MoZEES
Mobility Zero Emission Energy Systems

FME
FORSKNINGS-
SENTER FOR
MILJØVENNLIG
ENERGI
Norges forskningsråd

MoZEES Final Report

May 2025

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1. Foreword

The main objective with MoZEES was to be a national Center for environment-friendly energy research (FME), with focus on new battery and hydrogen materials, components, technologies, and systems for transport applications on road, rail, and sea. The overall goals for the research in the Center were driven by the needs and requirements to design and develop safe, reliable, and cost competitive zero-emission transport solutions.

Have we achieved the goals and objectives with the Center? What were the main outcomes and findings from the research over the Center's project period (2017-2024)? What were the main innovations and societal contributions? What were the main conclusions and recommendations for further work? Answers to these and other questions are found in this final report.

The MoZEES Final Report documents the extensive work carried out by the Research, Industry, and Public Partners in the Center. More than 40 Partners and 200 people have been involved in different research, development, demonstration, innovation, and commercialization activities related to MoZEES. This has resulted in more than 100 peer-reviewed scientific publications in international journals, 11 PhD theses (two more to come), 30 Master theses, 30 MoZEES reports, and around 100 lectures at international conferences in more than 30 countries around the world. References to all of these publicly available papers, reports, and presentations are found in the MoZEES Final Report. I strongly encourage everyone to do some gold digging.

I have been the MoZEES Center Director for the entire project period and would like to use this final opportunity to express my gratitude for being given the opportunity to take responsibility for this national endeavor. First, I would like to acknowledge the support and long-term commitment provided by the Research Council of Norway and my host institution Institute for Energy Technology (IFE). Next, I would like to thank the guidance provided by the MoZEES Board, particularly the Chairman of the Board, and the MoZEES Innovation and Scientific Committees. A special thanks goes to the MoZEES Management Team consisting of the four Research Areas Leaders, the leader of the Research Training Network (MoZEES RTN), and the two Coordinators who have been involved in the Center on a day-to-day basis. Finally, I would like to thank all the researchers, PhD students, post.doc. fellows, and other colleagues among the MoZEES Partners for their significant and important contributions.

We have together created a MoZEES Family and produced lots of valuable and useful results. I hope that the close friendships and collaborations established and nurtured during the Center will continue. The collaborative atmosphere established in the Center is for me an important part of the MoZEES legacy. However, the work on battery and hydrogen technology and zero emission transport systems has not yet been completed. We need to continue to push for zero emission technology and solutions in the future.

It has been an honor and a privilege to be the Captain of the MoZEES ship over these past eight years!

Best regards
Øystein Ulleberg

2. Summary

Popular Science Summary

Norway has access to vast amounts of renewable power, some of which can be used to produce electricity and hydrogen for transport. When the Center was established in 2017, battery and hydrogen technologies had already been demonstrated for use in light-duty zero emission transport applications. However, Norway's ambitious targets for low- and zero-emission transport required research and development of battery and hydrogen technologies for heavy-duty transport sectors (road, rail, and sea). This was the motivation for establishing a long-term national research effort on zero-emission energy systems for transport.

The main objective with MoZEES was to be a Center for environment-friendly energy research with focus on new battery and hydrogen materials, components, technologies, and systems for transport applications on road, rail, and sea. The Center contributed to the design and development of safe, reliable, and cost competitive zero-emission transport solutions. There was also a strong focus on the development of young researchers. In MoZEES there were completed 11 PhD theses[1], and 12 post-doctoral fellowships, and 28 master theses over the 8-year project period (2017-2024). The main focus areas for the research activities in the Center were:

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 has been a collaboration between 4 research institutes (IFE, SINTEF, TØI, and FFI), 3 universities (UiO, NTNU, and USN), 7 public partners, 2 private interest organizations, and 21 commercial and industrial partners[2], 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 was the host for FME MoZEES throughout the project period.

A national study on the effects of the energy research in Norway was conducted in 2024/2025. The main objective with this study was to evaluate the effects of the research conducted within the national FME Centers and their associated projects. The effects of the research was evaluated with respect to environmental, technical, and economic parameters (emissions, efficiency, security of supply, cost reductions, and business potential). MoZEES scored well on all of the these evaluation criteria, particularly on the technical and environmental parameters.

Finally, MoZEES contributed to the development of new battery and hydrogen technologies and systems, and supported several Industry Partners in the Center with relevant research for innovations and pre-commercial developments. The Center also provided valuable and useful input to Public Partners for the planning of next generation zero emission transport systems.

1) Two additional MoZEES PhD theses will be completed in 2025 and 2026
2) There were 21 Industry Partners in MoZEES in the second half of the Center (2020-2024)

Populærvitenskapelig sammendrag (Norwegian)

Norge har tilgang til store mengder med kraft fra fornybare kilder, som blant annet kan benyttes til å produsere elektrisitet og hydrogen til transportformål. Da senteret startet opp i 2017 var det kun tilgjengelig batteri- og hydrogenteknologi for bruk i lettere kjøretøyer. Norges ambisiøse mål for lav- og nullutslipp i transport har krevd forskning og utvikling på batteri- og hydrogenteknologi for tyngre anvendelser innen transport (vei, bane og sjø). Dette var motivasjonen for å etablere et nasjonalt forskningssenter som kunne arbeide langsiktig på nullutslipp i transport.

Hovedformålet med MoZEES, et forskningssenter for miljøvennlig energi (FME), var å bidra til utvikling av nye batteri- og hydrogenmaterialer, -komponenter og -systemer for applikasjoner innen transportsektoren (vei, bane og sjø). Forskningssenteret bidro til design og utvikling av sikre, pålitelige og kostnadseffektive nullutslippsløsninger for transport. Det har også vært et sterkt fokus på utdanning. I MoZEES ble det fullført 11 doktorgradsavhandlinger[3], 12 postdoktorgradsoppgaver og 28 masteroppgaver i løpet av prosjektperioden (2017-2024).

Fokusområdene for forskningen i senteret har vært:

1. Nye materialer og prosesser for industrielle nisjemarkeder for batteri og hydrogen
2. Batteri- og hydrogenkomponenter og -teknologier for eksportrettede produkter
3. Batteri- og hydrogensystemer for applikasjon i eksisterende og nye transportmarkeder (vei, bane og sjø), med et spesielt fokus på maritime applikasjoner
4. Nye systemløsninger og tjenester, med fokus på bærekraftige og tekno-økonomiske farbare veier mot nullutslipp i transportsektoren

MoZEES har vært et samarbeid mellom 4 forskningsinstitusjoner (IFE, SINTEF, TØI og FFI), 3 universiteter (UiO, NTNU og USN), 7 offentlige partnere, 2 private interesseorganisasjoner og 21 nærings- og industripartnere[4], inkludert leverandører av materialer, nøkkelkomponenter, teknologi, og systemer innen batterier og hydrogen. Der har også vært etablert formelle samarbeidsavtaler med fire utenlandske universiteter: RWTH Universitet i Aachen (Tyskland), Universitet i Uppsala (Sverige), Universitet i California Davis (USA) og Universitet i Genova (Italia). Institutt for energiteknikk (IFE) ved Kjeller var vertskap for FME MoZEES i hele prosjektperioden.

En nasjonal studie om effektene av energiforskningen i Norge ble gjennomført i 2024/2025. Hovedformålet med denne studien var å evaluere effektene av forskningen utført innenfor de nasjonale FME-sentrene og deres tilknyttede prosjekter. Effektene av forskningen ble evaluert med hensyn til miljømessige, tekniske og økonomiske parametere (utslipp, effektivitet, forsyningssikkerhet, kostnadsreduksjoner og forretningspotensial).

MoZEES scoret godt på alle disse evalueringskriteriene, spesielt på de tekniske og miljømessige parameterne. MoZEES bidro til utvikling av flere nye batteri- og hydrogenteknologier og systemer, og støttet flere av industripartnerne i senteret med relevant forskning for innovasjoner og pre-kommersielle utviklinger. Senteret ga også verdifulle og nyttige innspill til offentlige partnere for planleggingen av neste generasjon nullutslippstransportsystemer.

3) Ytterligere 2 doktorgradsavhandlinger skal fullføres i 2025 og 2026
4) Det var 21 industripartnere i MoZEES i siste halvdel av prosjektperioden (2020-2024)

3. Vision and Goals

MoZEES has for the period 2017-2024 been the national Center for environment-friendly energy research (FME) on new battery and hydrogen materials, components, technologies, and systems for existing and future zero-emission transport applications on road, rail, and sea (Figure 1).

The vision and main motivation for the research in the Center was to develop zero emission solutions for heavy-duty transport, and especially on the use of batteries and hydrogen in maritime applications. There was also a strong focus on battery material research to facilitate the development of new industrial battery value chains in Norway and the EU.

The overall goal of MoZEES was to contribute to the design and operation of safe, reliable, and cost competitive zero-emission transport solutions. The specific focus areas for the research activities in the Center was in the development of:

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

The main objectives, scope of work, and long-term goals in MoZEES were kept consistent throughout the Center period (2017-2024), and very few adjustments needed to be made after the midway evaluation (2020).

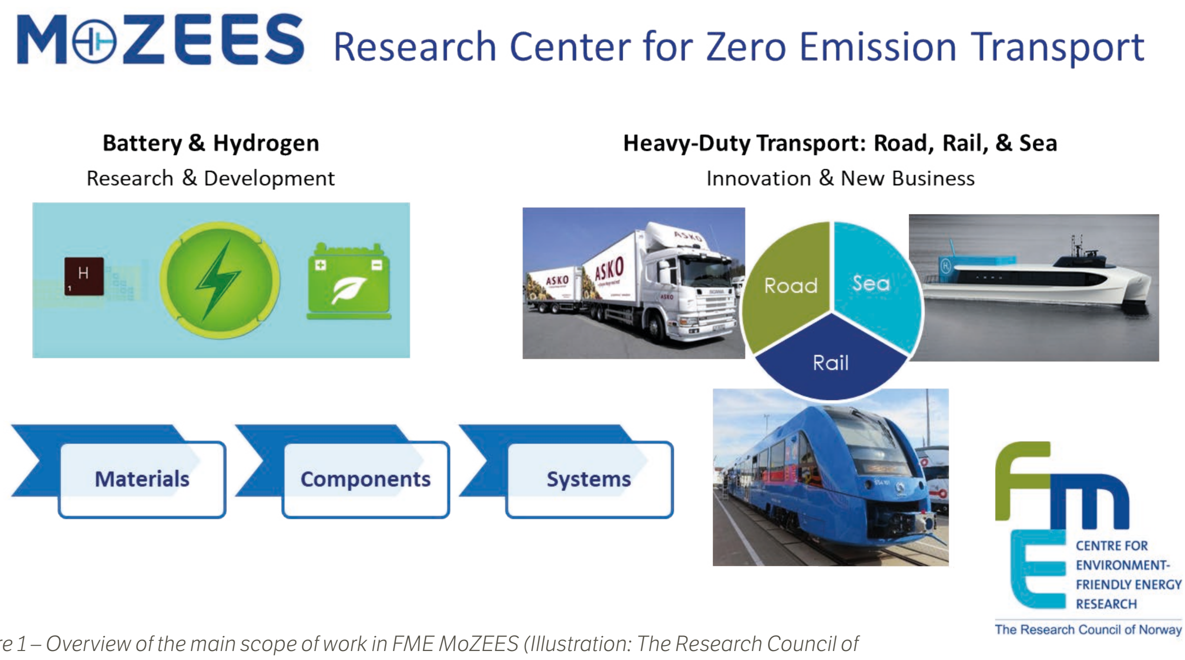


Figure 1 – Overview of the main scope of work in FME MoZEES (Illustration: The Research Council of Norway; Photos: ASKO, Brødrene Aa, Alstom).

The goals for the research and innovation activities in the Center were summarized in a set of MoZEES roadmaps. These roadmaps were first developed for the mid-way evaluation of the Center (2020) and later updated towards the end of the project period (2023):

1. MoZEES Zero Emission Heavy-Duty Transport Roadmap (Figure 2)
2. MoZEES Battery Material Technology Roadmap (Figure 7)
3. MoZEES Hydrogen Technology Roadmap (Figure 8)

At the starting point of MoZEES (2016) there were very few heavy-duty trucks, only a few battery electric ferries, and no hydrogen ferries in operation in Norway. Hence, the long-term (2030) vision in the Center was to contribute to the realization of the national goal at the time: 50% zero emission heavy-duty trucks (HD truck new sales) and 75% zero emission ferries and high speed crafts (HSC) in 2030[5].

In the MoZEES Zero Emission Heavy-Duty Transport Roadmap the overall research goals were to develop cost-effective systems, durable technology, and safe systems, while the innovation activities focused on accelerating the introduction of battery- and hydrogen electric trucks and vessels (ferries and HSCs) into the market.

The overall research goals in MoZEES Battery Material Technology Roadmap was to develop and demonstrate new durable high energy Li-ion battery cells (with 25% Si-anodes and high-voltage LNMO-cathodes), to support the long-term (2030) industrial goals was to develop new Li-ion battery material and cell manufacturing capacities in Norway and Europe.

In the MoZEES Hydrogen Technology Roadmap the overall research goal was to increase the durability, lifetime, efficiency, and costs of the key hydrogen technologies under study (mainly PEM fuel cells and water electrolysis), and contribute to the long-term goals on large-scale green hydrogen production in Norway and Europe (40 GW with new water electrolysis capacity in 2030).

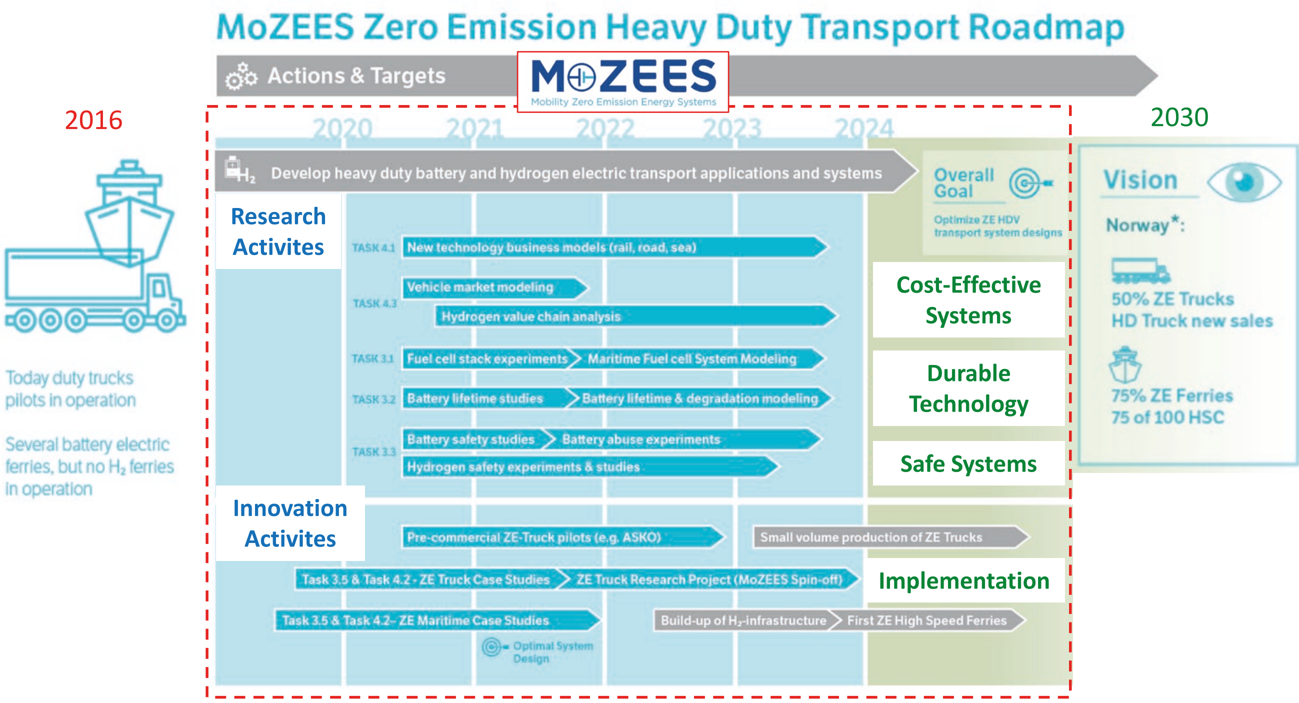


Figure 2 – MoZEES Zero Emission Heavy-Duty Transport Roadmap (Illustration: IFE/MoZEES)

5) In 2023 the Norwegian government revised the national 2030-roadmap to also include biofuels.

4. Center Effects and Overarching FME Goals

A national study on the effects of the energy research in Norway was conducted in 2024/2025[6)]. The main objective with this study was to evaluate the effects of the research conducted within the national FME Centers and their associated projects. MoZEES contributed to the study with input on results from research on zero emission energy technology for transport systems. The effects of the research was evaluated with respect to environmental, technical, and economic parameters (emissions, efficiency, security of supply, cost reductions, and business potential). Below is a summary of the key impacts and effects of MoZEES, including some highlights (cases).

General Effects

The development of zero emission transport solutions is crucial for cutting the overall emissions in Norway and globally. The performance and costs of zero emission technology for passenger cars and light duty vehicles are approaching the levels of fossil fuel vehicles. However, developing similar technology for heavy-duty transport applications has proven to be more challenging.

The main goal with MoZEES was to contribute to the development of new value chains and systems for heavy-duty transport applications on road, rail, and sea. The research in the Center focused on the development of battery and hydrogen materials, technologies, and systems, including integrated zero emission energy and transport systems.

Specific Effects (Cases)

Below is a description of a few selected cases representing MoZEES-related innovations in zero emission transport. The key technologies in the first two cases are based on long-term research efforts in Norway and have over the past 5 years been brought forward in two new Norwegian companies. The last four cases have a direct link to the research conducted in MoZEES. A summary of the cases is provided in Table 1 and described in more detail below.

Table 1 – Effect Study on Zero Emission Transport with selected cases

Case	Topic	Summary
1	Silicon-based Nanomaterials for Lithium-ion Batteries	Production of silicon-based nanomaterials to replace graphite in battery anodes
2	PEM Water Electrolysis for Heavy-Duty Transport and Industry	Development of PEM water electrolysis technology and systems, with production of equipment starting up in Norway
3	EIS Tool for Fuel Cell Lifetime Studies	Instrumentation and analysis methods and tools for better condition monitoring of PEM fuel cells
4	Laboratory for Battery and Hydrogen Gas Explosion Tests	Experimental setup and expertise in Norway for studying battery and hydrogen gas explosions
5	AISEEM Tool for Calculating Energy and Emissions in Maritime Transport	Modeling tool to analyze vessel movements and calculate energy use in selected ports, to assess the need for charging and refueling infrastructure
6	ZETruck Method for Integrated Cost and Environmental Analysis of Zero Emission Truck	Framework for studying cost and environmental effects of replacing diesel with zero emission trucks using battery and hydrogen technology

6) Studie av effekter av energiforskning: National study in 2024/2025 with evaluation of the impacts and effects of energy research conducted in Norway within the FME Centers and their associated projects

Emissions

All of the selected cases contribute to reduced greenhouse gas emissions (GHG) by replacing fossil fuel with zero emission solutions in the transport sector. Increased production of renewable hydrogen (green hydrogen) can reduce emissions, especially in hard-to-abate sectors (Case 2). New and more efficient battery material production techniques can also lead to lower emissions in large-scale production of batteries (Case 1).

Efficiency

New water electrolysis technology for hydrogen production use less energy than other alternatives, which increase the overall energy efficiency. The PEM water electrolysis technology from Hystar enables hydrogen production with lower energy consumption (Case 2). The AISEEM and ZETruck tools developed within MoZEES can be used for planning of energy efficient systems in the maritime (Case 5) and heavy-duty road transport (Case 6).

Security of Supply

The security of supply is increased by facilitating for hydrogen production and by making batteries more durable. For example, new monitoring methods that provide better information on the state of health in PEM fuel cells lead to better utilization of the end use equipment (Case 3). The developed MoZEES methods and tools for calculating energy consumption can also be used for planning of more reliable and robust transport systems (Case 4 and 6).

Cost Reductions

The R&D in most of the selected cases can reduce the costs in the production and/or use of battery and hydrogen technology in many transport applications. Production of nanomaterials has the potential to reduce the costs of silicon production for batteries (Case 1). New PEM water electrolysis technology will enable hydrogen production with lower energy consumption and thus lower costs (Case 2). Extended fuel cell life will lead to lower operating costs (Case 3).

Business Potential

All of the cases contribute in one way or another to the development of new battery and hydrogen value chains and businesses in Norway. Cenate's patented process for producing silicon-based nanomaterials has significant international potential (Case 1). Small and medium-scale production can take place in Norway, but large-scale production should be located in markets abroad with access to silane on an industrial scale. Hystar's has patented their technology and the company now has over 60 employees (Case 2). Production of PEM water electrolysis systems equivalent to approximately 100 MW is planned at Høvik near Oslo, with further up-scaling to an annual production capacity of 4.5 GW by 2027. Finally, the ZETruck method can be used to assess business cases for roll-out of zero emission heavy-duty trucks in Norway.

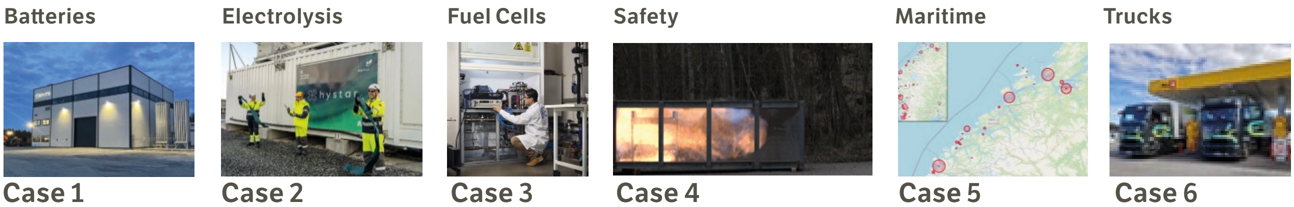


Figure 3 – Cases selected by MoZEES for national study on effects of energy research in Norway (Photos: Cenate (1), Hystar (2), IFE (3), USN (4), TØI(5 and 6))

5. Basic Facts about the Center

The MoZEES research center was a eight year (2017-2024) collaboration between 4 research institutes (IFE, SINTEF, TØI, and FFI), 3 universities (UiO, NTNU, and USN), 7 public partners, 2 private interest organizations, and 21 commercial and industrial partners[7)], including key battery and hydrogen materials, components, technology, and systems suppliers. The Center also established formal collaboration agreements (MoUs[8)]) 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 was the host of organization for the Center (Table 2).

The MoZEES consortium and partnership was remarkably consistent throughout the FME Center period from 2017-2024. There were no fundamental changes in the participation from the Research and Public Partners, except for a few name changes for the two County Councils. The situation with the Industry Partners was also very stable, except for a few positive additions. Statkraft and Hydro joined the Center in 2019, while Equinor joined in 2020. Furthermore, some of the smaller companies (SMEs[9)]) in MoZEES gradually grew into larger and more robust companies, e.g., Corvus Energy, Cenate, and Morrow Technologies. The additions and changes made to the partnership in the Consortium strengthened the Center significantly.

Table 2 – Basic facts about MoZEES and its partners and main collaborators (per 2024)

37 Partners
- Hosted by IFE
- 4 Research Institutes
- 3 Universities
- 6 Public Partners
- 21 Commercial & Industrial Partners
- 2 Private Interest Organizations
- The Research Council of Norway

175 People
- Research Partners: *Professors, Scientists, Researchers, PhDs, Post.docs.*
- User Partners: *Technologists, Engineers, Business Developers, Public Officials*

International Research Partners
- Uppsala University (Sweden)
- RWTH Aachen University (Germany)
- University og Genova (Italy)
- UC Davis (USA)

FME Center Collaboration
- NTRANS (NTNU)
- Bio4Fuels (NMBU)
- University og Genova (Italy)
- HYDROGEN (SINTEF)

FME Center Collaboration
- Battery Norway (Eyde Cluster)
- Ocean HyWay Cluster (Hub for Ocean)
- H2Cluster (Kjeller Innovasjon)

7) The complete list of all the Industry Partners (28 different companies) that have participated in MoZEES over the full project period (2017-2024) is found in Appendix 1
8) Memorandum of Understanding (MoM)
9) Small and Medium Enterprise (SME)

Organization

The organization of MoZEES is shown in Figure 4. The Center consisted of a General Assembly with one representative from each Partner, an Executive Board, a Center Management, Research Area Leaders, and dedicated committees for scientific oversight, innovation, education, and outreach. The four Research Areas were led by senior scientists from the Research Partners.

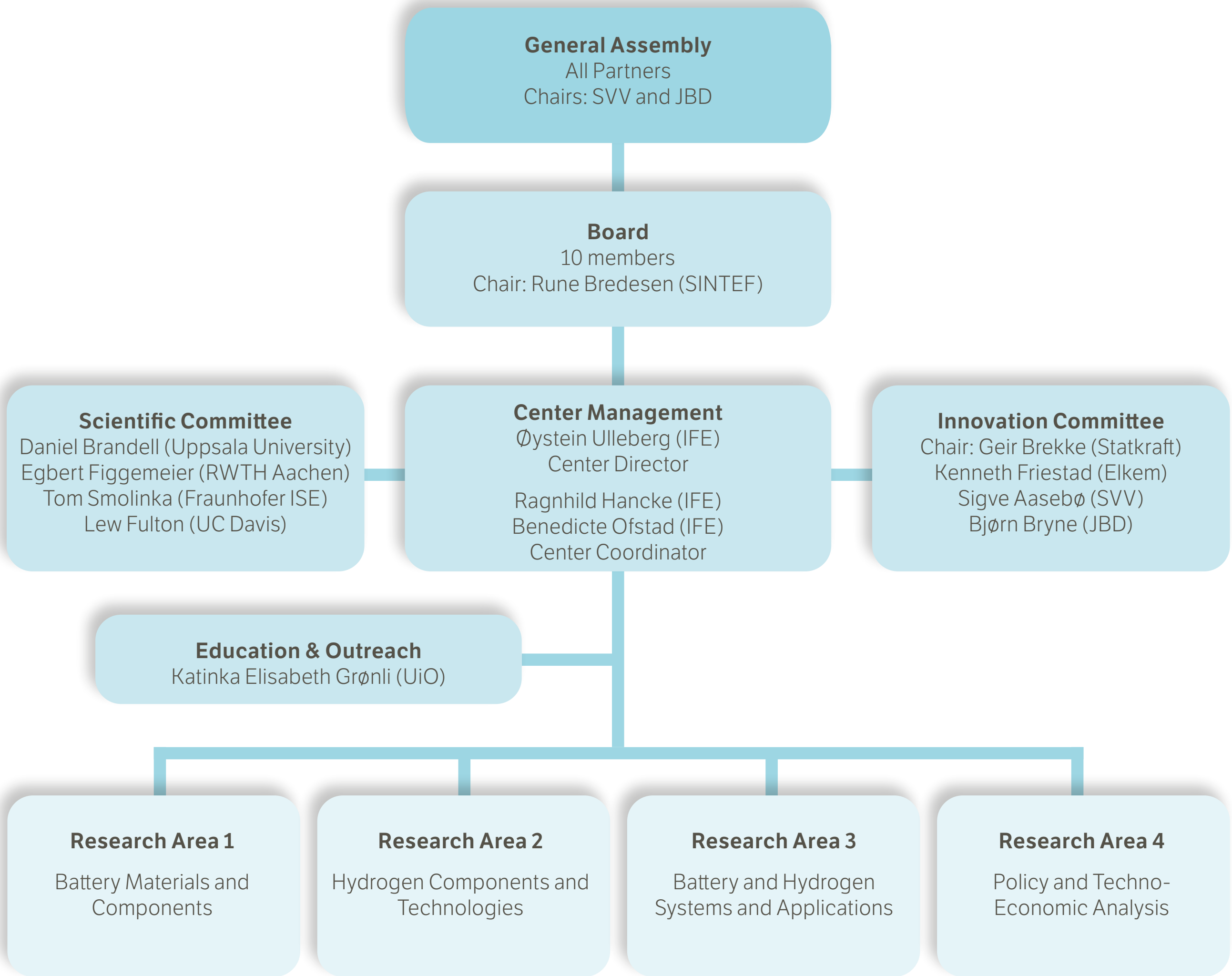


Figure 4 – Organization of MoZEES[10)]

10) Research Area leaders from NTNU (RA1), SINTEF (RA2), IFE (RA3), and TØI (RA4)

Board Members

The MoZEES Executive Board consisted of 10 members from the Research Partners (4), Industry Partners (4) and the Public Partners (2). A representative from The Research Council of Norway acted as an observer in the Board meetings. An overview of the tenures for the fixed and alternative representatives in the Board is provided in Table 3.

Table 3 – Overview of Board Members in MoZEES throughout the Center period

<table>
<tr><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th></tr>
<tr><td colspan="8">Rune Bredesen, SINTEF</td></tr>
<tr><td colspan="8">Arve Holt, IFE[11]</td></tr>
<tr><td colspan="3">Jostein Mårdalen, NTNU[12]</td><td colspan="3">Einar Hjorthol, NTNU</td><td colspan="2">Eva Dugstad, UiO</td></tr>
<tr><td colspan="2">Jo Døhl, UiO</td><td colspan="2">Gunnar Lindberg, TØI</td><td colspan="4">Bjørne Grimsrud, TØI</td></tr>
<tr><td colspan="2">Børre Gundersen, ABB</td><td colspan="2">Matko Barisic, ABB</td><td colspan="2">Jan F. Hansen, ABB</td><td colspan="2">Lars O. Valøen, Corvus</td></tr>
<tr><td colspan="3">Jorunn Voje, Elkem</td><td colspan="5">Marit Dolmen, Elkem</td></tr>
<tr><td colspan="6">Patrick Bernard, Saft</td><td colspan="2">Arshad Saleem, Hydro</td></tr>
<tr><td colspan="6">Anders Søreng, Nel</td><td colspan="2">Egil Rasten, Nel</td></tr>
<tr><td colspan="4">Per I. Helgesen, Enova</td><td colspan="2">Petter Hersleth, Enova</td><td colspan="2">Geir Brekke, Statkraft</td></tr>
<tr><td colspan="2">Gina Ytterborg,
Statens Vegvesen (SVV)</td><td colspan="2">Ragnhild Wahl,
Jernbanedirektoratet (JBD)</td><td colspan="2">Pål Danielsen,
Jernbanedirektoratet (JBD)</td><td colspan="2">Sigve Aasebø,
Statens Vegvesen (SVV)</td></tr>
</table>

11) Martin Kirkengen attended the 1st Board Meeting on behalf of IFE
12) Tor Grande attended on behalf of NTNU in a brief interim period from May 2019 to June 2020

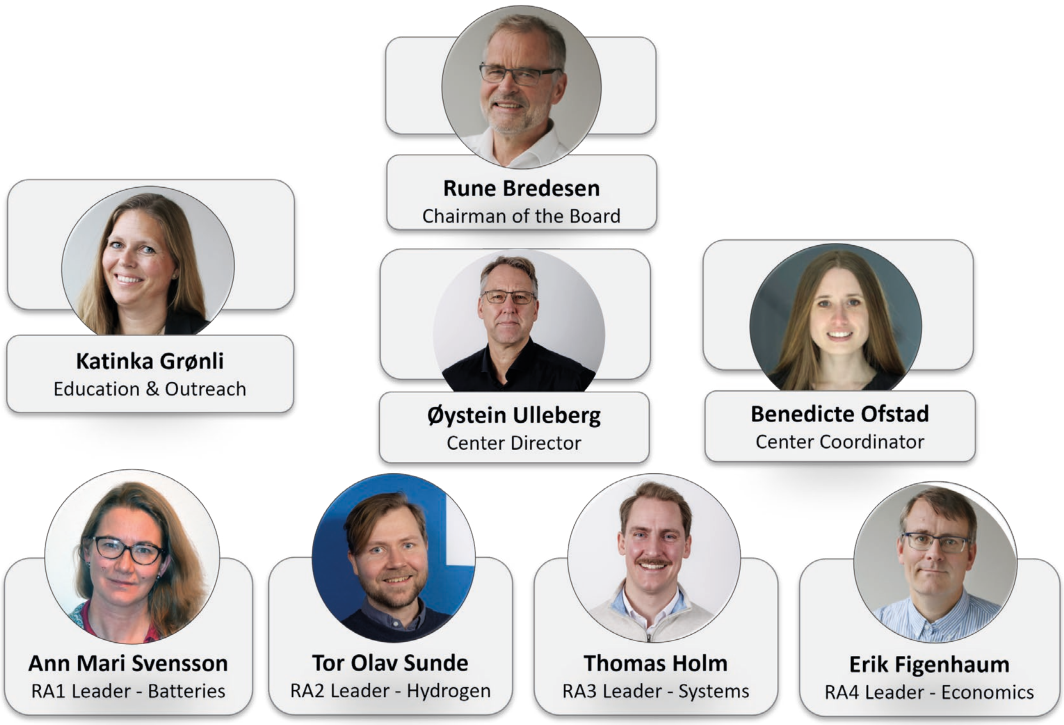


Figure 5 – MoZEES Management Team, Research Area Leaders, and Chairman of the of the Board in the final two years of the Center[13)]

Cooperation within the Center

Close collaboration between the partners in an FME center is a key to success. In MoZEES there were set up effective systems for cooperation between the Research Partners and User Partners from industry, commercial, and public sector. The post.doc. fellows, PhD-candidates, and their supervising professors were also an integral part of the Center. The Director and Center Management stimulated to open and transparent collaboration between all of the Partners. A culture of "trust and sharing of knowledge" was established and upheld throughout the project.

Interaction between the Partners was facilitated through regular meetings in the Research Areas, Center Management, Executive Board, Innovation Committee, Annual Meetings, and General Assembly. In addition, there were organized numerous workshops and seminars on selected topics to establish concrete collaborations between the Partners. This ensured that the research tasks were aligned with the strategic direction in the Center and also aligned with the needs of the User Partners. Several of the Industry Partners played an active role in the research within the Center, including close collaboration with PhD students and researchers.

Most of the MoZEES events and annual meetings included closed sessions, exclusive to members of the Consortium. This format gave ample time for in-depth internal discussions, which contributed to great openness and willingness among the Industry Partners to share their insights. A MoZEES Innovation Forum was also established as a dedicated arena to actively engage the Industry Partners in more R&D activities. The main objective with the MoZEES Innovation Forum was to align the battery and hydrogen research activities in the Center with national innovation efforts and to generate spin-off projects in collaboration with relevant industrial clusters in Norway and abroad.

13) Acknowledgements to the other RA leaders: Fride Vullum-Bruer (RA1, 2017.2018), Magnus Thomassen (RA2, 2017-2020), Øystein Ulleberg (RA3, 2017-2019), and Ragnhild Hancke (RA3, 2019-2022).

Research Partners

IFE
SINTEF
NTNU
UNIVERSITETET I OSLO
tøi
USN
FFI

Industry Partners

ABB
ASKO – vi forsyner Norge med mat
baldur BALDUR COATINGS AS
CENATE
Cerpotech
Corvus Energy SUMISHO CORVUS ENERGY CO., LTD.
DNV
Elkem
equinor
Hydro
HEXAGON
JM Johnson Matthey
MORROW
nel
OCEAN HYWAY CLUSTER
saft
Selfa
Teer coatings
KUNNSKAPSBYEN LILLESTRØM
ZEM
Statkraft
UNIBUSS
Vysus Group

Public Partners

AKERSHUS FYLKESKOMMUNE
enova
Jernbane-direktoratet
KYSTVERKET
OSLO HAVN
Statens vegvesen
Trøndelag fylkeskommune Tröndelagen fylhkentjïelte

Public Partners

UPPSALA UNIVERSITET
UCDAVIS
UNIVERSITÀ DEGLI STUDI DI GENOVA
RWTH AACHEN UNIVERSITY

6. Financing of the Center

A summary of the total funding of MoZEES is provided in Table 4 below. More details in Appendix 1.

Table 4 – Funding of MoZEES (MNOK)

Contributor	Cash	In-kind*	Total
Host	0	13	13
Research partners	0	56	56
Companies	12	32	44
Public partners	14	5	19
RCN	120	0	120
Sum	144	108	252

7. Results – Key Figures

A summary of the main results (key figures) from MoZEES is provided in Table 5 below. More details in Appendix 4.

Table 5 – MoZEES key results and figures

	2017	2018	2019	2020	2021	2022	2023	2024	Total
Scientific publications (peer reviewed) [14)]	6	7	14	11	20	18	11	13	**100**
Dissemination measures for users	47	96	72	28	38	43	24	26	**374**
Dissemination measures for the general public	12	4	11	10	4	0	2	6	**49**
No. of new/improved methods/ models/prototypes finalised	3	1	1	3	0	0	3	3	**14**
No. of new/improved products/ processes/ services finalised	3	0	3	1	2	0	1	1	**11**
Post.Doc. studies completed[15)]	0	3	1	1	1	2	1	3	**12**
PhD-degrees completed[16)]	0	0	0	1	1	4	2	3	**11**
Master degrees	1	1	5	4	3	6	6	3	**29**

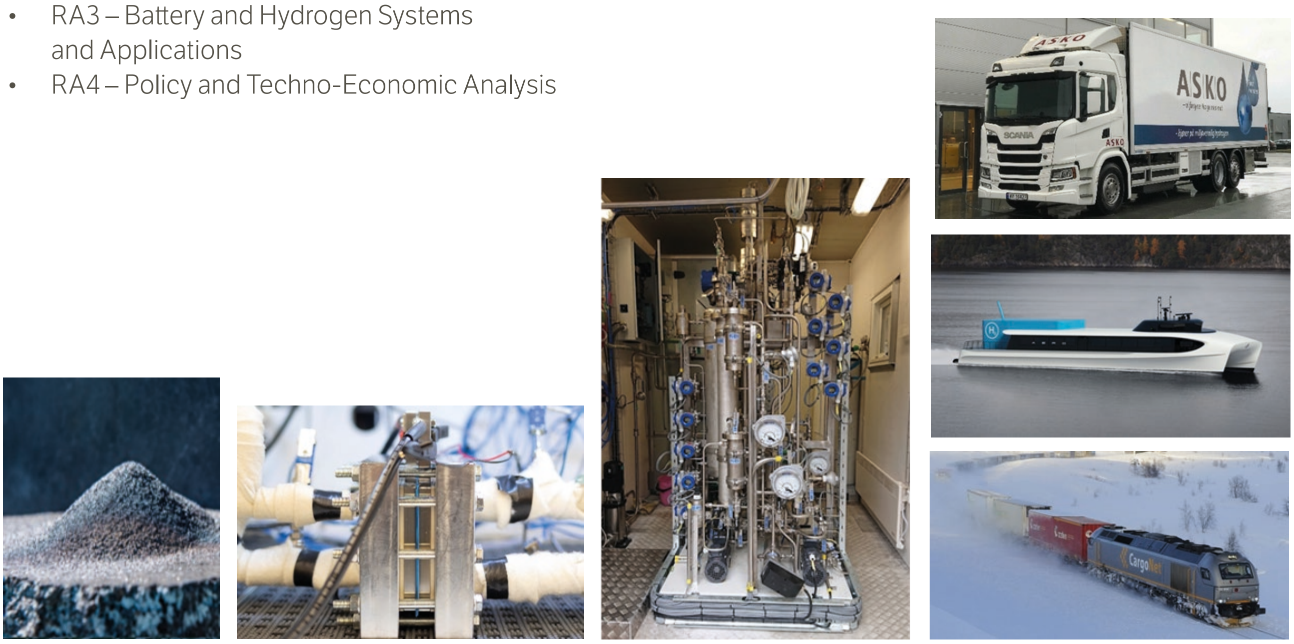
14) Additional two publications in Q1 2025 and a few more expected to come later in the year
15) More details on Post.Doc., PhD, and Master Studies provided in Appendix 2 and References
16) Two more PhD degrees to be completed, one in 2025 and one in 2026

8. Research Areas

The four main Research Areas in MoZEES (listed below and illustrated in Figure 6 were kept constant throughout the project period. Furthermore, only small adjustments and changes in the specific research tasks within the research areas were made.

- RA1 – Battery Materials and Components
- RA2 – Hydrogen Components and Technologies
- RA3 – Battery and Hydrogen Systems and Applications
- RA4 – Policy and Techno-Economic Analysis

Adjustments and changes in the research tasks were made to consolidate the research on Li-ion batteries in RA1, fuel cells and water electrolysis in RA2, and fuel cell systems in RA3. These changes came as a result of better communication and alignment between the Research and Industry Partners on how the research should be performed. More details are provided in the MoZEES Roadmaps shown below.



(a) **(b)** **(c)** **(d)**

Figure 6 – MoZEES research areas focused on (a) Li-ion battery materials, (b) PEM[17] fuel cells and water electrolysis technology, (c) Battery and hydrogen systems, and (d) Heavy-duty transport applications on road, rail, and sea[18] using battery and hydrogen key technologies and systems from (a), (b), and (c).(Photos: Elkem (a), SINTEF (b), IFE (c), ASKO (top d), Norwegian Railway Directorate (middle d), Brødrene Aa (bottom d).

Technology Roadmaps

The following battery and hydrogen technology road maps were developed as part of work in the Center. The MoZEES Roadmaps were first launched in 2020 and later updated in 2023.

17) Proton Exchange Membrane (PEM)
18) Short range, near coastal operations

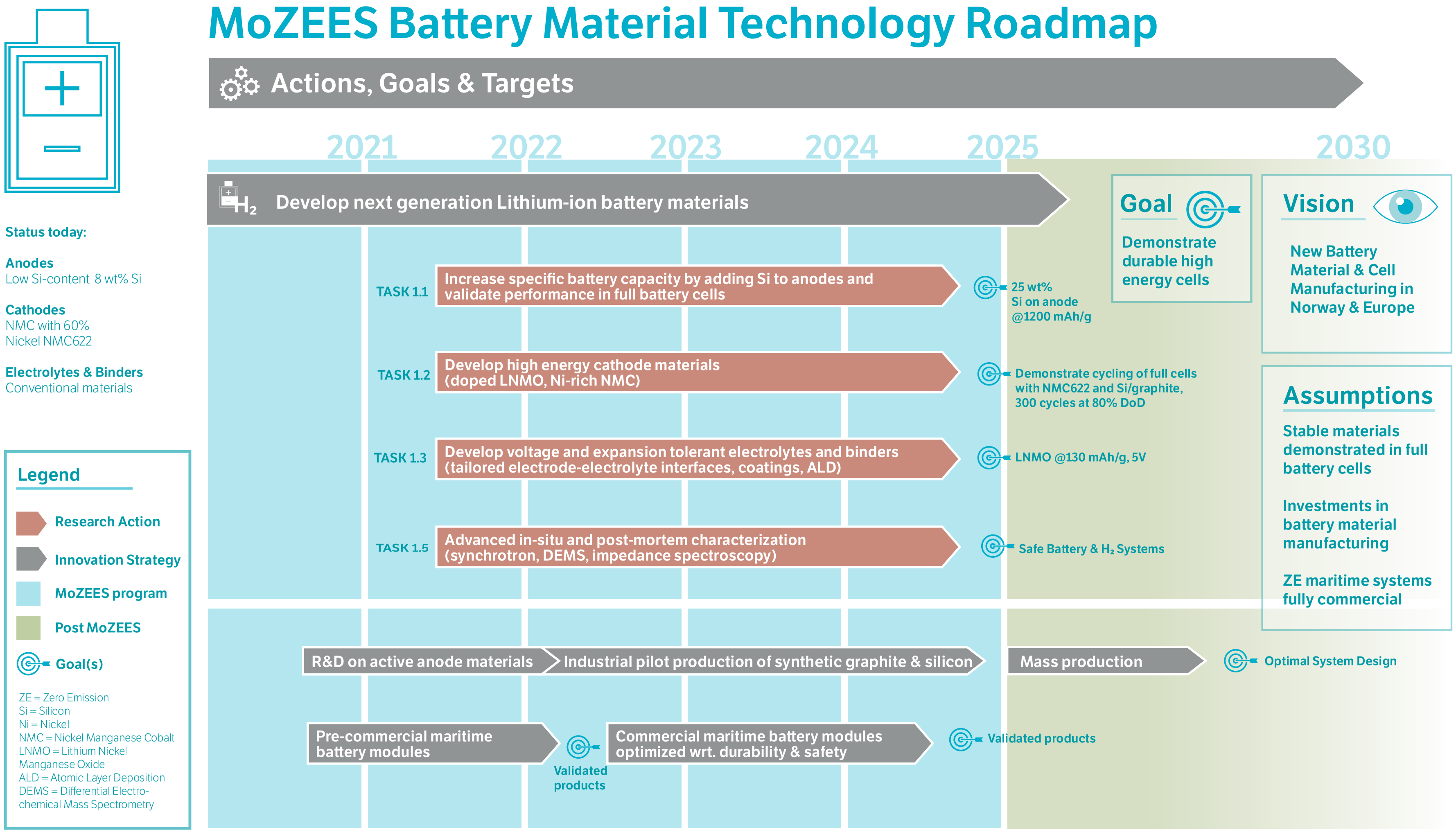


Figure 7 – MoZEES Battery Material Technology Roadmap (Illustration: IFE/MoZEES)

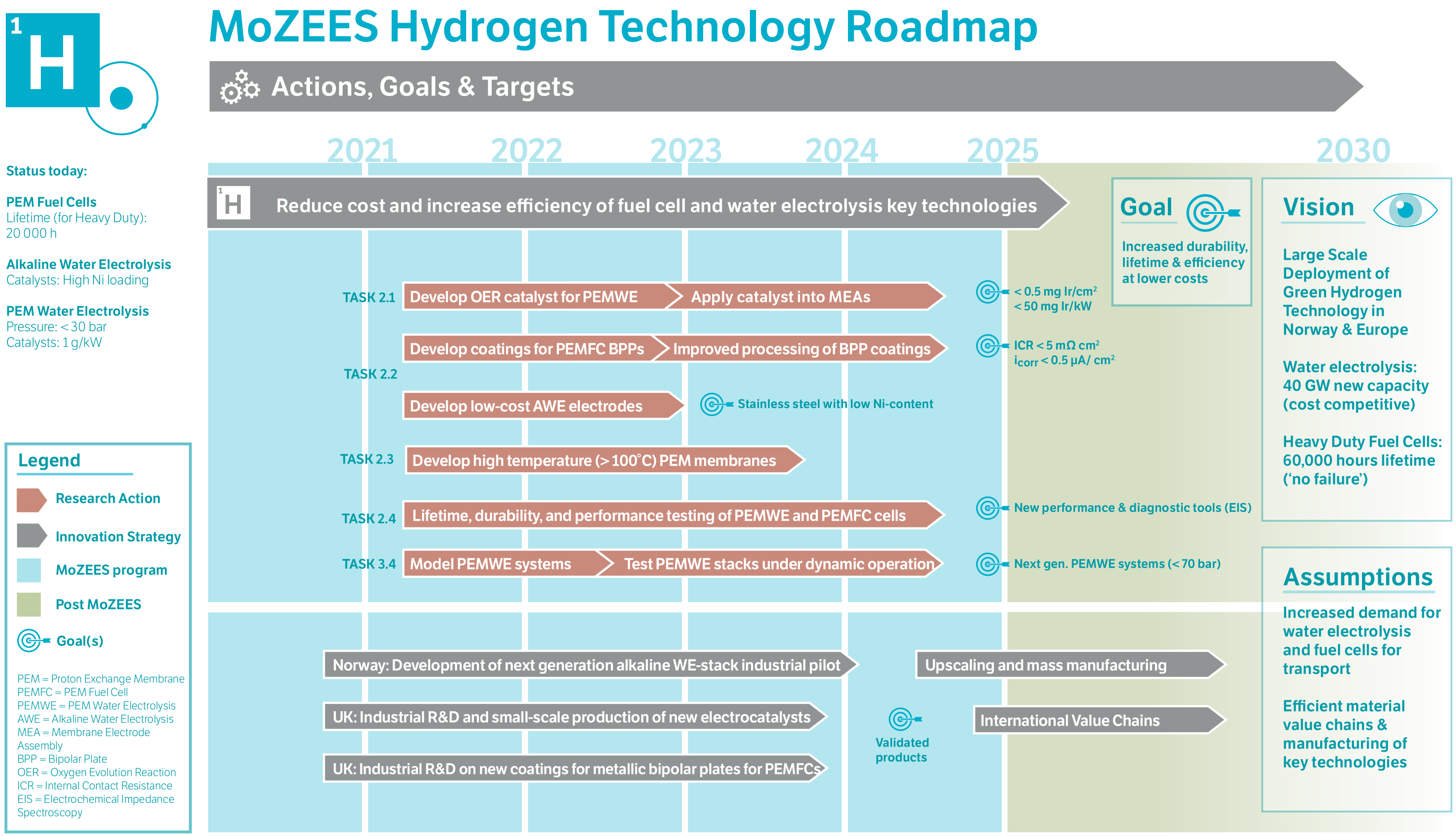


Figure 8 – MoZEES Hydrogen Technology Roadmap (Illustration: IFE/MoZEES)

RA1 –Battery Materials and Components

The main objective with RA1 was to develop novel battery technology to improve battery performance and reduce production cost, with focus on improved materials solutions for the next generation batteries. The roadmap for the MoZEES battery material research is provided above (Figure 7) and a summary of the main research activities in RA1 are illustrated below (Figure 9). The main RA1 research objectives and goals for the second half of the Center period were to:

- Improve the understanding of reaction mechanisms in Si-electrodes by using advanced characterization techniques (e.g., pair distribution functions, neutron scattering, impedance spectroscopy)
- Demonstrate adequate pre-lithiation procedures for Si-based electrodes
- Improve the understanding of how different binders influence the performance of both silicon anodes and cathode materials (e.g., high Ni-NMC[19] and LNMO[20])
- Improve the stability of LNMO high voltage cathodes with alternative electrolytes
- Evaluate Al-doping of LNMO cathodes
- Perform experimental work with fundamental modelling
- Perform round Robin test with electrodes provided by Industry Partners

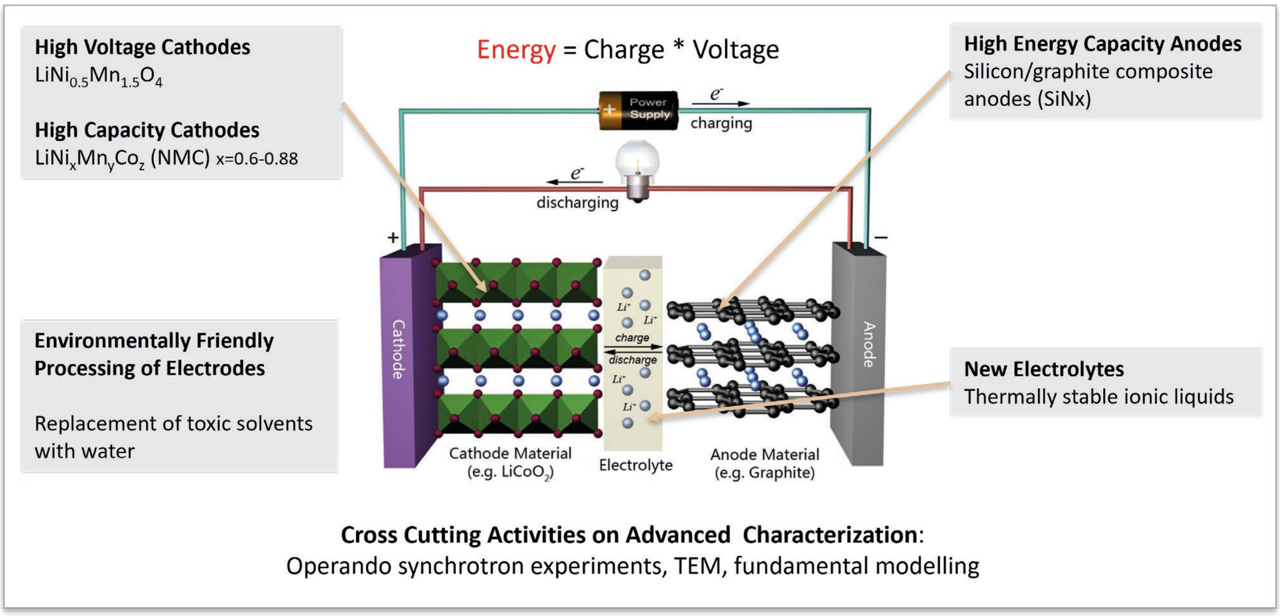


Figure 9 – Overview of key research areas on battery materials and components in RA1 (Illustration: NTNU)

19) Nickel-rich Nickel Manganese Cobalt (NMC)
20) Lithium Manganese Nickel Oxides (LNMO)

RA1 Research Achievements and Highlights

The research conducted within the framework of RA1 has so far been published in 3 PhD thesis [1-3] (two more PhDs at UiO are still in progress[21]), two reports [4, 5], 38 scientific publications[22] [6-43], and about 45 presentations at international conferences. One patent originates from the research activities in RA1. Results were also disseminated in numerous presentations at international conferences and national meetings and seminars. A total of 5 PhD candidates and 3 Post Docs in RA1 were funded by MoZEES. Furthermore, 20 master students were affiliated with the RA1 research area [44-62]. Below is a summary of the main research achievements in RA1.

Task 1.1 – Silicon Anode Materials for Li-ion Batteries

In Task 1.1 low cost metallurgical grade silicon supplied by Elkem was studied in combination with alternative electrolytes in a PhD at NTNU [2]. Thermally stable ionic liquid and improved stability during charge and discharge was demonstrated. New types of silicon nitride (SiNx) materials were developed at IFE during the project period and the quality of the SiNx material produced today show great promise with respect to practical application in Li-ion batteries. At UiO the research on silicon electrodes by a post-doctoral fellow (Alok Tripani) resulted in a US patent related to specific additives for the electrodes.

IFE has demonstrated excellent cycling performance for their in-house synthesized SiNx materials, with optimized stoichiometry of silicon nitrides (Figure 10). This is a promising candidate anode material for next generation Li-ion batteries since it will be more stable compared to anodes with pure silicon, but with a somewhat lower capacity. The SiNx materials gave good cycling stability for 1000 cycles, and only minor morphological changes were observed for 400 nm sized particles after 1000 cycles [8, 10, 11, 13, 15, 32-35].

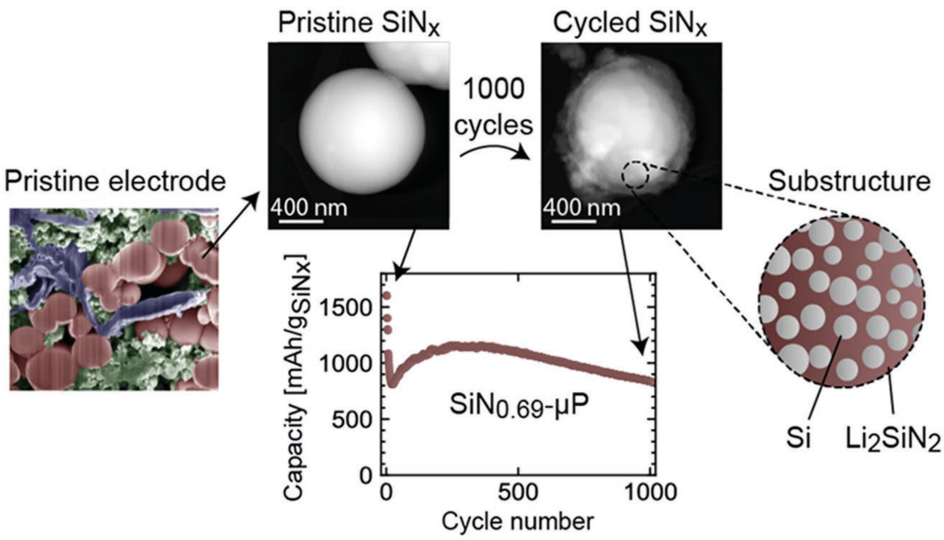


Figure 10 – Demonstration of excellent cycling performance with optimized stoichiometry of silicon nitrides (SiNx) [35] (Illustration: IFE)

21) One PhD will be completed in 2025 and another one in 2026 (more details in Appendix 2).
22) Two more publications are have been submitted and more publications from the PhDs are expected

Task 1.2 – High Energy Cathodes

The main focus of Task 1.2 was to develop the next generation cathode material of $LiMn_{1.5}Ni_{0.5}O_4$ (LMNO). This material is currently suffering from challenges related to cycling stability. One approach taken was to improve the cycling stability of LMNO by partly substituting Ni with other metals. This was done by substituting some of the Ni with Al, Co, and even Mn ($LiMn_{1.5}Ni_{0.5-x}M_xO_4$, where M=Al, Co, Mn and 0≤x≤0.5). This was the main topic in a PhD study at UiO, which will be completed in 2025 (PhD-candidate Halvor Høen Hval). In this study suitable stoichiometries have been identified using advanced synchrotron characterization techniques. At SINTEF a study was performed to identify degradation mechanisms and how they relate to charging procedures of batteries based on Ni-rich layered NMC cathodes.

Aqueous processing for NMC622 cathodes from an industry-relevant rapid processing perspective was also investigated at SINTEF. This technique may have a significantly positive impact on the environmental. The experimental results showed that with shorter "wet" times than those previously reported (ca. 45 minutes vs. 3 hours or more), high quality cathodes could still be obtained. The resulting NMC cathode showed a good capacity retention of 78% over nearly 400 cycles. The process is considered to be promising, provided that it can be optimized to avoid unreacted residues in the electrode [31].

Task 1.3 – Voltage and Expansion Tolerant Electrolytes and Binders

In Task 1.3 the research focused on LNMO cathodes. Two viable routes were identified for improving the cycling stability of the LNMO cathodes under study. The first route was related to development of protective coatings, where thin coatings (nm scale) of TiO_2 was demonstrated to improve the cycling stability [1]. This was then combined with the best performing ionic liquids identified in the PhD [1] to improve the cycling stability of LNMO cathodes a post.doc. at NTNU (Inger

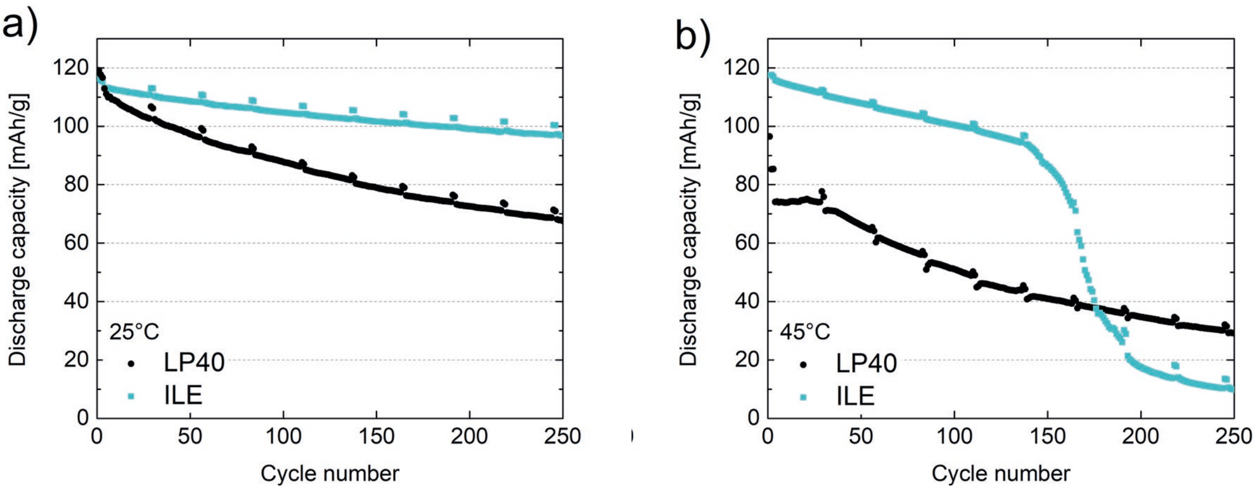


Figure 11 – Ionic liquids with good properties identified: 1.2 M LiFSI in Pyr13FSI, combined with LNMO cathodes, compared to LP40 electrolyte [2]. (Illustrations: Rogstad, NTNU)

Emma Nylund). The conclusion from the work at NTNU was that electrolytes based on ionic liquids give excellent thermal stability, while they at the same time improve the cycling stability of both silicon anodes and LNMO cathodes (Figure 11). Post mortem investigation of the LNMO cathodes by TEM[23)] could not reveal any significant degradation after cycling in ionic liquid electrolytes [12, 18, 21, 23, 24].

At SINTEF another viable route for aqueous processing of Ni-rich NMC was identified. The hypothesis is that by replacing toxic solvents with water the environmental footprint of the battery production can be reduced. However, in practice this has proven to be very challenging for Ni-rich NMC type materials. However, by adding orthophosphoric acid to the slurry to both buffer the pH and precipitate transition metals at the NMC surface was identified as a possible new method.

Task 1.4 – Nickel Metal Hydride Batteries

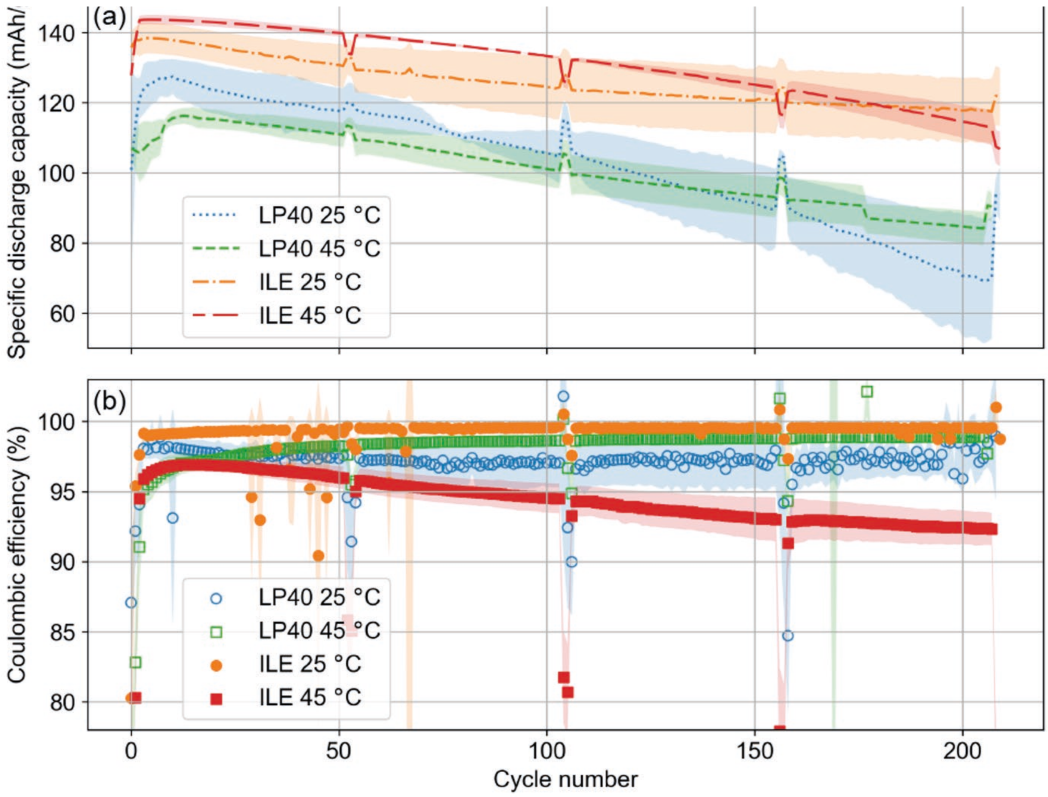
In the first half of the Center period there was conducted and completed a PhD study at NTNU on nickel metal hydride battery materials [3], in close collaboration with IFE and BASF-Ovonic in the US. The work in this PhD focused on the development of high capacity, high power, and cost efficient metal hydride anodes. Excellent electrochemical performance of a new metal hydride alloy ($Ti_{0.15}Zr_{0.85}La_{0.03}Ni_{1.2}Mn_{0.7}V_{0.12}Fe_{0.12}$) with a discharge capacity reaching 420 mAh/g was demonstrated. The excellent kinetics of charge and discharge observed in this alloy was found to be related to the catalytic effect of LaNi (1-2 wt.%) which facilitates the H exchange in the alloy. Increased electrochemical performance was achieved by nano structuring with use of rapid solidification. The NiMH materials studied avoided the use of expensive rare earth metals. Unfortunately, the NiMH activity needed to be terminated when BASF left the project in 2019.

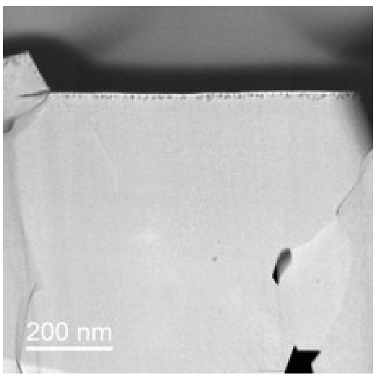
Task 1.5 – Characterization of Battery Materials

In Task 1.5 the main objective was to apply and develop advanced battery material characterization techniques, including the use of operando synchrotron characterization techniques, TEM, and atomistic modelling tools. Experiments conducted by UiO at the ESRF[24)] helped to reveal the chemical changes in silicon anode materials. This work was a collaborative effort between UiO (PhD-candidate Casper Skautvedt) and IFE. Detailed structures of various LNMO materials synthesized by the PhD in Task 1.2 (PhD-candidate Hval) were also studied at ESRF. Furthermore, extensive TEM studies were conducted at NTNU in order to gain new insights into the degradation mechanisms of LNMO on an atomistic scale (Figure 12). At UiO the fundamental modelling tools have been applied to reveal details of the lithiation intercalation mechanisms by using molecular dynamic (MD) simulations combined with reactive force field (ReaxFF) (Post. Doc. Heesoo Park).

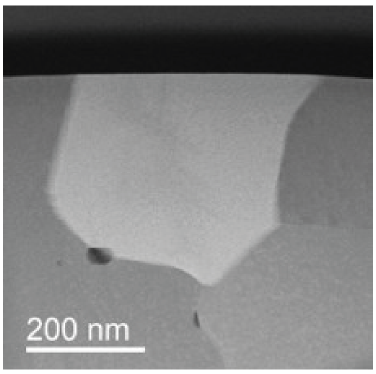
The work on developing advanced operando techniques has successfully progressed at UiO. One such advanced methodology is operando total scattering computed tomography (TSCT). By using this TSCT technique on silicon anodes, the chemical changes taking place in the electrodes during lithiation could be visualized, and a 3D-mapping of the electrode components including amorphous active and inactive materials was made. Subtle, structural transformations at the atomic scale during lithiation could be revealed by careful analysis of so-called pair-distribution functions (PDF). In this way, more precise knowledge of the lithiation of silicon can be obtained, such as the new bonds forming in the alloys, as well as onset potentials for the reactions [8, 20, 27, 41]. It should also be mentioned that research work in RA1 by a post-doctoral fellow Alok Mani Tripathi and Professor Helmer Fjellvåg at UiO led to a US patent in 2022 on "Battery with electrode having additive showing improved electrical properties"[25)].

23) Transmission Electron Microscopy (TEM)
24) European Synchrotron Radiation Facility (ESRF)
25) US Patent number: US20240222711A1





LP40 after 210 cycles @25˚C



ILE after 210 cycles @25˚C

Figure 12 – Results from advanced characterization of LNMO cathodes cycled in 1.2 M LiFSI in P111i4FSI, compared to LP40 (Illustration/ Photos: Nylund, NTNU)

RA2 –Hydrogen Components and Technologies

The main objective with RA2 has been to lower the cost and increase the efficiency of low temperature PEM fuel cells and alkaline and PEM water electrolyzers. All of the specific research tasks in RA2 ran throughout the project period, except for the technical work on pressurized hydrogen storage composite cylinders which was terminated after the completion of a PhD at NTNU in 2020. Some theoretical work on pressurized hydrogen storage was continued in studies in RA3 and RA4. In the second half of the Center (2021-2024) the main focus of the research in RA2 was on material development for electrochemical devices:

- High-performance catalysts enabling ultra-low precious metal loading
- Low cost, corrosion-resistant bipolar plates
- Low cost, high-performance membranes

A key research activity in RA2 was to perform *in-situ* tests of advanced oxygen evolution catalysts and to test bipolar plates and electrodes for fuel cells and water electrolyzers made by industry partners. In the second half of the Center there was also an increased focus in RA2 on generating experimental PEM fuel cell performance data (Figure 13) that could be used in the degradation and lifetime models required for the system level modeling in RA3.

Figure 13 – Testing and evaluation of the performance of PEM fuel cells was a key research activity in MoZEES (Photo: Norwegian Fuel Cell and Hydrogen Centre, SINTEF, Trondheim).

RA2 Research Achievements and Highlights

The research activities in RA2 included the completion of 2 post-doctoral fellowships, 3 PhD theses [63-65], one master thesis [66], and 5 reports [67-71]. The work performed in RA2 resulted in 19 scientific publications [72-90] and around 30 presentations at international scientific conferences. Below is a summary of the main research achievements in RA2.

Task 2.1 – High-Performance Catalysts

Proton exchange membrane water electrolysis (PEMWE) requires the use of rare and expensive PGM[26] catalysts. Iridium (Ir) is favored for its exceptional catalytic activity and stability and is utilized in the oxygen evolution reaction at the anode where conditions are notably harsh. Since Ir is a metal with limited supply (high risk material) it is necessary to reduce the use of the material in large-scale deployment of PEM water electrolysis. The research in MoZEES in this area has focused on two routes in parallel:

1. Preparation of catalysts by galvanic replacement
2. Investigation of the possibility to use ruthenium pyrochlores to reduce the iridium loading

In the first approach SINTEF developed a method for depositing nanoparticles of platinum group catalysts on oxide support particles, a promising method for reducing the loading of the catalysts. This research later turned out to also be applicable to iridium. A collaborative effort with one of the Industry Partners in the Center showed that high-quality oxide powders from Cerpotech can be used as catalyst supports for PEM water electrolysis.

In the second approach the focus was on synthesis and characterization of ruthenium based ($Ru_2Y_2O_7$) pyrochlore catalysts. Ultrasonic spray deposition was used to prepare CCMs[27] where the Ru pyrochlore catalyst was used to dilute state-of-art iridium oxide (IrO_2) materials. SINTEF collaborated with other Industrial Partners on this topic and received good inputs from Johnson Matthey and Nel. The composite catalyst was characterized in full cell tests. The initial results were promising, but more work is needed to optimize the CCMs to achieve higher activity and durability than pure IrO_2. Both routes are promising and are continued in spin-off projects.

Task 2.2 – Low-Cost Bipolar Plates and Electrodes

The work on bipolar plates was concentrated on two specific topics

1. Low-cost bipolar plates for PEM fuel cells (Figure 14).
2. Low-cost electrodes for alkaline electrolyzers

In PEM fuel cells the bipolar plates are typically made from coated titanium which typically contribute to about 25% of the cost and 50-80% of the weight of the fuel cell stack; hence, material reductions are needed. In the first half of the Center a novel in-situ method for measuring the interfacial contact resistance between the bipolar plate and the gas diffusion layer of an operating PEM fuel cell was developed [78]. Promising results were also achieved with stainless steel bipolar plates coated by Teer Coatings, one of the international Industrial Partners in the Center. Challenges related to coating processes and lifetime and coatings on aluminum bi-polar plates was the key focus in the second half of the Center. A key output from this research activity in MoZEES were the AST[28] protocols developed for testing of degradation in bipolar plates.

26) Platinum Group Metals (PGMs)
27) Catalyst Coated Membranes (CCMs)
28) Accelerated Stress Test (AST)

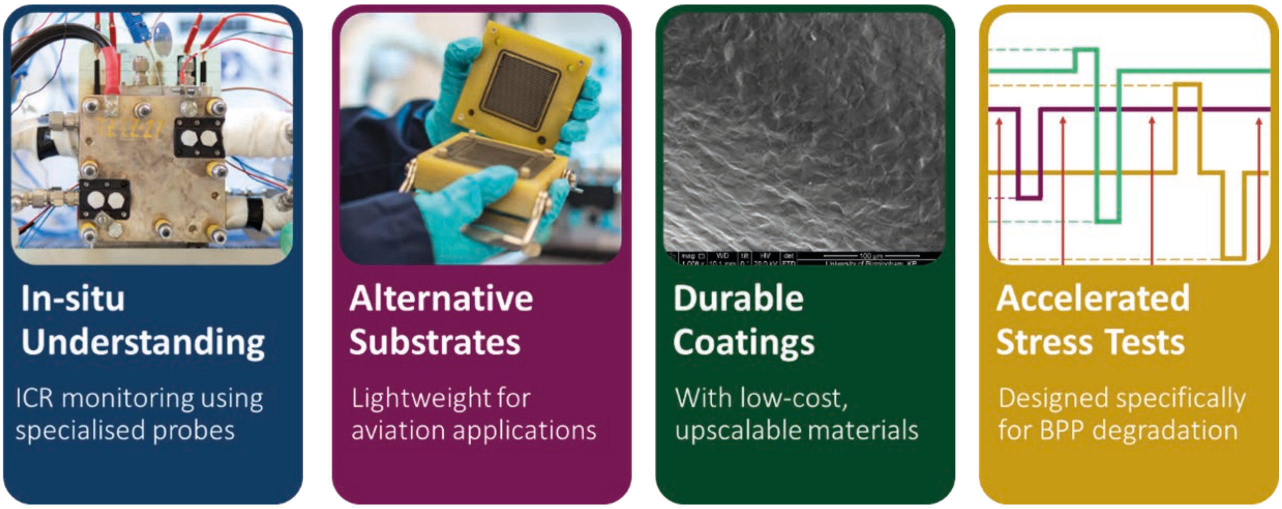


Figure 14 – Overview of key research trends for bipolar plates in PEM fuel cells (Illustrations/Photos: McCay, SINTEF)

A PhD at NTNU on new alkaline water electrolysis materials was completed in 2022 [65]. The focus of this PhD was to study the activation of stainless-steel electrodes, as this is a less costly alternative to the commonly used nickel electrodes. In the activation process, the morphology and chemical composition of the electrode is modified, to make the surface of the steel electrode more active toward the hydrogen and oxygen evolution reactions. The research results from this PhD were of high interest to Nel, the main Industry Partner in MoZEES on water electrolysis. The research in this area led to two publications [87, 90] and several presentations.

Task 2.3 – Low-Cost Membranes

The PhD at UiO on high-temperature proton exchange membranes (PEM) was one of the most fundamental and exploratory studies in MoZEES. The initial focus of the PhD was to develop high-temperature membranes by using composite membranes with ceramic nanoparticles as fillers in polymer membranes. This led to a review paper that received the Membranes 2021 Best Paper Award [82].

However, detailed studies on the effect of the ceramic fillers revealed that it was necessary to get a much deeper understanding of the conductivity of protons on the surface of the ceramics to unlock the potential of the ceramic fillers. Hence, the focus of the PhD was shifted to the field of surface protonics [79-81, 83-85].

Task 2.4 – Lifetime, Durability, and Performance

The main objective with this task was to understand how operating conditions affect the lifetime of PEM fuel cells and water electrolyzers. In MoZEES the focus was on fuel cell for heavy-duty applications, including maritime applications, with the goal to extend the lifetime of PEM fuel cells from 20 000 to more than 40 000 hours (Figure 8). To achieve long life times in fuel cells it necessary to monitor the performance of the fuel cells during operation and link this to their degradation mechanisms. In the first half of the Center there were set up some single-cell PEM fuel cell experiments at SINTEF to study the degradation mechanisms using advanced electrochemical characterization techniques. From these experiments it was possible to extract the most relevant parameters as inputs for the degradation modelling and experimental stack testing activities in RA3 (performed in the second half of the project period).

In the first half of the Center (2018) there was also performed some preliminary work at IFE on in-plane neutron imaging of an operating PEM water electrolysis cell at the Paul Scherrer Institute (PSI) in Switzerland, with the objective to characterize the water transport as a function of current density and water flow rate. This work was not continued, but a detailed understanding of the requirements for setting up such PEMWE imaging experiments was obtained.

In the second half of the MoZEES project period the focus in RA2 and RA3 (joint activity) shifted towards the development of new performance and diagnostics tools based on electrochemical impedance spectroscopy (EIS). Two different techniques to evaluate the fuel cell efficiently were developed at SINTEF and IFE:

1. Multisine Electrochemical Impedance Spectroscopy (EIS)
2. Distribution of Relaxation Times (DRT)

In Multisine-EIS the signals are sent in many frequencies simultaneously to give more and faster results (Figure 15). A common paper documenting the viability of the methodology was published [75]. In the DRT method the Fourier-transformations can be used on the impedance results, making it easier to distinguish between different degradation mechanisms in the fuel cells. The results from the DRT-analyses showed that the technique can be used in detailed studies on both fuel cells and water electrolyzers and can be performed both on single cells and smaller stacks.

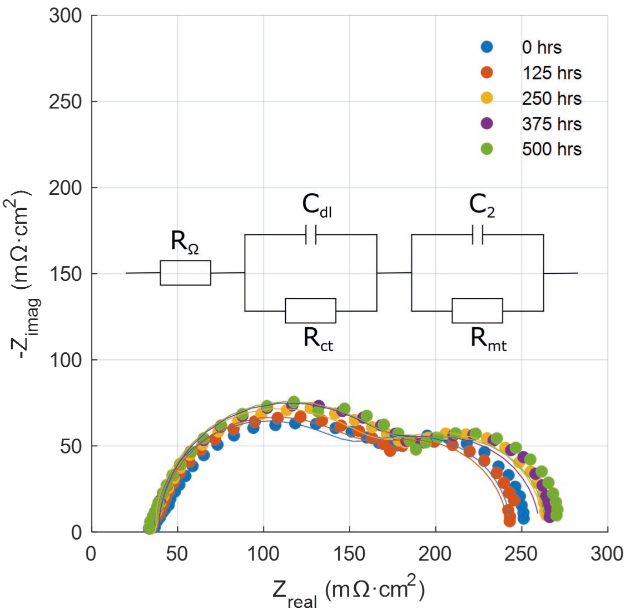


Figure 15 – In-situ electrochemical characterization of PEM fuel cells using multisine-EIS [75].

Task 2.5 – Hydrogen Storage Tanks

A PhD at NTNU with focus on fatigue mechanisms in hydrogen composite cylinders was completed in 2020. This work showed that DIC-monitoring (Digital Image Correlation) can be used to recognize material strains and early fatigue damage. This result was highly interesting and relevant for several of the Industry Partners in the Center, particularly Hexagon. One of the main conclusion from the work was that the fatigue properties measured locally via the DIC-method can be used to better predict damage growth under fatigue around a defect. The prediction can be done by novel ways to model fatigue damage growth in a finite element program. The scientific work resulted in three peer-reviewed scientific publications [76, 77, 89].

RA3 – Battery and Hydrogen Systems and Applications

The main objective with RA3 was 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. The research activities in RA3 linked the materials and component development in RA1 and RA2 with the systems and applications analyses in RA4. The main goals with the research in RA3 throughout the Center was to design:

- Optimal control systems for battery and fuel cell systems with respect to long lifetime
- Safe and low risk heavy-duty battery and hydrogen systems
- Low cost renewable energy (RE) based water electrolysis and hydrogen supply systems

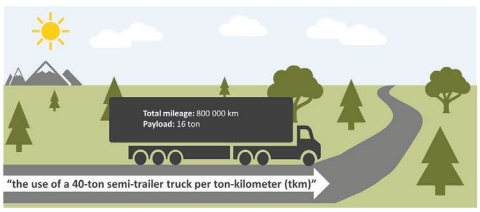
The work plans in RA3 were annually updated with input from the Research and Industry Partners in the Center. With the addition of three new large energy companies in MoZEES in 2019 (Statkraft and Hydro) and 2020 (Equinor) there was an increased interest from the Industrial Partners for more research on RE-based PEM water electrolysis systems and Li-ion batteries materials and systems. A MoZEES Zero-Emission Heavy-Duty Transport Roadmap (Figure 2) was developed with input from RA3 and RA4 in 2020 and provided the following main direction for the individual research tasks within RA3 for the second half of the Center:

- Operation of hybrid maritime PEM fuel cell/Li-ion battery systems; optimization of lifetime for both fuel cells and batteries
- Safety and risk analyses, experiments, and modeling related to battery and hydrogen in heavy-duty vehicle (trucks), maritime, and railway applications
- Design and operation of water electrolysis processes suitable for renewable energy based dynamic operation; optimization with respect to lifetime of PEMWE stacks

The RA3 work plan also included cross-cutting activities on some selected case studies. These MoZEES Case Studies included technical (RA3) and techno-economic (RA4) analyses on the use of battery and hydrogen technology in different heavy-duty zero-emission transport applications:

1. Maritime Case Study (2018-2020)
2. Zero-Emission Truck Case study (2020-2024)
3. Railway Case study (2023-2024)

High Speed Crafts
- Hydrogen Safety
- Energy Calculations
- Techno-Economics



Heavy-Duty Trucks
- Battery and Hydrogen vs. Diesel
- Life Cycle Analysis
- Techno-Economics

Freight Train
- Energy Calculations
- Battery Safety & Lifetime

Figure 16 – Overview of the MoZEES Case Studies: (1) Hydrogen high speed passenger ferries, (2) Zero emission heavy-duty trucks, and (3) Battery electric freight train (Nordlandsbanen).(Illustrations/Photos: Brødrene Aa, TØI, Norwegian Railway Directorate)

RA3 Achievements and Highlights

In RA3 there were completed 4 post-doctoral studies, 2 PhD theses [91, 92], and 8 MSc theses [93-100], 12 reports [101-112], 26 scientific peer-reviewed publications [113-138], and more than 100 presentations at international scientific and technical conferences. In addition, there was made a special effort to disseminate the work in RA3 on safety of hydrogen and Li-ion battery systems. The Center hosted two safety seminars in Lillestrøm, both open to the public. The first MoZEES Safety Seminar in 2021 had 50 participants and focused on first responders (fire departments), while the second MoZEES Safety Seminar in 2024 had 40 participants and focused on regulatory authorities. These hydrogen and battery safety seminars offered an opportunity for internal and external MoZEES stakeholders to meet and get updated information in a rapidly changing field (e.g., safety in battery-electric vehicles and ferries).

Task 3.1 – Advanced Fuel Cell Control Systems

In the first few years of the Center (2017-2020) data on different ships suitable for zero-emission operation was collected and analyzed. Specific load profiles and duty cycles for the power system in a high-speed passenger vessel operating in/out of Florø was established based on AIS[29] data provided by Kystverket[30] for the MoZEES Maritime Case Study (Task 3.5). A battery/fuel cell electric system model was established in Matlab Simulink, and initial tests for using machine learning to predict performance of PEM fuel cells were carried out. In 2020 an internal MoZEES report on "Diagnostics and prognostics of fuel-cell systems" was completed at SINTEF, and initial PEM fuel cell short stack testing protocols with generic dynamic load profiles was carried out.

The design, development, and integration of a national laboratory and experimental setup for characterization and validation of PEM fuel cell stacks and system was commissioned and completed at IFE in 2021/2022. This included the development of detailed P&ID[31] diagrams, acquisition of suitable fuel cell balance of plant components, and electrical and mechanical integration of the system components. The PEM Fuel Cell System Laboratory at IFE also included a LabView control program, which was used to implement different EMS[32] strategies developed in a dedicated MoZEES post.doc. study (Mustapha Jamma, 2023-2024).

In the post.doc. study at IFE a set of battery/fuel cell power and control system modeling tools in Matlab Simulink were completed (Figure 17) and used to perform detailed simulation studies on how to optimize the EMS-strategies in hybrid systems with respect to battery and fuel cell lifetime. The performance of the PEM fuel cell stack and key BoP[33] systems were then tested and evaluated using power load profiles derived from simulation of various maritime use cases and hybrid battery/fuel cell system operations. A complimentary review at SINTEF on the design of fuel cell control systems was also completed.

Finally, the suitability of multi-sine EIS as a diagnostic technique for in-situ monitoring and fault detection during fuel cell operation was experimentally validated. In RA2 it was demonstrated that full multi-sine EIS spectra (50 kHz - 500 mHz) can be collected and analyzed using simple equivalent circuit models in 50 seconds [75]. In RA3 it was demonstrated that this EIS-technique also can be applied to larger PEM fuel cell stacks. This work continues in FME HYDROGENi.

29) Automatic identification System (AIS)
30) Norwegian Coastal Administration (Kystverket)
31) Process and Instrumentation Diagram (P&ID)
32) Energy Management Systems (EMS)
33) Balance of Plant (BoP)

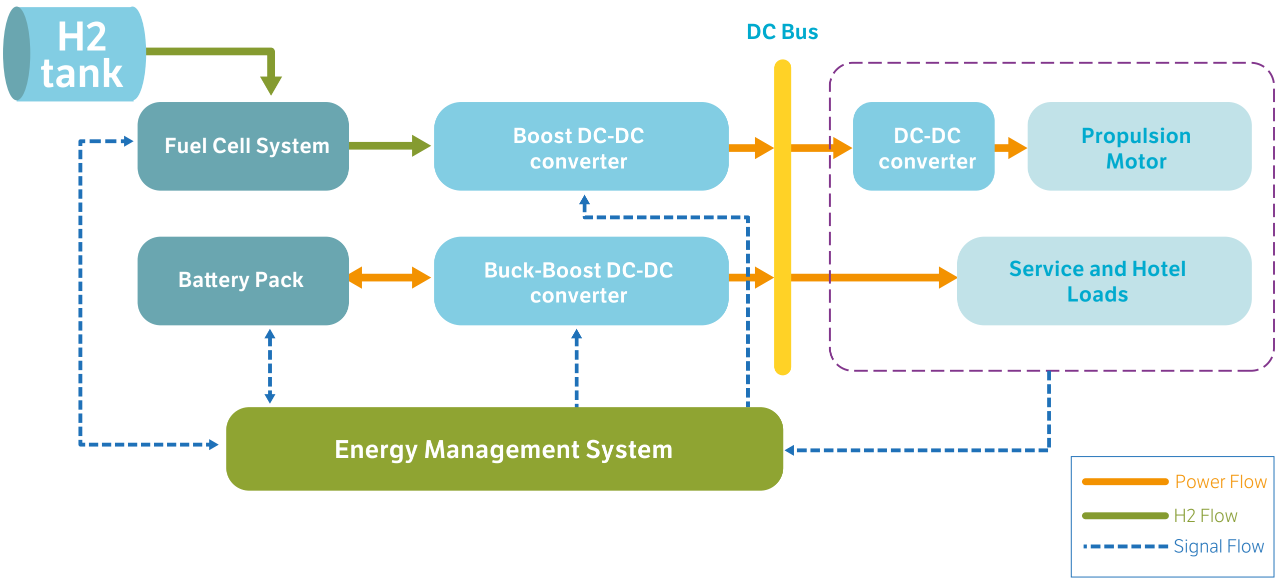


Figure 17 – Single line diagram for Matlab Simulink modeling of hydrogen based battery/fuel cell hybrid power systems for propulsion of smaller ships and vessels (Illustration: Jamma, IFE)

Task 3.2 – Battery Cell Lifetime, Durability, and Safety

Battery lifetime and safety is closely interrelated, as severe degradation in Li-ion battery cells can lead to unsafe operation and hazardous incidents (e.g., thermal runaways). This is particularly true for NMC-type batteries. Many years of data collected from testing of Li-ion batteries at IFE was made available to MoZEES in the beginning of the Center. A data driven battery cycle life ANN[34] -model was developed in an in-kind post.doc. at IFE (Mohsen Vatani, 2018-2019). A paper on the state of health (ageing) prediction of li-ion batteries based on ANN-modeling using two sets of battery testing data (LFP and NMC) was published [136]. Complementary battery post-mortem studies were performed at SINTEF, first on fresh 18650 Li-ion cells with an NMC-graphite chemistry (2018) and later on cycled battery cells (2019). The cells were studied with X-ray computer tomography (CT) before they were opened and electrodes and electrolyte studied and analyzed by respectively SEM/EDS[35] and GC/MS[36] .

In 2019 it was decided to acquire a MoZEES Li-ion battery reference cell with a known cell chemistry, with the objective to develop and validate battery cell performance testing methods and to publish results with no restrictions. The Li-ion battery reference cell selected was a small tailor-made pouch cell (142 mm × 125 mm) with a graphite anode, NMC622-cathode, and electrolyte with known additives and solvents; 50 pouch cells were purchased from CustomCells (Germany). The first post-mortem study in 2020 revealed that there were some quality issues with the cells; the first tests only gave 100 cycles (at 80% remaining capacity).

34) Artificial Neural Network (ANN)
35) Scanning Electron Microscopy (SEM) / Energy Dispersive X-ray Spectroscopy (EDS)
36) Gas Chromatography (GC)/ Mass Spectrometry (MS)

Figure 18 – The 6 meter explosion test rig at FFI was used to study deflagration of hydrogen gas mixtures using high speed cameras, with and without barriers and/or obstructions (Photo: USN).

Battery ARC[37)] cell safety tests were therefore performed; no extraordinary safety hazards were discovered and the reference cell testing could continue. A full battery cell cycle life test program was performed at IFE and NTNU in 2021 and 2022. The final experiments on the MoZEES Li-ion reference battery cells and studies on its ageing, degradation, and safety was performed in 2023 and 2024. The main outcome of this common MoZEES battery work was the development of a standard method and cycling protocols for Li-ion battery lifetime and degradation testing.

Task 3.3 – Battery and Hydrogen Safety

A degraded and/or damaged battery can lead to leakage of explosive mixtures of gases into the surrounding environment, which can lead to hazardous and unsafe *situations* (e.g., gas leaks into battery rooms in maritime applications). It is therefore very important to access the impact of such gas leakages. Explosion characteristics of gases vented from Li-ion batteries was studied in a PhD at USN (Mathias Henriksen, 2017-2021). Experimental work on flame acceleration in an explosion rig was performed and an open source CFD[38)] -code (OpenFoam) for simulation of explosions was developed and validated [121-125, 127].

Hydrogen safety was the topic in another in-kind PhD at USN (Agnieszka Lach, 2019-2022), which focused on hydrogen dispersion, jet fires, and explosions in mechanically or passively vented confined spaces [128-130]. Three papers from MoZEES on hydrogen safety were presented at the ISFEH[39)] 2022 organized by USN in Oslo. In the final two years of the Center (2023-2024) there were executed new experiments in a 6 meter long explosion rig at FFI. In addition, FFI and USN organized several internal workshops on CFD-modelling of hydrogen flame propagation in the small (1 m) channel at USN. The experiments demonstrated different types of explosions and illustrated (via photos from high-speed cameras) how obstructions influence the flame propagation. The methods, tools, and results from this research in MoZEES can be used to provide guidelines on how to design safe rooms and areas for batteries or hydrogen systems.

37) Accelerating Rate Calorimeter (ARC)
38) Computational Fluid Dynamics (CFD)
39) International Seminar on Fire and Explosion Hazards (ISFEH)

Task 3.4 – Novel Efficient Low Temperature Water Electrolysis Processes

The research activities in this task focused on testing of low-temperature PEM water electrolysis stack technology and modeling of PEMWE[40] systems. A new national hydrogen research infrastructure (NFCH laboratories[41]) at SINTEF in Trondheim and IFE at Kjeller was built, commissioned, and actively used for the research in MoZEES (Figure 19).

In 2019 the first baseline tests and electrochemical characterization of a state-of-the-art PEMWE cell were carried out at SINTEF. A technical semi-empirical PEMWE-model was developed at IFE in EES[42] and completed in 2020. This model enables simulation of PEM water electrolysis cells, stacks and estimation of the overall system performance and energy use. This PEMWE-model has also been integrated with a techno-economic models so that the levelized cost of hydrogen can be calculated for various system sizes, configurations, and operating strategies. The MoZEES PEMWE-model was converted to an executable EES-program and made available for testing and validation by the other Partners in MoZEES.

Figure 19 – Testing and evaluation of the performance of PEM water electrolysis was a key research activity in MoZEES (Photo[43]: Norwegian Fuel Cell and Hydrogen Centre, IFE, Kjeller).

40) Proton Exchange Membrane Water Electrolysis (PEMWE)
41) Norwegian Fuel Cell and Hydrogen (NFCH) laboratories
42) Engineering Equation Solver (EES) program
43) Persons in photo: Thomas Holm and Ragnhild Hancke, RA3 leaders at IFE

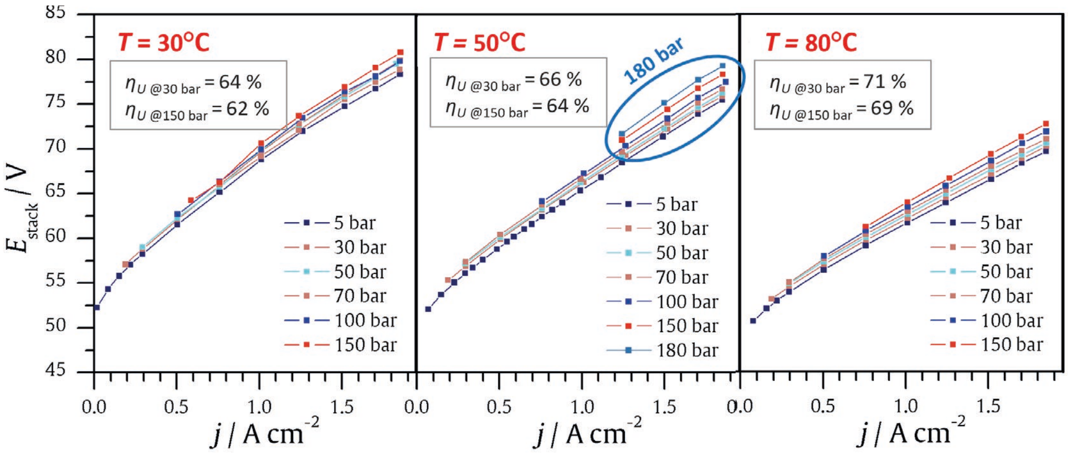


Figure 20 – Performance of a prototype high-pressure PEM water electrolyzer stack voltage efficiencies (η) at different operating pressures (p) and temperatures (T) [118]. (Illustrations: IFE).

Result from techno-economic modelling of high-pressure PEMWE systems was published in 2022 [119]. Operational data from a typical commercial PEMWE system was received from Nel, the main Industry Partner in MoZEES on this topic. The data included information about the system performance during cold start, warm restart, and different load cycle tests and was useful in the validation of the PEMWE system models developed.

In 2021 and 2022 the performance of a prototype differential high-pressure PEMWE stack from Nel was experimentally tested in a unique high-pressure (200 bar) PEMWE system laboratory at IFE. Detailed analysis of the experiments showed how the voltage efficiency was affected by the operating pressure and temperature (Figure 20). The results showed that there is a relatively small increase in the energy demand for an increase in operating pressure (2 kWh/kgH2 for pressure increase from 30 bar to 150 bar). Similarly, the energy consumption decreased with increasing operating temperature (4.4 kWh/kgH2 for increase in temperature from 50°C to 80°C) [118].

Dynamic test protocols and load profiles derived from a JRC[44] Technical Report on "EU Harmonised Protocols for Testing of Low Temperature Water Electrolysers" were used as basis for the PEMWE stack testing campaigns in MoZEES. This made it possible to assess stack and system performances and directly compare the results to those from other research and industry stakeholders adopting the same testing protocols. The final water electrolysis research activities at SINTEF in 2023 and 2024 focused on the modelling of dynamic operation of PEMWE systems, including cold start up, idling/warm start-up, load transients, and shut down. A publication on safety aspects related to cathode water recycling was published as part of this work [133].

44) Joint Research Center (JRC) in Europe

Figure 21 – MoZEES field trip to Unibuss' battery electric bus charging facility at Alnabru in Oslo (Photo: Ulleberg, IFE)

Task 3.5 – Design of Specific Applications (Use Cases)

In the first phase of the Center there was a special focus on maritime applications, namely the MoZEES Maritime Case Study. The maritime case study in RA3 was completed in 2019 and resulted in several publications related to the safety, design, energy consumption, and techno economics of hydrogen-driven high-speed passenger ferry concepts [113, 114, 139]. From 2022 the research on battery and/or hydrogen-driven fuel cell systems for maritime applications was continued in external projects, such as the IPN[45] OMB6-project (2022-2024) and the FME HYDROGENi-project (2022-2030).

In 2020 the focus shifted to hydrogen and fuel cell driven heavy-duty trucks. Important background information for this work was collected in a two-day MoZEES Heavy Duty Transport Workshop in Oslo in 2019. A hybrid fuel cell/battery powertrain model was established in Matlab Simulink as part of a LCA[46] study carried out in a post. doc study at IFE and UiO (Gaylord Booto, 2019-2020). Similar modeling of a fuel cell system for a bus was performed by a master student at UiO and IFE [100], who set up a complex heavy-duty fuel cell powertrain model based on building blocks from the open source QSS[47] library [109]. The model was validated for a fuel cell electric bus using the Braunschweig driving cycle, which is frequently used as test cycle for city buses featuring "stop-and-go" driving.

45) Innovation Project for the Industrial Sector (IPN) funded by the Research Council of Norway
46) Life Cycle Analysis (LCA)
47) Quantitative Social Science (QSS), i.e., GitHub

In 2022 it was decided to transfer the MoZEES Zero Emission Truck Case Study to RA4, and to focus on LCA and techno-economic analyses (Figure 24). Unibuss, with long experience on battery electric buses (Figure 21), produced in a 2024 an internal MoZEES report on "Operation of Battery Electric Buses in Cold and Winter Conditions", with focus on the experiences in Oslo from the extreme winter of 2023/2024 [111]. The report highlights challenges related to high energy consumption, charging infrastructure failures, and difficult road conditions, as well as measures being implemented to strengthen operations for future winter seasons.

Safety and risk analyses were a central part of the case studies in RA3 throughout the period of the Center. In 2020 there was done some preliminary work for the MoZEES Railway Case study. A collaboration between VysusGroup, USN, ASKO, SVV[48], and JBD[49] was established, with the objective to develop a scenario matrix for hydrogen-driven trucks and trains in tunnels. On the basis of this matrix Vysus carried out CFD analyses to evaluate the consequences of hydrogen releases in the different scenarios. An internal MoZEES report presenting the results of these analyses was completed in 2020 [104]. From 2021 the activities in Task 3.5 were more closely linked to the hydrogen- and battery safety studies in Task 3.3, including studies on the release of hydrogen in road and railway tunnels.

In 2022 the work on railway related applications ramped up (according to the original MoZEES project description). It should here also be pointed out that the Norwegian Railway Directorate and IFE managed to ensure Norwegian participation in the Europe's Rail program and the Rail4EARTH-project (2023-2026), which included MoZEES-related research activities on Li-ion battery and hydrogen fuel cell electric systems. The main Norwegian contribution to the Rail4EARTH-project has been on partial electrification of passenger trains using Li-ion batteries, but some hydrogen research activities are also included (e.g., hydrogen fueling of light-duty passenger trains). A MoZEES Railway Case Study related to partial electrification of Nordlandsbanen[50] was performed from 2023-2024. The main objective here was to study Li-ion battery lifetime and safety issues and challenges related to the design and operation of battery electric systems for trains [102].

48) The Norwegian Public Roads Administration (Statens vegvesen, SVV)
49) The Norwegian Railway Directorate (Jernbanedirektoratet, JBD)
50) Northern railway in Norway (Nordlandsbanen)

RA4 – Policy and Techno-Economic Analysis

The main objectives with RA4 was to perform techno-economic and life cycle analyses to provide factual based input to public and private stakeholders and derive advice to decision makers on the most economically and environmentally viable pathways towards battery- and/or hydrogen electric zero emission transport systems.

In 2020 the structure of RA4 was reorganized to improve the exchange of knowledge between the Research and User Partners, without compromising on the original scope of work. The six original research tasks were consolidated into four new task. This change made it easier to study barriers and opportunities within case studies in a more effective and dynamic way than before. The new RA4 research tasks for the second half of the Center period (2021 – 2024) focused on:

1. Screening of New Concepts and Business models
2. Deep Dive Case Studies
3. Transport and Energy Methods and Supporting ICT[51] Solutions
4. Roadmaps and Dissemination

Evaluation of battery- or hydrogen/fuel cell electric zero emission trucks was a major common research activity in MoZEES (Figure 22) and towards the end of the Center (2023-2024) TØI took responsibility to complete a MoZEES ZETruck[52] Case Study, with focus on Norway and Norwegian conditions. The ZETruck case study included detailed techno-economic analyses of both battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) and life cycle analysis (LCA) of the complete battery and hydrogen value chains.

In RA4 there were also made some studies on the required energy use in the existing high-speed passenger ferry fleet in Norway and investigations on the possibility to use batteries and hydrogen for zero emission operations.

Figure 22 – Evaluation of zero emission trucks based on batteries (top) and hydrogen fuel cells (right) were a large part of the scope of work in MoZEES. (Photos: Figenbaum, TØI (top) and ASKO Midt-Norge AS (bottom).)

51) Information and Communication Technology (ICT)
52) Zero Emission Truck (ZETruck)

RA4 Achievements and Highlights

The research in RA4 was published in 9 reports [140-148] and 19 scientific peer-reviewed articles [139, 149-166] and presented at more than 15 international conferences. There was also completed 3 PhD studies [167-169]. Below is a summary of the three main research achievements in RA4 (the dissemination activities are summarized in Chapter 11).

Task 4.1 – Screening of New Concepts and Business models

The main objective with this research activity was to identify and explore new concepts and business models that could provide new insights on the techno-economic characteristics, development and deployment of battery and hydrogen electric based energy systems in the transportation sector. The work included pre-studies, participation in international collaborative report writing, and publication of R&D performed by the MoZEES Research and Industry Partners. Annual status report on zero emission road transport in Norway were published as a chapter in the annual reports of the IEA Hybrid and Electric Vehicle Technology Collaboration Program. These annual reports tracked the market development of zero emission vehicles in Norway from 2019 to 2024. In MoZEES there was also set aside some resources to analyze different battery electric topics relevant for heavy-duty transport: Use of fast chargers for different geographies and seasons [153], market organization [152], battery electric light commercial vehicle [152], and Norwegian BEV policy processes [154]. There was also performed a study on zero-emission technology status for trains [148].

Task 4.2 – Deep Dive Case Studies

The main objective with this research activity was to perform comprehensive and holistic case studies on technology development, costs, barriers, and opportunities for some selected zero emission heavy-duty applications. The research methods developed in RA4 were adapted to each case study, with focus on battery and hydrogen electric heavy-duty trucks, buses, and maritime applications. The methods and tools developed can be used to identify challenges, opportunities, and suitable policies for the different zero emission transport solutions.

The design of public procurement schemes and their effectiveness in promoting clean transport was studied across various heavy-duty transport modes, including maritime transport [149] and freight transport [157]. The results show that careful design of public procurement schemes can have a large impact if implemented properly. In addition, several life cycle analyses were performed to assess the environmental impacts of the battery and hydrogen value chains chosen in MoZEES. The LCA analysis were carried out for both zero-emission buses [151] and heavy-duty trucks [150]. The results show that in a Norwegian context, with nearly 100% renewable electric grid, the battery electric and hydrogen (electrolyzer based) fuel cell propulsion systems perform similarly with respect to GHG[53)] -emissions and other environmental impact parameters and much better than fossil fuel-based propulsion. The LCA modeling tools developed in MoZEES are modular and expandable to future heavy-duty transport applications, including near-coastal maritime operations.

A general method on how to determine the energy use in maritime applications was also developed in MoZEES. This work started with a case study at IFE on a high-speed passenger ferry in RA3 (MoZEES Maritime Case Study described above) before a more generic method and a dedicated AISEEM[54)] -tool was developed at TØI in RA4 and other research spin-off projects (e.g., ZEVS[55)]). The AISEEM-tool was successfully used to map the energy demand for the fleet of high speed passenger vessels in Norway, and can also be used to estimate

53) Green House Gas (GHG)
54) Automatic Identification System Energy and Emissions Model (AISEEM)
55) Enabling Zero Emission passenger Vessel Services (ZEVS)

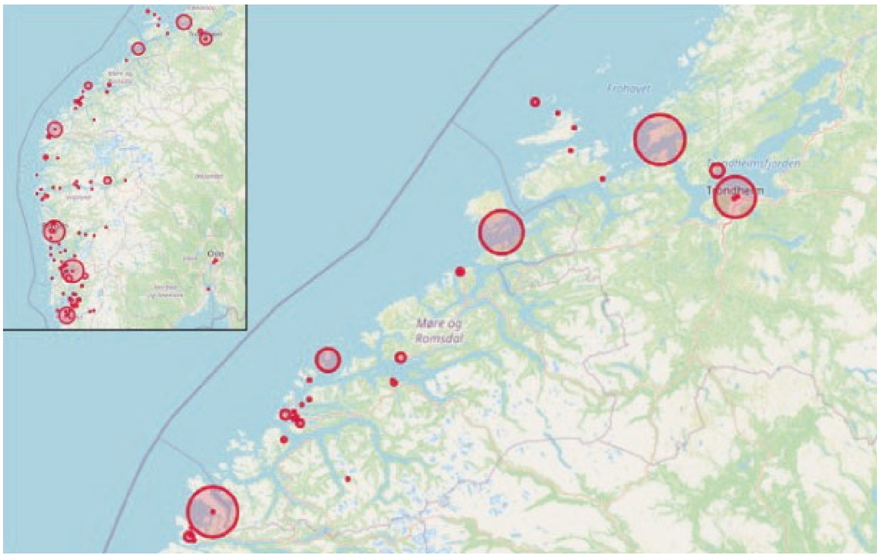


Figure 23 – Mapping of daily energy demand in harbors serving high-speed passenger vessels along the west coast of Norway using the AISEEM-tool developed in MoZEES. (Photo: Nordland County Council; Illustration: TØI).

the energy demand for other fleets of vessels operating along the coast (Figure 23). This modeling method has also been expanded and applied to road transport using vehicle GPS data. Methods and models for calculating the TCO[56] of electric vehicles have also been developed, including detailed studies based on data from existing battery electric buses in Oslo [166].

An integrated TCO and LCA method was developed for the evaluation of zero emission heavy-duty trucks in the so-called the MoZEES ZETruck Case Study (Figure 24). The ZETruck-method can be used to perform combined analyses of the TCO, tax neutral cost, societal cost, and the environmental impacts of various zero-emission truck alternatives using LCA. The ZETruck-model input consists of truck and energy costs, LCA inventories, policies, and user operational schemes. Preliminary LCA and TCO results from the ZETruck case study were presented at two international conferences in 2024 (TRA[57] and EVS37[58]) and the final results will be published in international journals in 2025. The MoZEES ZETruck Case Study was supported by a market and technical status study of zero emission (ZE) trucks [144], interviews with early ZE truck users [143] and series produced ZE truck owners and managers in 2021 and 2023 [145, 146].

56) Total Cost of Ownership (TCO)
57) The Transport Research Arena (TRA), Dublin
58) The 37th International Electric Vehicle Symposium & Exhibition (EVS37), Seoul

The conclusion from the RA4 studies mentioned above was that there has been a positive development in zero emission truck technology the last few years, particularly on battery electric trucks (from first to second generation BETs[59)). In comparison, the MoZEES Partners and other key stakeholders were much less certain about the prospects for hydrogen and fuel cell trucks, since these require access to low-cost hydrogen to be competitive with BETs that today (2025) are available for local, regional, and 500-1000 km long-haul operations. The results from the RA4 modeling show that battery electric trucks will under the current framework conditions be commercially competitive in Norway between 2027 and 2030, without public support.

Hydrogen electric trucks cannot be ruled out as an option for future zero emission heavy-duty trucks as they may be needed to decarbonize extra heavy vehicles (e.g., timer trucks) and/or trucks operating over very long distances (e.g. trucks transporting goods across large countries in Europe). Independent studies by Industry Partners in MoZEES such as Statkraft show that combinations of battery electric charging and hydrogen refueling infrastructure may be more cost-effective than battery electric charging alone, since this makes better use of the electrical infrastructure on site. Hydrogen fuel cell trucks may be more suitable for Europe than for Norway.

Task 4.3 – Transport and Energy Methods and Supporting ICT Solutions

The main objective with this research task was to develop new research methods, models, and tools that can contribute to the integration of transportation and energy system models and behavioral and economic models. Research with focus on various aspects of transport energy optimization and modeling was carried out by three PhD candidates at NTNU. The topics for these three PhD studies were: (1) first PhD study in RA4 was on “Multi-period facility location problems with capacity expansion: Locating hydrogen production in Norway” [169] and produced several peer-reviewed papers [162-165]. The second PhD focused on “Renewable fuels in hard-to-abate transport sectors: Techno-economic analyses from production to consumption in trucking, shipping, and aviation” [167] and produced several articles [158-161], while the third and last PhD focused on “The influence of transport policies on car ownership and travel behavior: Insights from three empirical studies” [168]. The new methods, models, and tools, developed by the PhDs in RA4 were used to support and increase the quality of the Deep Dive Case Studies (Task 4.2).

59) Battery Electric Trucks (BETs)

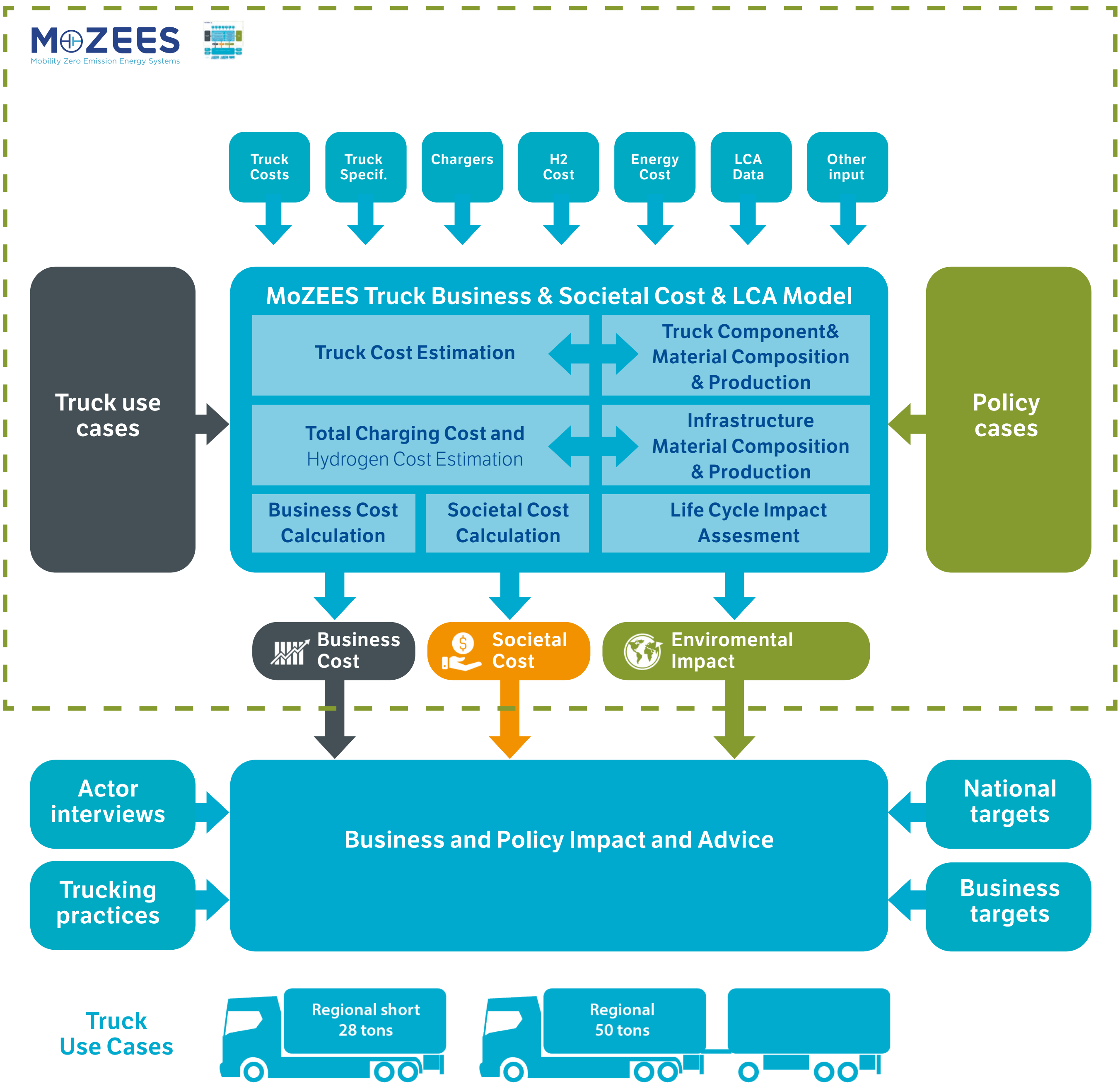


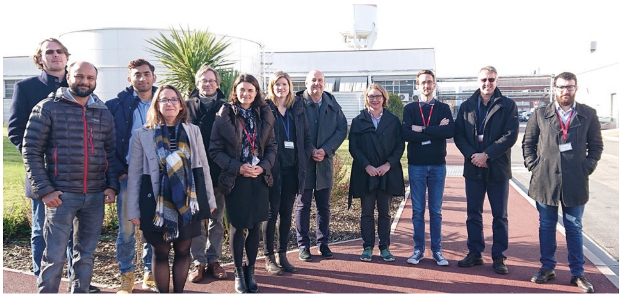
Figure 24 - MoZEES Zero Emission Truck Case Study (Illustration: TØI).

9. International Cooperation

MoZEES has benefited from strong international collaboration, both through industrial and academic partnerships. Key international Industry Partners such as SAFT in France, Teer Coatings and Johnson Matthey in the UK, and Nel in the USA were actively involved in MoZEES activities throughout the project period, contributing with technical insights and engaging in knowledge exchange. In addition, the Center included several multinational companies, such as ABB, Elkem, Hydro, Statkraft, and Equinor, which opened up for extensive international networks.

The large international scientific and academic networks combined by the Research Partners in the Center was also extensively used. Four formal bi-lateral agreements (MoUs) were established with the following International Partners: (1) Uppsala University in Sweden, (2) UC Davis in the USA, (3) RWTH Aachen in Germany, and (4) The University of Genova in Italy. These collaborations included exchange of PhD-students and researchers (more info in Chapter 10). Three of the members in the Scientific Committee came from the International Partners.

The international network in MoZEES was extensively used to organize and participate in international meetings, workshops, seminars, and conferences (more details in Chapter 11). Examples of successful international MoZEES meetings include the technical battery meetings and workshops at SAFT in Bordeaux (2019) and RWTH Aachen (2022) and MoZEES Final Conference in Oslo (2024) (Figure 25).



Technical workshop at SAFT in Bordeaux (2019)

Lab tour at RWTH Aachen in Germany (2022)

Figure 25 – Photos from successful international MoZEES meetings (Photos: IFE)

10. Training of Researchers

Figure 26 – Participants at the NorRen[60)] summer school hosted by the FMEs MoZEES and Bio4Fuels in June 2019 (Photo: UiO)

The training and education of researchers and students associated with MoZEES was closely integrated with the overall strategic program and scientific work in the Center. A cross-disciplinary MoZEES Research Training Network (RTN) was established and provided a dedicated arena for collaboration, learning, and professional development for PhD students, post.doc. fellows, and early-career researchers in the Center. The MoZEES RTN, which was established by UiO:Energy and jointly coordinated by UiO and IFE, included active participation and involvement from the Research, Industry, and Public Partners. In this way there was a coherent collaboration between all partners in the Center, from students to researchers to end users.

The MoZEES RTN provided an interactive arena where PhD students and young researchers could engage in valuable exchanges with each other, national and international academic mentors, and relevant User Partners. Several PhD candidates were co-supervised by either industrial specialists, or international academic partners. The RTN hosted dedicated seminars and brought together MoZEES members and partners, including the Center Management, selected people from industry and public sector, international research partners, and members of the Scientific Committee. The RTN members were highly active and given priority to present their work at MoZEES meetings, such as the MoZEES Digital Lunch Talks, Battery Days, Safety seminars, Annual Meetings, and the Final Conference.

MoZEES was also an active partner in the interdisciplinary Norwegian Research School in Renewable Energy (NorRen), and MoZEES students participated in almost all of the NorRen summer schools. Two of the NorRen Summer Schools were dedicated to zero-emission transport. The first summer school in 2019 was a collaboration with FME Bio4Fuel, while the second one in 2022 was in collaboration with FME NTRANS. MoZEES' national and international Research Partners, along with several Industry and Public Partners, contributed actively by giving lectures and hosting site visits during the MoZEES-related summer schools in 2019 and 2022.

60) Norwegian Research School in Renewable Energy (NorRen)

During the early phase of the Center there was a strong emphasis on public outreach training. The MoZEES RTN launched its own website and blog, developed YouTube videos, wrote opinion pieces, and successfully pitched research at local and national events such as the National Researcher Grand Prix and the UiO:Energy Forum. These outreach activities increased the visibility of the Center and created new opportunities for the those involved in the MoZEES RTN.

As the Center and its PhD candidates matured the focus shifted toward scientific outreach and professional academic writing. In collaboration with the Academic Writing Centre at UiO the MoZEES RTN organized a two-day academic writing workshop to promote storytelling in science and provide practical tools to support the writing process. There was also introduced regular digital "Shut Up and Write" sessions on Fridays during the COVID-period, creating a shared space for focused writing. The MoZEES Digital Lunch Talks were also launched during this period, which was an informal monthly meeting series where all MoZEES members were welcome to present and discuss their latest research activities and results.

Through the MoZEES RTN there was also established a dedicated funding scheme for international and industry exchange with the aim to foster increased interaction and mobility among the PhD candidates and young researchers. Over the Center period nine (9) PhD candidates received economic support through the MoZEES RTN program, including two industry exchanges. In line with recommendations from the mid-term evaluation, the Center also actively supported young researchers with project extensions in cases where the COVID-19 pandemic caused significant delays beyond what was covered by their respective univesitites.

A key goal in MoZEES was to build long-term competence by recruiting and educating outstanding PhD candidates for future roles in the transport and energy sectors. The PhD candidates in the Center were not only trained to become scientific researchers within their fields of expertise, but also to contribute directly to the realization of research goals in MoZEES and across related industries. The feedback from the RTN post. doc. fellows and PhDs was that the broad network of Research and User Partners in MoZEES represented a unique opportunity, both for their scientific work during the project and for their future careers. A showcase of the successful MoZEES career developments (Table 7) shows that all members of the MoZEES RTN have moved on to relevant careers in 18 different organizations.

Table 6 – Employment of MoZEES PhD-candidates

Type of Organization	**Name of Organization** (no. of MoZEES RTN fellows recruited)
MoZEES Industry Partners	Morrow Batteries (2)
Other Industrial Companies	Vista Analyse (1) , Inventas (1), Hystar (1) , Freyr (3)
MoZEES Research Partners	USN (2), UiO (1), NTNU (1)
International Organizations	German Aerospace Center (1) Institut Teknologi Sepuluh Nopember, Indonesia (1)

11. Communication and Popular Dissemination

Figure 27 – Communication of results at the MoZEES Annual Meeting 2023 in Son, Norway (Photo: Ulleberg, IFE).

Communication and dissemination of research was a high priority in MoZEES throughout the period of the Center. In addition to producing high-quality scientific outputs, the Center worked actively to make the research outputs accessible and engaging to a broader audience, including policymakers, industry stakeholders, students, and the general public.

Researchers from MoZEES have shared their findings widely, both nationally and internationally. About 100 presentations were held at international conferences and seminars in 70 cities and 25 different countries around the world (Appendix 3). The MoZEES work was presented at 20 major international conferences, contributing to global discussions on energy systems, battery technology, hydrogen, and zero-emission transport solutions. For example, RA4 research was prominently featured at key international events such as the Electric Vehicle Symposiums (EVS), the Transportation Research Board Meeting (Washington, 2020), the Transportation Research Arena (Lisbon, 2022; Dublin, 2024), and the Computational Logistics conferences.

There was also organized a range of structured national communication activities. These included annual seminars and webinars, as well as recurring meeting series featuring presentations on research, technology, and market developments delivered by research, industry, and public partners (Figure 27). As part of these efforts the RA4 research group produced a zero emission transport policy roadmap in 2020.

Finally, MoZEES researchers and partners contributed to a great deal of attention in different media (more than 50 different types of new bulletins were recorded), helping to raise public awareness and increase interest in zero-emission transport solutions. This media outreach included radio interviews, podcast appearances, features in major newspapers and magazines, as well as presentations at public events such as Researcher Night.

12. Positive Effects for the Research Partners

Positive Effects for the Host Institution (IFE)

IFE has greatly benefited from MoZEES, both scientifically and strategically. The Center has served as a national arena for research on battery and hydrogen technology and zero emission energy systems for transport applications, areas that IFE had an ambition to develop further at the start of the Center. By bringing together key research and industrial stakeholders in this field IFE has reinforced the institute's role as central actor in the Norwegian energy research landscape. IFE has with MoZEES increased and strengthened the collaboration with old and new research, university, industry, and public partners. The role as host institution has also contributed to strengthening IFE's internal research coordination and project management capacity, particularly the capacity to run large interdisciplinary research projects. MoZEES provided IFE an excellent platform to demonstrate the institute's competency on battery and hydrogen technology and systems. This has led to several large follow-up research projects, such as FME HYDROGENi and FME BATTERY. Finally, as host institution for MoZEES, it has been possible for IFE to establish strong synergies with other national and international research efforts, positioning the institute for future strategic collaborations and funding opportunities.

Positive Effects for key Research Partners

Below is a summary of the positive effects that MoZEES has had on three of the other Research Partners (SINTEF, NTNU, and TØI). These three Research Partners were each responsible for leading one of the four Research Areas in the Center and therefore had a special obligation and commitment to MoZEES (Figure 28). It should also be noted that the feedback from the other three Research Partners (UiO, USN, and FFI) was also very positive. All of the seven Research Partners were given the opportunity to expose their research ideas and results to the MoZEES Consortium. In conclusion, the Research Partners are today (2025) more much more established and well-known in the MoZEES research areas than at the beginning of the Center (2017).

Figure 28 – Positive feeback from key Research Partners in MoZEES; here represented by the Center Director (middle) and the Research Area leaders from NTNU, SINTEF, IFE, and TØI (from left to right) (Photo: IFE).

SINTEF

MoZEES has been an important arena where many of the most important research and industrial partners in Norway have gathered. This has led to many constructive scientific and marked oriented discussions, which has helped to ensure that SINTEF's research in MoZEES has kept industrially relevant. MoZEES has given SINTEF the opportunity to showcase important parts of the foundation's competence to Norwegian and international industrial companies and has strengthened the collaboration with the other Research Partners. The network that has been established in MoZEES has been used to generate several spin-off R&D projects, where many of the Partners in MoZEES have been involved. A notable example is the Green platform project SUMBAT, where SINTEF, in collaboration with IFE and other MoZEES Partners have established a large battery research project. Finally, MoZEES has functioned as a hub where synergies between other related projects in the same field could be leveraged.

NTNU

MoZEES has allowed for sharing research plans and results with the other Partners. The Center created a platform and research network to discuss and receive feedback and was a very useful meeting place for active collaborations with experienced researchers and experts from industry. The PhD candidates affiliated with RA1 were given the opportunity to collaborate closely with other researchers, and also work with samples supplied by other partners. Furthermore, in RA1 (led by NTNU) there was a close collaboration with international research groups, in particular Uppsala University and RWTH Aachen, where leading researchers *participated* in discussions, and exchange visits were undertaken for some of the PhD students. In RA4 the PhD students also collaborated closely with international colleagues, for example TU Wien. The collaborations established in MoZEES have enabled NTNU to build and expand networks locally, nationally, and internationally. The PhD students at NTNU affiliated with the Center have also received valuable training in scientific writing and presentation via the MoZEES RTN. Overall, MoZEES has provided NTNU with an excellent scientific and professional network.

TØI

MoZEES has made it possible for TØI to further develop the institute's expertise on transport economic issues related to zero emission transport, both in the public and private sector. About halfway into the Center period a new Department for Technology was established at TØI. Furthermore, as a result of MoZEES one of the existing research groups at TØI started to focus more on transport technology and zero-emission solutions for heavy-duty transport (road and maritime). MoZEES has given TØI an opportunity to establish a professional environment for life cycle analyses (LCA). Collaboration with IFE researchers also include doing LCA in battery projects led by IFE and development of a model for energy consumption analysis in the maritime and road transport sectors. TØI has also gained new expertise, which has led to new maritime research projects in collaboration with other MoZEES Partners, including IFE. In summary, TØI has in MoZEES built up new expertise within the heavy-duty road transport segment. The research work in this area (MoZEES Zero Emission Truck Case Study) has led to the development of new methods and tools for calculating business and societal costs of zero-emission trucks. This competence is now built into other transport models used in many different projects for the public sector.

13. Positive Effects for the Industry and Public Partners


Figure 29 – MoZEES Day Zero – Panel discussion with Research, Industry, and Public Partners, with the Norwegian Research Council and the Ministry of Energy (Photos: Vogt, UiO)

The FME centers are expected to demonstrate potential for innovation and value creation and to carry out their research activities in close collaboration between research groups across different disciplines, industry, and public organizations. A review of the positive effects of MoZEES for the Industry and Public partners show that the R&D in the Center has had a positive impact on the innovation activities among the Partners, led to development of new and improved products, processes, and services, strengthened the knowledge base for the Partners, improved access to competent personnel and research institutions, resulted in relevant recruitment of qualified personnel, and improved the network of the Partners. The review of these effects were formally recorded via a MoZEES seminar in November 2024 (MoZEES Day Zero[61)]) and in an online MoZEES User Partner Survey in December 2024. Some highlights from these reviews are provided below.

Highlights from MoZEES Day Zero

One of the main objectives with an FME is to demonstrate how R&D activities in the Center has the potential for innovation and value creation. To achieve this it is necessary to bridge the gap between academic and industry partners (Figure 29).

Here are some important takeaways (paraphrased statements) made by the main Industry Partner (Hydro) at MoZEES Day Zero:

Research collaborations through programs such as FME MoZEES are a key part of our competence building activities and contribute to innovation and value creation. Many young researchers are educated through these research programs which form an important recruitment base for the growing battery industry

FME centers are important for the R&D activities in our company because they make us better understand the capabilities of the various research groups, enable us to set up spin-off projects, and provide us with access to advanced laboratories. The MoZEES Consortium has provided us with new innovative ideas and given us a longer term perspectives on our technology development

FMEs are designed for long-term research but should also support short- to-medium term needs by allowing for some technology screening and short innovation projects that may generate spin-off projects. The MoZEES Pre-Projects scheme set up in 2022 and 2023 was very successful and lead to quick and useful results.

61) MoZEES Day Zero – Bridging Academia and Industry in Zero-Emission Transport, 4 Nov 2024, Oslo.

Highlights from MoZEES User Partner Survey

Below are some highlights from the MoZEES User Partners survey conducted in December 2024:

- *MoZEES has increased the national competence on zero emission transport on road, rail, and sea. The new knowledge created has been used in large, public evaluations and advisory, and to generate R&D projects on energy/battery technology (Norwegian Railway Directorate).*
- *The Center has provided up-to-date knowledge and status of the key energy technologies needed for the green shift and has produced relevant research on zero emission transport systems and value chains (Norwegian Coastal Administration).*
- *The close integration of our maritime innovation network with the MoZEES research network has made it possible for us to connect industry and research partners that did not know of each other before, leading to new maritime concepts and projects (Ocean Hyway Cluster).*
- *MoZEES has contributed to keeping up the momentum on the development of zero-emission shipping (Port of Oslo).*
- *The ambition in Oslo and Akershus is to become the world's first capital region where all of the transport is emission-free by 2030. MoZEES has provided relevant and valuable input to our work in meeting these goals (Akershus County Council).*
- MoZEES has contributed to our transport systems planning, technology development in regional business sectors, and application of zero emission technologies in the public transport segment[62)] (Trøndelag County Council).
- *The techno-economic studies carried out in the Center show how difficult it is to establish good business cases for maritime and heavy-duty road charging/refueling infrastructure. The research in MoZEES on battery and hydrogen safety has been particularly useful (Statkraft).*
- In MoZEES we discovered that our battery class rules for the maritime sector also can be used as a starting point for developing rules in the railway sector (DNV).
- The Center gave us the possibility to get in close contact with key actors in the marine industry and transport sector. This has created new business opportunities for us (Vysus Group).
- MoZEES has provided us with new competence and detailed insight into Li-ion battery technology for road transport (Unibuss) and PEM fuel cell systems for the maritime (ABB).
- The networking activities with the Norwegian battery community in MoZEES was very useful. The Center gave us the opportunity to visit national laboratories and exchange information with relevant research institutes, *universities*, and companies in Norway (SAFT, France).
- MoZEES has provided us with a unique platform to discuss battery cell production and testing. The improved testing techniques developed has led to rapid product development (Cenate).
- We have benefited from the PEM catalyst developments in MoZEES, which has led to new collaborations and EU-projects on fuel cells and electrolyzers (Johnson Matthey, UK).
- The MoZEES Innovation forum and MoZEES Pre-Projects created a number of interesting ideas for potential spin-off projects (Elkem).

62) Including public purchase agreements on buses, ferries, and highs-speed passenger boats

14. The Role of the Center

When MoZEES was established (2017) the battery and hydrogen technologies for transport applications were still emerging and their integration into large-scale commercial transport systems remained limited. Battery electric passenger vehicles had gained some traction but the broader use of zero-emission energy systems was at a very early stage, particularly in heavy-duty road transport and maritime applications. The research landscape was fragmented and there were few structured arenas for collaboration across academia, industry, and the public sector.

The main objective with MoZEES was to the close the above mentioned gap by providing a coordinated national research platform on battery and hydrogen technology for development, demonstration, and innovation of zero emission transport systems and applications (Figure 30). Over the course of the Center period (2017-2024) the technological and political landscape for zero-emission transport shifted significantly. The Center operated *during* a period of accelerating electrification, increased attention to hydrogen as an energy carrier, and a growing policy push toward decarbonization, both in Norway and internationally.

The latest energy crisis (2021/2022), triggered by *geopolitical* incidents (war in Ukraine), further highlighted the importance of strengthening and securing domestic and European energy systems. This accelerated the urgency for the development of clean, flexible, and scalable alternatives to fossil fuels. The research in MoZEES has been directly relevant in supporting for increased *preparedness* and resilience by providing new technology knowledge, and system competence. The Center has demonstrated new material and technology *production* methods and zero-emission transport system *concepts* that can be implemented in the near future, both in Norway, Europe, and other parts of the world.

A multi-disciplinary and cross-sectorial approach to *solving* "the problem[63]" has been undertaken in MoZEES. This has helped to position the Norwegian Research and Industry Partners to be at the forefront of *innovation* in zero-emission transport systems. The Research Partners have expanded their competence, international networks, and infrastructure, while several of the Industry Partners have used MoZEES as a platform to test new technologies, build internal expertise, acquire talent, and inform strategic decisions.

MoZEES has also played a key role in training a new generation of researchers with skills highly relevant to both academia, research, industry, and the public sector. These researchers are now contributing to research, development, and innovation ecosystems in Norway; *several* MoZEES alumni today have leadership or specialist roles in different organizations. Finally, the establishment of many new and relevant battery and hydrogen spin-off projects have further solidified the legacy of MoZEES and extended its impact beyond the lifetime of the Center.

Figure 30 – MoZEES vision in a nutshell

63) Reduction of emissions from transport ("the problem") and development of possible zero-emission transport system ("the solution") was the main scope of work in MoZEES.

15. Future Prospects

MoZEES has contributed to building a solid foundation for new research and innovation on battery and hydrogen technology. The Center has also provided an excellent knowledge base for further development of integrated zero-emission energy and transport systems on road, rail, and sea.

The battery and hydrogen industry in Norway and Europe is today (2025) experiencing some challenges, due to disruptive changes in climate policy in the US and shifting markets. However, the knowledge base and industrial networks established in MoZEES are strong, which hopefully will help the Industry Partners to solve these challenges with new innovative solutions.

In addition to the technological progress achieved in MoZEES, the Center has fostered close partnerships between research institutions, industry actors, and public stakeholders. This collaborative environment can and should be used as a platform for continued common

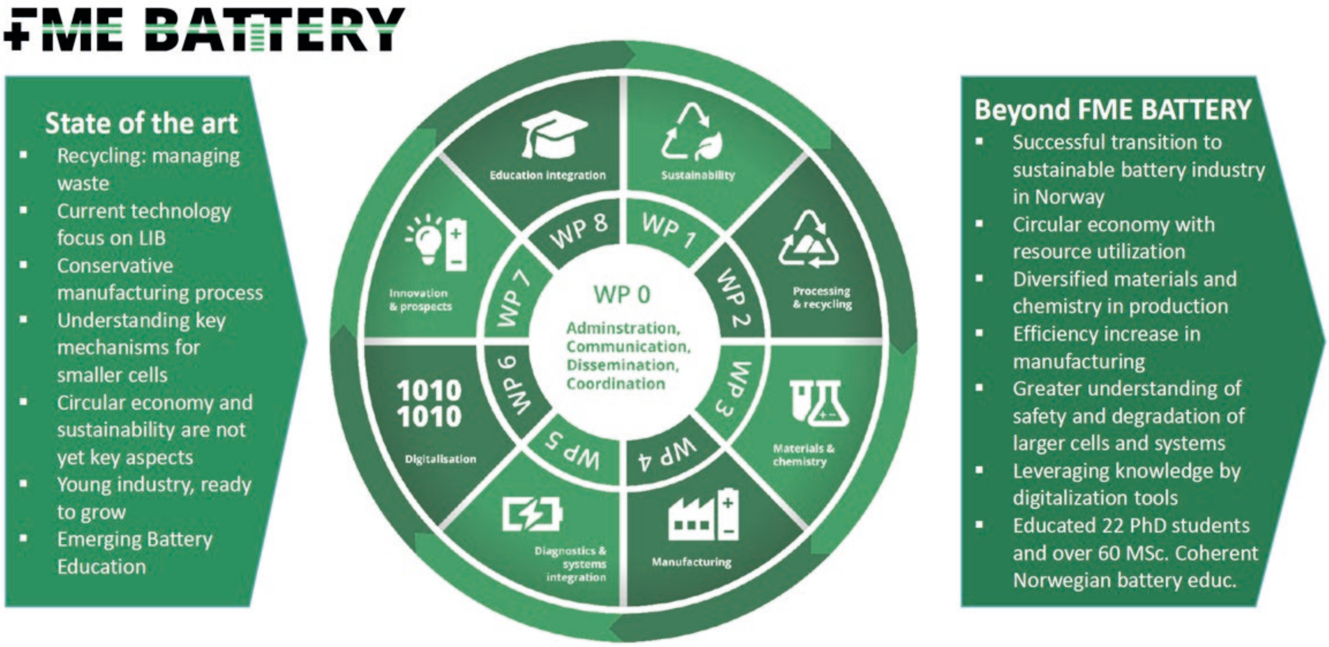


Figure 31a – The MoZEES research work on batteries and hydrogen is continued in two new national FME research centers. FME BATTERY scope of work shown above (Illustration: NTNU and IFE) research and innovation. The MoZEES network should be nurtured in new project initiatives to ensure that the progress made during the Center's lifetime can continue in the years to come.

Fortunately, many of the MoZEES activities and partnerships will continue through two newly established centers, namely the FME BATTERY and FME HYDROGENi. These two FME centers include many of the MoZEES members and have plans to carry forward the research on battery and hydrogen technology and development of new sustainable energy solutions (Figure 31).

Some of the research activities on zero emission maritime transport will also be continued in FME MarTrans, while MoZEES activities on hydrogen safety and techno-economic analyses on hydrogen value chains will be continued in FME HyValue.

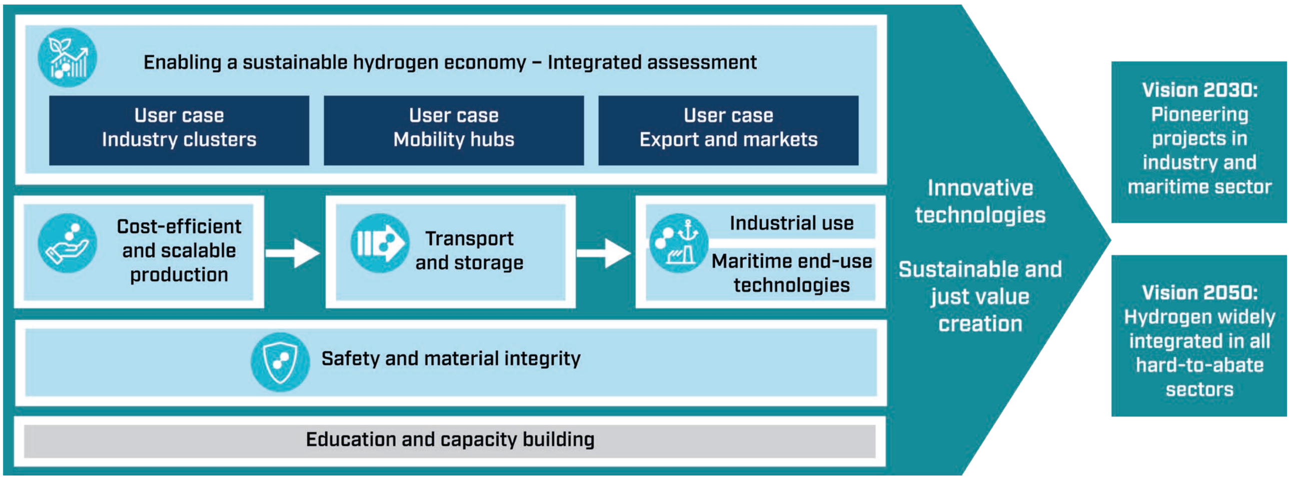


Figure 31b – The MoZEES research work on batteries and hydrogen is continued in two new national FME research centers. FME HYDROGENi scope of work shown above (Illustration: SINTEF)

16. Conclusions

MoZEES has played an important role as a long-term, structured national effort to strengthen research, innovation, and collaboration on zero-emission energy systems for transport. Being part of the FME scheme provided a strong framework for aligning research with national priorities and industry needs. The Center structure offered both stability and flexibility, which allowed for continuous development of strategy and working plans through a collaborative and iterative process. Annual planning cycles were closely linked to input from the User Partners and the scientific progress within the work packages, ensuring that the research remained relevant and well-coordinated across tasks and disciplines.

The organization of long-term research tasks in the Center were clearly defined in the four main research areas. The overall work program and cross-cutting activities between the research areas and tasks was closely monitored and followed up by the Center Director and RA leaders, in close collaboration with the Board, Innovation Committee, and key User Partners. Regular meetings between the Management Team, RA leaders, Task leaders, and the Researchers ensured transparent progress reporting and good agreement in the updating of the Annual Work Plans. The "hands on" management style practiced by the Director and the RA Leaders also ensured a close follow up of the working plans and a significant scientific output This final result was more than 100 peer-reviewed scientific publications, among others.

In MoZEES there was also built a strong identity and culture; "Welcome to the MoZEES Family" was the catch phrase when new people joined the Center. Over time MoZEES developed into a strong and recognizable arena for collaboration between research, industry, and public actors within battery and hydrogen technologies and zero emission energy systems for transport. Activities and events such as the MoZEES Research Training Network, Annual Meetings, Battery Days, Digital Lunch Talks, and other seminars and meetings strengthened the internal communication, fostered new connections, and created a common MoZEES identity.

The project management was systematic and well-structured throughout the period, supported by clear routines and a strong administrative foundation. The Center also placed emphasis on communication, both internal and external, through regular updates, partner meetings, digital tools, and dissemination efforts. Securing active participation from the partners was a continuous process, and close collaboration with individual companies and institutions helped ensure engagement at different levels of their organizations. This included bilateral meetings, involvement in specific tasks, participation in strategic discussions, and visibility at events.

In summary, the FME program has been essential for creating the long-term commitment and shared ambition needed to advance complex, interdisciplinary topics such as zero-emission transport. MoZEES has demonstrated the value of the FME-model in bringing together partners with complementary strengths and aligning them toward common goals with both scientific and societal relevance. IFE and the MoZEES Partners acknowledge the support from the Research Council of Norway. Without the FME funding it would not have been possible to organize a national research center with such an impact, both nationally as well as internationally.

Acknowledgements:

MoZEES Mobility Zero Emission Energy Systems

FME Centre for Environment-Friendly Energy Research – The Research Council of Norway

The Research Council of Norway

Appendix 1 – Statement of Accounts

A summary of the the costs and funding (kNOK) of the operation of MoZEES for the complete project period (2017-2024) are found in Table 5 and Table 6, respectively.

Table 7 – Summary of the costs (kNOK) in MoZEES for the total project period (2017-2024)

Partner	RA1	RA2	RA3	RA4	Com & Dis	Adm & Mgmt
IFE[64)]	10816	3775	17039	6636	1910	16173
SINTEF	0	0	11158	0	0	50
NTNU[65)]	0	0	470	20519	289	1683
UiO[66)]	8135	10963	7959	7358	178	1152
TØI[67)]	18958	7812	250	0	4555	800
USN[68)]	7	0	7398	0	0	0
FFI[69)]	12538	6749	2200	9699	135	1023
ABB AS	0	0	3650	1225	0	
AGA AS	0	0	118	207	0	
Asko Midt-Norge AS	115	0	608	670	0	
Baldur Coatings AS	481	0	0	0	0	
BASF (USA)	1154	0	0	0	100	
Bellona	188	0	49	221	0	
Cenate AS	434	225	0	80	0	
Ceramic Powder Technology AS	290	362	151	0	0	
Corvus Energy AS	0	0	117	0	0	
Coorstek Membrane Sciences AS	0	0	246	0	0	
DNV AS	1558	0	196	0	0	
Dynatec Engineering AS	493	65	65	65	0	
Elkem AS	4824	50	159	0	200	
Equinor Energy AS	373	321	393	41	0	
Graphene Batteries AS	357	0	0	47	0	
Grenland Energy AS	0	0	128	32	0	
Hexagon Raufoss AS	78	465	311	73	0	
Johnson Matthey Pub. Ltd. Co. (UK)	0	688	347	0	0	
Ocean Hyway Cluster	0	0	180	72	0	
Hydro Energi AS	222	29	141	226	0	

64) Institute for Energy Technology (IFE)
65) Norwegian University of Science and Technology (NTNU)
66) University of Oslo (UiO)
67) The Institute of Transport Economics (TØI)
68) University of South-Eastern Norway (USN)
69) Norwegian Defence Research Establishment (FFI)

Partner	RA1	RA2	RA3	RA4	Com & Dis	Adm & Mgmt
Kunnskapsbyen Lillestrøm AS	0	0	340	662	0	
Maritim Forening Sogn og Fjordane	0	0	797	0	0	
Morrow Technologies AS	152	0	0	8	0	
NEL ASA	0	780	1342	0	0	
PBES Norway AS	0	0	59	0	0	
SAFT (France)	493	0	146	52	0	
Selfa Arctic AS	0	0	313	440	0	
Statkraft AS	0	0	155	427	0	
Teer Coatings Ltd. (UK)	0	702	0	367	0	
Unibuss AS	0	0	0	272	0	
Vysusgroup AS	0	0	1400	213	0	
ZEG Power AS	0	0	150	72	0	
ZEM Energy AS	0	0	1454	49	0	
Enova SF	0	0	50	100	50	
Jernbanedirektoratet[70]	2794	924	5297	959	150	
Kystverket[71]	1642	2532	2197	910	0	
Oslo Havn KF[72]	2805	2468	178	1931	0	
Statens vegvesen[73]	4943	1617	398	1541	150	
Trøndelag fylkeskommune[74]	0	10	4275	1293	0	
Viken fylkeskommune[75]	0	0	3406	128	905	

70) The Norwegian Railway Directorate
71) The Norwegian Coastal Administration
72) Port of Oslo
73) The Norwegian Public Roads Administration
74) Trøndelag County Authority
75) Viken County Authority

Table 8 – Summary of the funding (kNOK) of the Center for the total project period (2017-2024)

Partner	RA1	RA2	RA3	RA4	Com & Dis[76)]	Adm &Mgmt[77)]
IFE	6573	799	3105	2129	0	198
SINTEF	3428	3923	4205	2182		
NTNU	3249	3975	1675	3725		117
UiO	7164	746	0	0	4848	
TØI				7937		164
USN	0	0	5661	0		
FFI	0	0	2402	0	0	0
ABB AS	0	0	4050	1625		
AGA AS	0	0	118	207		
Asko Midt-Norge AS	115	0	608	670		
Baldur Coatings AS	481	0	0	0		
BASF (USA)	1154	0	0	0		
Bellona	188	0	209	221		
Cenate AS	434	225	0	80		
Ceramic Powder Technology AS	290	362	151	0		
Corvus Energy AS	0	0	117	0		
Coorstek Membrane Sciences AS	0	0	246	0		
DNV AS	1558	0	196	0		
Dynatec Engineering AS	493	65	65	65		
Elkem AS	5624	850	959	0		
Equinor Energy AS	873	821	893	541		
Graphene Batteries AS	357	0	0	47		
Grenland Energy AS	0	0	128	32		
Hexagon Raufoss AS	78	465	311	73		
Johnson Matthey Pub. Ltd. Co. (UK)	0	688	347	0		
Ocean Hyway Cluster	0	0	180	152		
Hydro Energi AS	672	479	591	676		
Kunnskapsbyen Lillestrøm AS	0	0	340	662		
Maritim Forening Sogn og Fjordane	0	0	797	0		
Morrow Technologies AS	152	0	0	8		

76) Communication (Com) and Dissemination (Dis)
77) Administration (Adm) and Management (Mgmt

Partner	RA1	RA2	RA3	RA4	Com & Dis[76]	Adm &Mgmt[77]
NEL ASA	0	1180	1742	0		
PBES Norway AS	0	0	59	0		
SAFT (France)	893	0	546	52		
Selfa Arctic AS	0	0	313	440		
Statkraft AS	0	0	155	427		
Teer Coatings Ltd. (UK)	0	702	0	367		
Unibuss AS	0	0	0	272		
Vysusgroup AS	0	0	1400	213		
ZEG Power AS	0	0	625	72		
ZEM Energy AS	0	0	1454	49		
Enova SF	0	0	50	100		
Jernbanedirektoratet	3794	1924	6297	1959		
Kystverket	1642	2532	2197	910		
Oslo Havn KF	2805	2468	178	1931		
Statens vegvesen	5943	2617	1398	2541		
Trøndelag fylkeskommune	0	10	4675	1693		
Viken fylkeskommune	1000	1000	4406	1128		

Appendix 2 – Academic Studies and Degrees

Below is summary of the Post.Doc., PhD, and MSc studies and degrees completed during the total project period of the MoZEES Center(2017-2024).

Table 9 – Overview of the 12 post-doctoral fellowships funded by the MoZEES Center

Name	Gender	Nationality	Funding period	RA	Scientific topic	Main contact	Organization
Alok Mani Tripathi	M	India	2018-2021	RA1	Advanced characterization of Li-ion batteries	Truls Norby	UiO
Asbjørn Slagtern Fjellvåg	M	Norway	2022	RA1	Accelerated rate calorimetry of cathodes	Anja Olafsen Sjåstad	UiO
Athanasios Chatzitakis	M	Greece	2018-2019	RA1	Photo electrochemistry and solid state ionics	Truls Norby	UiO
Egbert Ruben van Beesten	M	Netherland	2022-2024	RA4	Value chain optimization in ZE transport networks	Asgeir Tomasgard	NTNU
Einar Vøllestad	M	Norway	2017-2018	RA2	Proton conducting composite membranes	Truls Norby	UiO
Gaylord Kabongo Booto	M	Kongo	2018-2020	RA4	Life Cycle Analysis	Kari Espegren	IFE
Heesoo Park	M	South Korea	2021-2023	RA1	Materials design for battery electrodes	Alexey Koposov	UiO
Inger-Emma Nylund	F	Norway	2022-2024	RA1	Stable HF free electrolytes for Li-ion batteries	Ann Mari Svensson	NTNU
Julia Wind	F	Norway	2017-2018	RA1	Advanced characterization techniques	Alexey Koposov	UiO
Mathias Henriksen	M	Norway	2022	RA3	Explosion hazards of Lithium ion batteries	Knut Vågsæther	USN
Mustapha Jamma	M	Morocco	2023-2024	RA3	Design and validation of energy management systems	Øystein Ulleberg	IFE
Sepideh Jafarzadeh	F	Iran	2016-2018 (in-kind)	RA2	Fuel cells and hydrogen in shipping	Ingrid Schjølberg	NTNU

Table 10 – Overview of the PhD candidates funded by MoZEES

Name	Gender	Nationality	Funding period	RA	Scientific topic	Main Advisor	Organization
Agnieszka Weronika Lach	F	Polish	2019-2022 (in-kind)	RA3	Hydrogen Safety in Confined Spaces	Knut Vågsæther	USN
Carina Geiss[78)]	F	Germany	2020-2022	RA1	Operando studies of silicon (Si) as anode material for Li-ion batteries	Helmer Fjellvåg	UiO
Casper Skautvedt[79)]	M	Norway	2022-2024	RA1	Operando studies of anode materials based on Si for solid-state Liion batteries	Alexey Koposov	UiO
Daniel Tevik Rogstad	M	Norway	2017-2021	RA1	Silicon Anodes and Ionic Liquid Electrolytes for Li-ion Batteries	Ann Mari Svensson	NTNU
Eivind Hugaas	M	Norway	2017-2020	RA2	Long term material properties of pressure vessels made of composite material	Andreas Echtermeyer	NTNU
Eleonora Gadducci	F	Italy	2020-2022 (in-kind)	RA2	Polymeric electrolyte membrane fuel cells (PEMFC)	Magistri Loredana	UNIGE
Elise Ramleth Østli	F	Norway	2017-2022	RA1	Stabilizing Strategies for the High-Voltage Cathode Material LiNi0.5–xMn1.5+xO4 (LNMO)	Sverre Magnus Selbach	NTNU
Halvor Høen Hval[80)]	M	Norway	2018-2022	RA1	Developing high-voltage cathode materials	Helmer Fjellvåg	UiO
Hamid Reza Zamanizadeh	M	Iran	2018-2021	RA2	Cost-effective electrodes for alkaline water electrolysis	Frode Seland	NTNU
Jonas Martin	M	Germany	2020-2024	RA4	Renewable fuels in hard-to-abate transport sectors: Techno-economic analyses from production to consumption in trucking, shipping, and aviation	Anne Neumann	NTNU
Manuel Lenti[81)]	M	Italy	2021-2022	RA3	Design and validation of energy management systems for maritime fuel cell systems to optimize operations and service lifetime costs	Ingrid Schjølberg	NTNU
Mathias Henriksen	M	Norway	2017-2021	RA3	A study of premixed combustion of gas vented from failure LIBs	Dag Bjerketvedt	USN
Šárka Štádlerová	F	Czech	2020-2023	RA4	Multi-period facility location problems with capacity expansion: Locating hydrogen production in Norway	Asgeir Tomasgard	NTNU
Vegard Østli	M	Norway	2018-2023	RA4	The influence of transport policies on car ownership and travel behavior: Insights from three empirical studies.	Colin Green	NTNU
Wijayanti, Ika Dewi	F	Indonesia	2017-2020 (in-kind)	RA1	Novel Zr-based AB_2 Laves Type Alloys as Advanced Negative Electrodes for Ni-MH Batteries	Volodymyr Yartys	NTNU/IFE
Xinwei Sun	F	China	2018-2021	RA2	Development of Low-Cost, High-Performance Composite Membranes for PEM Fuel Cells	Truls Norby	UiO

78) PhD by Carina Geiss was discontinued (for private reasons), but converted into a new PhD by Casper Skautvedt
79) PhD by Casper Skautvedt to be completed in 2026
80) PhD by Halvor Høen Hval to be completed in 2025
81) PhD by Manuel Lenti was discontinued (for private reasons), but converted to a 2-year post.doc. by Mustapha Jamma

Table 11 – Overview of the 29 master theses associated with MoZEES and completed at UiO, NTNU, and USN

Name	Gender	Nationality	Year[82]	RA	Scientific Topic	Main Advisor	University
Abilash Kanish Thiagarajan	M	Norway	2023	RA1	Structural Changes in Graphite-based Anodes of Li-ion Batteries Elucidated through Operando XRD	Alexey Koposov	UiO
Amund Raniseth	M	Norway	2023	RA1	Synthesis, Structural Characterization, Electrochemical Properties, and Thermal Stability of Al-substituted LiMn1.5Ni0.5O4	Helmer Fjellvåg	UiO
Casper Skautvedt	M	Norway	2022	RA1	Synthesis and Characterization of BiFeO3 as Anode Material in Na-ion Batteries[83]	Alexey Koposov	UiO
Charith Rajapaksha	M	Sri Lanka	2024	RA3	The Use of Inert Gas for Mitigating Fires and Gas Explosions	Mathias Henriksen	USN
Christian Eide Stueland	M	Norway	2018	RA3	Change in Flame Front Area Over Time with Premixed Combustion Across an Obstacle	Knut Vågsæther	USN
Christian Wulf	M	Chile	2024	RA1	Optimizing the carbon additive in LiNi0.5Mn1.5O4 batteries	Ann Mari Svensson	NTNU
Hanna Kvam Herskedal	F	Norway	2022	RA1	Sintering Properties and Li-ion Conductivity of Solid-State Electrolytes with Composition Li7–xLa3Zr2–xTaxO12 (x=0.25 and x=0.6)	Ann Mari Svensson	NTNU
Helene L. Langli	F	Norway	2022	RA1	Side Reactions on Two Types of Carbon Conductive Additives in Ionic Liquid-Based Electrolytes for High Voltage Li-ion Battery Cathodes	Ann Mari Svensson	NTNU
Henrik Hovrud	M	Norway	2019	RA3	Simulating Gas Dispersion and *Explosion* with OpenFOAM	Knut Vågsæther	USN
Ida Hæstad	F	Norway	2020	RA3	Modelling of Hydrogen Bunkering *System* for Maritime Applications	Knut Vågsæther	USN
Ida Kværnes Haugsrud	F	Norway	2024	RA1	Optimizing the Carbon Additive in LiNi0.5Mn1.5O4 Batteries	Ann Mari Svensson	NTNU
Ingrid Flatebø Holsen	F	Norway	2020	RA1	Borated Salt Additives in LiFSI Based Electrolytes and Their Compatibility with Silicon Anodes, Aluminum Current Collectors and NMC Cathodes in Li-ion Batteries	Ann Mari Svensson	NTNU
Joachim S. Bjørklund	M	Norway	2021	RA1	Effect of Binders Chemistry on the *Performance* of Silicon Anodes in Li-ion Batteries Prepared from Micron-Sized Silicon	Ann Mari Svensson	NTNU
Jonas Flatgård Jensen	M	Norway	2023	RA3	Proton Exchange Membrane Water Electrolyzer Modeling	Øystein Ulleberg	UiO
Jonathan Johnsplass	M	Norway	2017	RA3	Battery Safety	Knut Vågsæther	USN
Jørgen Kristoffer Tuset	M	Norway	2021	RA3	Modelling and Validation of a Fuel Cell Electric Bus	Øystein Ulleberg	UiO

82) Year when MSc thesis was completed
83) In Norwegian

Name	Gender	Nationality	Year[82]	RA	Scientific Topic	Main Advisor	University
Live Mølmen	F	Norway	2019	RA1	Studies of the Effect of Melt Spinning on the Electrochemical Properties of the AB2 Laves Phase Alloys	Ann Mari Svensson	NTNU
Marthe Nybrodahl	F	Norway	2022	RA1	The effect of MgO-addition on sintering properties and Li-ion conductivity of solid-state electrolytes with composition $Li_{6.25}Al_{0.25}La_3Zr_2O_{12}$	Kjell Wiik	NTNU
Martin Raaen	M	Norway	2022	RA1	Silicon Nanowires Grown-on-Graphite as Composite Anodes for High-Energy Lithium Ion Batteries	Ann Mari Svensson	NTNU
Mats Aspeseter Rødne	M	Norway	2023	RA1	Silicon-based Titania Coated Anodes for Lithium-ion Capacitors	Samson Lai	UiO
Mika Serna Malmer	M	Norway	2023	RA1	Combining LiNi0.5Mn1.5O4 Cathodes with Phosphonium-based Ionic Liquids in Li-ion Batteries	Ann Mari Svensson	NTNU
Mudiyanselage Chinthaka Atta-nayake	M	Sri Lanka	2024	RA3	Experimental Study of Deflagration to Detonation Transition of Hydrogen-Air Gas Explosion	Mathias Henriksen	USN
Nora Kvalvik	F	Norway	2023	RA1	In situ Formation of a Polypyrrole-Coating on a Carbon-Coated LiNi0.5Mn1.5O4 Cathode in Li-ion Batteries as a Strategy for Enhanced Cycling Stability	Ann Mari Svensson	NTNU
Philip Keck	M	USA	2019	RA1	DFT Study of the Defect Chemistry in the Lithium-Garnet LLZO with Dopants Al, Zn, and Mg	Sverre Magnus Selbach	NTNU
Silje Nordnes Bryntesen	F	Norway	2019	RA1	Synthesis of NMC111 Cathodes for Lithium-Ion Batteries	Ann Mari Svensson	NTNU
Steinar Åsmund Fagervold	M	Norway	2019	RA1	Synthesis and Characterisation of NMC622 Cathodes for Lithium-Ion Batteries	Sverre Magnus Selbach	NTNU
Stian Simonsen	M	Norway	2020	RA2	Nafion®-Ceramic Composite Electrolytes for Proton Exchange Membrane Fuel Cells at Elevated Temperatures Composite Polymer Membranes	Truls Norby	UiO
Vegard Vesterdal Viki	M	Norway	2022	RA1	Computational Prediction and *Characterisation* of Novel Li-ion Solid *Electrolytes* based on Earth Abundant LiSiNO	Sverre Magnus Selbach	NTNU
Øyvind Lindgård	M	Norway	2020	RA1	The Effect of Li Salts, Cosolvents, and Additives on the Performance of Silicon Anodes in Ionic Liquid Electrolytes for Lithium-ion Batteries	Ann Mari Svensson	NTNU

Appendix 3 – Conferences

Below is an overview of the number of MoZEES presentations held at international conferences from 2017-2024. A list of the main international conferences attended is also provided.

Table 12 – Summary of the number of MoZEES presentations held at international conferences

Country	Presentations	Country	Presentations
USA	17	Greece	2
Germany	14	Italy	2
France	10	Poland	2
Denmark	6	Russia	2
Australia	5	Bosnia and Herzegovina	1
Canada	5	Hungary	1
Switzerland	5	Netherlands	1
Austria	4	Slovenia	1
Japan	4	Spain	1
China	3	Taiwan	1
Finland	3	Vietnam	1
Sweden	3	Greece	2
Czech Republic	2	Italy	2
USA	17	Poland	2
Germany	14	Russia	2
France	10	Bosnia and Herzegovina	1
Denmark	6	Total number of presentations	96

International Conferences attended by MoZEES Partners	Country
Advanced Battery Power Conference	Germany
Australian Hydrogen Research Conference (AHRC)	Australia
Battery Safety Summit	USA
Electric Vehicle Symposium (EVS)	France, USA, Norway, Korea
Electrochemical Society Meetings (ECS)	USA, Canada, Sweden
European Fuel Cell Forum (EFCF)	Switzerland
European Symposium on Electrochemical Engineering (ESEE)	France, Italy, Australia
European Transport Conference (ETC)	Greece, Italy
IAEE European Energy Conference	Greece, Japan
IEEE Conferences	France, USA, Norway, Korea
International Battery Accociation Meeting (IBA)	California
International Conference on Electrolysis (ICE)	Denmark, Norway, USA
International Conference on Hydrogen Safety (ICHS)	Norway, Germany
International Conference on Marine Energy	Norway
International Conference on Solid State Ionics	USA
International Meeting on Lithium Batteries (IMLB)	Japan
International Seminar on Fire and Explosion Hazards (ISFEH)	Russia, Norway, Italy
Nordic Battery Conference (Nordbatt)	Denmark, Finland, Norway
World Hydrogen Energy Conference (WHEC)	Mexico

Appendix 4 – Publications

Below is the list of MoZEES publications submitted to peer-reviewed international journals (102 publications), PhD theses (11), Master theses (29), and MoZEES reports (28):

RA1 References

1. Østli, E.R., ***Stabilizing Strategies for the High-Voltage Cathode Material LiNi0.5–xMn1.5+xO4 (LNMO)***. 2022, Norwegian University of Science and Technology (NTNU): Trondheim, Norway.
2. Rogstad, D.T., ***Silicon Anodes and Ionic Liquid Electrolytes for Li-ion Batteries***. 2024, Norwegian University of Science and Technology (NTNU): Trondheim, Norway.
3. Wijayanti, I.D., ***Novel Zr- based AB2 Laves type Alloys as Advanced Anodes for High Energy - High Power Metal Hydride Batteries***. 2020, Norwegian University of Science and Technology (NTNU): Trondheim, Norway.
4. Lindgård, Ø., et al., ***Evaluation of LiTFSI as Electrolyte Salt in EmiFSI-based Ionic Liquid Electrolytes to be used with Silicon Anodes for Lithium-Ion Batteries***, in ***NTNU report***. 2020, NTNU: Trondheim.
5. Tron, A., et al., ***New Binder Materials for Cathodes***, in ***SINTEF Report (MoZEES Task 1.3)***. 2019.
6. Brennhagen, A., et al., ***Understanding the (De)Sodiation Mechanisms in Na-Based Batteries through Operando X-Ray Methods.*** Batteries & Supercaps, 2021. **4**(7): p. 1039-1063.
7. Dai, T., et al., ***Antiperovskite active materials for metal-ion batteries: Expected advantages, limitations, and perspectives.*** Energy Storage Materials, 2024. **68**.
8. Das, S., et al., ***Directing SEI formation on Si-based electrodes using atomic layer deposition.*** Chemical Communications, 2024. **60**(100): p. 15011-15014.
9. Dhillon, S., et al., ***Modelling capacity fade in silicon-graphite composite electrodes for lithium-ion batteries.*** Electrochimica Acta, 2021. **377**: p. 9.
10. Foss, C.E.L., et al., ***Anodes for Li-ion batteries prepared from microcrystalline silicon and enabled by binder's chemistry and pseudo-self-healing.*** Scientific Reports, 2020. **10**(1): p. 8.
11. Gobena, H., et al., ***Cycling performance of silicon-carbon composite anodes enhanced through phosphate surface treatment.*** Battery Energy, 2023. **2**(3).
12. Hua, W., et al., ***Insights on microstructural evolution and capacity fade on diatom SiO2 anodes for lithium-ion batteries.*** Scientific Reports, 2023. **13**(1): p. 12.
13. Huld, F.T., et al., ***Revealing Silicon's Delithiation Behaviour through Empirical Analysis of Galvanostatic Charge–Discharge Curves.*** Batteries, 2023. **9**(5): p. 13.
14. Lai, S.Y., et al., ***Advanced and Emerging Negative Electrodes for Li-Ion Capacitors: Pragmatism vs. Performance.*** Energies, 2021. **14**(11): p. 24.
15. Lai, S.Y., et al., ***Morphology engineering of silicon nanoparticles for better performance in Li-ion battery anodes.*** Nanoscale Advances, 2020. **2**(11): p. 5335-5342.
16. Medina, J., et al., ***Accelerating the adoption of research data management strategies.*** Matter, 2022. **5**(11): p. 3614-3642.
17. Østli, E.R., et al., ***On the Durability of Protective Titania Coatings on High-Voltage Spinel Cathodes.*** ChemSusChem, 2022. **15**(12).
18. Østli, E.R., et al., ***Stabilizing the Cathode Interphase of LNMO using an Ionic-liquid based Electrolyte.*** Batteries & Supercaps, 2023. **6**(7): p. 11.

19. Østli, E.R., et al., ***Limitations of Ultrathin Al2O3 Coatings on LNMO Cathodes.*** ACS Omega, 2021. **6**(45): p. 30644-30655.
20. Park, H., A.C.T. van Duin, and A. Koposov, ***Toward Atomistic Understanding of Materials with the Conversion–Alloying Mechanism in Li-Ion Batteries.*** Chemistry of Materials, 2023. **35**(7): p. 2835-2845.
21. Pollen, H.N., et al., ***Interphase Engineering of LiNi0.88Mn0.06Co0.06O2 Cathodes Using Octadecyl Phosphonic Acid Coupling Agents.*** ACS Applied Energy Materials, 2023. **6**(23): p. 12032-12042.
22. Richter, F., et al., ***Measurements of ageing and thermal conductivity in a secondary NMC-hard carbon Li-ion battery and the impact on internal temperature profiles.*** Electrochimica Acta, 2017. **250**: p. 228-237.
23. Rogstad, D.T., M.-A. Einarsrud, and A.M. Svensson, ***Evaluation of selected ionic liquids as electrolytes for silicon anodes in li-ion batteries.*** Journal of the Electrochemical Society, 2021. **168**(11): p. 15.
24. Rogstad, D.T., M.-A. Einarsrud, and A.M. Svensson, ***High-Temperature Performance of Selected Ionic Liquids as Electrolytes for Silicon Anodes in Li-ion Batteries.*** Journal of the Electrochemical Society, 2022. **169**: p. 11.
25. Saleem, U., et al., ***Direct lithium extraction (DLE) methods and their potential in Li-ion battery recycling.*** 2025. **361**.
26. Skurtveit, A., et al., ***Benefits and Development Challenges for Conversion-Alloying Anode Materials in Na-Ion Batteries.*** Frontiers in Energy Research, 2022. **10**: p. 7.
27. Skurtveit, A., et al., ***Stepwise Structural Relaxation in Battery Active Materials.*** ACS Materials Letters, 2025. **7**: p. 343-349.
28. Stokes-Rodriguez, K., et al., ***Comparative Study of High Voltage Spinel-Lithium Titanate Lithium-ion Batteries in Ethylene Carbonate Free Electrolytes.*** Batteries & Supercaps, 2024: p. 13.
29. Tezel, A.O., et al., ***Solid Electrolyte Interphase (SEI) Formation on the Graphite Anode in Electrolytes Containing the Anion Receptor Tris (hexafluoroisopropyl) borate (THFIPB).*** Journal of the Electrochemical Society, 2020. **167**(13): p. 13.
30. Thøgersen, R.V., H.H. Hval, and H. Fjellvåg, ***Elucidation of the Reaction Mechanisms in Antifluorite-Type Li5+xFe1-xCoxO4 Positive Electrodes for Li-Ion Batteries.*** Batteries & Supercaps, 2024.
31. Tolchard, J.R., et al., ***New insights into orthophosphoric acid assisted rapid aqueous processing of NMC622 cathodes.*** RSC Sustainability, 2023. **1**(2): p. 378-387.
32. Ulvestad, A., et al., ***Substoichiometric Silicon Nitride – An Anode Material for Li-ion Batteries Promising High Stability and High Capacity.*** Scientific Reports, 2018. **8**: p. 13.
33. Ulvestad, A., et al., ***Long-term cyclability of substoichiometric silicon nitride thin film anodes for Li-ion batteries.*** Scientific Reports, 2017. **7**(1).
34. Ulvestad, A., et al., ***Crystallinity of silicon nanoparticles: Direct influence on the electrochemical performance of lithium ion battery anodes.*** ChemElectroChem, 2020. **7**(21): p. 4349-4253.
35. Ulvestad, A., et al., ***Stoichiometry-Controlled Reversible Lithiation Capacity in Nanostructured Silicon Nitrides Enabled by in Situ Conversion Reaction.*** ACS Nano, 2021. **15**(10): p. 16777-16787.
36. Volodin, A.A., et al., ***Study of hydrogen storage and electrochemical properties of AB2-type Ti0.15Zr0.85La0.03Ni1.2Mn0.7V0.12Fe0.12alloy.*** Journal of Alloys and Compounds, 2019. **793**: p. 564-575.

37. Wagner, N.P., ***Rest in phase transition: Should charging habits in next generation EVs be adapted?*** Journal of Power Sources Advances, 2024. **27**: p. 6.
38. Wan, C., et al., ***Electrochemical studies and phase-structural characterization of a high-capacity La-doped AB(2) Laves type alloy and its hydride.*** Journal of Power Sources, 2019. **418**: p. 193-201.
39. Wijayanti, I.D., et al., ***Studies of Zr-based C15 type metal hydride battery anode alloys prepared by rapid solidification.*** Journal of Alloys and Compounds, 2019. **804**: p. 527-537.
40. Wijayanti, I.D., et al., ***The electrochemical performance of melt-spun C14-Laves type TiZr-based alloy.*** International Journal of Hydrogen Energy, 2019. **45**(2): p. 1297-1303.
41. Wragg, D.S., et al., ***Tracking Lithiation of Si-Based Anodes in Real Time by Total Scattering Computed Tomography.*** Journal of Physical Chemistry C, 2023. **127**(48): p. 23149-23155.
42. Young, K.-H., et al., ***Cell Performance Comparison between C14- and C15-Predomiated AB2 Metal Hydride Alloys.*** Batteries, 2017. **3**(4): p. 15.
43. Young, K.-H., et al., ***Comparison of C14- and C15-Predomiated AB2 Metal Hydride Alloys for Electrochemical Applications.*** Batteries, 2017. **3**(3): p. 19.
44. Wulf, C., ***Optimizing the Carbon Additive in LiNi0.5Mn1.5O4 Batteries***. 2021, Norwegian University of Science and Technology (NTNU).
45. Bryntesen, S.N., ***Synthesis of NMC111 Cathodes for Lithium-Ion Batteries***. 2019, Norwegian University of Science and Technology (NTNU).
46. Fagervold, S.Å., ***Synthesis and Characterisation of NMC622 Cathodes for Lithium-Ion Batteries***. 2019, Norwegian University of Science and Technology (NTNU).
47. Flatebø, I.H., ***Borated Salt Additives in LiFSI Based Electrolytes and Their Compatibility with Silicon Anodes, Aluminum Current Collectors and NMC Cathodes in Li-ion Batteries***. 2020, Norwegian University of Science and Technology (NTNU).
48. Haugsrud, I.K., ***Optimizing the Carbon Additive in LiNi0.5Mn1.5O4 Batteries***. 2024, Norwegian University of Science and Technology (NTNU).
49. Herskedal, H.K., ***Sintering Properties and Li-ion Conductivity of Solid-State Electrolytes with Composition Li7–xLa3Zr2–xTaxO12 (x=0.25 and x=0.6)***. 2022, Norwegian University of Science and Technology (NTNU).
50. Keck, P., ***DFT Study of the Defect Chemistry in the Lithium-Garnet LLZO with Dopants Al, Zn, and Mg***. 2019, Norwegian University of Science and Technology (NTNU).
51. Kvalvsik, N., ***In situ Formation of a Polypyrrole-Coating on a Carbon-Coated LiNi0.5Mn1.5O4 Cathode in Li-ion Batteries as a Strategy for Enhanced Cycling Stability***. 2023, Norwegian University of Science and Technology (NTNU) / Institute for Energy Technology (IFE).
52. Langli, H.L., ***Side Reactions on Two Types of Carbon Conductive Additives in Ionic Liquid-Based Electrolytes for High Voltage Li-ion Battery Cathodes***. 2022, Norwegian University of Science and Technology (NTNU).
53. Lindgård, Ø., ***The Effect of Li Salts, Cosolvents, and Additives on the Performance of Silicon Anodes in Ionic Liquid Electrolytes for Lithium-ion Batteries***. 2020, Norwegian University of Science and Technology (NTNU).
54. Mølmen, L., ***Studies of the Effect of Melt Spinning on the Electrochemical Properties of the AB2 Laves Phase Alloys***. 2019, Norwegian University of Science and Technology (NTNU).

55. Nybrodahl, M., ***The effect of MgO-addition on sintering properties and Li-ion conductivity of solid-state electrolytes with composition*** $Li_{6.25}Al_{0.25}La_3Zr_2O_{12}$. 2022, Norwegian University of Science and Technology (NTNU).
56. Raaen, M., ***Silicon Nanowires Grown-on-Graphite as Composite Anodes for High-Energy Lithium Ion Batteries***. 2022, Norwegian University of Science and Technology (NTNU).
57. Raniseth, A., ***Synthesis, Structural Characterization, Electrochemical Properties, and Thermal Stability of Al-substituted LiMn1.5Ni0.5O4***. 2023, University of Oslo (UiO).
58. Rødne, M.A., ***Silicon-based Titania Coated Anodes for Lithium-ion Capacitors***. 2023, University of Oslo (UiO).
59. Serna Malmer, M., ***Combining LiNi0.5Mn1.5O4 Cathodes with Phosphonium-based Ionic Liquids in Li-ion Batteries***. 2023, Norwegian University of Science and Technology (NTNU).
60. Skautvedt, C., ***Synthesis and Characterization of BiFeO3 as Anode Material in Na-ion Batteries (in Norwegian)***. 2022, University of Oslo (UiO).
61. Thiagarajan, A.K., ***Structural Changes in Graphite-based Anodes of Li-ion Batteries Elucidated through Operando XRD***. 2023, University of Oslo (UiO).
62. Viki, V.V., ***Computational Prediction and Characterisation of Novel Li-ion Solid Electrolytes based on Earth Abundant LiSiNO***. 2022, Norwegian University of Science and Technology (NTNU).

RA2 References

63. Hugaas, E., ***Long Term Material Properties of Pressure Vessels Made of Composite Material***. 2022, Norwegian University of Science and Technology (NTNU): Trondheim, Norway.
64. Sun, X., ***Development of Low-Cost, High-Performance Composite Membranes for PEM Fuel Cells***. 2023, University of Oslo: Oslo, Norway.
65. Zamanizadeh, H.R., ***Cost-Effective Electrodes for Alkaline Water Electrolysis***. 2022, Norwegian University of Science and Technology (NTNU): Trondheim, Norway.
66. Simonsen, S., ***Nafion®-Ceramic Composite Electrolytes for Proton Exchange Membrane Fuel Cells at Elevated Temperatures-Composite Polymer Membranes***. 2020, University of Oslo (UiO).
67. Fortin, P., ***Results From Model Lifetime Testing of Single Cell PEM Fuel Cells***, in ***SINTEF report***. 2020.
68. Fortin, P., ***Understanding Charge, Mass, and Heat Transfer in PEM Fuel Cells Through Transient Voltage Analysis***, in ***SINTEF report***. 2023.
69. Reksten, A.H., et al., ***TiO2-Ni-Ir Catalysts for Oxygen Evolution Electrocatalysts for PEM Electrolysers Prepared by Reduction of Nickel Phases and Galvanic Replacements***, in ***SINTEF report***. 2020.
70. Sunde, T.O. and A.H. Reksten, ***OER Catalyst Prepared from Cerpotech Nb-doped NiTiO3-powder by Exsolution and Galvanic Replacement***, in ***SINTEF report***. 2024.
71. Sunde, T.O., et al., ***Synthesis, CCM Fabrication and In-Situ Testing of Ru2Y2O7-d/IrO2 Composite Electrodes in PEM Electrolyser Cells***, in ***SINTEF report (MoZEES Task 2.1)***. 2022.
72. Andersen, H., et al., ***A highly efficient electrocatalyst based on double perovskite cobaltites with immense intrinsic catalytic activity for water oxidation.*** Chemical Communications, 2020. **56**(7): p. 1030-1033.

73. Asheim, K., et al., ***Improved electrochemical performance and solid electrolyte interphase properties of electrolytes based on lithium bis(fluorosulfonyl)imide for high content silicon anodes.*** RSC Advances, 2022. **12**(20): p. 12517-12530.
74. Chatzitakis, A.E. and S. Sartori, ***Recent Advances in the Use of Black TiO2 for Production of Hydrogen and Other Solar Fuels.*** ChemPhysChem, 2019. **20**(10): p. 1272-1281.
75. Fortin, P., et al., ***Multi-Sine EIS for Early Detection of PEMFC Failure Modes.*** Frontiers in Energy Research, 2022. **10**.
76. Hugaas, E. and A. Echtermeyer, ***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. **5**: p. 14.
77. Hugaas, E. and A. Echtermeyer, ***Filament wound composite fatigue mechanisms investigated with full field DIC strain monitoring.*** Open Engineering, 2021. **11**(1): p. 401-413.
78. McCay, K., et al., ***In-Situ Monitoring of Interfacial Contact Resistance in PEM Fuel Cells.*** Journal of the Electrochemical Society, 2021. **168**(6): p. 8.
79. Norby, T., ***Protonic conduction on oxide surfaces - role and applications in electrochemical energy conversion.*** Progress in Energy, 2024. **6**: p. 043002.
80. Norby, T., X. Sun, and E. Vøllestad, ***A brick layer model for surface conduction in porous ceramics.*** Solid State Ionics, 2023. **398**: p. 8.
81. Sun, X., et al., ***Quantifiable models for surface protonic conductivity in porous oxides - case of monoclinic ZrO2.*** Physical Chemistry, Chemical Physics - PCCP, 2022. **24**(19): p. 11856-11871.
82. Sun, X., et al., ***Composite Membranes for High Temperature PEM Fuel Cells and Electrolysers: A Critical Review.*** Membranes, 2019. **9**(7).
83. Sun, X., et al., ***Surface protonic conductivity in chemisorbed water in porous nanoscopic CeO2.*** Applied Surface Science, 2022. **611**: p. 1-12.
84. Sun, X., et al., ***Earth-abundant electrocatalysts in proton exchange membrane electrolyzers.*** Catalysts, 2018. **8:657**(12): p. 1-41.
85. Thøgersen, A., et al., ***In-situ electron loss spectroscopy reveals surface dehydrogenation of hydrated ceria nanoparticles at elevated temperatures.*** Journal of Physics and Chemistry of Solids, 2022. **170**: p. 1-7.
86. Yang, D., et al., ***The Influence of bipolar plate wettability on performance and durability of a proton exchange membrane fuel cell.*** International Journal of Hydrogen Energy, 2024. **95**: p. 1284-1298.
87. Zamanizadeh, H.R., et al., ***Tailoring the oxide surface composition of stainless steel for improved OER performance in alkaline water electrolysis.*** Electrochimica Acta, 2022. **424**: p. 10.
88. Zenith, F., et al., ***Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries: Case studies in Norway and USA.*** Proceedings of the Institution of mechanical engineers. Part F, journal of rail and rapid transit, 2019. **234**(7): p. 791-802.
89. Hugaas, E., N.P. Vedvik, and A.T. Echtermeyer, ***Progressive Fatigue Failure Analysis of a Filament Wound Ring Specimen with a Hole.*** Journal of Composites Science, 2021. **5**(9): p. 251.
90. Zamanizadeh, H.R., et al., ***Performance of activated stainless steel and nickel-based anodes in alkaline water electrolyser.*** Journal of Power Sources, 2023. **564**: p. 232828.

RA3 References

91. Henriksen, M., *A Study of Premixed Combustion of Gas Vented from Failed Li-Ion Batteries*. 2021, University of South-Eastern Norway: Porsgrunn, Norway.
92. Lach, A.W., *Hydrogen Safety in Confined Spaces*. 2022, University of South-Eastern Norway: Porsgrunn, Norway.
93. Attanayake, A.M.C., *Experimental Study of Deflagration to Detonation Transition of Hydrogen-Air Gas Explosion*. 2024, University of South-Eastern Norway (USN).
94. Hæstad, I., *Modelling of Hydrogen Bunkering System for Maritime Applications*. 2020, University of South-Eastern Norway (USN).
95. Hovrud, H., *Simulating Gas Dispersion and Explosion with OpenFOAM*. 2019, University of South-Eastern Norway (USN).
96. Jensen, J.F., *Proton Exchange Membrane Water Electrolyzer Modeling*. 2023, University of Oslo (UiO).
97. Johnsplass, J., *Li-ion Battery Safety*. 2017, University of South-Eastern Norway (USN).
98. Rajapaksha, C., *The Use of Inert Gas for Mitigating Fires and Gas Explosions*. 2024, University of South-Eastern Norway (USN).
99. Stueland, C.E., *Change in Flame Front Area Over Time with Premixed Combustion Across an Obstacle*. 2018, University of South-Eastern Norway (USN).
100. Tuset, J.K., *Modelling and Validation of a Fuel Cell Electric Bus*. 2021, University of Oslo (UiO).
101. Andrenacci, S., *Selection and Implementation of EU Protocols for PEM Water Electrolysis Tests*, in *SINTEF report*. 2021.
102. Fagerström, J., et al., *Battery Lifetime Estimations for Freight Train on Partially Electrified Railway Route*, in *IFE-report (MoZEES Task 3.5)*. 2025.
103. Hansen, O.R., *GKP7H2 High Speed Passenger Ferry: Concept Risk Assessment*, in *Lloyds Register Report 106575/R1*. 2018.
104. Hansen, O.R., *Tunnel Safety Evaluations related to Trains and Heavy-Duty Vehicles*, in *Vvsys report (MoZEES Task 3.3)*. 2020.
105. Helgesen, H., *Threat Assessment of Lithium-ion Battery Powered Train*, in *DNV report 2024-2084*. 2024.
106. Hjelkrem, O.A., et al., *Modelling of a Fuel Cell Electric Bus Using the QSS Toolbox*, in *SINTEF report (MoZEES Task 3.1)*. 2020.
107. Holm, T., *Degradation and Failure Analysis of a High-Pressure PEM Water Electrolyzer Stack*, in *IFE/F-2024/014*. 2024.
108. Martinsen, S.Y., et al., *Physical Characterization of Fresh (and Cycled) Battery Cells*, in *SINTEF report (MoZEES Task 3.2)*. 2018.
109. Tuset, J.K., *Modelling of a Fuel Cell Electric Bus Using the QSS Toolbox*, in *IFE/F-2020/102*. 2020.
110. Vatani, M., P.J.S. Vie, and Ø. Ulleberg, *Cycling Lifetime Prediction Model for Lithium-ion Batteries Based on Artificial Neural Networks*, in *IFE report (MoZEES Task 3.2)*. 2018.
111. Wendelborg, L.A., *Transition to Zero Emission: Operation of Battery Electric Buses in Cold and Winter Conditions*, in *Unibuss report (MoZEES Task 3.5)*. 2024.

112. Weydahl, H., et al., *Comparison of Thermal Runaway Initiation Methods for a Cylindrical Li-ion Cell*, in *FFI report 21/01702*. 2021.
113. Aarskog, F.G., et al., *Energy and cost analysis of a hydrogen driven high speed passenger ferry.* International Shipbuilding Progress, 2020. **67**: p. 27.
114. Aarskog, F.G., et al., *Concept risk assessment of a hydrogen driven high speed passenger ferry.* International Journal of Hydrogen Energy, 2019: p. 1-14.
115. Bratland, M., D. Bjerketvedt, and K. Vågsæther, *Structural response analysis of explosions in hydrogen-air mixtures in tunnel-like geometries.* Engineering structures, 2021. **231**.
116. Gaathaug, A.V., et al., *Detonation Propagation in Stratified Reactant Layers.* Linköping Electronic Conference Proceedings, 2017(138): p. 162-167.
117. Halvorsen, I.J., et al., *Electrochemical low-frequency impedance spectroscopy algorithm for diagnostics of PEM fuel cell degradation.* International Journal of Hydrogen Energy, 2020. **45**(2): p. 1325-1334.
118. Hancke, R., et al., *High-pressure PEM water electrolyser performance up to 180 bar differential pressure.* Journal of Power Sources, 2024. **601**: p. 9.
119. Hancke, R., T. Holm, and Ø. Ulleberg, *The case for high-pressure PEM water electrolysis.* Energy Conversion and Management, 2022. **261**: p. 13.
120. Henriksen, M., A.V. Gaathaug, and J. Lundberg, *Determination of underexpanded hydrogen jet flame length with a complex nozzle geometry.* International Journal of Hydrogen Energy, 2018: p. 1-9.
121. Henriksen, M., et al., *Numerical study of premixed gas explosion in a 1-m channel partly filled with 18650 cell-like cylinders with experiments.* Journal of Loss Prevention in the Process Industries, 2022. **77**: p. 104761.
122. Henriksen, M., et al., *Laminar burning velocity of the dimethyl carbonate–air mixture formed by the Li-ion electrolyte solvent.* Combustion, explosion, and shock waves, 2020. **56**(4): p. 383-393.
123. Henriksen, M., et al., *Explosion characteristics for Li-ion battery electrolytes at elevated temperatures.* Journal of Hazardous Materials, 2019. **371**: p. 1-7.
124. Henriksen, M., et al., *Laminar burning velocity of gases vented from failed Li-ion batteries.* Journal of Power Sources, 2021. **506**: p. 1-11.
125. Henriksen, M., et al., *Simulation of a premixed explosion of gas vented during Li-ion battery failure.* Fire safety journal, 2021. **126**: p. 1-12.
126. Jafarzadeh, S. and I. Schjølberg, *Operational profiles of ships in Norwegian waters: An activity-based approach to assess the benefits of hybrid and electric propulsion.* Transportation Research Part D: Transport and Environment, 2018. **65**: p. 500-523.
127. Johnsplass, J.S., et al., *Simulation of burning velocities in gases vented from thermal run-a-way lithium ion batteries.* Linköping Electronic Conference Proceedings, 2017(138): p. 157-161.
128. Lach, A. and A.V. Gaathaug, *Effect of Mechanical Ventilation on Accidental Hydrogen Releases—Large-Scale Experiments.* Energies, 2021. **14**(11): p. 13.
129. Lach, A. and A.V. Gaathaug, *Large scale experiments and model validation of Pressure Peaking Phenomena-ignited hydrogen releases.* International Journal of Hydrogen Energy, 2021. **46**(11): p. 8317-8328.

130. Lach, A., A.V. Gaathaug, and K. Vågsæther, ***Pressure peaking phenomena: Unignited hydrogen releases in confined spaces – Large-scale experiments.*** International Journal of Hydrogen Energy, 2020. **45**(56): p. 32702-32712.
131. Lian, T., et al., ***Changes in Thermal Stability of Cyclic Aged Commercial Lithium-Ion Cells.*** ECS Transactions, 2019. **89**(1): p. 73-81.
132. Marocco, P., et al., ***Online measurements of fluoride ions in proton exchange membrane water electrolysis through ion chromatography.*** Journal of Power Sources, 2021. **483**: p. 10.
133. Pettersen, T., et al., ***Simulation study on preventing explosive mixture formation in PEM electrolysers' water recovery tanks.*** International Journal of Hydrogen Energy, 2024. **84**: p. 1021-1032.
134. Ulleberg, Ø. and R. Hancke, ***Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway.*** International Journal of Hydrogen Energy, 2019. **45**(2): p. 1201-1211.
135. Vågsæther, K., A.V. Gaathaug, and D. Bjerketvedt, ***PIV-measurements of reactant flow in hydrogen-air explosions.*** International Journal of Hydrogen Energy, 2018: p. 8.
136. Vatani, M., P.J.S. Vie, and Ø. Ulleberg, ***Cycling Lifetime Prediction Model for Lithium-ion Batteries Based on Artificial Neural Networks.*** IEEE PES Innovative Smart Grid Technologies Conference Europe, 2018: p. 6.
137. Wind, J., et al., ***Cellpy – an open-source library for processing and analysis of battery testing data.*** Journal of Open Source Software (JOSS), 2024. **9**(97): p. 6.
138. Zenith, F., ***Battery-powered freight trains.*** 2021. **6**: p. 1003–1004.

RA4 References

139. Sundvor, I., et al., ***Estimating the replacement potential of Norwegian high-speed passenger vessels with zero-emission solutions.*** Transportation Research Part D: Transport and Environment, 2021. **99**(October): p. 1-17.
140. Bjerkan, K.Y., et al., ***Zero-Emission Passenger Vessels for Public Tendered Services. State of the Art of Technology and Current Use.***, in ***SINTEF report***. 2018, SINTEF: Trondheim.
141. Bjerkan, K.Y., et al., ***Public Tendered Maritime Passenger Services. Opportunities and Barriers for Zero-Emission Operation***, in ***SINTEF report***. 2019, SINTEF: Trondheim.
142. Fridstrøm, L., et al., ***Decarbonization of Transport - Position Paper*** in ***MoZEES/CenCES report***. 2019, MoZEES: Trondheim.
143. Hovi, I.B., et al., ***User Experiences from the Early Adopters of Heavy-Duty Zero-Emission Vehicles in Norway. Barriers and Opportunities.*** , in ***TØI report 1734/2019***. 2019, Transport Economic Institute: Oslo.
144. Jordbakke, G.N., et al., ***Technological Maturity Level and Market Introduction Timeline of Zero-Emission Heavy-Duty Vehicles.***, in ***TØI report 1655/2018***. 2018, Transport Economic Institute: Oslo.
145. Pinchasik, D.R., et al., ***Green Trucking? Technology Status, Costs, User Experiences***, in ***TØI report 1855/2021***. 2022, Transport Economic Institute: Oslo.

146. Pinchasik, D.R., et al., *Progress and Future Prospects for the Adoption of Battery-Electric Trucks in Norway - User Experiences, Developments, Barriers and Needs*, in *TØI report 2036/2024*. 2024, Transport Economic Insitute: Oslo.
147. Pinchasik, D.R., I.B.Hovi, and E. Figenbaum, *User Experiences from the First Series-Produced Battery-Electric Trucks - Interviews in 2021 with the first Norwegian Users.*, in *TØI report 1908/2022*. 2022, Transport Economic Institute: Oslo.
148. R.J.Thorne, A.H. Amundsen, and I. Sundvor, *Battery Electric and Fuel Cell Trains: Maturity of Technology and Market Status.*, in *TØI report 1737/2019*. 2019, Transport Economic Institute: Oslo.
149. Bjerkan, K.Y., et al., *Governance in Maritime Passenger Transport: Green Public Procurement of Ferry Services.* World Electric Vehicle Journal, 2019. **10**(4): p. 1-15.
150. Booto, G.K., K.A. Espegren, and R. Hancke, *Comparative life cycle assessment of heavy-duty drive trains: A Norwegian study case.* Transportation Research Part D: Transport and Environment, 2021. **95**: p. 23.
151. Ellingsen, L.A.-W., et al., *Life cycle assessment of battery electric buses.* Transportation Research Part D: Transport and Environment, 2022. **112**(November): p. 1-13.
152. Figenbaum, E., *Can battery electric light commercial vehicles work for craftsmen and service enterprises?* Energy Policy, 2018. **120**: p. 58-72.
153. Figenbaum, E., *Battery Electric Vehicle Fast Charging–Evidence from the Norwegian Market.* World Electric Vehicle Journal, 2020. **11**(2): p. 27.
154. Figenbaum, E., *An Empirical Study of the Policy Processes behind Norway's BEV-Olution.* World Electric Vehicle Journal, 2024. **15**(37): p. 1-56.
155. Figenbaum, E., et al., *Empirical Analysis of the User Needs and the Business Models in the Norwegian Charging Infrastructure Ecosystem.* World Electric Vehicle Journal, 2022. **13**(10): p. 1-24.
156. Hovi, I.B., et al., *Experiences from battery-electric truck users in Norway.* World Electric Vehicle Journal, 2020. **11**(5).
157. Karlsson, H., et al., *Green Public Procurement for Accelerating the Transition towards Sustainable Freight Transport.* World Electric Vehicle Journal, 2022. **13**(9).
158. Martin, J., E. Dimanchev, and A.F. Neumann, *Carbon abatement costs for renewable fuels in hard-to-abate transport sectors.* Advances in Applied Energy, 2023. **12**: p. 15.
159. Martin, J., et al., *Modeling cost-optimal fuel choices for truck, ship, and airplane fleets: The impact of sustainability commitments.* Energy, 2024. **308**: p. 17.
160. Martin, J., A. Neumann, and A. Ødegård, *Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model.* Working Paper Series, 2022.
161. Martin, J., A.F. Neumann, and A. Ødegård, *Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: A holistic cost model.* Renewable and Sustainable Energy Reviews, 2023. **186**: p. 21.
162. Stadlerova, S., et al., *Locating Hydrogen Production in Norway Under Uncertainty.* Lecture Notes in Computer Science (LNCS), 2022. **13557**: p. 306-321.

163. Stadlerova, S., S.D. Jena, and P. Schütz, ***Using Lagrangian relaxation to locate hydrogen production facilities under uncertain demand: a case study from Norway.*** Computational Management Science, 2023. **20**(1).
164. Stadlerova, S. and P. Schütz, ***Designing the Hydrogen Supply Chain for Maritime transportation in Norway.*** Lecture Notes in Computer Science (LNCS), 2021. **13004**: p. 36-50.
165. Stadlerova, S., P. Schütz, and A. Tomasgard, ***Multi-period facility location and capacity expansion with modular capacities and convex short-term costs.*** Computers & Operations Research, 2023. **163**.
166. Thorne, R.J., et al., ***Facilitating adoption of electric buses through policy: Learnings from a trial in Norway.*** Energy Policy, 2021. **155**(August 2021): p. 1-11.
167. Martin, J., *Renewable Fuels in Hard-to-Abate Transport Sectors: Techno-Economic Analyses from Production to Consumption in Trucking, Shipping, and Aviation*. 2024, Norwegian University of Science and Technology: Trondheim, Norway.
168. Østli, V., *The Influence of Transport Policies on Car Ownership and Travel Behavior*. 2025, Norwegian University of Science and Technology: Trondheim, Norway.
169. Štádlerová, Š., *Multi-Period Facility Location Problems with Capacity Expansion: Locating Hydrogen Production in Norway*. 2023, Norwegian University of Science and Technology: Trondheim, Norway.

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