MOZEES
Mobility Zero Emission Energy Systems

FORSKNINGSSENTER FOR MILJØVENNLIG ENERGI
Norges forskningsråd

# Annual Report 2021

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# Message from the Chair of the Board

Norway is often described as an "energy nation" with its large fossil and renewable energy resources. The required global shift from fossil to renewable energy has particular importance for Norway as many new sustainable value chains must be established in this transition. It is no doubt that batteries and hydrogen technology are keys in this transformation, and that the research and development in MoZEES is highly relevant to industry and the society, far beyond the focus area of zero-emission heavy duty transport. In a report from the Norwegian Government to the Parliament (Stortingsmelding nr. 36: "Energi til arbeid - langsiktig verdiskapning fra norske energiressurser") published last year summarises these possibilities and the potential of national value creation based on our energy resources. MoZEES, as a Centre for Environment-friendly Energy Research (FME) is part of the Government's strategy to reduce climate changes, and therefore the Research Council's Midway evaluation of the centre last year was of particular importance. The Midway evaluation included an assessment by an international Expert panel that provided important recommendations and comments to the Centre, both on the quality of operation and as guide to further development. The Evaluation report stated several positive and encouraging comments that acknowledge the good work in MoZEES, e. g. *"New and innovative results and scientific advancements have been achieved in all four research areas"* and *"The level of scientific research in overall is impressive"*. The Expert panel also underlined the importance of staying relevant and to increase focus on innovations due to the fast development in the MoZEES research areas. I believe that our actions to develop the MoZEES research Roadmaps and establish the Innovation Committee will strengthen focus on relevance and innovation within the Centre and through spin-off activities from the Centre.

As in 2020, the pandemic also slowed down some planned activities last year. Therefore, I am very glad that the Director and his leader team together with university partners took resolute action to financially support some PhD candidates hindered in their progression by COVID-19. Further, the MoZEES Battery Days, extended with an open-day for participants outside MoZEES, again provided an important meeting arena for the growing battery community. The Director and his team were also able to organise a MoZEES Hydrogen and Battery Safety Seminar, and later a successful two-day Annual Meeting in Trondheim for information sharing, discussions, interesting site visits, and pleasant social gathering just days before Norway closed down again. The many impressive presentations at these and other occasions, for example at the MoZEES Digital Lunch Talks, make me proud to take part in the MoZEES team. All in all, 2021 turned out as another successful year that resulted in further development of the Centre.

On behalf of the Board, I would like to thank the Research Council and the Expert panel for their comments and recommendations, the User partners providing indispensable capability and contributions, the students and researchers for the high-quality scientific work, and the Director Øystein Ulleberg with his leader group and administrative staff for their large efforts to ensure that MoZEES Centre stays relevant and fulfils its ambitions and commitment to society.

Rune Bredesen
*Chairman of the Board*

# Letter from the Center Director

*Many milestones in MoZEES were achieved in 2021. The year started with a successful mid-term review and ended with the submission of three PhD-theses [all successfully defended in Q1 2022]. We also had a record number of 20 publications in peer-reviewed international journals. This shows that our long-term research and focus on scientific work is really starting to pay off. Our industry partners are also reaching many of their milestones, and I am very happy that research results from the Center can be applied in both battery and hydrogen related innovation activities among our industry and public user partners. Highlights from the MoZEES research and innovation activities in 2021 are provided in this report. Keep reading if you are interested to learn more about our latest achievements!*

*In 2021 the Research Council of Norway (RCN) conducted a midterm evaluation of all the FME-centers. MoZEES received excellent feedback from the external panel and in June we received the formal go-ahead from RCN to continue the operation of the Center for another 3-year period (2022-2024). The MoZEES Roadmaps for battery and hydrogen technology and zero emission transport system were established prior to the mid-term review, published in April 2021, and communicated at several large meetings throughout the year. The main objective with the MoZEES Roadmaps is to align our research and innovation activities for the remaining project period (until 2024). However, the roadmaps are also instrumental in the definition of common visions and goals with external partners and stakeholders interested to develop battery and hydrogen technology and zero emission energy systems for transport. Thanks to the MoZEES Board for insisting on getting these roadmaps in place!*

*The main research activities in MoZEES have progressed nicely the last year. The production of silicon for use in Li-ion batteries is happening and we are well on the way to assembly our own full battery cells. A large research study on nickel metal electrodes for alkaline water electrolysis was recently completed. These research activities are all highly relevant for Norwegian industry. The research on batteries and fuel cells for maritime applications is also continuing. In 2021 there was performed thermal runaway experiments on Li-ion batteries and a risk study on hydrogen trucks and trains in tunnels. MoZEES has also taken the initiative to disseminate information with industry and public partners on battery and hydrogen safety. These are just some examples of our activities. Keep reading if you want learn more!*

*The main resource in MoZEES are the people. In 2021 there were more than 80 researchers and students actively involved in different research tasks in the Center, including about 15 professors, 20 senior scientists, and 25 young researchers. In addition, about 25 technology experts from the industry partners participated and contributed to the research. In 2021 there were 14 PhD-students, 3 post-doctoral fellowships, and 8 master students associated with the Center. Participants come from 20 different countries, which makes MoZEES a highly international research center.*

*With so many people involved it is important to find good places to meet and discuss ongoing activities and future ideas. Unfortunately, the COVID-19 pandemic continued to make it difficult for us to meet in 2021. Fortunately, this did not prevent us from having a large and successful MoZEES Battery Days 2021 webinar in*

*April and organizing the MoZEES Annual Meeting 2021 as a physical meeting in Trondheim in November. Hurray! The Annual Meeting attracted more than 150 participants the first day (open meeting) and more than 100 participants the second day (closed meeting) and turned into a highly international meeting with participants from 20 different countries (50% from Norway). This shows that there is a growing interest for the MoZEES topics, both nationally and internationally.*

*Thank you to everyone that has participated in and contributed to MoZEES over the last year. Your efforts are greatly appreciated.  I truly believe that we are on the right track, both with respect to our key battery and hydrogen technology developments, system applications, and planning for future zero-emission transport energy systems for road, rail, and sea.  I am also very excited over the many positive commercial and governmental developments taking place on batteries and hydrogen in Norway these days and hope that MoZEES can continue to be relevant with our research.  Finally, I would like to thank and wish good luck to those of you who have left MoZEES to seek new opportunities in the "new green jobs market".*

*The future is bright for the MoZEES-people!*

*Øystein Ulleberg (IFE)*

# About MoZEES

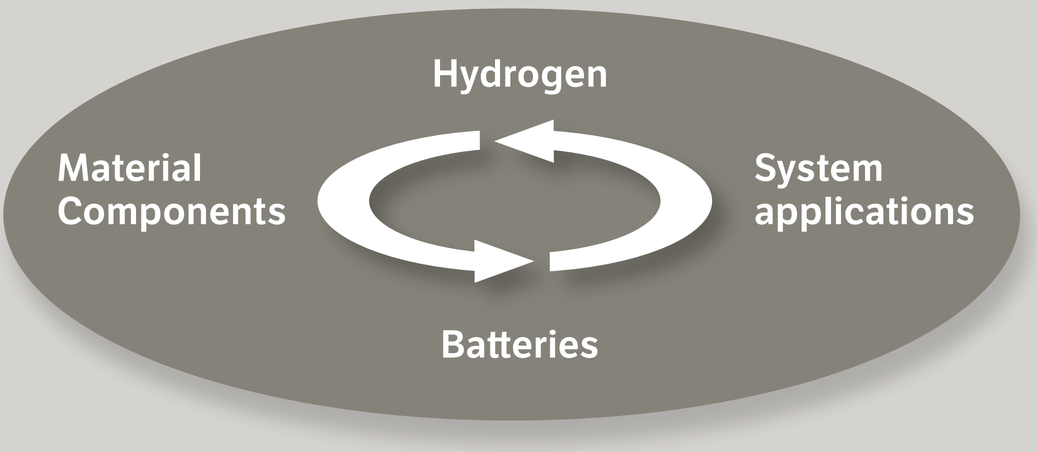
Norway has access to vast amounts of renewable power, some of which can be used to produce electricity and hydrogen for transport. Battery and hydrogen technologies have been demonstrated for use in light duty zero emission transport applications. In Norway there are ambitious goals for low- and zero-emission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

The main objective with MoZEES is to be a Center for environment-friendly energy research with focus on new battery and hydrogen materials, components, technologies, and systems for existing and future transport applications on road, rail, and sea. The Center contributes to the design and development of safe, reliable, and cost competitive zero-emission transport solutions. There is also a strong focus on education 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), 6 public partners, 2 private interest organizations, and 21 commercial and industrial partners, including key battery and hydrogen materials, components, technology, and systems suppliers. There has also been established formal collaboration agreements (MoUs) with four international universities: RWTH University Aachen (Germany), University of Uppsala (Sweden), University of California Davis (USA), and University of Genova (Italy). Institute for Energy Technology (IFE) at Kjeller in Norway is the host for FME MoZEES.

In MoZEES there is a special focus on research and development of zero emission solutions for heavy-duty transport, and 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. Below are some highlights from 2021:



In 2021 RCN conducted a midterm evaluation of the FME-centers. MoZEES received excellent feedback from the external panel and the Center is now continuing the work with the latest approved 3-year work plan towards 2024. A MoZEES Roadmap for battery and hydrogen technology was developed prior to the FME midway evaluation. These roadmaps have been published in the MoZEES Annual Report for 2020 and presented in various seminars and meetings. In 2021 there were also produced many scientific publications, demonstrating high quality on the research.

The MoZEES Annual Meeting 2021 was held as a physical meeting in Trondheim and attracted more than 150 participants during the open part of the meeting (Day 1) and more than 100 participants for the closed meetings (Day 2). Day 1 was an international meeting with participants from 20 different countries (50% from Norway). This shows that there is a growing interest for the research in MoZEES, both nationally and internationally. The research results developed over time are now being used by several of the industry and user partners. The MoZEES Innovation Forum, which was established in 2020, is designed to capture the new ideas created in the Center.

Production of Silicon for use in Li-ion batteries og assembly of full battery cells is a key activity in MoZEES. A large research study on nickel metal electrodes for alkaline water electrolysis was recently completed. These research activities are all highly relevant for Norwegian industry. The research on batteries and fuel cells for maritime applications is also continuing. In 2021 there have also been performed thermal runaway experiments on Li-ion batteries and a risk study on hydrogen trucks and trains in tunnels. MoZEES has also taken the initiative to disseminate information with industry and public partners on battery and hydrogen safety.

In 2021 there were more than 80 researchers and students active in different research tasks in MoZEES, including ca. 15 professors, 20 senior researchers and 25 young researchers. In addition, about 25 technology experts from the industry partners participate and contribute to the research. In 2021 there were 14 PhD-students, 3 post-doctoral fellowships, and 8 master students associated with the Center. Participants come from 20 different countries, which makes MoZEES a very international research center.

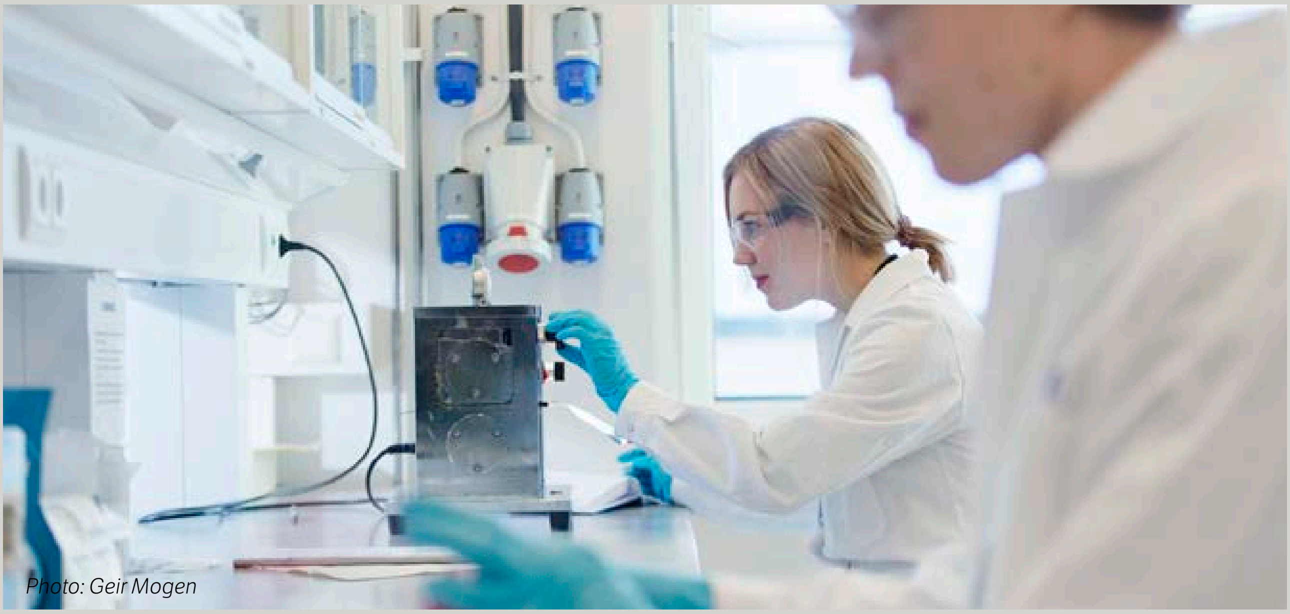


*Photo: Geir Mogen*

# Partners

## Industry and Public Partners

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

## National Research Partners

tøi Institute of Transport Economics
Norwegian Centre for Transport Research

UiO : University of Oslo

USN University of South-Eastern Norway

NTNU
Norwegian University of Science and Technology

IFE Institute for Energy Technology

SINTEF

FFI Forsvarets forskningsinstitutt
Norwegian Defence Research Establishment

## International Research Partners

UPPSALA UNIVERSITET

UCDAVIS
UNIVERSITY OF CALIFORNIA

RWTHAACHEN UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

## Members of the Center Management Team


*Øystein Ulleberg (IFE)*


*Ragnhild Hancke (IFE)*


*Ann Mari Svensson (NTNU)*


*Tor Olav Sunde (SINTEF)*


*Erik Figenbaum (TØI)*


*Katinka Elisabeth Grønli (UiO)*

## Members of the Executive Board


*Arve Holt (IFE)*


*Patrick Bernard (Saft)*


*Pål Danielsen (Jernbanedir.)*


*Einar Hjorthol (NTNU)*


*Bjørne Grimsrud (TØI)*


*Anders Søreng (NEL Hydrogen)*

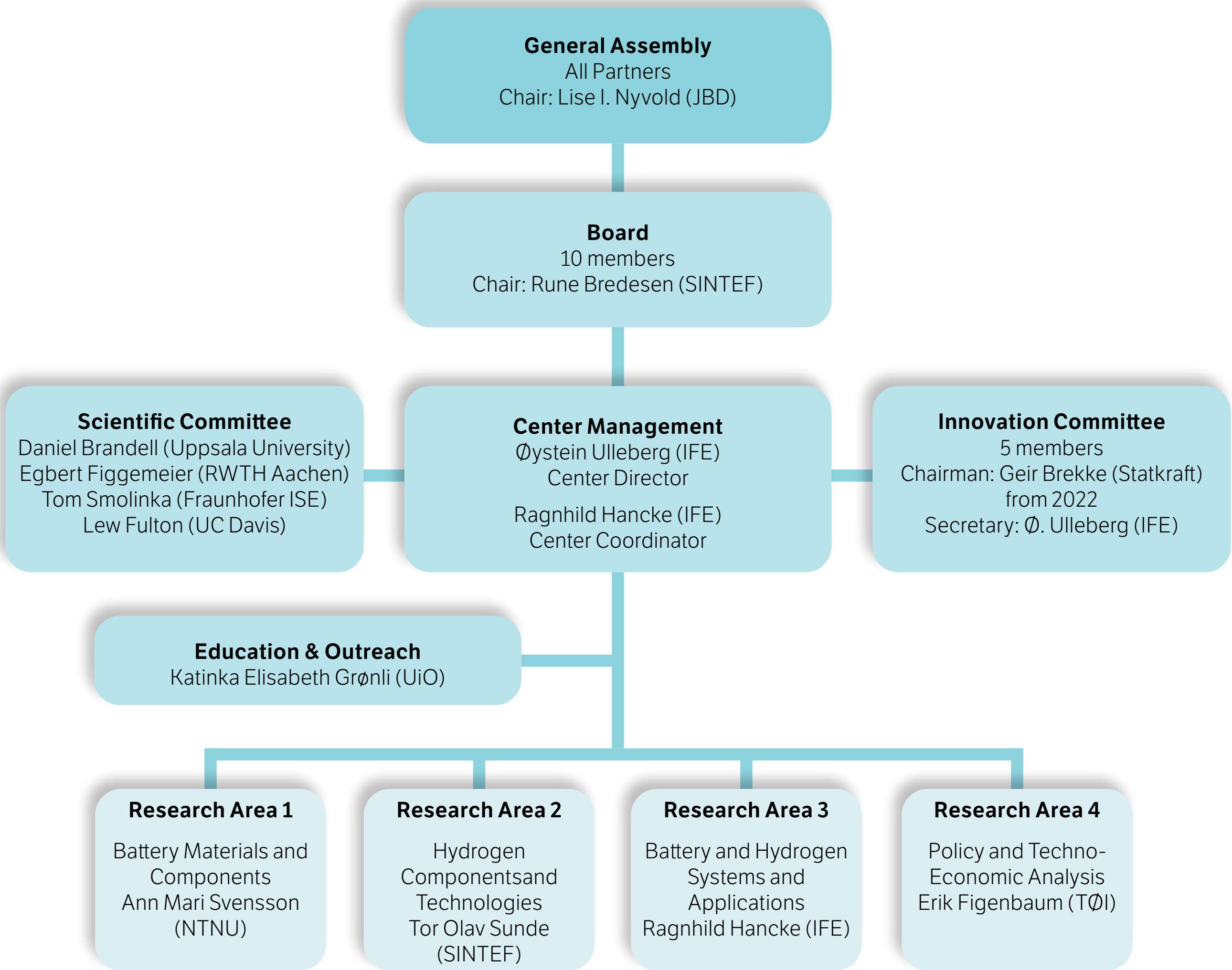

*Petter Hersleth (ENOVA)*


*Marit Dolmen (Elkem)*


*Rune Bredesen (SINTEF)*


*Jan Fredrik Hansen (ABB)*

# Organization



# Education

The main objective with the MoZEES Education and Dissemination program is to enhance career developing activities for young researchers in recruitment positions at the Centre and to create synergies between the research areas, partner institutions, and external stakeholders.

Another important objective is to increase the visibility of the Center and by that increase MoZEES impact and opportunities. The educational and outreach activities in the Center are jointly administered by the UiO and IFE.

UiO:Energy has created a MoZEES Research Training Network (RTN) with the purpose to increase the cooperation across all research areas in MoZEES. An important task for MoZEES RTN is to support the candidates to qualify as scientific researchers within their field of expertise, and at the same time contribute to realizing the goals of the different research areas in the Center.

### The MoZEES Research Training Network includes the following activities:

- Management of the MoZEES Mobility Program for young researchers; International Academic Mobility Grants have been awarded to three MoZEES PhD-students so far and one PhD-student has received support for Industry mobility. The incoming PhD-student Eleonora Gadducci from University of Genoa, came to IFE in 2020, but had to return before she completed her stay due to the COVID-19 situation. She successfully completed the second part of her stay in 2021, including participation at the MoZEES Annual Meeting in Trondheim.


*Illustration: Halvor Høen Hval*

- Facilitation of meetings between the Scientific Advisory Committee and researchers, students, and user partners during the MoZEES Annual Meeting and regular workshops.
- Organization of special courses and summer schools, including a MoZEES PhD Summer School on Sustainable Transport (2019) (collaboration with FME Bio4Fuels) and MoZEES RTN workshops on how to pitch scientific work to the public (2019) and professional scientific writing (2020).
- Support of PhDs with prolongation related to signifi cant delays caused by the COVID-19 situation. Following the recommendations from the mid-term evaluation, MoZEES have actively supported PhD fellows beyond prolongations provided by their home-institutions. In 2021, five PhD fellows were awarded prolongations corresponding to 40 work weeks. A second round of prolongations will be awarded upon evaluation in 2022.
- Organization of Digital Lunch Talks running monthly as an informal meeting place for all members of MoZEES where current research and new results are presented and discussed. PhDs and young rese archers are prioritized as presenters. Both international and industrial partners attend on a regular basis, and have also contributed with presentations. The Digital Lunch Talks were established in 2020, in 2021 we hosted 8 talks with a total of 15 presentations.

One of the key objectives in MoZEES is to build competence by recruiting and educating new PhD candidates, postdoctoral fellows, and young researchers. In 2021 we there have been 14 PhD-students, 3 postdoctoral fellows and 9 master students directly associated with MoZEES. There is also a trend that more and more PhD and master students, including international students, would like to be associated with different research tasks in the Center. The recruitment of new students to the three university partners UiO, NTNU, and USN has also had a "spill-over effect" to the research institutes SINTEF and IFE. There are several cases where MoZEES students, PhD- and postdoctoral -fellows have migrated from the universities to the research institutes. Some PhDs have also continued their work in the centre as postdocs. During 2021, three of the PhD students within battery research have been hired by relevant industry partners.

Photo: Daniel Rogstad

*MoZEES is co-sponsor of the Interdisciplinary NorRen Summer School which in 2021 attracted 29 PhD students and focused on sustainable Energy (Photos: Øystein Moen)*

# New PhDs and Postdocs 2020-2021

**Several new clever, young, and aspiring PhD students and postdoctoral researchers were recruited to MoZEES in 2020-2021, and they are all contributing to the production of high quality and high impact research in MoZEES.**

**Dr. Heesoo Park** started working as a researcher in the group of Alexey Koposov at UiO in 2021. His project focuses on understanding chemical reactions and building theoretical models for Lithium-ion batteries at the atomistic level. In addition, he is an expert in computational quantum chemistry and machine-learning techniques.

**MSc. Ruben van Beesten** started working as a postdoctoral researcher in RA4 and in the group of Asgeir Tomasgard at NTNU in 2021. His project is focused on value chain optimization in zero emission transportation networks.

**MSc. Manuel Lenti** started his PhD in RA3 and at NTNU in 2021 under the supervision of Professor Ingrid Schjølberg. The project focuses on the design and validation of energy management systems for maritime fuel cell systems to optimize operations and service lifetime costs.

**M.Sc. Carina Geiss** started her PhD in RA1 and at UiO in 2020 under the supervision of Professor Helmer Fjellvåg and Associate Professor Alexey Koposov. She is studying the use of Silicon (Si) as anode material for Li-Ion batteries, and the main focus is on in-operando studies of the materials in order to better understand the processes taking place during charging and discharging.

**MEng. Jonas Martin** started his PhD studies in RA4 and at NTNU – Department of Industrial Economics and Technology Management in 2020 under the supervision of Professor Anne Neumann. The project focuses on a techno-economic analysis of a zero-emission transport system to investigate how sustainable mobility can become competitive.

**MSc. Šárka Štádlerová** started her PhD studies at NTNU in 2020 under the supervision of Associate Professor Peter Schütz and Professor Asgeir Tomasgard. The project focuses on Optimization of Zero emission transport systems and value chain in maritime transportation.

# MoZEES Battery Days 2021

The MoZEES Battery Days 2021 was organized as a webinar over two days from 21-22 April. The first day was a closed meeting with focus on ongoing research in MoZEES, while the second day focused on innovation activities in MoZEES. About 100 people participated in the event, 60 from MoZEES and 45 external participants.

The program on the first day covered both material and more applied oriented research conducted in MoZEES. Material research on silicon anodes and solid polymer/composite electrolytes, LNMO/LTO cathodes in carbonate-based electrolytes, and Li metal anodes and solid-state electrolytes was presented in the first half of the day. Real-world experiences from the operation of battery systems, results from testing of the MoZEES reference cell, and a methodology for the evaluation of battery lifetime, degradation, and failure was presented in the second half of day 1.

The second day of MoZEES Battery Days 2021 was the "2nd Meeting in the MoZEES Innovation Forum" with focus on: (1) Battery Material Production and (2) Large-Scale Li-ion Cell Production. The MoZEES Battery Innovation Forum included presentations on how to establish sustainable Li-ion battery material and cell production (Elkem, Morrow, Freyr, Beyonder, and Hydro), synthesis and industrialization of new battery materials (Cerpotech, Cenate), and future advanced Li-ion technologies (SAFT). There was set aside plenty of time for discussion. The many relevant questions from the external international industry participants showed that the MoZEES innovation areas are of high relevance for the battery industry in Europe.

One highlight from 2nd MoZEES Innovation Forum on 22 April 2021: "Industrializing Silicon Nano RobustTM" by Cenate. Cenate's goal is to be a global leader in low-cost production of advanced silicon materials for batteries. On 23 December 2020 Cenate received 42 MNOK in fresh capital, primarily from four new investors (Elkem, Nysnø, Bonheur ASA, and Must Invest) to establish a new pilot production plant to qualify advanced silicon materials (nanoparticles) for customers. Protecting IP while at the same developing a product for commercial customers with a "confidential problem" was highlighted as a key challenge in this development.

*After moving out from IFE and spending a year in a temporary containerized lab (left), Cenate has now moved into a new customer qualification plant in Holtskogen (right). Photo: Cenate*

# MoZEES Annual Meeting 2021

The Annual Meeting for MoZEES was successfully organized as a two-day physical meeting at Thon Hotel Prinsen in Trondheim on 3-4 November and attracted more than 150 participants during the open part of the meeting (Day 1) and more than 100 participants for the closed meetings (Day 2). Day 1 was an international meeting with participants from 20 different countries.

The Annual Meeting was arranged just days before Norway was closed down again due to COVID-19, and the physical meeting format was highly welcomed by the participants who was given a long-awaited opportunity to socialize with colleagues and engage in discussions on the latest developments within zero emission transport. It should also be mentioned that the Oslo delegation came together by night train to the meeting and demonstrated their commitment to zero emission transport!

The open part of the conference on 3 November included parallel sessions on battery- and hydrogen technologies and systems (see program below). After the parallel sessions, the participants had the opportunity to attend one of the four technical tours:

1. Battery production line at SIEMENS Energy
2. Hydrogen refueling station for trucks and forklifts at ASKO
3. Demonstration site for wind/hydrogen system (EU project “REMOTE”) at Rye
4. Battery and hydrogen laboratories at SINTEF and NTNU

The second day on 4 November was a closed MoZEES meeting dedicated to internal discussions within the MoZEES Consortium. The latest research developments in MoZEES was presented in a plenary session in the morning and discussed in further detail in parallel RA-sessions in the afternoon.

*Left: Wind/hydrogen demonstration project at Rye. Right: Hydrogen Refueling station at ASKO. Photo: Ragnhild Hancke, Solveig Meland.*


*Picture: Fredrik Aarskog presenting TECO2030's plans for manufacturing of maritime fuel cells during the Hydrogen Session on Day 1. Photo: IFE*

The program for the parallel sessions on battery- and hydrogen technologies during the open Meeting on 3 November is shown below.

### Battery Meeting

- Dr. Tobias Placke (MEET Battery Research Center, University of Münster): "Challenges and Strategies to Develop High-Performance and More Sustainable Battery Technologies"
- Prof. Egbert Figgemeier (Forschungszentrum Jülich, Helmholtz Center Münster): "High-energy Li-ion batteries comprising silicon containing anodes and insertion type cathodes"
- Jon Fold von Bülow (Head of R&D, Morrow Batteries) "Commercializing sustainable battery technologies"
- Bridget Deveney (Elkem): "Localizing the supply of anode materials for a sustainable robust value chain"
- Daniel Green (Siemens Energy): "We Energize the Marine Industry – How to Stay Ahead?"
- Fride Vullum-Bruer (SINTEF Energi): "Environmental gain of electrification in maritime sector"
- Linda Ager-Wick Ellingsen (TØI): "Life Cycle Analysis of Li-ion Batteries"

### Hydrogen Meeting

- Prof. Oluf Jensen (Department of Energy Conversion and Storage, DTU): "Hydrogen, from romance to solution"
- Dr. Magnus Karlström (Lindholmen Science Park AB): "Research and demonstration of electrification and hydrogen for heavy-duty vehicles in Sweden"
- Fredrik Aarskog (TECO2030): "TECO2030 marine fuel cell system"
- Jan Torgersen (NTNU): "Topologically Optimized Electrochemical Energy Converters: Geometry driven performance optimization from Nano to Microscale"
- Erik Zimmerman (Permascand): "Permascand– Enabler of green hydrogen transition"
- James Stevens (Johnson Matthey): "Catalyst Coated Membranes: Recent Developments at JM"
- Jan Carsten Gjerløw (Evig Grønn): "H2 Truck – eco-system for deployment of hydrogen trucks in Norway"
- Anna Douglas (E-mobility Scale-up, Scania): "Scania FC Trucks for Norway"

# Safety seminar for first responders

Battery and hydrogen safety is a key research area in the Center, and MoZEES has taken the initiative to disseminate information and dialogue with emergency personnel, industry and public authorities on battery and hydrogen safety. On 9 September 2021, a national seminar was arranged aimed at first responders with the intention of making the fire and rescue service aware of the new challenges that battery and hydrogen technologies can pose. During the seminar, experts provided an insight into the challenges presented by new green technologies and how regulations contribute to reducing both the probability and consequence of an accident. In addition, the fire and rescue service informed about the challenges the service is experiencing faced with such incidents. The seminar was arranged as a «hybrid meeting» (both physical and digital participation) in collaboration with the Norwegian Forum for Battery Safety, the NFR project SH2IFT and the EU projects HyTUNNEL and HyRESPONDER, and attracted more than 80 participants.

*Smoke diver clothing vs. Chemical protective suit (Illustration: Arjen Kraaijeveld, HVL)*

*Photo by Matt C on Unsplash*

# Digital Lunch Talks 2021

The MoZEES Lunch Talk series was launched in the spring of 2020 and is intended as an informal, low threshold meeting place for researchers and user partners in MoZEES. The Lunch Talks give the attendants an opportunity to catch up on the recent developments and ongoing research activities in the Center, and engage in discussions on the relevant topics.

The program for the 2021 Lunch Talks is shown below.

26-01-2021:
**Jonas Martin, PhD student at NTNU**
*- Zero-emission fuels in the transport sector - A spatial market diffusion model for Norway*

**Janis Danebergs, Researcher at IFE**
*- Zero emission heavy-duty trucks and the energy system*

16-02-2021
**Mathias Henriksen, PhD student at The University of South-Eastern Norway (USN)**
*- Li-ion gas explosion in an open-ended Channel.*

16-03-2021
**Wei He, Equinor**
*- Optimizing marine battery operations using 6 years' operational data from two commercially operating vessels (OMB6)*

**Halvor Høen Hval, PhD student at UiO**
*- Digging into the structural unknowns of the next battery superstar*

20-04-2021
**Mahsa Ebadi, Postdoctoral Fellow, NTNU**
*-Molecular modelling of solid polymer electrolytes*

**Christian Rosenkilde, Hydro**
*-Batteries in Hydro*

25.05.2021
**Carina Geiss, PhD student at UiO**
*-Solid-state-electrolytes as a pathway to extend the lifetime of Si-based electrodes?*

**Frida Sveen Hempel, PhD student at UiO**
*-Improving the understanding of ionic conductivity in layered solid-state electolytes by local structure characterization*

16.09 2021
**Øystein Ulleberg, IFE**
*-Presentation of MoZEES Roadmaps*

**Anders Søreng, Nel**
*-Comments on MoZEES Hydrogen Technology Roadmap*

12.10 2021
**Šárka Štádlerová, PhD student at NTNU**
*-Designing the hydrogen supply chain for maritime transportation in Norway*

**Gerardo A. Perez-Valdes, SINTEF**
*-Green Transport Economics: Norway-wide analysis of the Value Added consequences of Green Transport Policies*

16-11- 2021
**Helge Weydahl, FFI**
*-Comparison of thermal runaway initiation methods for a cylindrical Li-ion cell*

**Erik Ianssen, ZeroKyst/Selfa Arctic**
*-ZeroKyst – Innovation and collaboration between 11 strong companies for a technological shift in the seafood sector*

# MoZEES Innovation Activities

In 2020 there was established an industry driven MoZEES Innovation Forum which is steered by a MoZEES Innovation Committee. The main objective of the MoZEES Innovation Forum is to create a meeting place to coordinate the MoZEES battery and hydrogen research activities with national innovation activities and to create MoZEES spin-off projects with partners in relevant industrial clusters in Norway and abroad. In 2021 the MoZEES Roadmaps on batteries, hydrogen, and zero emission transport were published and presented at several national meetings and seminars, such as the MoZEES Battery Days 2021 & 2nd Innovation Forum in April, industry network meetings organized by Arena Ocean Hyway Cluster and Arena H2Cluster, and at the MoZEES Annual Meeting 2021 in November.

The main objective with the MoZEES Roadmaps is to align the research and innovation activities in the Center and to provide input to national strategic plans and roadmaps on batteries and hydrogen. The MoZEES Roadmaps focus on R&D of zero emission solutions for heavy duty transport, particularly 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 industrial battery value chains in Norway and abroad. Some examples of how MoZEES industry and user partners in 2021 have used research results produced by the research partners is provided below.

*Photos: Elkem's Silgrain® e-Si for Li-ion batteries (left) and testing in Li-ion battery cells (right)*

### Silicon production and use in Li-ion batteries

Two of the industry partners in MoZEES, Elkem and Cenate, are developing silicon (Si) powder for use as anode material in Li-ion batteries. Elkem is a large industrial company and use well-established metallurgical industrial processes as starting point for their production of Si-battery materials. Cenate is a new company (SME) that has developed a high temperature reactor where it is possible to produce Si-nanoparticles from silane ($SiH_4$).

In MoZEES these two companies have delivered silicon powder to UiO, SINTEF, and IFE which has been used in experiments with conventional electrolytes and solid polymer electrolytes. In 2021 there has also been conducted a Round Robin in MoZEES, with the goal to test full battery cells with silicon from Elkem as anode material. The results from these tests have provided valuable feedback to the industry partners.

### New method for measuring contact resistance in PEM fuel cells

In RA2 there has been developed an experimental setup and a method by SINTEF for measuring electrical contact resistance between bipolar plates and gas diffusion layers (GDLs) in proton exchange membrane (PEM) fuel cells. The unique aspect with this method is that the contact resistance can be measured *in-situ* under realistic operating conditions without modifications that will affect the measurement. The method has now been used to measure contact resistance in bipolar plates with coatings delivered by Teer Coatings, one of the international partners in MoZEES.

### National guidelines on battery and hydrogen safety

Battery and hydrogen safety is a key research area in RA3. In 2021 there were conducted experiments on thermal runway in Li-ion batteries. There was also performed a risk assessment on the use of hydrogen trucks and trains in tunnels. In 2021 MoZEES also took the initiative to disseminate information and start a dialog with first responders (fire departments), industry, and public organizations on battery and hydrogen safety. A safety seminar on this topic was organized in September. Results from research and other activities within MoZEES (e.g., operation of battery and hydrogen electric vessels) can be used as input to national guidelines on battery and hydrogen safety.

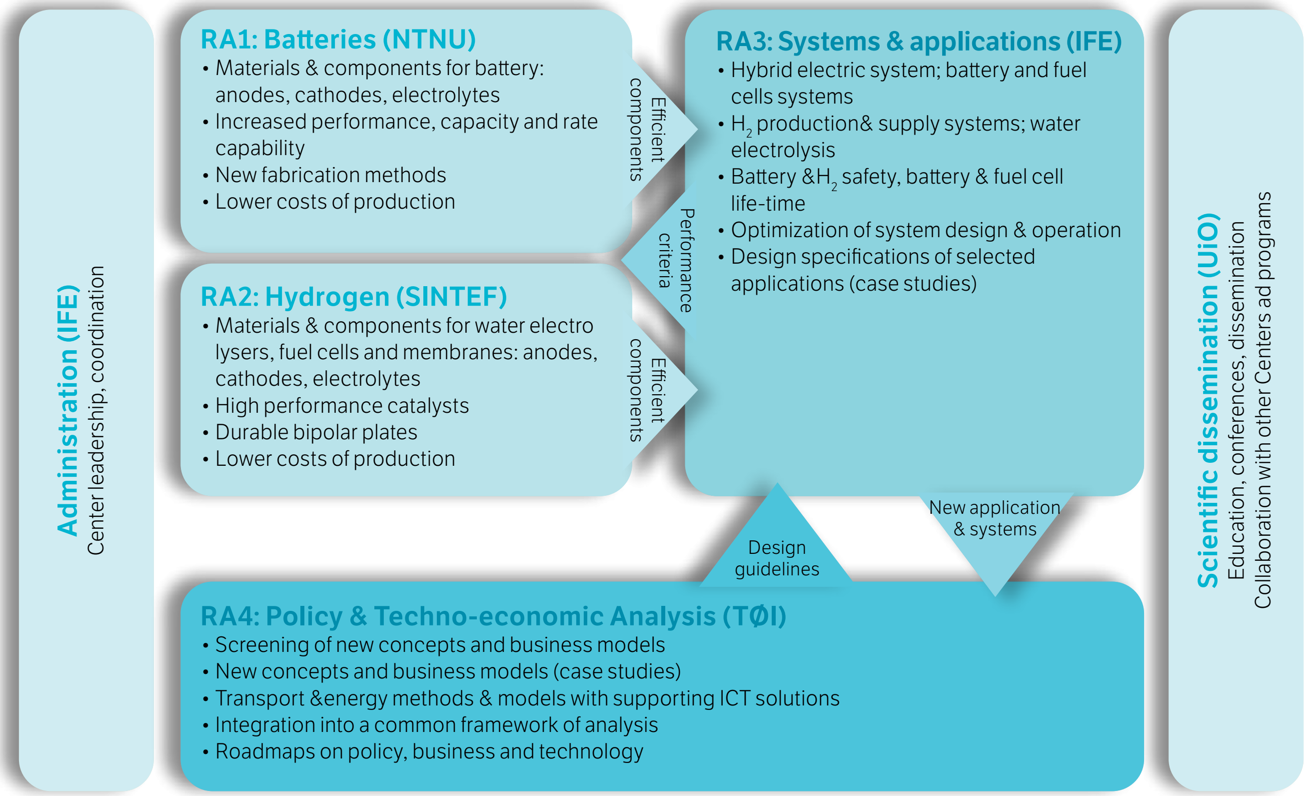
*Photos: Teer Coating's coating equipment.*



Photos: Teer Coating's coating equipment.

# Research Areas

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



# RA1 Battery Materials

The research area devoted to battery materials has its main focus on the next generation high energy Li-ion batteries based on anodes with a high silicon (Si) content, and a spinel cathodes $LiNi_{0.5-x}Mn_{1.5+x}O_4$ (LNMO), or Ni-rich NMC layered cathodes. Industry partners affiliated with MoZEES supplied materials (Elkem ASA and Cenate® supplied silicon powders, and CerPoTech supply ceramic materials), while the battery company SAFT supplied electrodes for the battery test program. Other industry partners actively involved in RA1 are the SME Baldur coating (atomic layer deposition of materials), Hydro and Morrow Batteries.

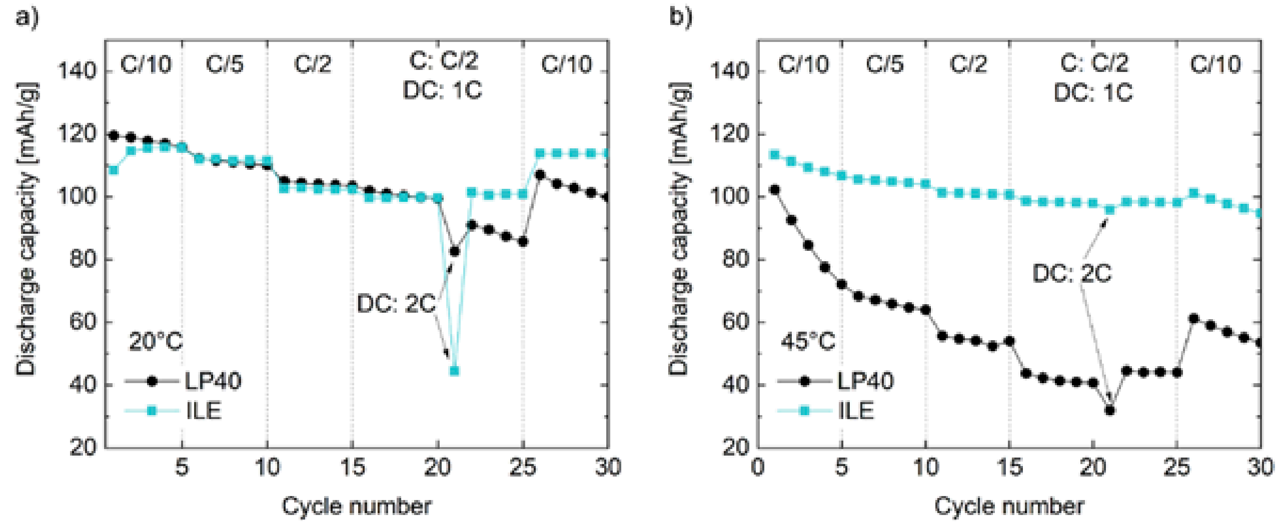
## Silicon anodes

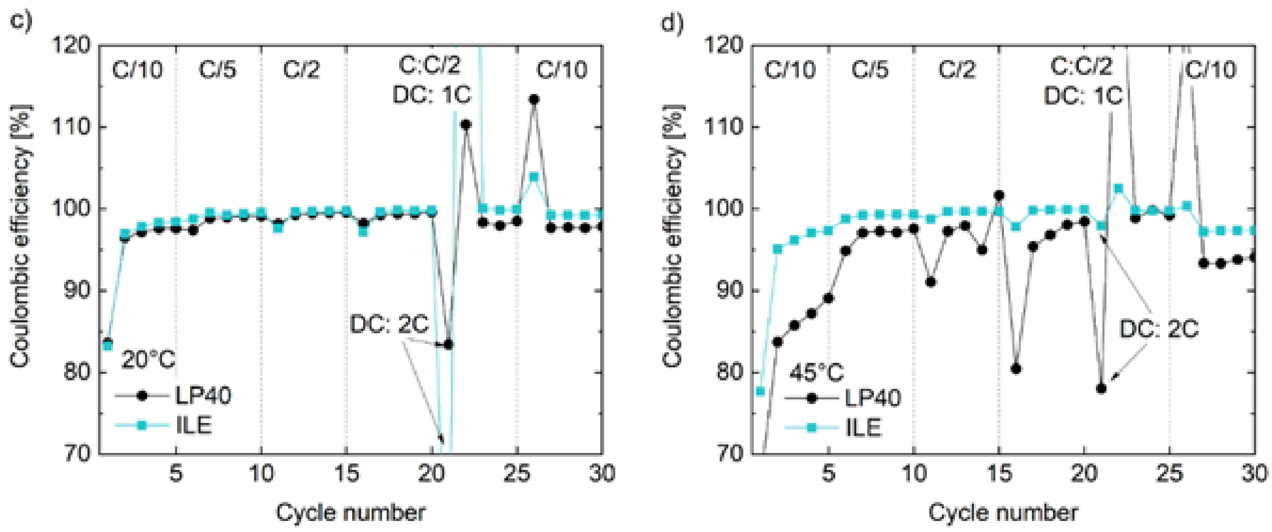
The activities within silicon anodes are focus on both the near-market and the future-market aspects. Due to the gradual depletion of available Li to lithium in Li-ion batteries when using silicon as an anode material, appropriate and scalable pre-lithiation methods are likely to be cruicial for the increase of of Si in the anodes. Methods for pre-lithiation have been investigated within MoZEES in 2021 (IFE). Other important research topics have been new Si alloys as candidate anode materials through an initial screening using thin films (IFE), as well as the combination of micron-sized silicon, LFP cathodes and a solid polymer electrolyte (SINTEF).

## Cathode activities

Electrolytes based on different ionic liquids have previously been extensively studied in combination with silicon anodes within MoZEES. As these electrolytes also show an excellent anodic stability, one of them, namely an electrolyte composed of 1.2 M Lithium bis (fluorosulfonyl)imide (LFSI) salt mixed with the ionic liquid N-Propyl-N-methylpyrrolidinium bis(fluorosulfonyl) imide (PYR13FSI) (ILE) has been evaluated as a suitable electrolyte for the high-voltage cathode material $LiNi_{0.5-x}Mn_{1.5+x}O_4$ (LNMO), supplied from Haldor Topsøe. The work was conducted at NTNU. The oxidative stability of ILE was evaluated by linear sweep voltammetry (LSV) and synthetic charge-discharge profile voltammetry (SCPV), and found to exceed that of 1 M $LiPF_6$ in 1:1 ethylene carbonate (EC):diethylcarbonate (DEC) (LP40).

*Figure 1. Discharge capacities at a) 20˚C and b) 45˚C and Coulombic efficiencies at c) 20˚C and d) 45˚C from rate-testing of LNMO||graphite full cells containing LP40 (black) and ILE (teal). The cells are cycled between 3.5 and 4.8 V vs Li/$Li^+$ with C-rates of C/10, C/5, C/2, 1C, and 2C with charging rate limited to maximum C/2.*



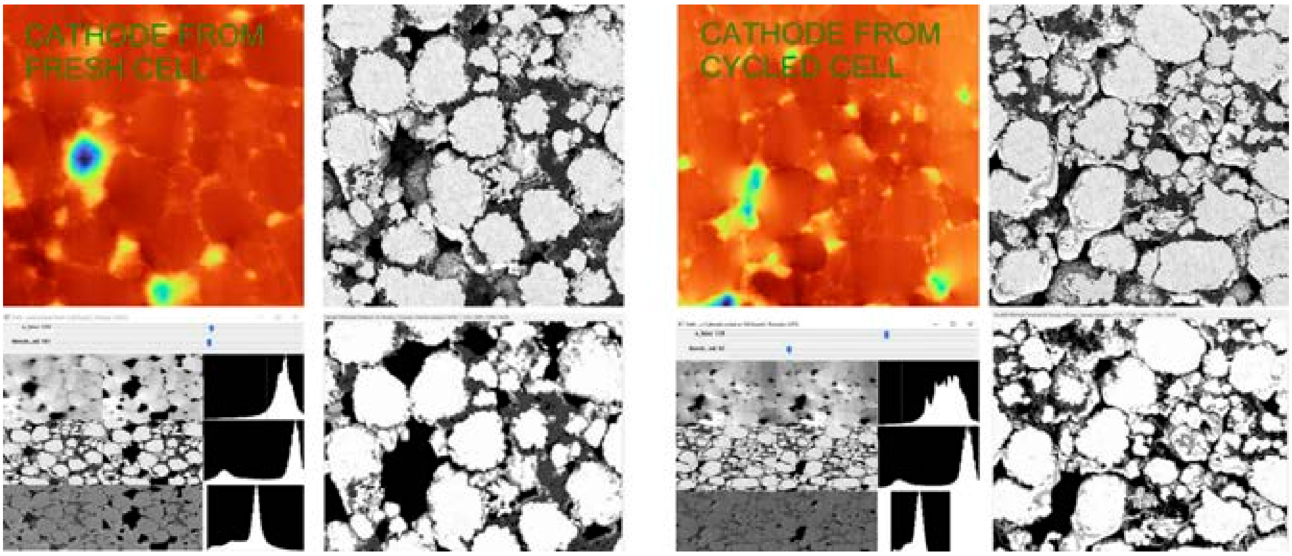



Improved cycling performance both as 20˚C and 45˚C was found for LNMO||graphite full cells with the IL electrolyte, as shown in Figure 1. Even though the high viscosity of the ILE limits the rate performance at 20˚C, ILE is considered a very promising alternative electrolyte for use in lithium-ion batteries (LiBs) with high-voltage cathodes such as LNMO.

## Advanced characterization

Related to the Round Robin test of MoZEES reference cells conducted in RA3 SINTEF has performed postmortem analysis in form of non-destructive X-ray computational tomography (see RA3 summary). The cells were also dismantled, electrodes removed, cut by Ar knife and investigated by cross-section SEM/EDS analysis. Using an image analysis tool, currently under development, it is possible to distinguish between active material particles, pores, conducting carbon and binder/dried electrolyte.

*Figure 2. Cross-section SEM imaging, and corresponding analysis, of cathode electrodes from fresh (left) and cycled (right) MoZEES reference cells (Annett Thøgersen, SINTEF).*



As exemplified by cathode cross-section imaging, Figure 2, increased amount of small fraction active material and significantly reduced porosity was observed because of the cycling.

UiO was awarded beam time at ESRF, and pair distribution function computed tomography experiments were performed (PDF CT). The prove-of-concept has been demonstrated and the publication is currently being written, while the electrochemistry of the optimized cell is yet to be optimized. In the upcoming Fall additional PDF experiment are planned to develop an understanding of the lithiation for mechanism conversion/alloying Si-based materials.

In addition, synchrotron diffraction data were collected for aluminum doped LNMO, where either nickel, manganese or both(50/50) are substituted by Al in the amounts of 0.05, 0.1, 0.2.

### Round Robin

Together with SAFT, partners in MoZEES (IFE, NTNU, UiO, SINTEF and Elkem) have continued a Round Robin test program, with NMC cathodes supplied by SAFT, and silicon-graphite composite anodes based on eSi-1030 from Elkem. Half-cell tests were completed with the selected electrodes.

## International Collaboration

### UNIVERSITY OF UPPSALA (UU)

Within the Battery Materials Research area, there has been an active collaboration with University of Uppsala, involving a visit by PhD student Harald Norrud Pollen, starting from November 2021, on the topic of Ni-rich layered oxides. There has also been a collaboration between NTNU and University of Uppsala in the field of LNMO cathodes.

University of Uppsala is partner in the newly started H2020 project Hydra (2020-2024), coordinated by SINTEF, and Prof. Daniel Brandell is in the advisory board of SINTEF's internal electrolyte project, Enerlyte-Next Generation Li-ion Electrolytes (2019-2022): *https://www.sintef.no/en/projects/2019/enerlyte-next-generation-li-ion-electrolytes/*

### SAFT

SAFT has contributed to the Round Robin test by supplying industrially relevant NMC cathodes. SAFT also contributed with a presentation entitled "SAFT's advanced and beyond lithium-ion technologies" at the 2nd Innovation Forum during the MoZEES Battery Days (21 and 22nd of April 2021).

### RWTH University Aachen

A young researcher from IFE, Samson Lai, stayed as a guest scientist at RWTH Aachen to strengthen the competence on pre-lithiation of silicon anodes. Different methods were explored and will lay the foundations for further collaboration and development of pre-lithiation techniques.

Professor Egbert Figgemeier from RWTH Aachen participated and gave a presentation at the MoZEES Annual Meeting 2021 (3-4th of November), "High energy Li-ion batteries comprising silicon-containing anodes and conversion type cathodes".

### HORIZON 2020 PROJECTS

HYDRA - Hybrid power-energy electrodes for next generation litium-ion batteries, coordinated by SINTEF: *https://www.sintef.no/en/projects/2020/hydra-/. Uppsala University and Elkem ASA are also partners*

# RA2 Hydrogen Components and Technologies

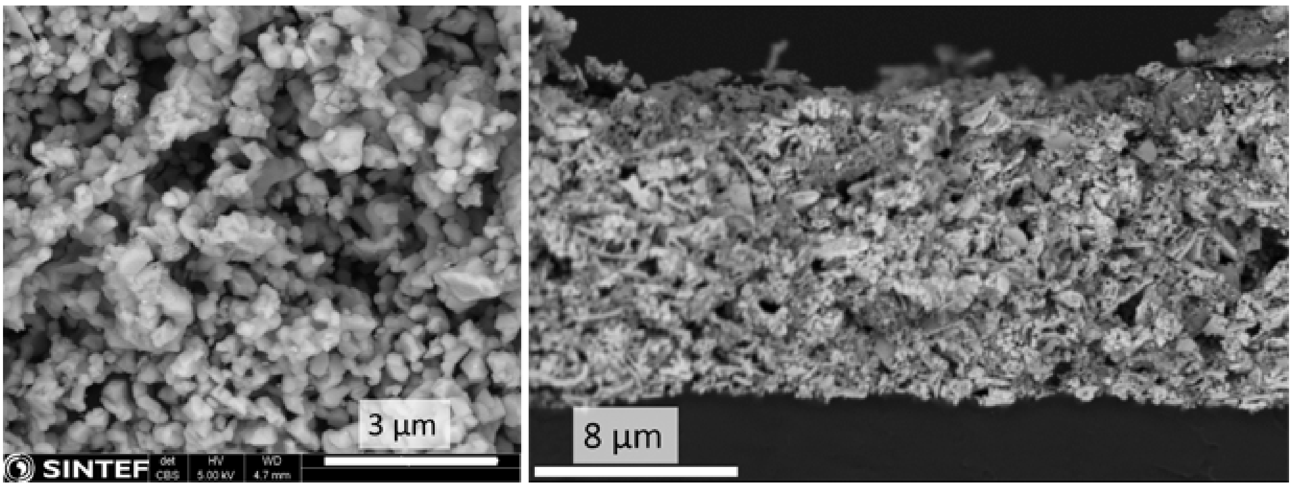
The main objective of RA2 is to enable the production of fuel cells, electrolysers and hydrogen storage tanks with lower cost and higher efficiency, thereby contributing to reaching the long-term targets (DOE & EU) for transportation fuel cells, hydrogen production from renewable energy sources and hydrogen storage. The work is prioritized within development of high performance electrocatalysts, low-cost bipolar plates and electrodes, and membranes, and previously included a task on high pressure composite hydrogen pressure vessels which has now ended.

## Task 2.1 - High performance catalysts

Rare and expensive catalysts are necessary in polymer electrolyte membrane water electrolysis (PEMWE), such as Ir for the oxygen evolution reaction (OER), being the state-of-the-art in terms of stability and activity. Ir is defined as a metal with an extremely high supply risk, and with loadings of 2 mgIr $cm_{-2}$ and 3 W $cm_{-2}$ power density (state-of-the-art), an annual increase of PEMWE capacity of 10 GW scale would already exceed the current worldwide Ir production. In contrast, EU alone has set a goal of increased electrolyser capacity up to 40GW by 2040. Lowering the use of Ir in PEM water electrolysis is therefore crucial for a large-scale deployment of this technology.

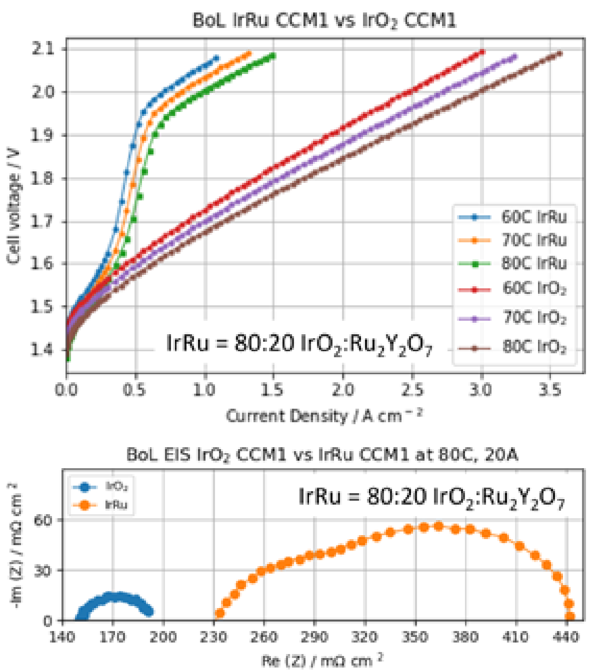
The purpose of this in MoZEES RA2 work is to prepare $Ru_2Y_2O_7$ powder, a new and promising class of candidate materials for the OER catalyst, prepare catalyst coated membranes (CCMs) and test them in situ under relevant PEMWE conditions. The hypothesis is that a composite CCM of $Ru_2Y_2O_7$ and $IrO_2$ can overcome the intrinsic limitations of $Ru_2Y_2O_7$ alone, retain a high activity and sufficient stability, and dilute the $IrO_2$ content to enable lower Ir loadings. The prepared powder contains primary particles in the range of 50-200 nm, but also agglomerates of various sizes, and was shown by XRD to have the pyrochlore structure as the major component. CCMs were prepared by spray coating a Nafion membrane with an 80:20 $IrO_2$: $Ru_2Y_2O_7$ mixture as the OER catalyst, as well as with pure $IrO_2$ as the reference benchmark, with Pt/C as the hydrogen evolution reaction (HER) catalyst. The $IrO_2$ catalyst was supplied by the MoZEES partner Johnson Matthey.

*Figure 1 SEM micrograph of prepared $Ru_2Y_2O_7$ catalyst powder (left) and cross-section of CCM with 80:20 IrO2 and $Ru_2Y_2O_7$ catalysts (right).*



Results from the in-situ characterization of the CCMS under relevant conditions are given below, with polarization curves in the top image and electrochemical impedance spectra (EIS) at the bottom, both at the beginning of life (BoL). The polarization curve shows that the CCM with 80:20 $IrO_2$: $Ru_2Y_2O_7$ mixture has a good performance in the activation region (at low current densities in the left of the figure) but starts to deviate from $IrO_2$ reference in the ohmic region. This indicated a high resistance in the catalyst layer, which is also supported by the EIS spectra. Although these initial results show that challenges remain, they are an excellent starting point for further optimization and represent a step towards understanding the feasibility of using Ru pyrochlores as a mean to reduce the dependency on $IrO_2$ as the PEM electrolyser OER catalyst.

*Figure 2. Polarisation curves (top) and electrochemical impedance spectra (bottom), both at the beginning of life (BoL) for 80:20 80:20 $IrO_2$ and $Ru_2Y_2O_7$ catalysts (labelled IrRu) and reference $IrO_2$ CCMs.*




## Task 2.2 – Low-cost bipolar plates and electrodes

### Alkaline electrolysers

Nickel metal is often used as electrodes for alkaline electrolysers, due to their good catalytic properties for both hydrogen and oxygen evolution reactions (HER and OER) and being stable in strongly alkaline solutions. In MoZEES we have investigated using stainless steel as the electrode, to lower the costs, while developing activation procedures to improve the surface to become more active towards HER and OER. During this activation procedure the morphology and chemical composition of the surface is modified, with alloying elements from the bulk of the steel being concentrated on the surface. This makes it possible to use less expensive steel, while at the same time get a surface with a high nickel content and good catalytic properties.

We have demonstrated the activation process for HER and OER, and both *ex-situ* and *in-situ*. The fact that this can be achieved *in-situ*, without elaborate pre-treatments, makes the activation process particularly suited for industrial application. The conclusion is that it seems feasible to use stainless steel to achieve high activity for HER and OER for alkaline electrolysers. Figure 3 shows how activated stainless steel on both electrodes give an improvement of 330 mA $cm_{-2}$ at 2.0 V compared to nickel electrodes. This work has been performed by PhD student Hamid R. Zamanizadeh at NTNU, under supervision of Professor Frode Seland, Svein Sunde, and Bruno Pollett. Hamid successfully defended his PhD thesis in February 2022. This work is highly relevant for Nel, an important partner in RA2, and in fact Egil Rasten from Nel was one of Hamid's opponents during the PhD defence.

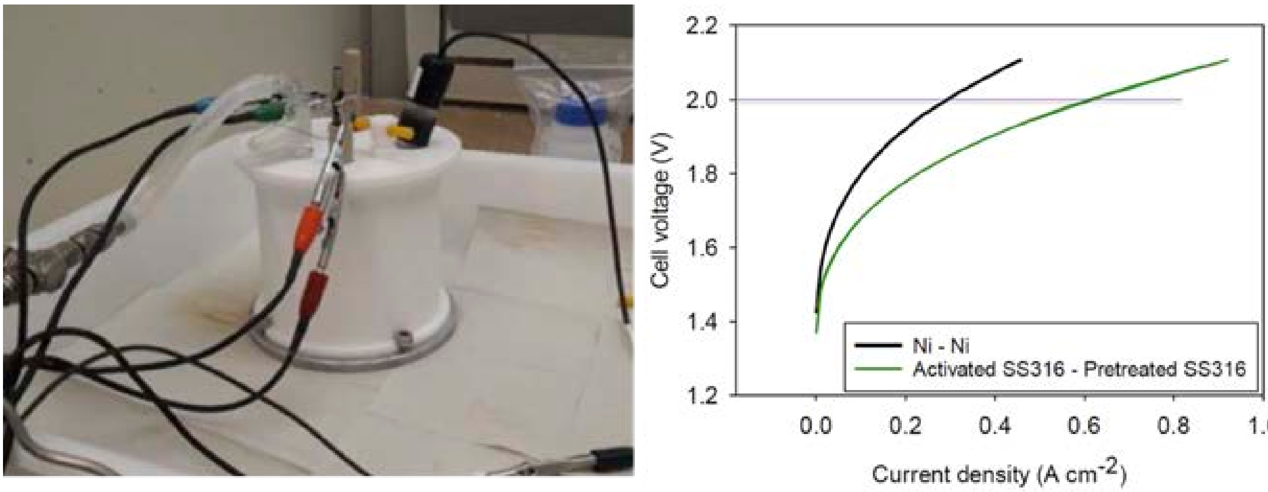



*Figure 3. Experimental set-up used for testing activated stainless steel electrodes for alkaline water electrolysis (left) and cell voltage with activated stainless steel and nickel electrodes (right).*

*Figure 4. Hamid R. Zamanizadeh's PhD defence*

## PEM fuel cells

Bipolar plates (BPPs) are a crucial component of a PEM fuel cell (PEMFC). Stainless steel has long been a preferred BPP material due to its low cost, manufacturability, and good physical properties. However, in the oxidising environment inside a PEMFC, stainless steel forms a protective oxide layer with a poor conductivity. This leads to increased interfacial contact resistance (ICR) between the BPP and the gas diffusion layer, therefore increased ohmic losses and reduced performance. The most common coatings used for stainless steel BPPs, to give a low ICR throughout its lifetime, are metallic (noble metal, carbides, nitrides) or carbon-based (graphite, conductive polymer).

In the MoZEES project, a novel carbon-based coating developed at Teer Coatings was tested by SINTEF at the Norwegian Fuel Cell and Hydrogen Centre and compared against two reference samples of uncoated and gold coated stainless steel. A series of drive cycles, including shutdown/start-up, were performed to accelerate the ageing processes, whilst simulating realistic operation for an automotive application. An in-situ ICR technique developed in the MoZEES project was used to produce real-time contact resistance measurements that are sensitive to changes in relative humidity and cell temperature, without significantly impacting on the FC performance. An article on the *in-situ* ICR technique was published early 2021. In this case, the technique was used to measure the ICR of the BPP throughout the lifetime of the FC to understand its impact on the total performance, by decoupling the contact resistance and membrane resistance from the ohmic resistance as measured by polarisation curves/EIS. Whilst the stainless steel BPP observes a steady increase in ICR from t = 0, the carbon and gold BPPs have much lower and more stable ICR throughout their lifetimes. The carbon coating developed at Teer coatings gives a lifetime almost twice that of gold coating, with limited changes to the contact resistance throughout over 800 hours of cycling.

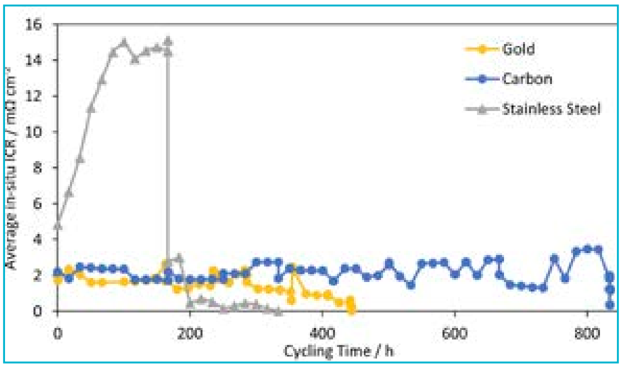



*Figure 5 The progression of the average in-situ ICR of the cathode side BPP over the lifetime of the fuel cell, for fuel cells assembled with gold (yellow), carbon (blue) or stainless steel (grey) bipolar plates.*

## Task 2.3 – Improved high-temperature membranes

This task is one of the more fundamental studies in RA2. PhD candidate Xinwei Sun from the Electrochemistry group at UiO is focusing on polymer-ceramic composite membranes for high temperature PEM applications. Conventional low-temperature PEM cells is typically operated at around 80 °C, and the traditional membrane is a proton-conducting Nafion®. Typical challenges are slow reaction kinetics, water flooding of the electrodes, complex heat management, gas crossover, and poisoning of the catalysts. Most of these issues could be mitigated by operating the PEMFCs at higher temperatures, but this is not possible for Nafion® as it would dehydrate above 100 °C. One of the most promising alternatives to Nafion® is acid-doped polybenzimidazoles (PBI), with the potential to be used up to 200 °C without dehydration. Adding ceramic fillers to the polymer membrane has been reported in several studies to improve the performance of the polymer membranes. As a part of her PhD work, Xinwei and her colleagues published a critical literature review on the effectiveness of the ceramic fillers, and in fact found few credible rationalisations of why or how they work. This review was awarded with the 2021 Best Paper award from the journal Membranes.

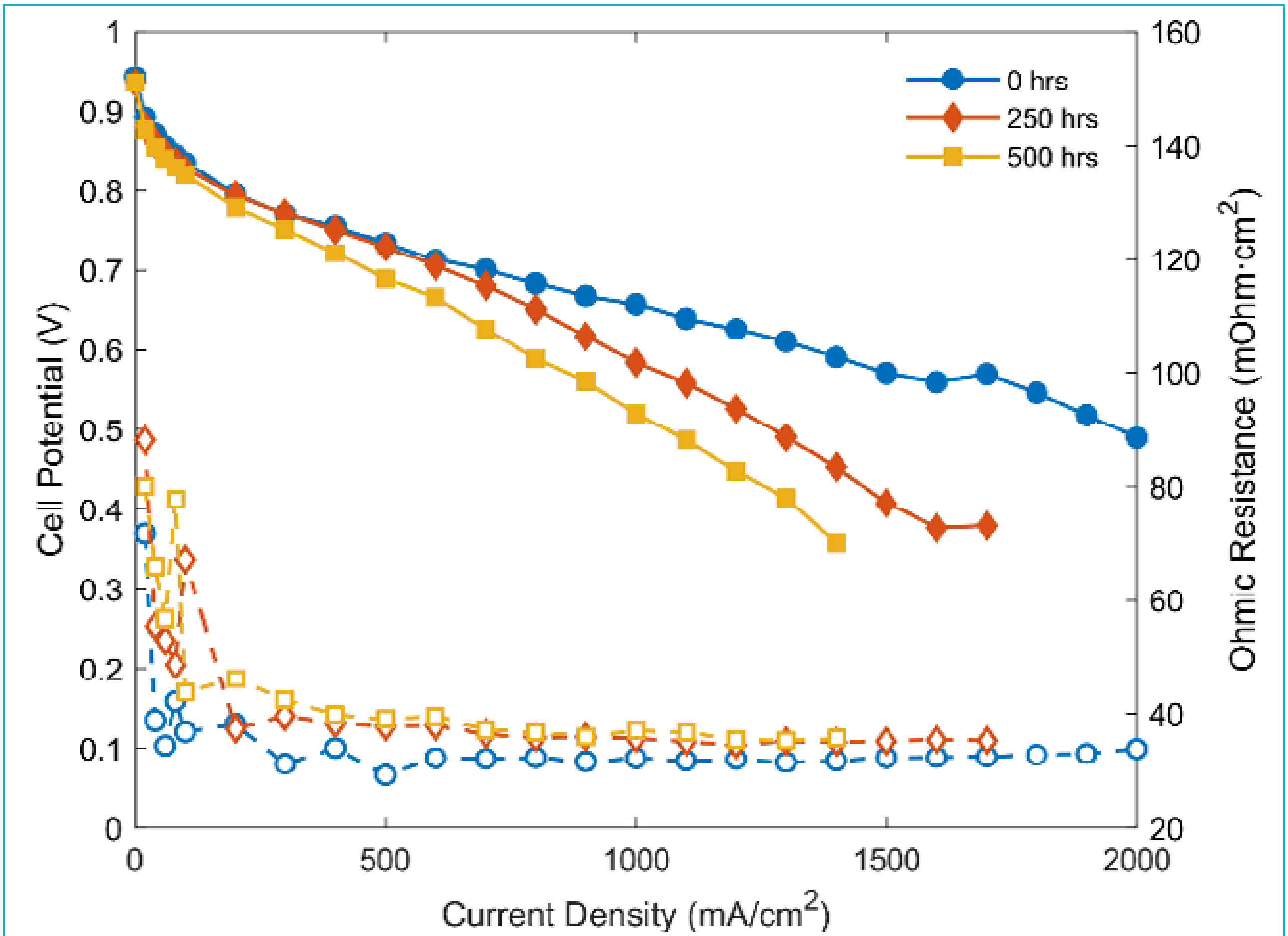
*PhD Candidate Xinwei Sun from UiO.*

## Task 2.4 – Lifetime, durability, and performance

In Task 2.4, a comprehensive experimental framework has been established, to enable a comprehensive understanding of the lifetime performance of PEMFCs under maritime operating conditions. From this, relevant degradation parameters from single cell PEMFC measurements can be extracted and used as input into the empirical fuel cell degradation models being developed in MoZEES RA3. These models offer three distinct advantages over alternative multi-physics models, in that empirical degradation models are: (i) computationally efficient, (ii) can be integrated into other modelling frameworks, and (iii) can support the quick parameterization of different systems.

Initial degradation results have been obtained under intentionally harsh conditions to simulate cathode flooding. The polarization data is shown in Figure 6 below, including the Ohmic resistance estimated from the high frequency resistance from EIS. The data illustrates a clear decrease in the overall fuel cell performance over time, however, there only appears to be a slight increase in the total Ohmic resistance of the fuel cell over time. By combining this with results from other advanced electrochemical techniques, we have been able decouple various degradation parameters and identify predominant degradation mechanisms. In conclusion, when operating under maritime relevant conditions, conducive to cathode flooding, it appears as though the major contributions to performance degradation can be attributed to the catalyst layer.

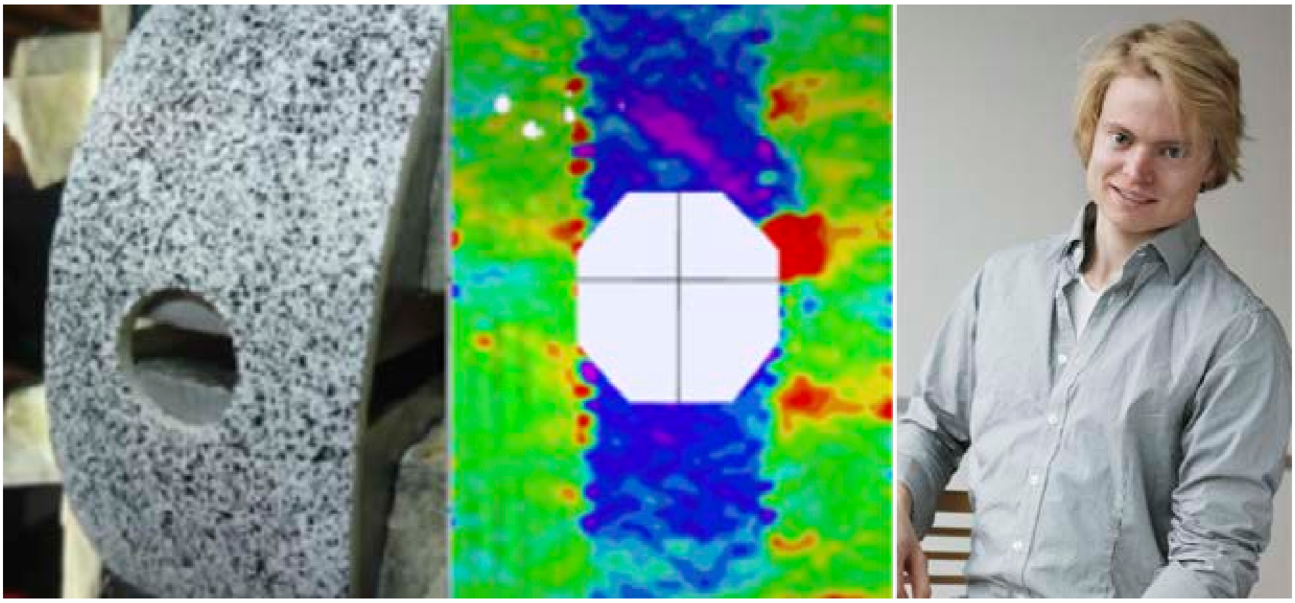
*Figure 6. Polarization curves (solid) and high frequency resistance (open) data obtained after 0 (blue), 250 (red), and 500 (yellow) hours.*



## Task 2.5 – Hydrogen storage tanks

At NTNU a PhD on fatigue mechanisms in hydrogen composite cylinders is recently finished. The work has shown that DIC (Digital Image Correlation) monitoring can be used to recognize material strains and early fatigue damage, a result highly interesting and relevant for industry partner Hexagon. The fatigue properties measured locally by DIC can also be used to better predict damage growth under fatigue around a defect. The prediction is done by novel ways to model fatigue damage growth in a finite element program. The scientific work was performed earlier in MoZEES with 1 paper accepted in 2020. Two more papers were accepted in 2021 and Eivind Hugaas successfully defended his PhD thesis in February 2022, thereby marking the end of this activity in MoZEES.

*Figure 7: PhD Eivind Hugaas (right) and the Glass Fibre specimen with speckles and the resulting degree of deformation plot (left).*



# RA3 – Battery and Hydrogen Systems and Applications

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

The RA3 research objectives are:
- Optimization of operation of maritime fuel cell systems; optimization with respect to lifetime of stacks and systems
- Risk analyses, experiments, and modelling related to battery and hydrogen system safety in heavy duty vehicle (trucks), maritime, and railway applications
- Optimization of design and operation of water electrolysis processes suitable for renewable energy based dynamic operation

## Task 3.1: Advanced fuel cell control systems

The main activities within Task 3.1 in 2021 was completing the PEM fuel cell (PEMFC) stack testing setup at IFE Hynor (part of the N-FCH infrastructure) and establishing a LabView-based control application which enables implementation and validation of fuel cell system control strategies. The fuel cell stack testing setup is designed to validate and optimize PEMFC-systems in a scale relevant for heavy-duty applications (tens of kW), with a special focus on systems suitable for integration into ships and maritime applications.

The test setup comprises a 20 kW PEMFC stack integrated with the power conditioning system and balance of plant (BoP) components required for the operation of the stack and generation of electrical energy using hydrogen fuel and oxygen from air. The main components of the cathode loop are the air compressor (supplying oxygen to the stack) and the humidifier (enabling water management within the cathode). The most important component of the anode side is the hydrogen recirculation pump which is used to circulate the gas in the anode loop while it is operating in a dead-end mode (with periodical hydrogen purging). The cooling loop is filled with deionised water which is circulated within the stack. The cooling loop is coupled with a primary cooling system via a heat exchanger which enables rejection of the heat by-product generated by the stack during its operation. The cathode, anode and cooling loops are equipped with pressure, temperature and flow transducers which enable precise monitoring of stack operating conditions while pressure controllers, pumps and valves enable control of these conditions. The PEMFC stack mounted in the test setup at IFE Hynor is show below (Figure 1).

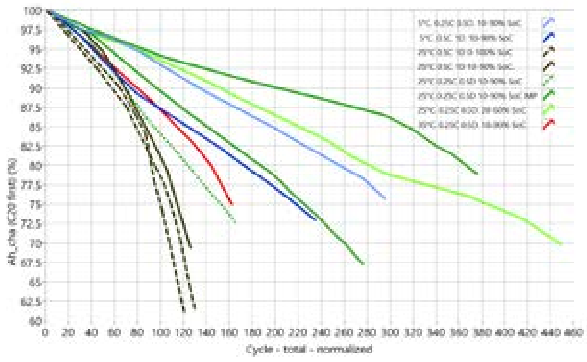
*Figure 1: 20 kW PEMFC stack (PowerCell) integrated in test bench at IFE Hynor*

Communication with the hardware system components is realized with the aid of the control application. The front panel of the developed LabView-based control application serves as a human machine interface (HMI), enables reading of the signals from the installed transducers as well as allowing control of the other system components. Finally, the application allows implementation and validation of different fuel cell system control strategies developed in MoZEES. The work planned within the project in 2022 includes commissioning of the PEMFC System at IFE Hynor and testing of EMS strategies for hybridized FC/battery system.

## Task 3.2 Battery Cell Lifetime, Durability and Safety

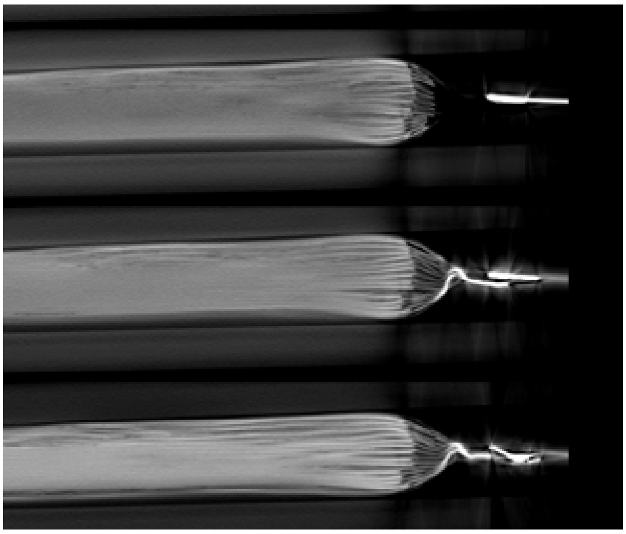
The testing of the MoZEES reference cells (tailor-made pouch cells with graphite anode, NMC cathode and electrolyte with all known additives and solvents) continued in 2021. The cycle life of the cells was tested under different conditions (Figure 2). The cycle life (until reaching 80% remaining capacity) spanned between 90 and 370 cycles.

*Figure 2: Cycle life of MoZEES Li-ion reference cells tested under different conditions*




Fresh and cycled cells were analyzed by non-destructive X-ray computational tomography, revealing cracking within the electrode layers, delamination, and poor alignment of the electrodes in the stack (Figure 3). The cells were also dismantled, electrodes removed, cut by Ar knife and investigated by cross-section SEM/EDS analysis revealing increased fraction of smaller particles and reduced porosity as a result of the cycling.

*Figure 3: X-ray CT scan from one end of a cycled MoZEES reference cell, Stein Rørvik, SINTEF*



## Task 3.3 Battery and Hydrogen Safety

At USN PhD candidate Mathias Henriksen successfully defended his PhD titled “A study of premixed combustion of gas vented from failed Li-ion batteries”. In this study he reported experimentally and theoretically determined combustion characteristics of gasses vented from Li-ion batteries undergoing thermal events. Both vented electrolyte and decomposed electrolyte was analyzed in his study. The knowledge of the combustion characteristics was used for modelling of explosions in complex geometries where a CFD-methodology was developed in the open CFD-software OpenFOAM. The CFD-methodology is intended for prediction of consequences of failure of Li-ion batteries. Explosion experiments was conducted to validate the CFD-methodology. This work is documented in the paper “Simulation of a premixed explosion of gas vented during Li-ion battery failure” published in Fire Safety Journal.

Experimental work on hydrogen safety for jet fires in mechanically ventilated compartments for releases from up to 700 bar pressure was conducted in 2021. This work is also part of the HyTunnel-CS project funded under FCHJU in EU H2020 program. The experimental results are used as recommendations for Regulations, Code and Standards for use of hydrogen

*Figure 4: Picture from flame propagation experiment in 1 m explosion channel with obstructions at USN.*

vehicles in confined spaces. The work is presented in the paper "Effect of Mechanical Ventilation on Accidental Hydrogen Releases-Large-Scale Experiments." Published in Energies. This work was also presented at the International Conference on Hydrogen Safety in Edinburgh.

A total of 5 journal papers was published in 2021 from USN on both Li-ion battery safety and hydrogen safety. Two of these papers are published in level 2 journals.

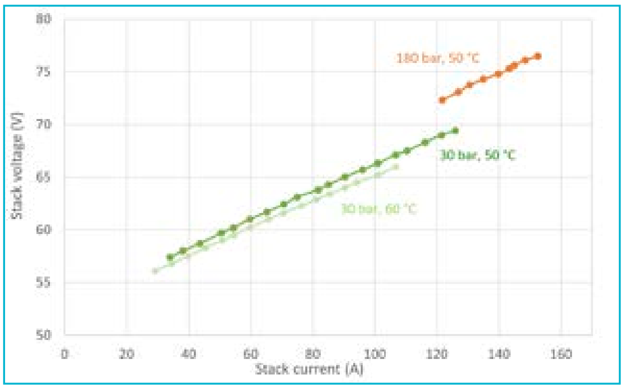
The Norwegian Defense Research Establishment (FFI) investigated the safety of a cylindrical Li-ion battery cell with iron phosphate-based chemistry by using various initiation methods for thermal runaway in 2021. The choice of initiation method for thermal runaway is very important for so-called propagation tests. Such tests, in which battery modules or installations are tested for their ability to prevent propagation of thermal runaway between cells or modules, are something all suppliers of maritime battery systems are required to carry out. In the experiments, thermal runaway was initiated in individual cells by means of various forms of external heating (nozzle heaters, flexible heating sheets, infrared radiation furnace, adiabatic heating) or by creating internal short circuits (internal heating element, nail penetration). Subsequently, the behaviour of the cells was observed and categorized according to a hazard level scale. The battery cells showed a large variation in behaviour, both for different methods and for identical methods. This shows that tests that are not repeated can give a wrong impression of the possible dangers of the battery.

## Task 3.4 Efficient low temperature water electrolysis processes

A flexible PEM water electrolysis (PEMWE) system platform for testing of high-pressure stacks up to 200 bar$H_2$) was completed and commissioned at IFE in 2020-2021. The test rig is integrated with a sophisticated power conditioning system which makes it possible to test hybrid electric topologies for the water electrolyzer system. The control system has a high functionality and is designed for in-depth studies of system performances and for tailoring and testing of control strategies which safeguards the system and maximizes efficiency and durability. In 2021 tests with a prototype stack from Nel Hydrogen were carried out up to 180 bar. The polarization curves (Figure 6) and associated system data recorded show that the stack energy use is 4.8 kWh/$Nm_3$, and that the water conditioning system has been properly designed and tuned to maintain the required water quality, temperature, and levels during a current sweep. The numerous temperature sensors in the test rig, together with accurate measurements of e.g., water levels and flowrates, makes the system ideal for validating detailed PEMWE process models developed within

MoZEES. This work was presented at a webinar during the 240th ECS Meeting on October 2021.

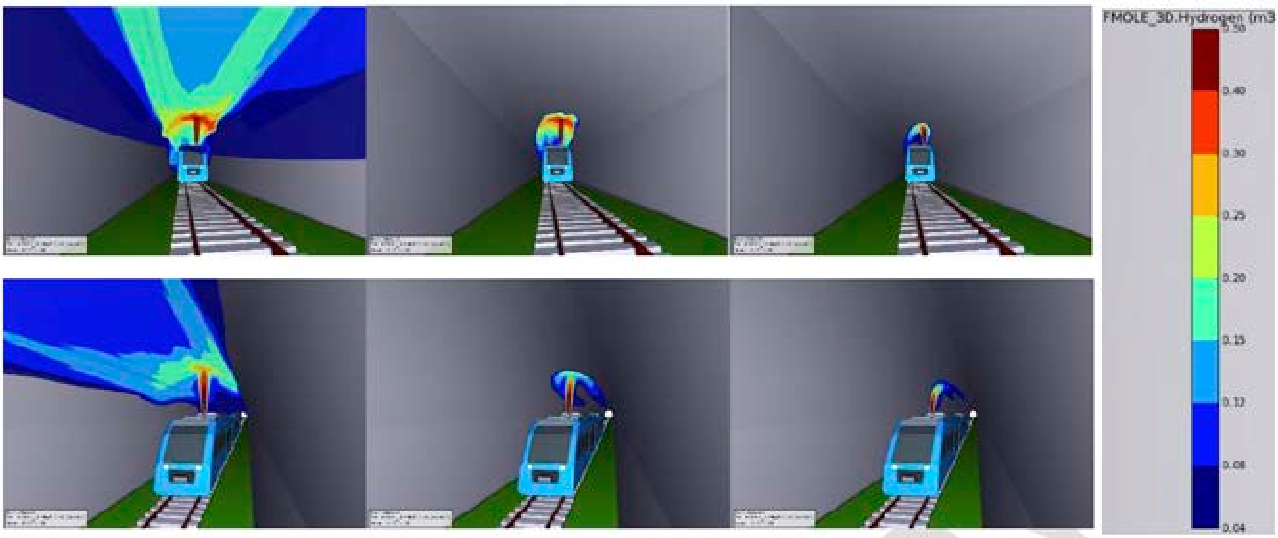
*Figure 5: Polarization curves for 12 kW PEM water electrolysis stack tested at different temperatures and pressures.*




## Task 3.5 Design Specification for Specific Applications

In 2021, Vysus Group evaluated possible hazards associated with hydrogen-powered heavy vehicles and trains in tunnels in dialogue with USN, ASKO, the Norwegian Railway Directorate and the Norwegian Public Roads Administration. CFD was used to analyse the consequences of explosive cloud evolution from TPRD (thermally-activated pressure relief device) releases for relevant hydrogen tank configurations in different types of tunnels. It was concluded that such releases will not represent a significant risk to people when the train is in motion, and that the valve opening should be limited so that the discharge rate is kept below 200 g/s. The figure below shows calculations made on the concentration of hydrogen when discharged into a train tunnel. The work with simulation of hydrogen explosions in tunnels will be continued in 2022 in a postdoctoral position at USN. This work is of great relevance to the Norwegian Public Roads Administration and the Norwegian Railway Directorate, both important public partners in MoZEES.

*Figure 6: Simulation of flammable clouds for a TPRD release from a 100 kg gas package ("gas bank") with a duration of 5 minutes (top) and 20 minutes (bottom). From left: train standing still, train with a speed of 36 km/h and trains with a speed of 90 km/h.*



# Doctoral Dissertation on Battery Safety

*On 25 November 2021 Mathias Henriksen (USN) held his trial lecture and defended his thesis for the degree philosophiae doctor (PhD) in the doctoral program Program Process, Energy and Automation Engineering. The thesis is entitled "A study of premixed combustion of gas vented from failure LIBs", and the dissertation could be followed both physically on campus Porsgrunn and digitally via Zoom.*

**Press release**
Have you ever wondered why Li-ion batteries cause fires and may even cause explosions? When Li-ion batteries fail, hot, reactive, and flammable gasses are vented, and fires and explosions can occur. In this Ph.D. study, the explosion capability of the gas vented from failed Li-ion batteries is the focus.

Li-ion batteries are today the leading electrical energy storage system due to high energy density, high specific energy, and low maintenance requirement compared to other traditional batteries. They are used in many products today, perhaps most commonly in electronic devices such as laptops, cell phones, and cameras. They are also an attractive option for large-scale energy storage, such as power grid systems and electric vehicles. However, the combination of flammable organic electrolytes and the release of oxygen at elevated temperatures in Li-ion batteries present a potential hazard. Various fires and explosions due to failing Li-ion batteries have been reported in the past.

This thesis presents results from two experimental setups, a 20-liter explosion sphere, and a 1-meter explosion channel. In the 20-liter explosion sphere, the explosion pressure, the rate of explosion pressure rise, and the laminar burning velocity (LBV) have been determined for various gas compositions vented from failed lithium-ion batteries. The results show that some of the gases vented have similar explosion characteristics as that of propane. In addition, the burning velocity for all gas compositions analyzed ranged from 0.3 m/s to 1.1 m/s, illustrating the influence of certain vented species and their concentrations.

The experimental results obtained from the 1-meter explosion channel were used to evaluate the prediction accuracy of a computational fluid dynamic (CFD) method for simulating an explosion from gases vented from failing LIBs using only open-source software. Three different gas compositions and three different channel geometries have been experimentally and numerically studied. Overall, the results show that the CFD method gave an acceptable model performance when comparing the experimental and numerical results.

The novelty of experimental and theoretical results contributes new and vital knowledge. The results are of practical importance in safety assessment and strongly needed as the new energy economy emerges.

The work was carried out at the University of South-Eastern Norway Campus Porsgrunn, Norway, part of the zero-emission program FME MoZEES.

*PhD Mathias Henriksen (USN)*

# RA4 Policy and Techno-Economic analysis

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

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

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

Specific case studies of new concepts and business models 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 technology experts in RA1 and RA2 and other experts among our MoZEES industry partners.

During 2021, there was established Life-Cycle-Assessment (LCA) as a new MoZEES research activity and analysis tool. RA4 has also interviewed early users of series produced battery electric trucks and looked at the present and future purchase price and Total Cost of Ownership (TCO) of battery electric, hydrogen fuel cell, biogas and biodiesel trucks compared to diesel trucks. A roadmap for the transport sectors necessary contribution to GHG emission reduction has been under development during 2021 and will be published at the Mobilitet2022 conference in May 2022. It is based on work done in several TØI and IFE projects in addition to MoZEES and is also a cooperation with the NTRANS FME.

SINTEF has expanded the knowledge development within public purchase contracts from maritime applications to road transport. MoZEES partners have incollaboration with FME NTRANS conducted a study on current practices of green public procurement in municipalities and how this contribute to shape sustainability practices among freight service providers.

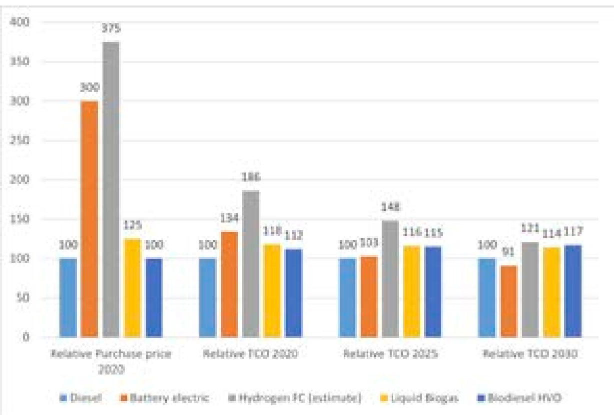
In addition, SINTEF has extended their analysis of green maritime transport performed in 2020, to include several types of green land-transport. To achieve this, the REMES macroeconomic equilibrium model has been updated and extended in its base dataset assumptions, as well as its hydrogen modelling and capital/investment system.

Each year RA4 contributes to the IEA HEV collaboration framework by writing a chapter reporting on the development of Electromobility and hydrogen in the transportation sector in Norway. This chapter is part of the IEA HEVs annual report on the global status for battery-electric, hybrid, plug-in hybrid and hydrogen transportation solutions and markets.

## User experiences and cost estimates for battery electric trucks

The relative purchase price of trucks with different energy carriers was investigated as part of interviews with the first buyers of battery electric and hydrogen truck and other information sources. The results presented the Table below shows that battery electric trucks, based on real market prices, had a purchase price three (3) times that of diesel trucks, and a total cost of ownership that was 34% higher. For hydrogen fuel cell trucks, the estimate was worse, whereas bioenergy options such as biogas and biodiesel had a much lower cost disadvantage. By 2025, the prospects for battery electric trucks are much better. On the average they will be almost competitive (from a TCO point of view) and by 2030 battery electric trucks are expected to be the cheapest to operate. Electrification will thus expand across the segment in all suitable applications towards 2030. Hydrogen is less developed, and the estimate is that they will still be very expensive in 2025 but nearly competitive with biofuels by 2030. The uncertainty for hydrogen is larger than for the other options due to a lack of real prices in the market.

*Figure 1: Relative Purchase Price and Total Cost of Ownership (TCO) 27 ton Truck (Diesel=100). Source: Pinchasik et al. 2021.*




In the interviews with owners of series produced battery electric trucks it became clear that these early purchases were strategic and based on the firm's climate and environmental objectives. Passionate staff contributed to the decision. Some of the firms bought these trucks to win public tenders that increasingly favors or demand environmentally friendly transport solutions. Longer than normal lead times for the procurement of trucks have been an issue.

The vehicle type and brand that have been selected has been steered by availability more than brand preferences. The trucks have performed well in daily business activities after having carried out some business operation adjustments. One-on-one replacement of diesel trucks with battery electric trucks has been easy for distribution in cities and for some construction work in inner cities. Drivers are in general happy with the vehicles work environment, and there have been few technical problems. Range is as expected somewhat shorter in real traffic than the range specified by manufacturers, but this has not been critical to the operations. Charging is done overnight in depots, but the users would like to have better access to fast charging during the day.

## Life Cycle Assessment of batteries

Life cycle assessment (LCA) is a method used for assessing the environmental impact potentials of various products and services. In 2021 TØI has compiled scalable cradle-to-gate inventory data for automotive Li-ion batteries and assessed their environmental impacts. The battery inventory data consider three types of Li-ion batteries: lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium titanium oxide (LTO). The specific capacities for the different battery technologies at pack level were estimated to be around 95, 155, and 55 Wh/kg for the LFP, NMC, and LTO batteries, respectively.

The cradle-to-gate impact assessment was performed across eight relevant environmental impact potentials. In terms of global warming potential, the cradle-to-gate carbon intensities were estimated to be around 195, 115, and 420 kg $CO_2$-eq/kWh for the LFP, NMC, and LTO batteries, respectively. For the other seven environmental impact potentials, we found that the NMC battery pack offers the lowest impact while the LTO and LFP batteries alternate between having the highest impact. Both the specific capacities and carbon intensities were compared to values reported in the literature and by the industry, which were in good agreement with our results.

The scalable cradle-to-gate battery inventories are used in an on-going cradle-to-grave LCA study of battery electric buses utilizing data from a bus operator in Oslo. In contrast to the cradle-to-gate assessment that only considers production, the full cradle-to-grave assessment incorporates lifetime and weight considerations of the batteries and will provide additional insights about the life cycle environmental performance of the considered Li-ion battery technologies. Initial results suggest that environmental performance of a battery technology is not transferrable for all battery sizes and associated driving ranges.

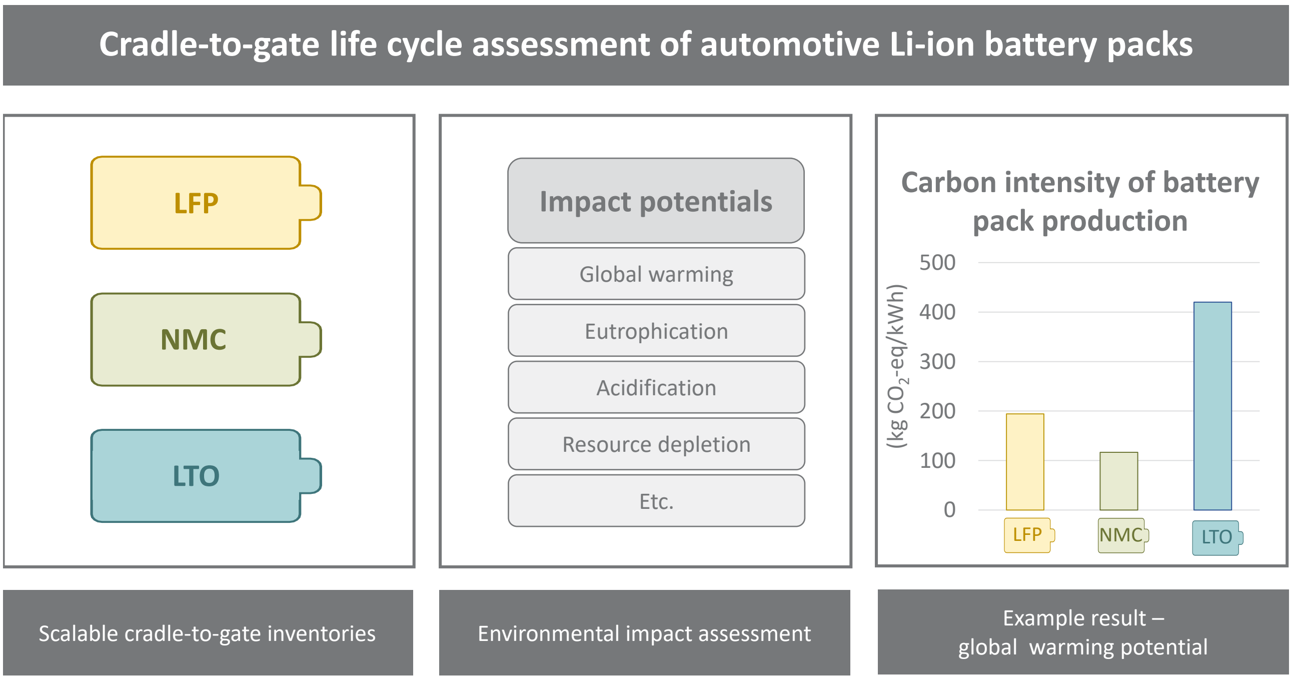
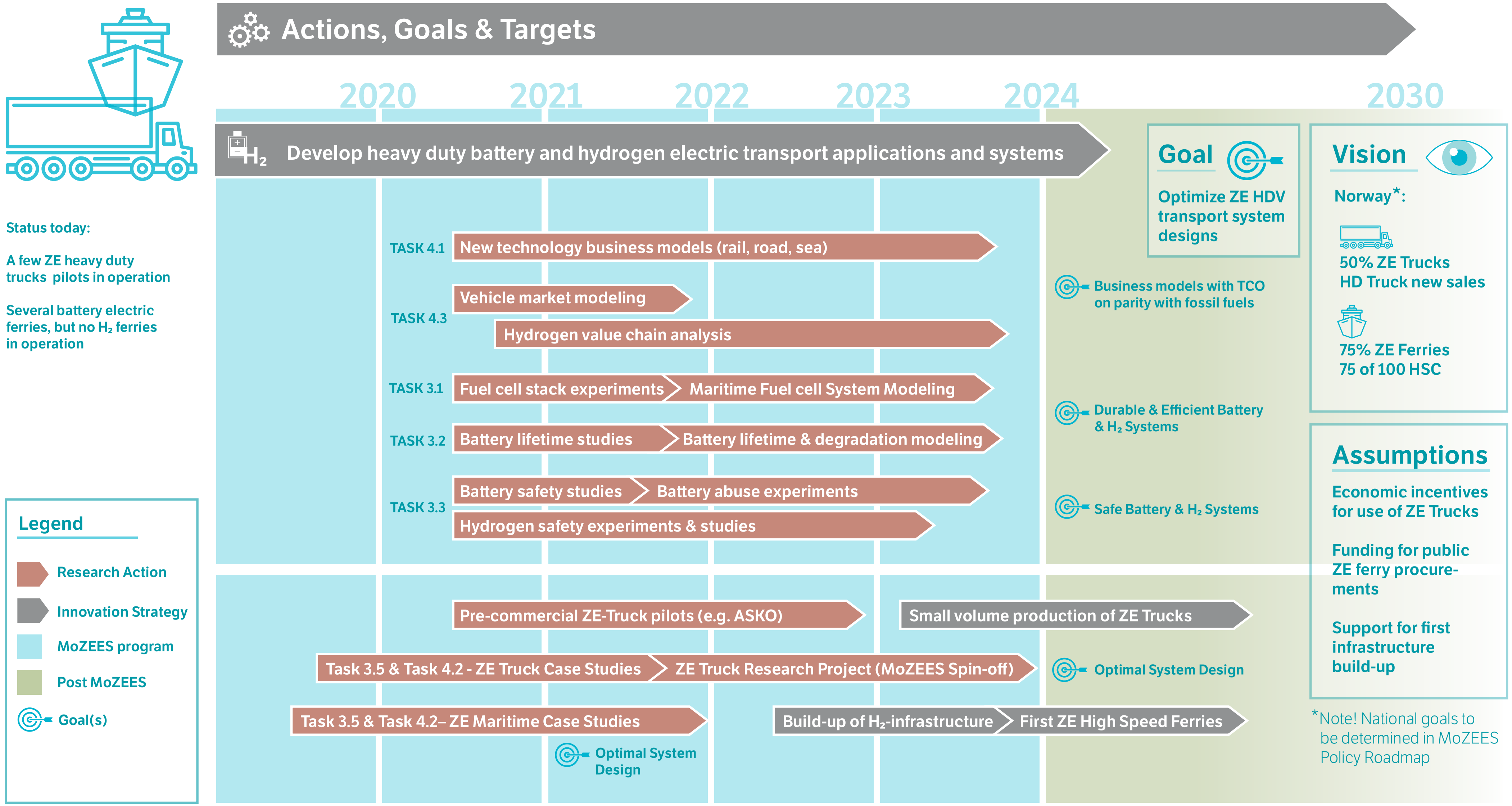


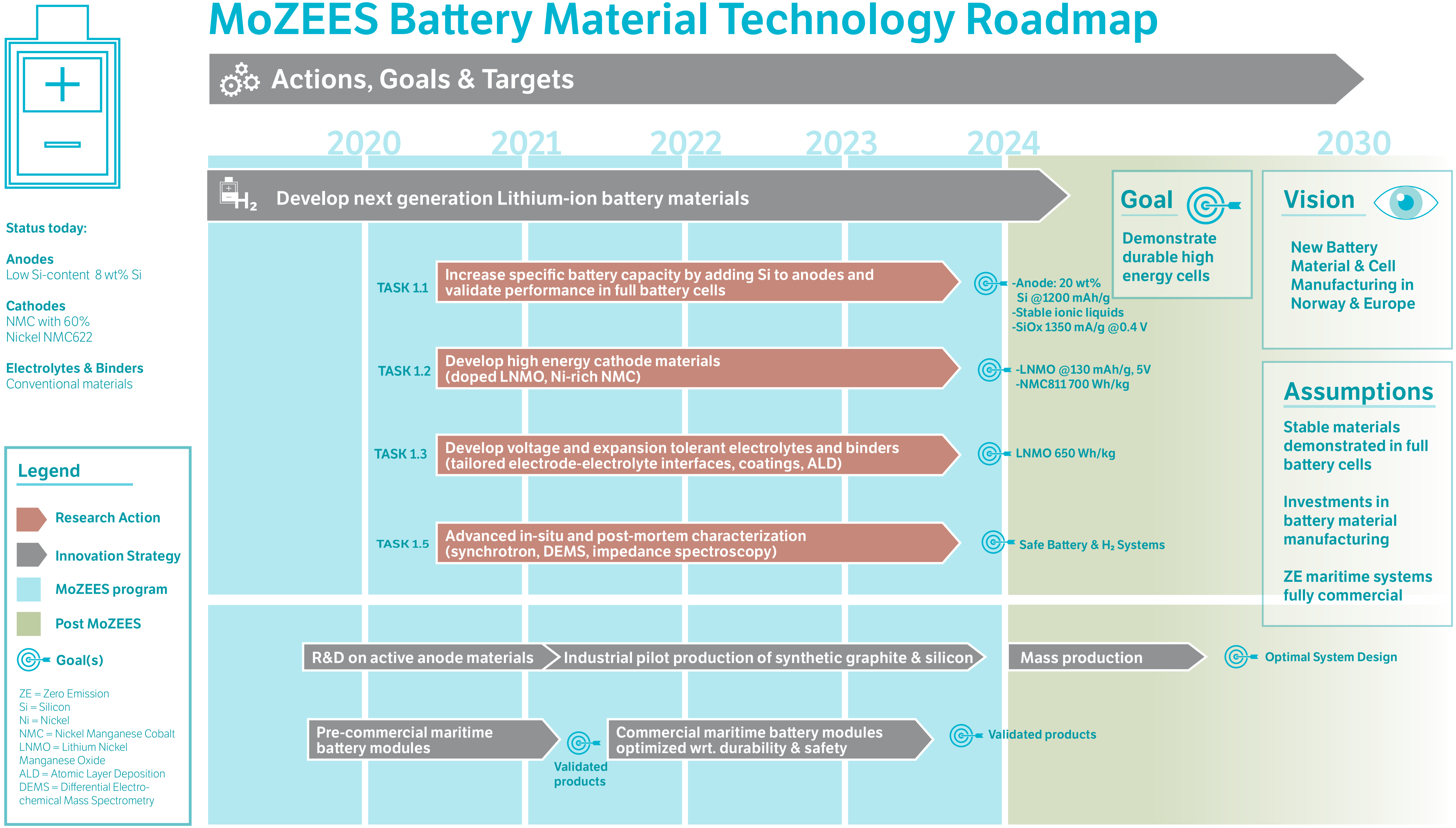

*Figure 2: Principle for life cycle assessment of automotive Li-ion batteries.*

# MoZEES Zero Emission Heavy Duty Transport Roadmap

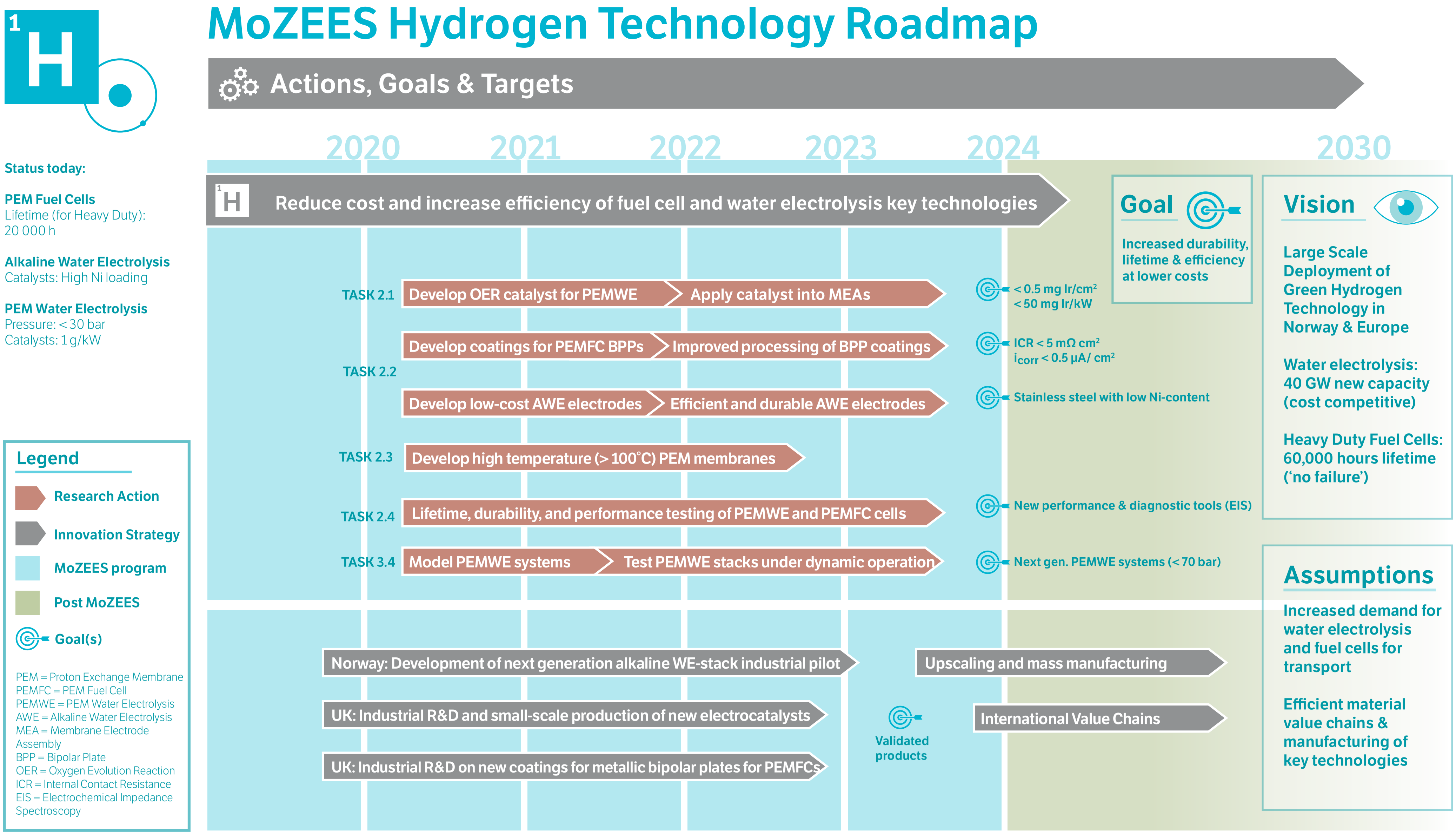



*(Figure 1).*

# MoZEES Battery Material Technology Roadmap




(Figure 2).


1 H
MoZEES Hydrogen Technology Roadmap
Actions, Goals & Targets
2020
2021
2022
2023
2024
2030
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
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
TASK 2.2
Develop coatings for PEMFC BPPs
Improved processing of BPP coatings
ICR < 5 mΩ cm²
icorr < 0.5 μA/ cm²
Develop low-cost AWE electrodes
Efficient and durable 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 |
| UiO | Alok M. Tripathi | M | India | 02.10.2018 | 31.03.2021 | Advanced characterization of Li-ion batteries |
| UiO | Heesoo Park | M | South Korea | 14.10.2021 | 15.10.2023 | Materials design for battery electrodes |

| PhD students with financial support from the Center Budget | | | | | | |
|---|---|---|---|---|---|---|
| Institution | Name | Sex M/F | Nationality | Start date | End date | Topic |
| NTNU | Elise Ramleth Østli | F | Norway | 21.08.2017 | 27.03.2022 | Water-based manufacturing routes for electrodes |
| NTNU | Hamid R. Zamanizadeh | M | Iran | 20.09.2018 | 14.11.2021 | Bipolar plates for alkaline water electrolysis |
| NTNU | Jonas Martin | M | Germany | 01.08.2020 | 31.07.2023 | Policy and techno-economic analysis |
| NTNU | Manuel Lenti | M | Italy | 01.09.2021 | 31.08.2024 | Optimization of maritime fuel cell systems |
| USN | Mathias Henriksen | M | Norway | 15.08.2017 | 25.11.2021 | Explosion hazards of Lithium-ion batteries |
| UiO | Halvor Høen Hval | M | Norway | 01.01.2018 | 15.04.2022 | High voltage cathode materials for Li-ion batteries |
| UiO | Xinwei Sun | F | China | 01.09.2018 | 08.12.2021 | Composite Proton conducting membranes |
| UiO | Carina Geiss | F | Germany | 21.09.2020 | 20.09.2023 | In-operando studies of Silicon anodes |

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

| Key researchers | | |
|---|---|---|
| Institution | Name | Main research area |
| FFI | Sissel Forseth | Battery safety |
| FFI | Espen Åkervik | Battery safety |
| FFI | Hannibal Fossum | Battery safety |
| SINTEF | Alejandro Oyarce | PEMFC and PEMWE testing, BPP, membranes, catalysts, and AST protocols |
| SINTEF | Kristin Y. Bjerkan | Social scientific transport research |
| SINTEF | Rune Bredesen | Functional oxides, solid state diffusion/kinetics, membranes, fuel cells and electrolyzers |
| SINTEF | Paul Inge Dahl | Materials synthesis and processing for batteries |
| SINTEF | Einar Vøllestad | Functional oxides |
| SINTEF | Sigrid Damman | Governance, institutional drivers and barriers |
| SINTEF | Katie McCay | PEMFC and PEMWE testing |
| SINTEF | Kaushik Jayasayee | Battery testing |
| SINTEF | Patrick Fortin | PEMFC and PEMWE testing |
| SINTEF | Thulile Khoze | PEMFE and PEMWE testing |
| SINTEF | Solveig Meland | Social scientific transport research |
| SINTEF | Vibeke S. Nørstebø | Operations research, economic analysis |
| SINTEF | Anders Ødegård | PEMFC Bipolar plates and PEMFC systems |
| SINTEF | Magnus S. Thomassen | RA coordination. PEMWE/PEMFC materials and systems |
| SINTEF | Julian R. Tolchard | Functional oxide materials, structural characterization |
| SINTEF | Werner A. Tobias | Operations research and mathematical programming, economics |
| SINTEF | Zenith Federico | Fuel cell control, techno-economic analyses |
| SINTEF | Christelle D. | Functional oxides |
| SINTEF | Gerardo A P.-Valdes | Operations research, economic analysis |
| SINTEF | Anita H. Reksten | PEMWE catalysts |
| SINTEF | Artur Tron | Batteries Development |
| SINTEF | Kyrre Sundseth | Techno-economic analyses |
| SINTEF | Nils P. Wagner | Li ion batterier utvikling av katoder og anoder |
| SINTEF | Tor O. Sunde | Catalyst development |
| SINTEF | Joachim G. Seland | Sample characterization by SEM and EDS |
| IFE | Abdelhamid Muhammad | Silicon anodes for Li-ion batteries |
| IFE | Carl Erik L. Foss | Silicon anodes for Li-ion batteries |
| IFE | Jan P. Mæhlen | Silicon anodes for Li-ion batteries |
| IFE | Janis Danebergs | Energy System Modeling |
| IFE | Julia Wind | Battery modelling and characterization |
| IFE | Kari Aa Espegren | Energy system modelling |
| IFE | Morten Tjelta | Corrosion in alkaline media |
| 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 | Thomas Holm | Electrochemistry |
| 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 | Lasse Fridstrøm | Vehicle fleet forecasting, vehicle and demand modelling, economic incentives |
| TØI | Linda A.-W. Ellingsen | Life Cycle Analysis |

| PhD students working on projects in the Center with financial support from other sources | | | | | |
|---|---|---|---|---|---|
| Institution | Name | Nationality | Period | Sex M/F | Topic |
| UiO | Rasmus V. Thøgersen | Norway | 2018-2022 | M | High-end catamaterials |
| UiO | Frida Hempel | Norway | 2018-2021 | F | Solid electrolytes |
| UiO | Anders Brennhagen | Norway | 2019-2022 | M | Anodes |
| USN | Agnieszka Lach | Norway | 2019-2022 | F | Hydrogen release in confined spaces |
| NTNU/TØI | Vegard Østli | Norway | 2018-2022 | M | Vehicle and demand modelling |
| NTNU | Šárka Štádlerová | Czech Rep. | 2020-2023 | F | Optimization of ZE transport systems in maritime applications |

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

| Master degrees | | | |
|---|---|---|---|
| Institution | Name | Sex M/F | Topic |
| NTNU | Martin Raaen | M | Porosity and thickness effects in LFP cathodes |
| NTNU | Joachim S. Bjørklund | M | Silicon Anodes for Li-ion Batteries |
| NTNU | Marthe Nybrodahl | K | Solid state electrolytes |
| NTNU | Hanna K. Herskedal | K | Solid state electrolytes |
| NTNU | Vegard Vesterdal Viki | M | Modelling of solid state electrolytes |
| UiO | Stian Simonsen | M | Composite Polymer Membranes |
| UiO | Amund Raniseth | M | Al-substituted LMNO |
| UiO | Casper Skautvedt | M | Bi-based anode conversion materials |
| UiO | Mats Aspeseter Rødne | M | Titanium (di)oxide coating of electrodes in Lithium Capacitors |
| UiO | Abilash Kanish Thiagarajan | M | Carbon-based materials for LIBs |
| UiO | Jørgen Kristoffer Tuset | M | Modelling of fuel cell electric bus |
| UiO | Jonas Flatgård Jensen | M | Modelling of PEM water electrolysis system |
| USN | Erik Nygaard | M | Hydrogen Safety, ATEX |

# Appendix 2: Statement of Accounts

| Funding | Amount |
|---|---|
| The Research Council | 15 998 |
| The Host Institution (IFE) | 1 522 |
| Research Partners | 8 275 |
| Industry partners | 5 498 |
| Public partners | 2 207 |
| **Total funding** | **33 500** |

| Costs | Amount |
|---|---|
| The Host Institution (IFE) | 7 179 |
| Research Partners | 22 125 |
| Industry partners | 3 788 |
| Public partners | 408 |
| **Total costs** | **33 500** |

*(All figures are given in kNOK)*

# Appendix 3: Publications

## 2021

**Lai, Samson Yuxiu; Cavallo, Carmen; Abdelhamid, Muhammad; Lou, Fengliu; Koposov, Alexey.**
Advanced and Emerging Negative Electrodes for Li-Ion Capacitors: Pragmatism vs. Performance. Energies 2021 ;Volum 14.(11)
UiO IFE

**Bratland, Magne; Bjerketvedt, Dag; Vågsæther, Knut.**
Structural response analysis of explosions in hydrogen-air mixtures in tunnel-like geometries. Engineering structures 2021 ;Volum 231.
USN

**Booto, Gaylord Kabongo; Espegren, Kari Aamodt; Hancke, Ragnhild.**
Comparative life cycle assessment of heavy-duty drivetrains: A Norwegian study case. Transportation Research Part D: Transport and Environment 2021 ;Volum 95.
ØSTFOLDFOR IFE

**Brennhagen, Anders; Cavallo, Carmen; Wragg, David; Sottmann, Jonas; Koposov, Alexey; Fjellvåg, Helmer.**
Understanding the (De)Sodiation Mechanisms in NaBased Batteries through Operando XRay Methods. Batteries & Supercaps 2021 ;Volum 4.(7) s.1039-1063
UiO IFE

**Dhillon, Shweta; Hernández, Guiomar; Wagner, Nils Peter; Svensson, Ann Mari; Brandell, Daniel.**
Modelling capacity fade in silicon-graphite composite electrodes for lithium-ion batteries. Electrochimica Acta 2021 ;Volum 377.
NTNU SINTEF

**Henriksen, Mathias; Vågsæther, Knut; Lundberg, Joachim; Forseth, Sissel; Bjerketvedt, D..**
Laminar burning velocity of gases vented from failed Li-ion batteries. Journal of Power Sources 2021 ;Volum 506. s.1-11
USN FFI

**Henriksen, Mathias; Vågsæther, Knut; Lundberg, Joachim; Forseth, Sissel; Bjerketvedt, Dag.**
Simulation of a premixed explosion of gas vented during Li-ion battery failure. Fire safety journal 2021 ;Volum 126. s.1-12
USN FFI

**Hugaas, Eivind; Echtermeyer, Andreas.**
Estimating SN curves for local fiber dominated fatigue failure in ring specimens representing filament wound pressure vessels with damage. Composites Part C: Open Access 2021 ;Volum 5.
NTNU

**Hugaas, Eivind; Echtermeyer, Andreas.**
Filament wound composite fatigue mechanisms investigated with full field DIC strain monitoring. Open Engineering 2021 ;Volum 11.(1) s.401-413
NTNU

**Lach, Agnieszka; Gaathaug, Andre Vagner.**
Effect of Mechanical Ventilation on Accidental Hydrogen Releases—Large-Scale Experiments. Energies 2021 ;Volum 14.(11)
USN

**Lach, Agnieszka; Gaathaug, Andre Vagner.**
Large scale experiments and model validation of Pressure Peaking Phenomena-ignited hydrogen releases. International Journal of Hydrogen. Energy 2021 ;Volum 46.(11) s.8317-8328
USN

**Marocco, Paolo; Sundseth, Kyrre; Aarhaug, Thor Anders; Lanzini, Andrea; Santarelli, Massimo; Barnett, Alejandro Oyarce; Thomassen, Magnus.**
Online measurements of fluoride ions in proton exchange membrane water electrolysis through ion chromatography. Journal of Power Sources. 2021 ;Volum 483.
SINTEF NTNU

**McCay, Katie; Lædre, Sigrid; Martinsen, Stig-Yngve; Smith, Graham; Barnett, Alejandro Oyarce; Fortin, Patrick.**
In-Situ Monitoring of Interfacial Contact Resistance in PEM Fuel Cells. Journal of the Electrochemical Society 2021 ;Volum 168.(6)
SINTEF

**Rogstad, Daniel Tevik; Einarsrud, Mari-Ann; Svensson, Ann Mari.**
Evaluation of selected ionic liquids as electrolytes for silicon anodes in li-ion batteries. Journal of the Electrochemical Society 2021 ;Volum 168.(11)
NTNU

**Stadlerova, Sarka; Schütz, Peter.**
Designing the Hydrogen Supply Chain for Maritime transportation in Norway. Lecture Notes in Computer Science (LNCS) 2021 ;Volum 13004. s.36-50
NTNU

**Sundvor, Ingrid; Thorne, Rebecca Jayne; Danebergs, Janis; Aarskog, Fredrik Gundersen; Weber, Christian.**
Estimating the replacement potential of Norwegian high-speed passenger vessels with zero-emission solutions. Transportation Research Part D: Transport and Environment 2021 ;Volum 99:103019. s.1-17
TØI IFE

**Thorne, Rebecca Jayne; Hovi, Inger Beate; Figenbaum, Erik; Pinchasik, Daniel Ruben; Amundsen, Astrid Helene; Hagman, Rolf.**
Facilitating adoption of electric buses through policy: Learnings from a trial in Norway. Energy Policy 2021 ;Volum 155.(August 2021) s.1-11
TØI

**Ulvestad, Asbjørn; Skare, Marte Orderud; Foss, Carl Erik Lie; Krogsæter, Henrik; Reichstein, Jakob; Preston, Thomas J.; Mæhlen, Jan Petter; Andersen, Hanne Flåten; Koposov, Alexey.**
Stoichiometry-Controlled Reversible Lithiation Capacity in Nanostructured Silicon Nitrides Enabled by in Situ Conversion Reaction. ACS Nano. 2021 ;Volum 15.(10) s.16777-16787
NTNU UiO IFE

**Zenith, Federico.**
Battery-powered freight trains. Nature Energy 2021
SINTEF

**Østli, Elise Ramleth; Tesfamhret, Yonas; Wenner, Sigurd; Lacey, Matthew J.; Brandell, Daniel; Svensson, Ann Mari; Selbach, Sverre Magnus; Wagner, Nils P..**
Limitations of Ultrathin Al2O3 Coatings on LNMO Cathodes. ACS Omega 2021 ;Volum 6.(45) s.30644-30655
NTNU SINTEF

## 2020

**Aarskog, Fredrik Gundersen; Danebergs, Janis; Strømgren, Trond; Ulleberg, Øystein.**
Energy and cost analysis of a hydrogen driven high speed passenger ferry. International Shipbuilding Progress 2020 ;Volum 67.
IFE

**Andersen, Håkon; Xu, Kaiqi; Malyshkin, Dmitry; Strandbakke, Ragnar; Chatzitakis, Athanasios Eleftherios.**
A highly efficient electrocatalyst based on double perovskite cobaltites with immense intrinsic catalytic activity for water oxidation. Chemical Communications 2020 ;Volum 56.(7) s.1030-1033
UiO

**Figenbaum, Erik.**
Battery Electric Vehicle Fast Charging–Evidence from the Norwegian Market. World Electric Vehicle Journal 2020 ;Volum 11.(2)
TØI

**Foss, Carl Erik Lie; Müssig, Stephan; Svensson, Ann Mari; Vie, Preben Joakim Svela; Ulvestad, Asbjørn; Mæhlen, Jan Petter; Koposov, Alexey.**
Anodes for Liion batteries prepared from microcrystalline silicon and enabled by binder's chemistry and pseudoselfhealing. Scientific Reports 2020 ;Volum 10.(1)
NTNU IFE

Halvorsen, Ivar Johan; Pivac, Ivan; Bezmalinovic, Dario; Barbir, Frano; Zenith, Federico.
Electrochemical low-frequency impedance spectroscopy algorithm for diagnostics of PEM fuel cell degradation. International Journal of Hydrogen Energy 2020 ;Volum 45.(2) s.1325-1334
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