiles and policy alternatives are designed to increase the understanding of how user profiles and policies impact the results. The model work has resulted in two conference papers that will be presented at the Transportation Research Arena (TRA) in Dublin and the Electric Vehicle Symposium (EVS) in Seoul in April 2024. The TRA paper covers the environmental impacts (LCA), whereas the EVS paper covers the cost calculations. Continued work in 2024 will merge the two parts to the MoZEES-ZET model.

The preliminary results in the EVS paper show that BETs may be the best option for replacing DTs for local and regional applications, and long-haul up to 500 km distances. Longer distances will require extensive and expensive MW charging, and BGTs or HFCETs may therefore be an option in this market. BETs have a clear adoption pathway, growing from local and regional fleet operation before expanding into long-haul operations. BGTs are already on the market and the fueling stations are expanding. HFCETs will need to start in long-haul transport segment where it can be competitive with other options, but this will require a significant build out of fueling stations selling low-cost hydrogen.

The preliminary LCA results show that BETs and HFCETs will offer significant climate benefits compared with DTs, particularly when assuming the Norwegian electricity for charging BETs and wind powered electrolysis for hydrogen production for use in HFCETs. While the BETs and HFCETs will offer clear climate benefits compared to DTs, their wider environmental performance is more complex, partly because both BETs and HFCETs have higher production impacts. Preliminary results suggest that BETs (particularly) and HFCETs (to a certain extent) may still offer lower impacts compared to DTs in impact categories that are significantly affected by fuel combustion (e.g., photochemical oxidant formation) but will suffer higher impact in impact categories particularly affected by metals (e.g., toxicity). These preliminary results do not account for infrastructure needs (i.e., chargers and hydrogen fueling stations). Both papers will in 2024 be further developed into peer-reviewed scientific articles. The MoZEES-ZET model development is complemented by interviews with users of series produced BETs, truck importers, leasing companies and relevant authorities, as well as analysis of data from the funding agency ENOVA and leasing companies. These data are used to understand user experiences and motivations as well as get insights into the opportunities, barriers, and cost of operating zero-emission trucks. This work will be documented in a separate scientific article.

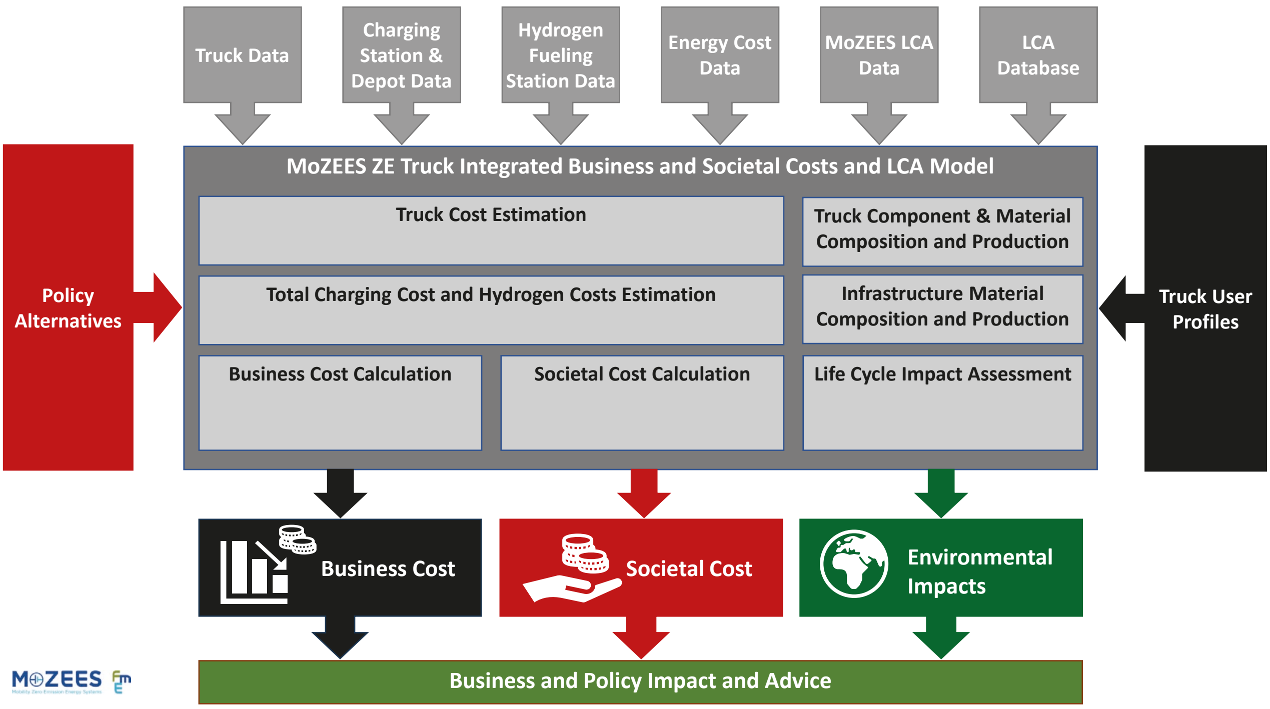
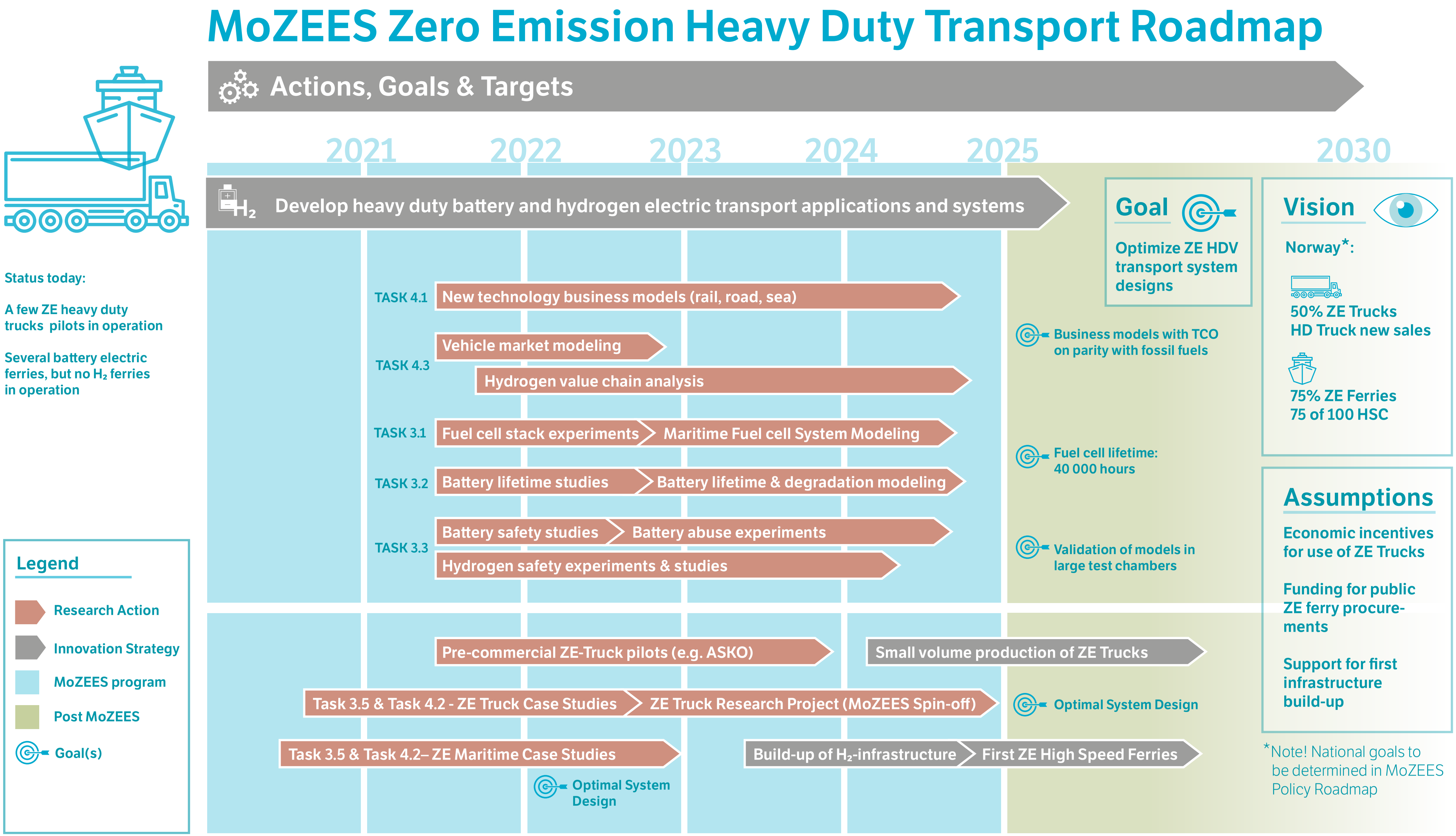
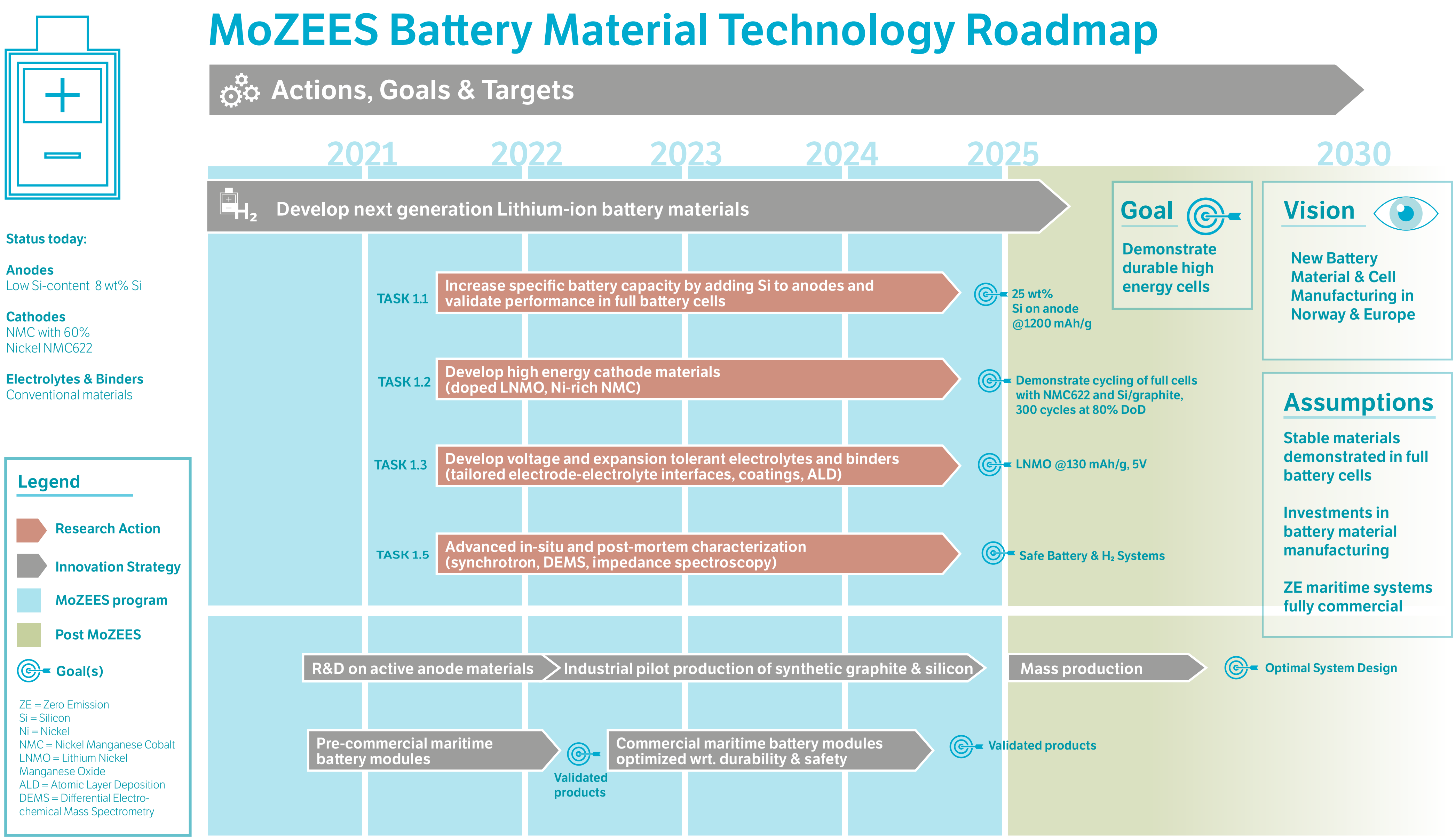


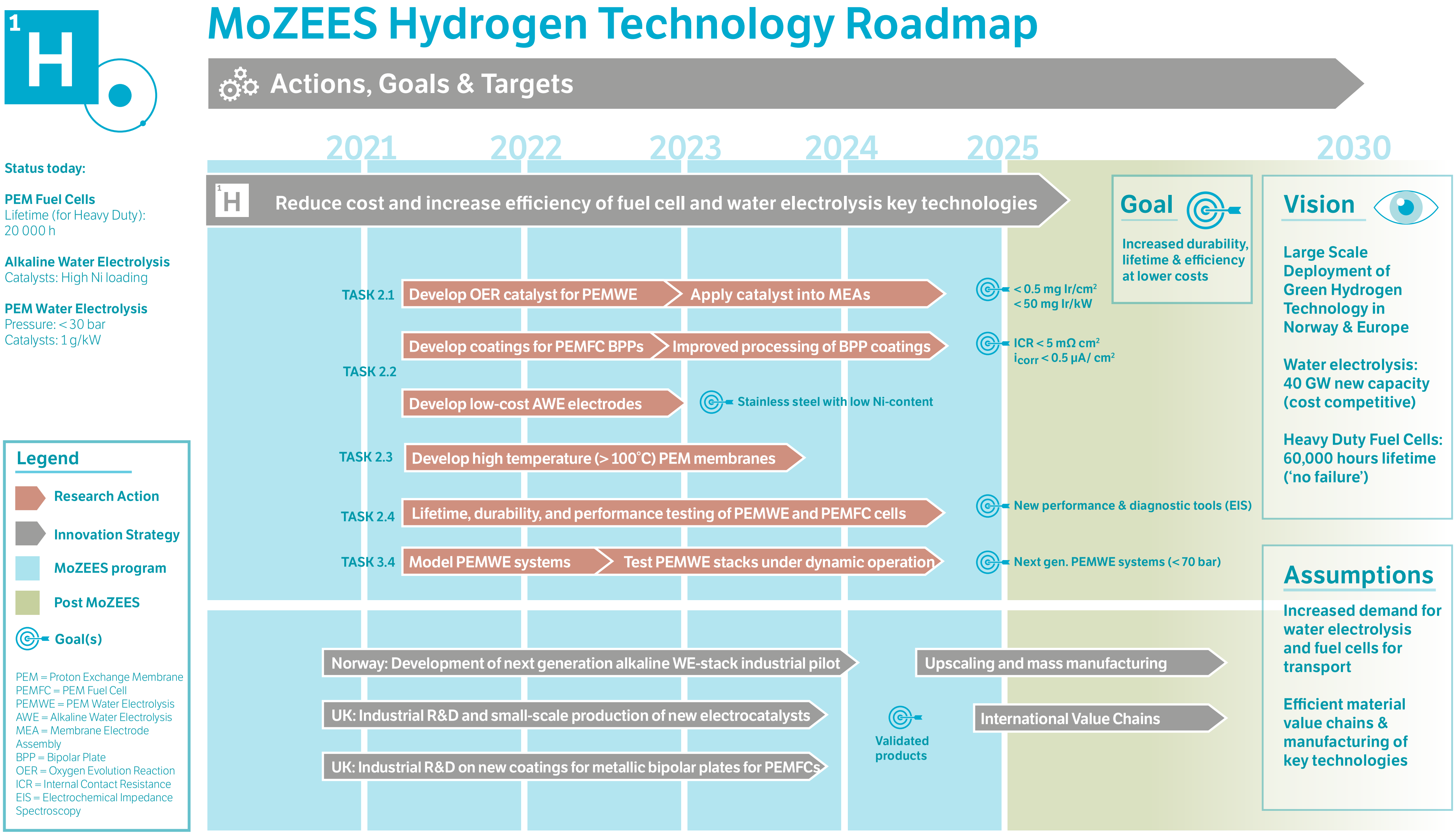
Figure 4.1 MoZEES-ZET model – An Integrated Business and Societal Costs model for Zero Emission Trucks


MoZEES Zero Emission Heavy Duty Transport Roadmap
Actions, Goals & Targets
2021
2022
2023
2024
2025
2030
Status today:
A few ZE heavy duty trucks pilots in operation
Several battery electric ferries, but no H₂ ferries in operation
H₂
Develop heavy duty battery and hydrogen electric transport applications and systems
TASK 4.1
New technology business models (rail, road, sea)
TASK 4.3
Vehicle market modeling
Hydrogen value chain analysis
TASK 3.1
Fuel cell stack experiments
Maritime Fuel cell System Modeling
TASK 3.2
Battery lifetime studies
Battery lifetime & degradation modeling
TASK 3.3
Battery safety studies
Battery abuse experiments
Hydrogen safety experiments & studies
Pre-commercial ZE-Truck pilots (e.g. ASKO)
Small volume production of ZE Trucks
Task 3.5 & Task 4.2 - ZE Truck Case Studies
ZE Truck Research Project (MoZEES Spin-off)
Task 3.5 & Task 4.2– ZE Maritime Case Studies
Optimal System Design
Build-up of H₂-infrastructure
First ZE High Speed Ferries
Goal
Optimize ZE HDV transport system designs
Business models with TCO on parity with fossil fuels
Fuel cell lifetime: 40 000 hours
Validation of models in large test chambers
Optimal System Design
Vision
Norway*:
50% ZE Trucks HD Truck new sales
75% ZE Ferries 75 of 100 HSC
Assumptions
Economic incentives for use of ZE Trucks
Funding for public ZE ferry procure-ments
Support for first infrastructure build-up
*Note! National goals to be determined in MoZEES Policy Roadmap
Legend
Research Action
Innovation Strategy
MoZEES program
Post MoZEES
Goal(s)

(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 & H_2 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
Validated products
International Value Chains
UK: Industrial R&D on new coatings for metallic bipolar plates for PEMFCs
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 batteries
UiO	Heesoo Park	M	South Korea	14.10.2021	15.10.2023	Materials design for battery electrodes
UiO	Mustapha Jamma	M	Morocco	28.02.2023	27.02.2025	Design and validation of energy management sys tems

PhD students with financial support from the Centre Budget						
Institution	Name	Sex M/F	Nationality	Start date	End date	Topic
NTNU	Jonas Martin	M	Germany	01.08.2020	31.01.2024	Policy and techno-economic analysis
UiO	Halvor Høen Hval	M	Norway	01.01.2018	20.12.2023	High voltage cathode materials for Li-ion batterie
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	Asgeir Tomasgard	Policy and techno-economic analysis
NTNU	Anne Neumann	Policy and techno-economic analysis
NTNU	Peter Schutz	Policy and techno-economic analysis
NTNU	Frode Seland	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	Maria Elise Dyvik	Energy, Environment, Climate
USN	Dag Bjerketvedt	Hydrogen and Battery safety
USN	Joachim Lundberg	Hydrogen and Battery safety
USN	Mathias Henriksen	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
FFI	Hannibal Fossum	Battery safety
IFE	Muhammad Abdelhamid	Silicon anodes for Li-ion batteries
IFE	Mari Lyseid Authen	Energy system modelling
IFE	Benedicte S. Ofstad	Railway case study
IFE	Carl Erik L. Foss	Silicon anodes for Li-ion batteries
IFE	Camilla Røhme	Development of technical/academic content for dissemination
IFE	David Wragg	Silicon anodes for Li-ion batteries
IFE	Jan P. Mæhlen	Silicon anodes for Li-ion batteries
IFE	Julia Wind	Battery modelling and characterization
IFE	Preben J. S. Vie	Battery modelling and characterization
IFE	Kari Aa Espegren	Energy system modelling

IFE	Kristina Haaskjold	Energy system modelling
IFE	Miguel Chang	Energy system modelling
IFE	Piotr Bujlo	Low temperature fuel cell and electrolysis systems
IFE	Ragnhild Hancke	Hydrogen systems – electrolyzers
IFE	Samson Lai	Silicon anodes for Li-ion batteries
IFE	Stine Fleischer Myhre	Energy system modelling
IFE	Thomas Holm	Electrochemistry
IFE	Theresa Nguyen	Silicon anodes for Li-ion batteries
IFE	Thulile P. Khoza	Low temperature water electrolysis processes
IFE	Ugur Halden	Energy system modelling
IFE	Zbigniew Rozynek	Silicon anodes for Li-ion batteries
IFE	Øystein Ulleberg	Hydrogen systems - fuel cells and electrolyzers
TØI	Erik Figenbaum	Electric vehicles, environmental characteristics of vehicles, technology diffusion
TØI	Inger Beate Hovi	Vehicle and demand modelling, SCGE-modelling, cost functions, economic incentives, user needs
TØI	Rebecca Thorne	Environment, Energy, Technology
TØI	Ingrid Sundvor	Environment, Energy, Technology
TØI	Daniel R. Pinchasik	Environment, Energy, Technology
TØI	Astrid H. Amundsen	Policy
TØI	Linda A.-W. Ellingsen	Life Cycle Analysis
SINTEF	Rune Bredesen	Functional oxides, membranes
SINTEF	Anders Brunsvik	Battery and battery material characterization
SINTEF	Emily Cossar	Electrolyser & FC system design
SINTEF	Paul Inge Dahl	Internal RA management, battery and battery material characterization
SINTEF	Agnes Digranes	Battery and battery material characterization
SINTEF	Truls Flatberg	System design optimization
SINTEF	Patrick Fortin	PEMFC and PEMWE testing
SINTEF	Patrick Hanetho	PEMFC and PEMWE modelling
SINTEF	Odd André Hjelkrem	HDV energy and emission modelling
SINTEF	Sepideh Jafarzadeh	Hydrogen in maritime applications
SINTEF	Hampus Karlsson	Transportation planning
SINTEF	Pål Emil Karstensen	PEMFC and PEMWE modelling
SINTEF	Michal Kaut	Stochastic modelling
SINTEF	Jannicke Hatlø Kvello	Battery and battery material characterization
SINTEF	Lauriane Lehembre	PEMFC and PEMWE testing
SINTEF	Anna Maria Lind	Physical characterization/ powder X-ray diffraction
SINTEF	Øyvind Lindgård	PEMFE and PEMWE testing
SINTEF	Sigrid Lædre	Techno-economic analyses
SINTEF	Katie McCay	PEMFE and PEMWE testing
SINTEF	Solveig Meland	Social scientific transport research
SINTEF	Magdalena Müller	PEMFC and PEMWE testing
SINTEF	Yash Raka	FC system modelling
SINTEF	Anita Hamar Reksten	PEMWE catalysts
SINTEF	Ola Martin Rennemo	HDV energy and emission modelling
SINTEF	Per Martin Rørvik	Functional oxide materials, PEMWE catalysts
SINTEF	Tor Olav Sunde	RA management and PEMWE catalyst development
SINTEF	Benjamin Bøe Synnevåg	FC system modelling
SINTEF	Simen Rostad Sæther	Energy transition, political science
SINTEF	Kristoffer M. Tangrand	HDV energy and emission modelling
SINTEF	Julian Richard Tolchard	Battery and battery material characterization
SINTEF	Nils Peter Wagner	Battery and battery material characterization
SINTEF	Federico Zenith	Fuel cell control, techno-economic analyses

PhD students working on projects in the Center with financial support from other sources					
Institution	Name	Nationality	Period	Sex M/F	Topic
UiO	Anders Brennhagen	Norway	2019-2023	M	Anodes
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

Master degrees			
Institution	Name	Sex M/F	Topic
UiO	Amund Raniseth	M	Al-substituted LMNO
UiO	Mats Aspeseter Rødne	M	Titanium (di)oxide coating of electrodes in Lithium Capacitors
NTNU	Ida Kværnes Haugsrud	F	Policy & techno-economic analysis
NTNU	Christian Wulff	M	Policy & techno-economic analysis

Appendix 2: Statement of Accounts

Funding	Amount
The Research Council	17 649
The Host Institution (IFE)	1 101
Research Partners	6 106
Industry partners	6 619
Public partners	2 036
Total funding	**33 511**

Costs	Amount
The Host Institution (IFE)	7 923
Research Partners	20 194
Industry partners	4 908
Public partners	486
Total costs	**33 511**

(All figures are given in kNOK)

Appendix 3: Publications in 2023

1. **Norby, T.; Sun, X.; Vøllestad, E.**
A Brick Layer Model for Surface Conduction in Porous Ceramics. *Solid State Ionics* **2023,** 398, 116269. https://doi.org/10.1016/j.ssi.2023.116269.
UiO and SINTEF

2. **Martin, J.; Dimanchev, E.; Neumann, A.**
Carbon Abatement Costs for Renewable Fuels in Hard-to-Abate Transport Sectors. *Advances in Applied Energy* **2023**, 12, 100156. https://doi.org/10.1016/j.adapen.2023.100156.
NTNU

3. **Gobena, H. T.; Lai, S. Y.; Koposov, A. Y.; Maehlen, J. P.; Ghamouss, F.; Lemordant, D.**
Cycling Performance of Silicon-Carbon Composite Anodes Enhanced through Phosphate Surface Treatment. *Battery Energy* **2023**, 2 (3), 20220062. https://doi.org/10.1002/bte2.20220062.
IFE and UiO

4. **Hua, W.; Nylund, I.-E.; Cova, F.; Svensson, A. M.; Blanco, M. V.**
Insights on Microstructural Evolution and Capacity Fade on Diatom SiO2 Anodes for Lithium-Ion Batteries. *Sci Rep* **2023**, 13 (1), 20447. https://doi.org/10.1038/s41598-023-47355-7.
NTNU

5. **Pollen, H. N.; Nylund, I.-E.; Dahl, Ø.; Svensson, A. M.; Brandell, D.; Younesi, R.; Tolchard, J. R.; Wagner, N. P.**
Interphase Engineering of LiNi0.88Mn0.06Co0.06O2 Cathodes Using Octadecyl Phosphonic Acid Coupling Agents. *ACS Appl. Energy Mater.* **2023**, 6 (23), 12032–12042. https://doi.org/10.1021/acsaem.3c02275.
NTNU and SINTEF

6. **Štádlerová, Š.; Schütz, P.; Tomasgard, A.**
Multi-Period Facility Location and Capacity Expansion with Modular Capacities and Convex Short-Term Costs. *Computers & Operations Research* **2024**, 163, 106395. https://doi.org/10.1016/j.cor.2023.106395.
NTNU

7. **Tolchard, J. R.; Vullum, P. E.; Arstad, B.; Wagner, N. P.**
New Insights into Orthophosphoric Acid Assisted Rapid Aqueous Processing of NMC622 Cathodes. *RSC Sustain.* **2023**, 1 (2), 378–387. https://doi.org/10.1039/D3SU00031A.
SINTEF and NTNU

8. **Martin, J.; Neumann, A.; Ødegård, A.**
Renewable Hydrogen and Synthetic Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Holistic Cost Model. *Renewable and Sustainable Energy Reviews* **2023**, 186, 113637. https://doi.org/10.1016/j.rser.2023.113637.
NTNU

9. **Huld, F. T.; Mæhlen, J. P.; Keller, C.; Lai, S. Y.; Eleri, O. E.; Koposov, A. Y.; Yu, Z.; Lou, F.**
Revealing Silicon's Delithiation Behaviour through Empirical Analysis of Galvanostatic Charge–Discharge Curves. *Batteries* **2023**, 9 (5), 251. https://doi.org/10.3390/batteries9050251.
IFE and UiO

10. **Østli, E. R.; Mathew, A.; Tolchard, J. R.; Brandell, D.; Svensson, A. M.; Selbach, S. M.; Wagner, N. P.**
Stabilizing the Cathode Interphase of LNMO Using an Ionic-Liquid Based Electrolyte. *Batteries & Supercaps* **2023**, 6 (7), e202300085. https://doi.org/10.1002/batt.202300085.
NTNU and SINTEF

11. **Park, H.; van Duin, A. C. T.; Koposov, A. Y.**
Toward Atomistic Understanding of Materials with the Conversion–Alloying Mechanism in Li-Ion Batteries. *Chem. Mater.* **2023**, 35 (7), 2835–2845. https://doi.org/10.1021/acs.chemmater.2c03603.
UiO

12. **Wragg, D. S.; Skautvedt, C.; Brennhagen, A.; Geiß, C.; Checchia, S.; Koposov, A. Y.**
Tracking Lithiation of Si-Based Anodes in Real Time by Total Scattering Computed Tomography. *J. Phys. Chem. C* **2023**, 127 (48), 23149–23155. https://doi.org/10.1021/acs.jpcc.3c06414.
UiO

13. **Štádlerová, Š.; Jena, S. D.; Schütz, P.**
Using Lagrangian Relaxation to Locate Hydrogen Production Facilities under Uncertain Demand: A Case Study from Norway. *Comput Manag Sci* **2023**, 20 (1), 10. https://doi.org/10.1007/s10287-023-00445-3.
NTNU

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MoZEES
Mobility Zero Emission Energy Systems

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