MoZEES
Mobility Zero Emission Energy Systems

FME
FORSKNINGS-SENTER FOR MILJØVENNLIG ENERGI
Norges forskningsråd

Annual Report 2020

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Message from the Chair of the Board

2020 will be remembered as the year the COVID-19 pandemic started. But I also look back at 2020 as the year the Norwegian industry in cooperation with research organisations made large efforts to promote the battery and hydrogen value chains as future large economic possibilities for Norway, as shown in the reports Grønne elektriske verdikjeder and Batteriverdikjeden Prosess 21 Ekspertnotat.

In the green transition several existing and new companies are starting up business in areas covered by MoZEES. MoZEES' relevance to industry and society is increasing, thus also the expectations on us to deliver on the MoZEES ambitions. The long-term MoZEES research Roadmaps developed for each of the four Research Areas (RA) point to these ambitions. I believe that our strength as a centre and our possibilities to reach our goals, lie in a research agenda developed by the private and public user partners together with the research partners.

To further strengthen and leverage on the cooperation and innovation activities in the Center, the MoZEES Innovation Forum was successfully established in 2020 as an arena for new ideas and possibilities to emerge. I am also very pleased by the enlargement of MoZEES' competent industry basis during 2019- 2020, including the addition of Statkraft, Hydro, and Equinor.

A learning from 2020 is that digital meetings can work if these are well planned. The Center Director and his team successfully managed to organise the 2020 MoZEES Annual Meeting on TEAMS. Excellent presentations from invited guest and MoZEES partners could be followed further in interesting digital discussions. Yet another example of efficient organisation of valuable communication to the centre partners is the MoZEES Digital Lunch Talk highlighting outstanding research and development activities.

In summary, 2020 has shown that MoZEES stands out as an important Center for Environment-friendly Energy Research with a strong partner base. On behalf of the Board, I would like to thank all partners, and the Director and his team for their enthusiasm and contributions to make the MoZEES Center a beacon for research focusing on battery and hydrogen technologies for heavy duty transport applications.

Rune Bredesen
Chairman of the Board

Letter from the Center Director

I wish I could say "yet another exciting year has passed", but that is not 100% the case. The COVID-19 pandemic has turned our lives upside down, so also for MoZEES and its partners. Like everyone else we have gone from physical to digital meetings. Where we normally would work in physical teams in project meeting, laboratories, and elsewhere, we are now working one-by-one on Teams and limiting our physical meetings to an absolute minimum. I think we all are tired of this situation and look forward to the day when we can meet again. The pandemic has also had a significant effect on the overall economy and many private businesses and people are struggling. Despite this very difficult situation, MoZEES has managed to cope quite well. We adapted fast to the new situation and managed to perform most of our planned activities and research tasks in 2020, despite a 15% decrease in the overall turn-over in the Center. I would therefore like to thank all partners and members in MoZEES, every one of you, for your perseverance in 2020! You really have shown a great commitment to the long-term work we all have embarked on.

The MoZEES Annual Meeting on 21-23 September 2020, which needed to take place in the form of a three-day webinar instead of a physical meeting at Son Spa, is a great example on how the MoZEES consortium was able to regroup and conduct their business as normal as possible. This event also gave us the motivation and incentive to rejuvenate the digital collaboration platform in the Center. A permanent MoZEES Teams for document sharing and communication in different channels was established shortly after the Annual Meeting. In some strange way I feel that I now can work more closely with you, despite not being able to meet you. With more than 140 members in the MoZEES Teams (and still counting) we have created an efficient and informal platform for communication. Instead of saying "just a phone call away" (or "just a short flight away"), we can now say "just a quick chat on Teams away". I encourage all of you to use this opportunity to find new friends in MoZEES.

One of the main milestones in 2020 was to prepare documentation and reports to the Research Council of Norway for the FME Midterm Review. A MoZEES self-evaluation report, an updated MoZEES 3-year Project plan, and 37 Partner self-assessment reports were prepared and submitted to the Research Council in December. The midway evaluation process and self-assessments gave us important new insight into what is working well in the Center and what can and should be improved. The self-evaluation showed that MoZEES is well organized with a strong scientific team and solid research program, but that we can be better in showing off our innovation activities. The official feedback from the external review and final recommendation from the Research Council of Norway for continued operation of the Center for the last three-year period (2022-2024) will be announced in June 2021. The preliminary feedback has been very positive, and I am very optimistic about the future for zero emission transport and the applications targeted in MoZEES: Battery and hydrogen technologies for heavy-duty transport on road, rail, and sea.

In the fall 2020 we started the process to develop a set of MoZEES roadmaps on battery and hydrogen technology and zero emission heavy duty transport solutions. I would like to thank those of you who contributed with very valuable input to these roadmaps. The final versions of the MoZEES Roadmap are officially published in this Annual Report. The market potential and the possibilities for new value creation in various battery value chains is significant, as pointed out in the reports referred to in the Message from the Chair of the Board. However, there does still not yet exist a national battery roadmap in Norway. I would therefore recommend that we align the MoZEES Battery Technology Roadmap with other large national battery initiatives to make a proper national battery roadmap. The ambition should here be to establish new and environmentally friendly battery material and cell production in Norway. If such battery manufacturing capability is combined with first-hand knowledge and experience from the application and use of batteries in advanced markets in Norway, such as maritime batteries, we will be in a very good position to develop some unique battery products and solutions to the world in near future.

In 2020 the Norwegian government launched a national hydrogen strategy and has in this context asked for input to a more detailed national hydrogen roadmap. This means that our timing with the publication of the MoZEES Hydrogen Technology Roadmap and MoZEES Heavy-Duty Transport Roadmap is excellent. In 2020 there was also established an industry driven MoZEES Innovation Forum and Innovation Committee, with the main objective to create new battery and hydrogen activities (MoZEES spin-off projects) with partners in relevant industrial clusters in Norway and abroad. In parallel to this, several key MoZEES research and industry partners were involved in the establishment of the H2Cluster, a national innovation network on hydrogen supported by Innovation Norway. I hope that many of you will use the MoZEES Innovation Forum and H2Cluster industry networks to develop new research, innovation, demonstration, and pre-commercial hydrogen transport projects. I strongly believe that MoZEES can make a difference in the realization of zero- emission heavy duty transport, using both battery and hydrogen technology.

The main asset in a research center such as MoZEES are the people. In 2020 there were about 80 researchers and students active in different research tasks in MoZEES, including ca. 10 professors, 20 senior researchers and 25 young researchers. In addition, about 25 technology experts from the industry partners have participated and contributed to the research. We currently have 16 PhD-students (9 fully funded) and 3 post-doctoral fellowships (2 fully funded) that are directly associated with the Center. We have also noted that there were 6 master students at NTNU, UiO, and USN that performed projects related to MoZEES in 2020. We strongly encourage more students and young researchers to join and get associated with MoZEES, including international students.

I would like to thank everyone that has contributed to the great progress in MoZEES so far, including students, key researchers, management team and board members.

The personnel situation in the Center is stable, but some changes are inevitable. People will always seek new jobs and opportunities when these appear, so also is the case for MoZEES. Fortunately, I have noticed that people leaving MoZEES typically end up in new green jobs. I find this to be a very encouraging and a healthy sign for a new green future. The natural movement of people out of MoZEES also creates opportunities for new recruitments into MoZEES. I therefore strongly encourage you to introduce more students and colleagues to the research and innovation activities in MoZEES. We have the capacity to accommodate many more people in the Center. We also strongly welcome more international collaboration.

Finally, I am happy that we have safely left 2020 behind us and now gradually can start to focus on life after COVID-19. Fortunately, it seems as if the “timeout” during the pandemic has made many more people realize that we need to intensify our efforts on the development of new climate neutral solutions. For MoZEES this means that we now probably will be getting some more help to speed up the investments in battery and hydrogen technology and zero emission transport solutions. Market trends show that we are slowly, but steadily going from technology push to market pull. Therefore, to those of you who are getting a bit tired of doing R&D in this field over many years: This is not the time to quit, but the time to endure.

When the going gets tough, the tough gets going!

Øystein Ulleberg
Center Director

About MoZEES

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

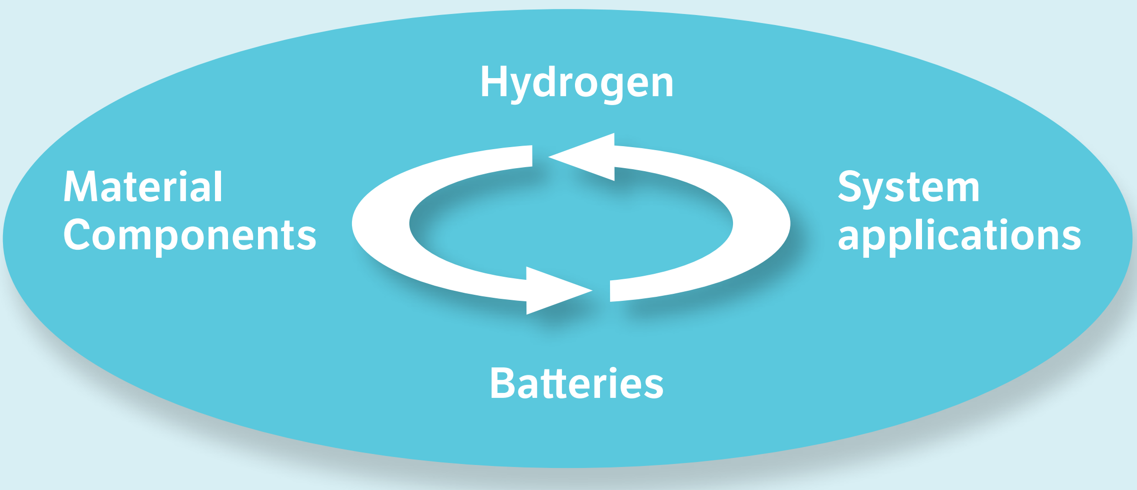
The main objective with MoZEES is to be a Center for environment-friendly energy research with focus on new battery and hydrogen materials, components, technologies, and systems for existing and future transport applications on road, rail, and sea. The Center contributes to the design and development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

The specific focus areas for the research activities are:

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

MoZEES is a collaboration between four research institutes (IFE, SINTEF, TØI, and FFI), three universities (UiO, NTNU, and USN), six public partners, 2 private interest organizations, and 22 commercial and industrial partners, including key battery and hydrogen materials, components, technology, and systems suppliers. There has also been established formal collaboration agreements (MoUs) with four international universities: RWTH University Aachen (Germany), University of Uppsala (Sweden), University of California Davis (USA), and University of Genova (Italy). Institute for Energy Technology (IFE) at Kjeller in Norway is the host for FME MoZEES.

In MoZEES there is a special focus on research and development of zero emission solutions for heavy-duty transport, and especially on the use of batteries and hydrogen in maritime applications. There is also a strong



focus on battery material research that can assist the development of new Norwegian industrial battery value chains. Below are some highlights from 2020:

Over the past few years (2017-2020) there has been performed systematic work in MoZEES on the development of new and safe solutions for use of hydrogen in high-speed crafts in Norway. The results from the research in this area has included everything from detailed technical evaluations, risk assessments, and safety analyses related to the design and operation of onboard hydrogen- and fuel cell systems to planning of necessary hydrogen infrastructure on shore. The results and methods developed can used in several other maritime applications.

At the MoZEES Annual Meeting 2020 there was for the first time organized a so-called MoZEES Industry & Innovation Day, with a specific focus on the possibilities to establish new battery value chains og industry in Norway. Presentations from the large established international companies and the small and promising new companies in MoZEES all showed great optimism for the future and willingness to establish new commercial and industrial battery activities in Norway.

In 2020 there was also established a mandate for a MoZEES Innovation Committee and an industry driven MoZEES Innovation Forum, which is to meet regularly to discuss possible innovations from MoZEES and to create new industry driven spin-off projects. The main strategy here is to coordinate the MoZEES research activities with different national innovation activities to create new battery and hydrogen activities with partners in relevant industrial clusters in Norway. There has in 2020 also been established specific MoZEES Roadmaps, that can be used as input to national roadmaps on batteries, hydrogen, and zero emission transport.

In 2020 there were about 80 researchers and students active in different research tasks in MoZEES, including ca. 10 professors, 20 senior researchers and 25 young researchers. In addition, about 25 technology experts from the industry partners have participated and contributed to the research. MoZEES has currently 16 PhD-students (9 fully funded) and 3 post-doctoral fellowships (2 fully funded) that are directly associated with the center. In 2020 there were 6 master students at NTNU, UiO, and USN that performed projects related to MoZEES.

Partners

Industry and Public Partners

KYSTVERKET

Jernbane-direktoratet

Statens vegvesen
Norwegian Public Roads Administration

Trøndelag fylkeskommune

GrapheneBatteries

Selfa Arctic

nel

Teer coatings

DNV·GL

OREEC
KUNNSKAPSBYEN

ASKO
-vi forsyner Norge med mat

Statkraft

JM
Johnson Matthey Fuel Cells
the power within

ABB

Cerpotech

hub for ocean

ENOVA

UNIBUSS

HEXAGON COMPOSITES

saft
a company of TOTAL

equinor

CENATE

ZEG Power

Hydro

PORT OF OSLO

LR Lloyd's Register

GRENLAND ENERGY

VIKEN FYLKESKOMMUNE

Elkem

baldur
BALDUR COATINGS AS

ZEM Marine

National Research Partners

TØI Institute of Transport Economics Norwegian Centre for Transport Research

UiO : University of Oslo

USN University of South-Eastern Norway

NTNU Norwegian University of Science and Technology

IFE Institute for Energy Technology

SINTEF

FFI Forsvarets forskningsinstitutt Norwegian Defence Research Establishment

International Research Partners

UPPSALA UNIVERSITET

UCDAVIS UNIVERSITY OF CALIFORNIA

RWTH AACHEN UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

Members of the Center Management Team


Øystein Ulleberg (IFE)


Ragnhild Hancke (IFE)


Ann Mari Svensson (NTNU)


Magnus Thomassen (SINTEF)


Erik Figenbaum (TØI)


Katinka Elisabeth Grønli (UiO)

Members of the Executive Board


Arve Holt (IFE)


Patrick Bernard (Saft)


Ragnhild Wahl (Jernbanedir.)


Einar Hjorthol (NTNU)


Gunnar Lindberg (TØI)


Anders Søreng (NEL Hydrogen)

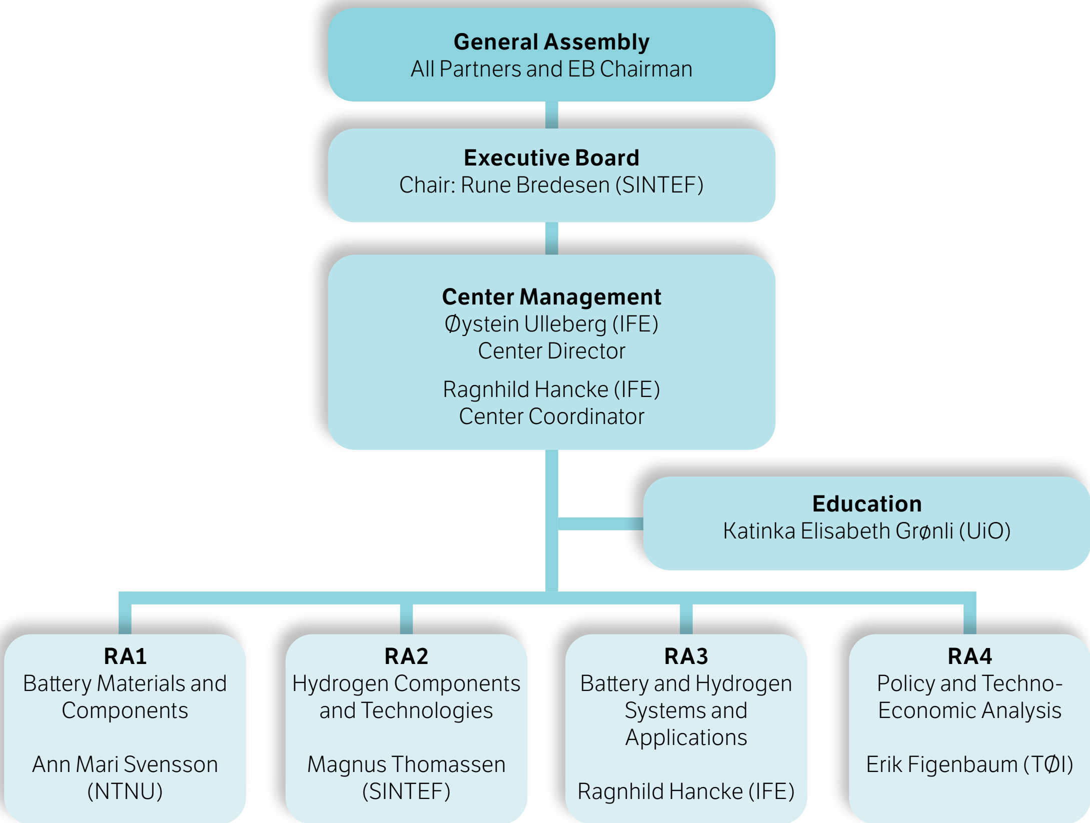

Per Ivar Helgesen (ENOVA)


Marit Dolmen (Elkem)


Rune Bredesen (SINTEF)


Jan Fredrik Hansen (ABB)

Organization



The Management Team and members of the Executive Board gathered at the MoZEES Annual Meeting 2019 (Photo: J.A. Wilhelmsen)

Education

The main objective with the MoZEES Education and Dissemination program is to enhance career developing activities for young researchers in recruitment positions at the Centre and to create synergies between the research areas, partner institutions, and external stakeholders. Another important objective is to increase the visibility of the Center and by that increase MoZEES impact and opportunities. The educational activities in the Center are jointly administered by the UiO and IFE. UiO:Energy has created a MoZEES Research Training Network (RTN) with the purpose to increase the cooperation across all research areas in MoZEES. A very important task for the MoZEES RTN is to ensure that the candidates are qualified to be scientific researchers within their field of expertise, and at the same time are able to contribute to realizing the goals of the different research areas in the Center.

The MoZEES Research Training Network includes:

- Management of the MoZEES Mobility Program for young researchers; International Academic Mobility Grants have been awarded to three MoZEES PhD-students so far.
- Facilitation of meetings between the Scientific Advisory Committee and researchers, students, and user partners during the MoZEES Annual Meeting and regular workshops
- Organization of special courses and summer schools, including a MoZEES PhD Summer School on Sustainable Transport (2019) (collaboration with FME Bio4Fuels) and MoZEES RTN workshops on how to pitch scientific work to the public (2019) and professional scientific writing (2020)

One of the key objectives in MoZEES is to build competence by recruiting and educating new PhD candidates, postdoctoral fellows, and young researchers. Over the first four years (2017-2020) there have been 19 PhD-students (9 fully funded), 7 postdoctoral fellows (5 fully funded), and 11 master students directly associated with MoZEES. This is higher than the original plans. There is also a trend that more and more PhD and master students, including international students, would like to be associated with different research tasks in the center.

The recruitment of new students to the three university partners UiO, NTNU, and USN has also had a "spill-over effect" to the research institutes SINTEF and IFE. There are already registered a few cases where MoZEES students and postdoctoral fellows have migrated from the universities to the research institutes. Some also plan for PhDs to continue their work in post.docs.

Elise Ramleth Østli working in the lab at Uppsala University in 2019

Academic Writing Workshop for PhD Students

(TEXT AND PHOTOS: KATINKA GRØNLI)

In collaboration with the Academic writing centre (UiO), MoZEES RTN organised a two-day academic writing workshop for seven PhD students from the Norwegian University of Science and Technology, the University of South-Eastern Norway and the University of Oslo.

The course consisted of lectures, exercises, discussions, on-on-one consultations and "shut-up-and write" sessions where the participants could work on their own manuscripts. The goal was to promote science writing as storytelling and to provide concrete tools to fuel the writing process.

Better at organising text

When asked what they take with them from two days of tutoring and writing exercises, feedback from the participants was overwhelmingly positive. They all felt that they have become better able at organising different parts of their articles, from the overall structure down to paragraph and sentence structure. Writing scientific articles has become more accessible, it was said, and useful tools had been introduced.

The course participants in particular enjoyed the use of examples from drafts that they had submitted beforehand, but also that writing mentors, Ingerid Straume and Cathinka Dahl Hambro, shared a lot from their own experiences as writers and editors. The outcome was excellent, both socially and academically, and the students were motivated to write, they stated.

An historical venue

The venue of the course was Dale-Gudbrands-Gard, a historical site in Hundorp. Rasmus Stauri, born and raised on the farm, gave an introduction to the history behind the ancient burial mounds on the premises, dating back to the Iron Age, and the meeting between St Olav and the Viking hersir (local Viking military commander) Dale-Gudbrand on the farm in 1021.

He also inspired the participants by telling the story about Gudbrandsdalen Folk high school, grounded by his namesake and grandfather in 1902, a cultural centre for popular adult education.

Rasmus Stauri and MoZEES RTN in front of a Viking tumulus (ancient burial mound). To the left, a modified Ground Penetrating Radar system can be spotted, scanning the area to prepare for the millenium anniversary of the meeting between St Olav and Dale-Gudbrand.

From left: Hamid Reza Zamanizadeh, Mathias Henriksen, Agnieszka Lach, Elise Ramleth Østli, Vegard Østli, Halvor Høen Hval, Daniel Tevik Rogstad, Ingerid Straume and Cathinka Dahl Hambro in front of the gymnasium, serving as the course writing room, at Dale-Gudbrand´s Gård.

MoZEES Annual Meeting 2020

The third Annual Meeting for MoZEES was successfully run as an open, online event on 21-23 September. The meeting attracted close to 150 participants from research and industry, and covered the latest developments and accomplishments within MoZEES' activities on battery- and hydrogen technologies and zero emission transport applications.

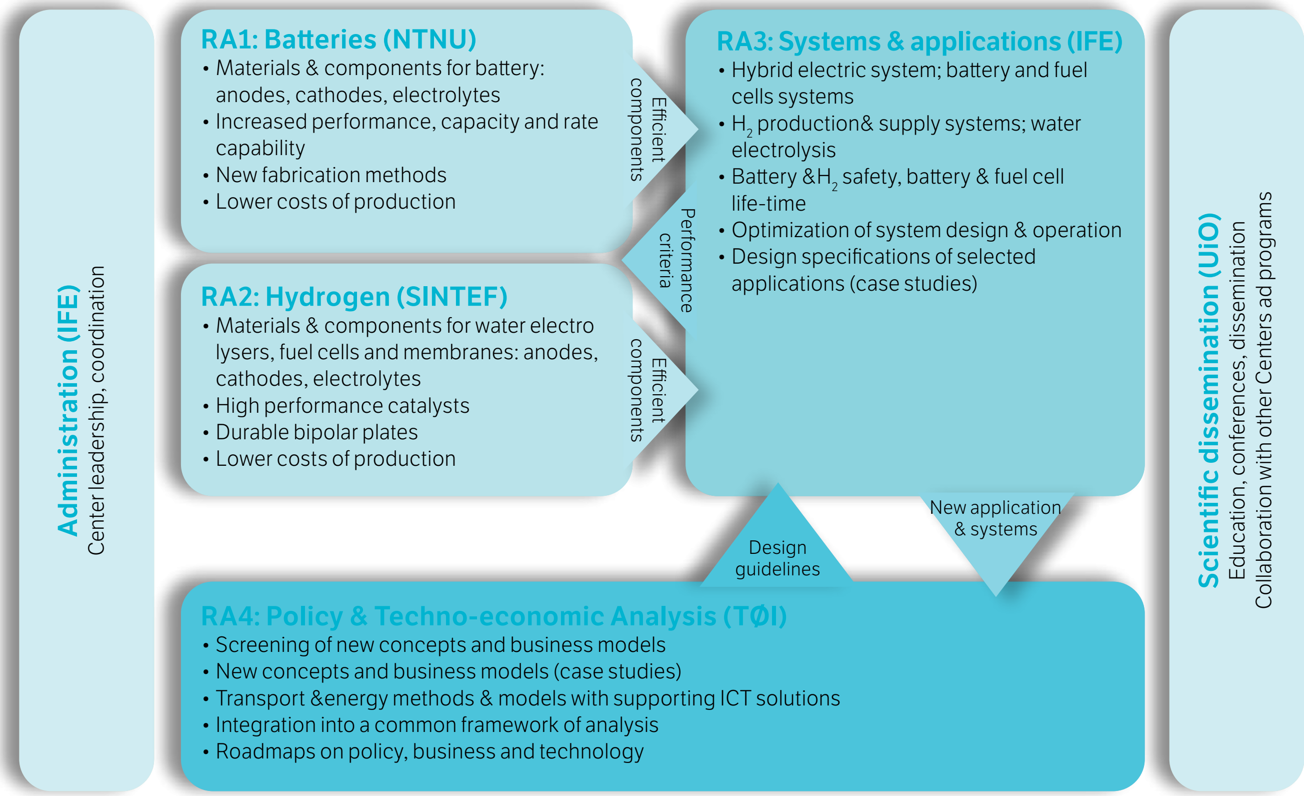
The Meeting was organized as a fully digital event with live talks supported by an active discussion forum. This format, combining the Microsoft Live Event and Teams platforms, provided the possibility to ask questions and engage in discussions with the presenters during and after the live presentations.

The first two meeting days were dedicated to presentations of the latest research results and advancements within the respective MoZEES Research Areas. We were delighted that the members of the Scientific Advisory Board agreed to open each of the sessions with a keynote lecture. New to this year's program was the incorporation of poster sessions were the presenters where challenged to prepare a 2 minutes poster pitch ("elevator pitch"). This addition to the meeting format was well received, and several of the posters were – just like many of the regular presentations – discussed in depth in the Teams channels.

The third meeting day marked the kick-off of the MoZEES Innovation Forum, where MoZEES user partners such as Elkem, SAFT, Morrow Batteries, Statkraft and Nel Hydrogen presented their ongoing and planned innovation activities. These sessions were extremely well received and provided a unique glimpse into the many exciting initiatives in Norway and abroad. They also confirmed that the ongoing activities and scope of work of MoZEES is very much in line with the needs and interests of the industry.

Research Areas

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



RA1 Battery Materials

The research area devoted to battery materials has its main focus on the next generation high energy Li-ion batteries based on anodes with a high silicon (Si) content, and a spinel cathodes $LiNi_{0.5-x}Mn_{1.5+x}O_4$ (LNMO), or Ni-rich NMC layered cathodes. Elkem provides Si materials readily available at low cost and with low environmental impact. Si materials have also been supplied by the SME Cenate®, partner in the project, aiming to develop nano-Si as anode material for Li-ion batteries. In addition, research partner IFE synthesize Si-based materials. The LNMO material is obtained from commercial sources (Haldor Topsøe), or synthesized by the research partners, or supplied by the industrial partner (SME CerPoTech). SME Baldur is also partner of Mozees (atomic layer deposition of materials). The battery company SAFT (France) is actively engaged in RA1, and the newly formed Norwegian company Morrow Batteries joined Mozees in 2020.

Silicon anodes

Research within RA1 at NTNU focus on electrolytes based on ionic liquids in combination with anodes of high Si content (73 wt%, eSi-400 from Elkem). Ionic liquids have an excellent thermal stability, implying that they have a potential for significantly improving the safety of battery packs. An overview of the investigated electrolytes is provided in Table 1.

A comparison of the thermal stability of the electrolytes, as given by the heat flow measured during differential scanning calorimetry experiments, is shown in Figure 1. As seen from the figure, none of the ionic liquid electrolytes decompose in the temperature range investigated (up to 200 °C), while the carbonate electrolyte is stable up to only around 70 °C.

Electrolyte	Composition
ILE1	LiFSI:PYR_{13}FSI (22:78 mol%)
ILE2	LiFSI:PYR_{13}TFSI (26:74 mol%)
ILE3	LiFSI:EMIFSI (20:80 mol%)
ILE7	LiFSI:P_{111i4}FSI (22:78 mol%)
STD2	1 M LiFSI in EC:DMC:FEC:VC (31:63:5:1 wt%)

Table 1.

Heat flow signatures

Name	Tc [°C]	Tg [°C]	Tm [°C]
ILE1	-	-93.2	-
ILE2	-14.3	-96.4	10.2
ILE3	-	-89.9	-
ILE7	-	-88.1	-
STD2	-33.2	-88.5	-23.4

Table 2.

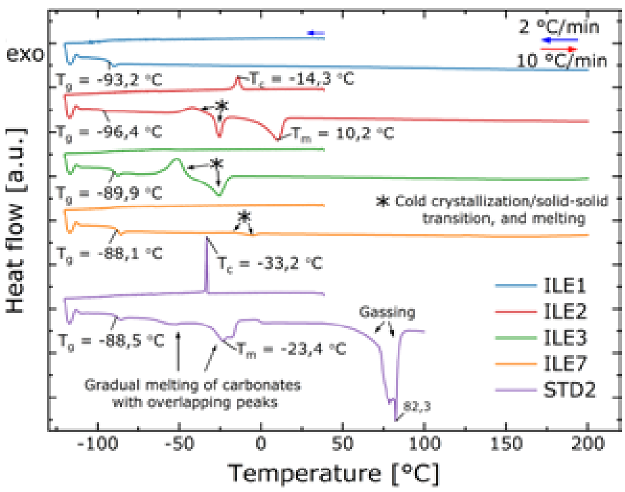


Figure 1. Heat flow as a function of temperature for 4 ionic liquids and one carbonate electrolyte as given in Table 1.

Drawbacks of the ionic liquids is the high viscosity and correspondingly low conductivity of the electrolytes, which hampers the practical use of these in batteries. Examples of electrochemical performance results are shown in Figure 2, which gives the measured capacity of silicon electrodes at various C-rates. As seen from Figure 2 a), the performance of the electrodes is reasonable for these ionic liquids at slow cycling, but poor at even moderate C-rates at room temperature. By increasing the temperature to 60 °C, two of the ionic liquids perform as good as the conventional carbonate electrolyte (Figure 2 b)). This can partly be explained by the significant increase of the Li+ ion mobility at 60 °C for these two ionic liquids.

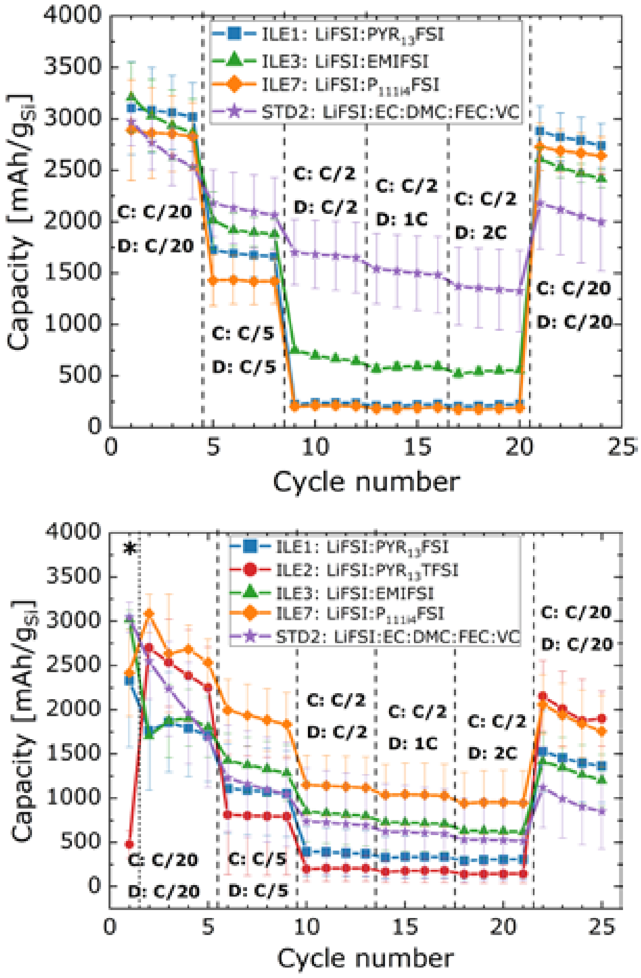


Figure 2. Comparison of discharge capacity for the electrolytes in Table 1 at a) 20 °C and b) 60 °C.

Sub-stochiometric silicon nitride have shown good promise as a candidate material for anodes in LIBs. New results on SiNx particles produced through co-deposition from gas, revealed its increased stability compared to conventional silicon materials, reaching more than 1000 cycles in half-cells (Figure 33) where both the electrode (Figure 44) and the individual particles (Figure 55) retained their original morphology even after 1000 cycles[1] .

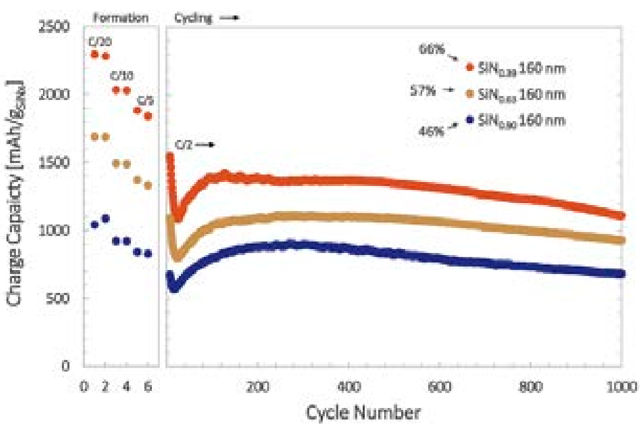


Figure 3. Cycle stability of SiN_x-based anodes with differing stoichiometry. The maximum capacity can be tuned by changing the Si to Ni ratio.

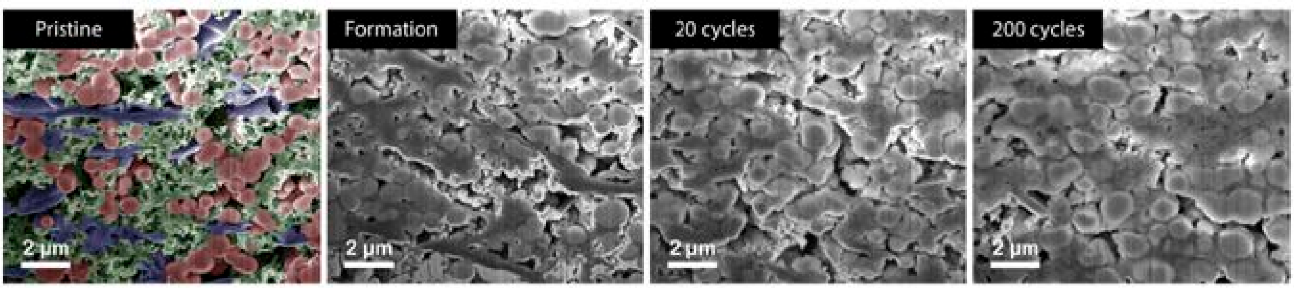


Figure 4. Electrode cross section of substochiometric SiN_x as a function of cycle number.

1) In-kind from the researcher project SAIL (280885, EnergiX)

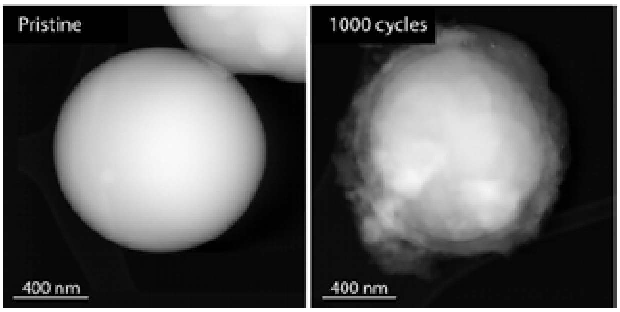


Figure 5. Pristine SiN_x particle vs. one cycled 1000 cycles.

Increasing the cycle life-time of Si-based anode material depends largely on controlling the surfaces of the silicon. By adding a layer of TiO_x using ALD, the long-term stability of Si thin films was improved[2)], as shown in Figure 6.

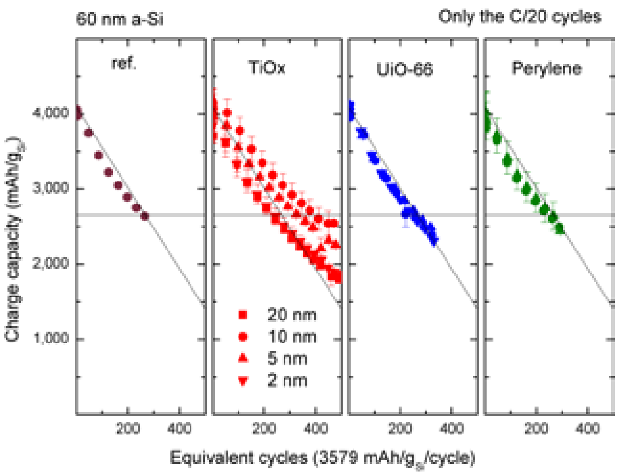


Figure 6. Influence of the long-term stability of Si-thin film anodes as a function of coating material (coated using ALD).

While there are numerous ways for stabilization of Si-based anodes and extension of lifetime of Si in Li-ion batteries, the concept of electrode modification is less explored. The electrode typically contains carbon and CMC binder in addition to the silicon and various additives. At UiO, a new electrode additive, organic in nature, has been studied. The additive significantly improved the electrochemical performance of the crystalline Si obtained from Sigma-Aldrich® or Cenate®. Continued research on this class of additives is foreseen at UiO. The work might have an immense economic importance, in view of the currently blooming battery industry. Therefore, a patent application will be filed at UiO with the help of INVEN2 AS prior to publication of the results in the form of a research article.

Results from electrochemical studies of the crystalline Si (obtained from Sigma Aldrich®) are shown in Figure 7 a)-d). The Si-based electrodes were tested in half-cell assembly against a lithium metal counter electrode, with a lithium reference electrode, and the electrolyte 1M $LiPF_6$/(EC: DMC) + 10 wt% FEC (electrolyte additive). The discharge-charge cycling was performed at constant current modes at C/10, C/5 and 1C for longer cycles, the C-rate calculation was based on the theoretical capacity of 3579 mAh/g of active Si weight in electrodes. The potential window for the charge/discharge cycles was 0.01 V to 1.0 V. The cell cycled at C/10 rate showed the highest significant gain in charge storage capacity, as shown in Figure 7 a). The charge retention at C/10 rate was ~2 times higher than the electrode without the additive after the 50 cycles of the discharge-charge. The cells were also compared at higher current rates of C/5 and 1C. The charge storage capacity of the cell at C/5 current rate also showed the similar enhanced charge storage performances as the C/10 cell, but with slightly lower capacity due to high current rate, as shown in Figure 7 b).

Specifically, the capacity retention was ~6 times higher than the conventional Si-based electrode, after 200 charge/discharge cycles. The cell was also tested at high current rate of 1C. The effect of the additive remained significant at this high rate as well. The capacity retention after the 500 cycles was demonstrated to be 1480 mAh/g. The comparative charge retention at this high current rate was around ~4 times better than the Si electrode without additive after 200 cycle.

The electrodes were also tested at increasing rates, followed by a low current cycles to check the capacity regain properties of the cell. The cell was tested at C/10, C/5, 1C and 2 C rates followed by stepwise reduction in current rates for 5 cycles at each rate (Figure 7 d)). The additive containing electrode behaved better than the bare Si electrode without additive in initial ascending current steps, but the more significant results were visible in capacity regain for the descending current rates. The electrode with the additive showed a very significant capacity

2) In kind from the KPN project "Silicon on the Road" (280985, EnergiX).

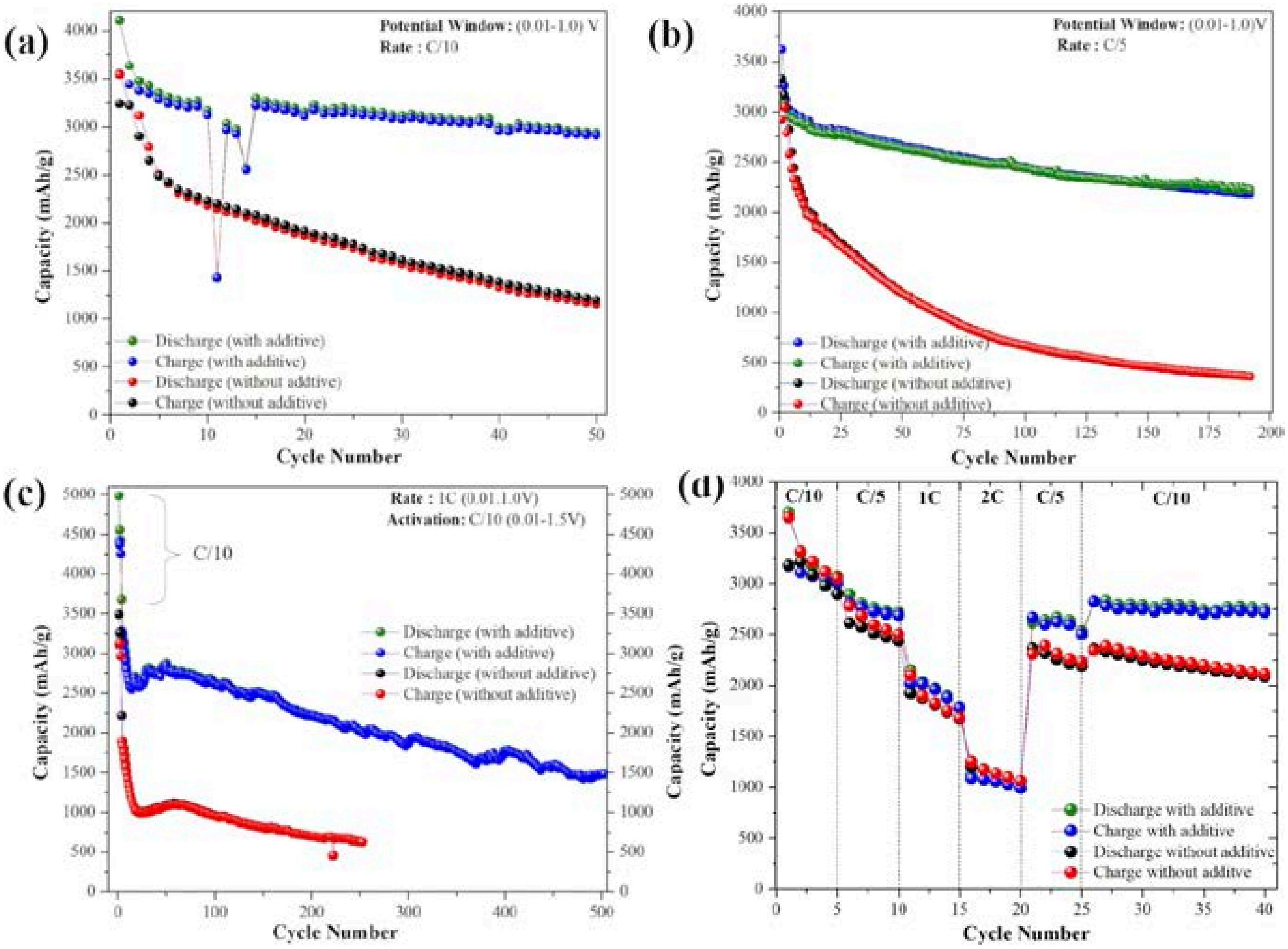


Figure 7. Electrochemical discharge-charge cycling of the silicon electrode at different current rates, a) C/10 b) C/5 c) 1C d) Power plot in potential window of 0.01-1.0V against to Li/Li$^+$.

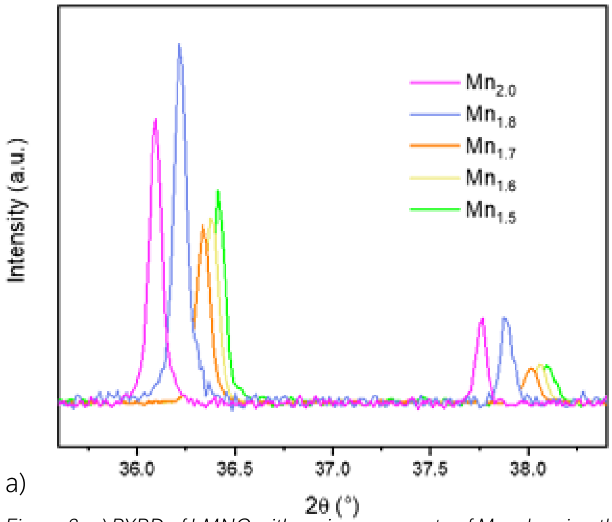
gain after passing the current of 2C and going to C/5 and C/10 current rates in comparison to the electrode without additive. This signifies that the additive potentially improves the robustness of the electrode toward the current stress for variable power applications.

Cathode activities

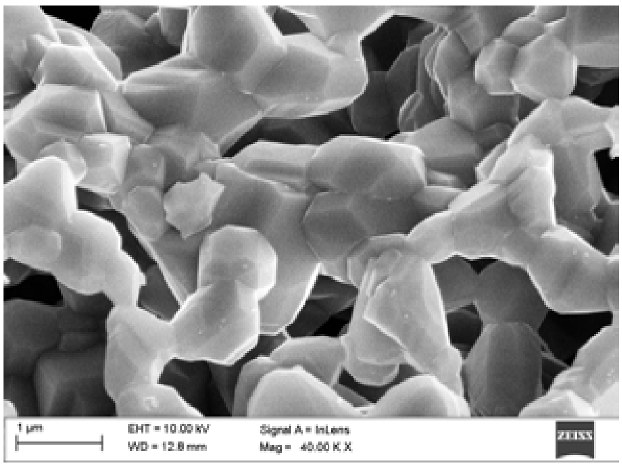
$LiMn_{1.5}Ni_{0.5}O_4$ (LMNO), the Ni-substituted version of the spinel $LiMn_2O_4$ (LMO), is a widely known and has already become a semicommercial cathode material for LIBs. However, besides increased energy density from the high-voltage activity of Ni, it suffers from stability issues and capacity fading. One approach to improve the cycling stability of LMNO is to partly substitute Ni with other metals, and that was performed through substitution with Al, Co and even Mn ($LiMn_{1.5}Ni_{0.5-x}M_xO_4$, where M=Al, Co, Mn and $0 \leq x \leq 0.5$). Such substitution not only changes the electrochemical behavior largely due to the varying activity ~ 3.9 V from the $Mn^{+3/+4}$ redox activity. The varying presence of Mn^{3+} also influences the structural stability to a great extent. These systems are very temperature sensitive in terms of e.g. (i) oxygen vacancies, (ii) cation ordering as well as (iii) degradation and rock-salt impurity formation. Having a full control of these parameters during synthesis is crucial to enable a commercialization of this material.

The origin of the abovementioned defects are still debated in the literature, and UiO has adopted a procedure for synthesis of relatively big batches (~15 g) of LMNO with different Mn/Ni-ratios in a reproducible manner. The structure was confirmed by XRD as shown in Figure 8a).

Big batches enable thorough systematic studies - various physical, spectroscopic and electrochemical characterization tools on the same batch of material. This will facilitate a much deeper understanding of how substitution influences the structural stability. In order to extend the understanding of this system's structure and electrode stability further, an LMNO sample with x=0.2 (Ni sites are replaced with Co) was synthesized through the same synthetic protocol. The material has a nominal composition of $LiMn_{1.5}Ni_{0.3}Co_{0.2}O_4$ (LMNO-$Co_{0.2}$) and was electrochemically tested in coin cells against Li/Li^+ counter electrode. The conventional battery electrolyte 1M $LiPF_6$/(EC:DMC) was used with a Celgard separator for galvanostatic testing (GCPL- galvanostatic charging with potential limitation) at C/5 charge and discharge rates in a potential window of 3.5-4.9 V vs. Li/Li^+. The material consists of well-crystalized submicron particles as was determined by SEM (Figure 8b)).



a)

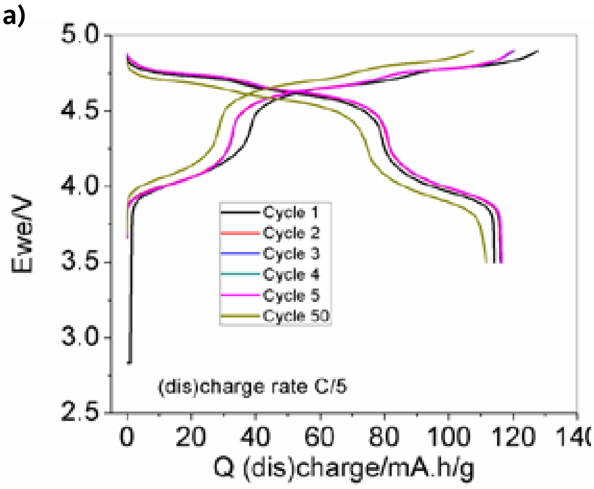


b)

Figure 8. a) PXRD of LMNO with various amounts of Mn, showing the shift of (311) and (222) planes the lower 2θ values as lattice parameters increase due to higher presence of Mn^{3+}; b) SEM image of $LiMn_{1.5}Ni_{0.3}Co_{0.2}O_4$ (LMNO-$Co_{0.2}$), representative for most samples.

Electrochemical analysis of the material by GCPL method reveals that the discharge capacity increases gradually from ~114 to ~117 mAh/g with the cycling up to 6th cycle. The material delivers a stable ~115 mAh/g capacity for up to 50 cycles as shown in Figure 9. Coulombic efficiency increases from ~88% to ~99% from 1 – 7 cycles and stays stable thereafter (Figure 9 b).

a)



b)

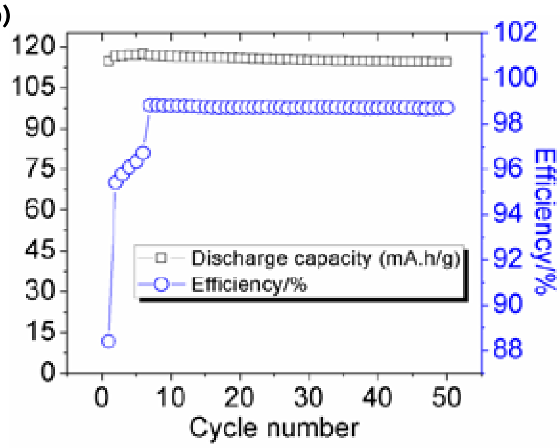


Figure 9. Electrochemical performance of $LiMn_{1.5}Ni_{0.3}Co_{0.2}O_4$. a) GCPL charge/discharge data at C/5 rate in potential window of 3.5-4.9 V for 50 cycles and, b) Discharge capacity and Coulombic efficiency as a function of a cycle number.

In collaboration with the University of Uppsala, NTNU has successfully coated the commercial LNMO ($LiNi_{0.43}Mn_{1.57}O_4$) material with thin layers of TiO_2 or Al_2O_3 to evaluate the effect of coating on the cyclability. Several thicknesses of coating have been tested (5, 10, and 20 ALD cycles). Figure 10 a) shows the TEM/EELS images of the TiO_2 coating, which is also the most promising one with respect to improving the stability without compromising the performance. It is furthermore verified that the coating will not affect the bulk properties of the LNMO, as seen from Figure 10b) and c)

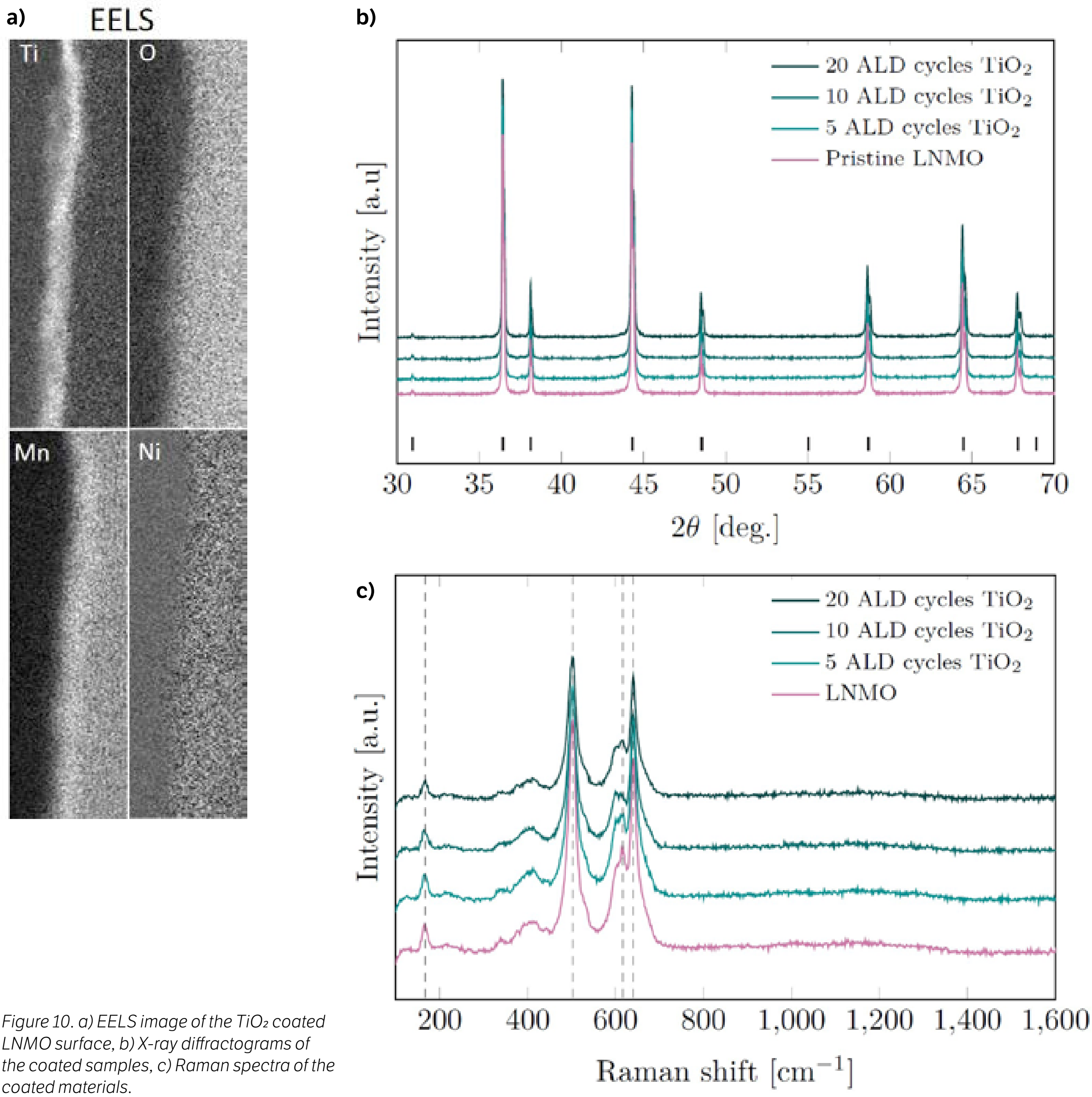


Figure 10. a) EELS image of the TiO_2 coated LNMO surface, b) X-ray diffractograms of the coated samples, c) Raman spectra of the coated materials.

Aqueous processing

SINTEF is working on alternatives to reduce the cost of battery cell production and one interesting area is the rapid aqueous processing of cathode electrodes which eliminates the need for NMP handling and recovery and shortens the mixing time of the slurries. NMC622 cathodes, using NMC622 provided by SAFT, were prepared from fast processed slurries using CMC binder and with or without the addition of 0.5% or 1% orthophosphoric acid as additive to create a protective surface layer on the cathode as well as lowering the pH to keep aluminum passivated under aqueous processing of the cathodes. The samples were compared to a PVDF reference sample. A protective surface layer was confirmed and the addition of orthophosphoric acid hindered hydrogen evolution under processing of cathodes. In comparison to other studies employing long mixing times of 10-24 h, we verified that the orthophosphoric acid excess to not completely reacted with the material surface upon the short mixing time of 30 min. The not reacted excess precipitates upon drying on the electrode surface in form of an alkaline metal containing hydrogen phosphate. This residue caused severe electrolyte decomposition over electrochemical cycling and must be omitted. It was further shown that increasing the drying temperature from 90 °C to 170°C will not solve the issue as it causes the residue to melt and leach lithium from the NMC structure causing the formation of Li_3PO_4 and lowering the reversible capacity likely by surface decomposition of the active material upon leaching, see Figure 11.

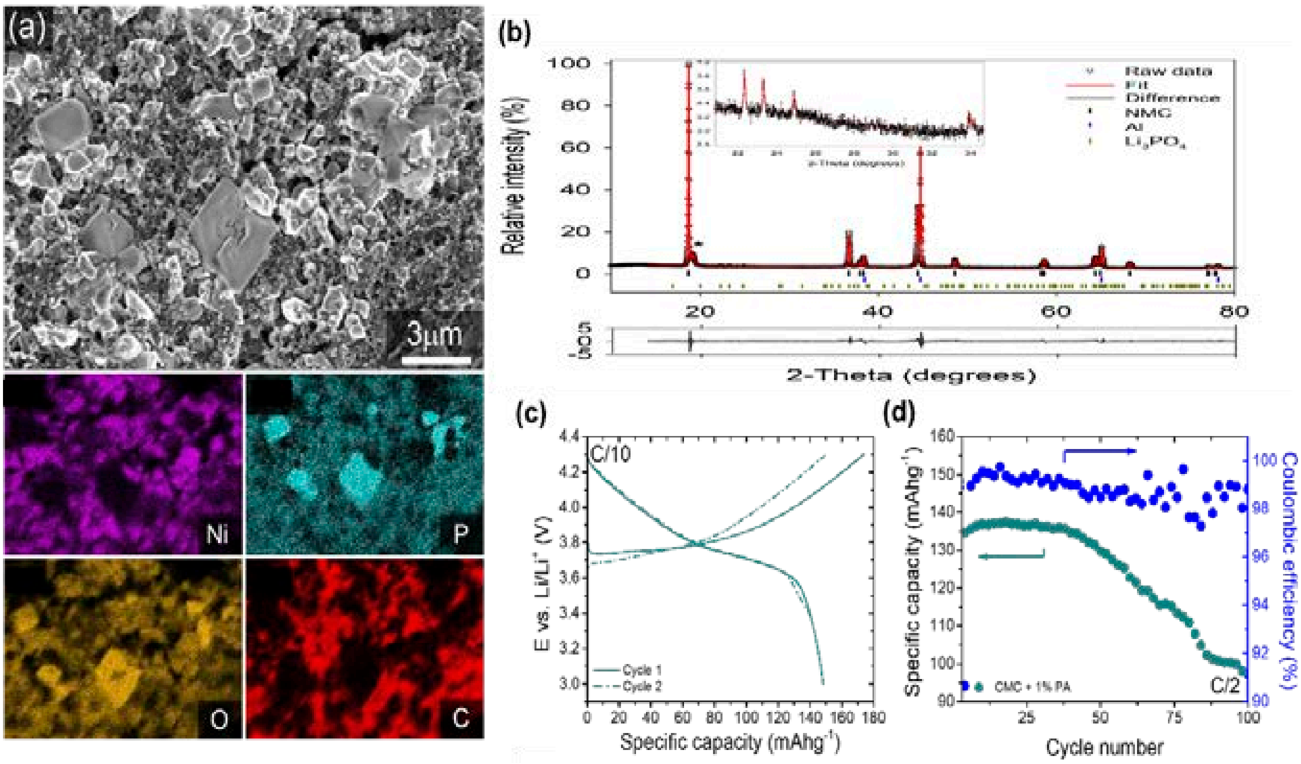


Figure 11. a) SEM-EDS mapping of the sample surface showing micron sized Li_3PO_4 crystals, b) Fitted Powder XRD pattern showing NMC and Li_3PO_4. c) Voltage profile of the first and second cycle of the sample. d) Capacity retention of the sample at a rate of C/2

However, it was possible to remove the originally formed hydrogen phosphate by rinsing in absolute ethanol which increased the cyclability of the sample deeming the process feasible with certain modifications. The results of the rinsed CMC +0.5% PA in half-cell setup are shown in figure 12. The first and second cycle voltage profile (Figure 12a)) reassemble the voltage profile before rinsing. The cell was cycled at a high rate of 1C for 400 cycles (Figure 12b)). The initial discharge capacity at 1C was 137.2 mAhg^{-1} and the cell recovered 80% of this capacity after 400 cycles.

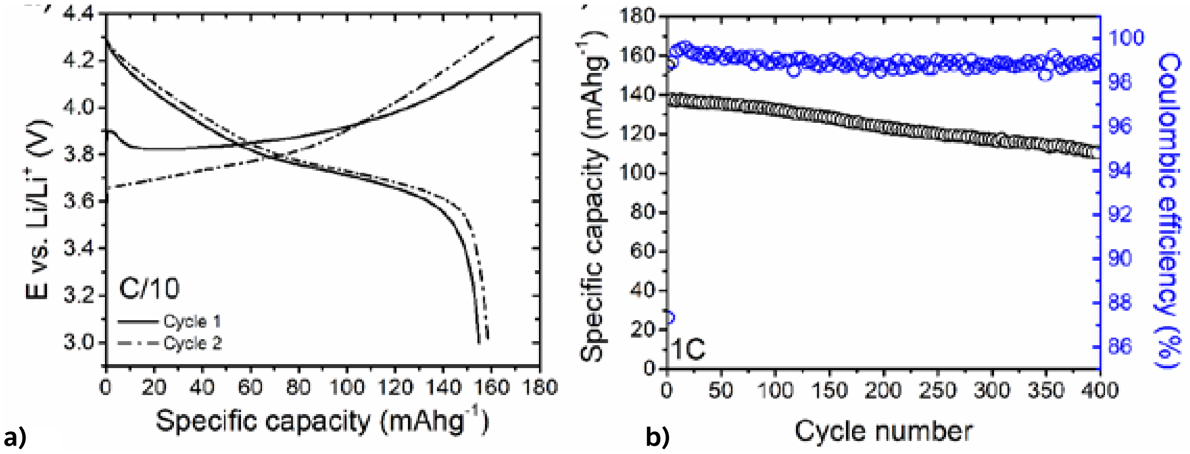


Figure 12. First and second cycle voltage profile of NMC622 electrode prepared with CMC and the addition of 0.5% PA, a) before rinsing with ethanol b) Specific capacity and Coulombic efficiency of cell prepared after rinsing the NMC622 electrode with ethanol, cycled at a high rate of 1C for 400 cycles.

Together with SAFT, partners in MoZEES (IFE, NTNU, UiO, SINTEF and Elkem) have conducted the first round of the Round Robin test for electrochemical characterization of graphite electrodes. The methodology for data analysis was established. Results from the rate-tests performed at IFE is exemplified in Figure 13 below. Further analysis and comparisons between the different partners are now in progress and a second Round Robin phase is being planned where the focus will be on Si-containing anodes in full cell geometry.

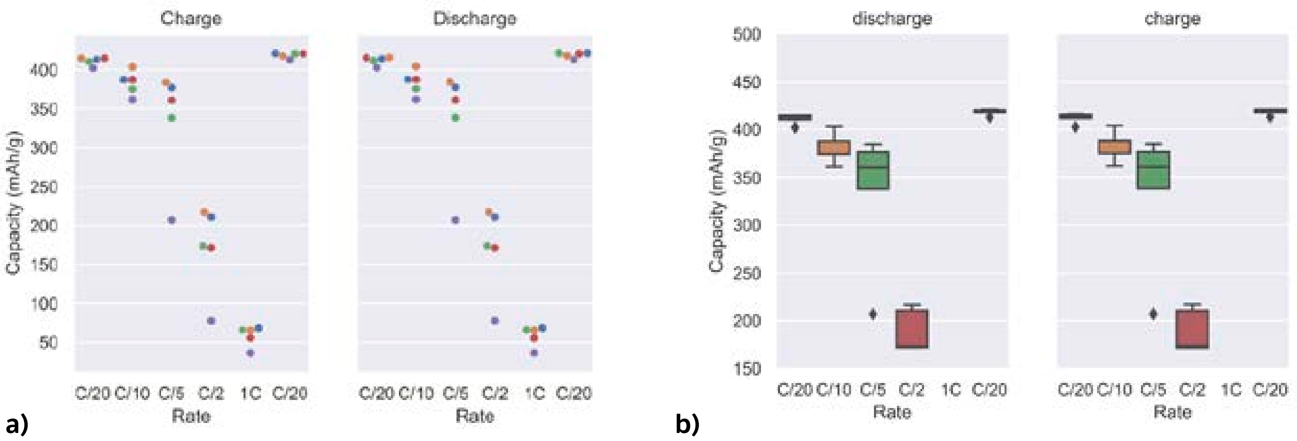


Figure 13. a) Swarm plot of the average capacity (of the repeated successive cycles at same rate) of the five cells b) Corresponding box plot ("average of average").

International Collaboration

UNIVERSITY OF UPPSALA (UU)

Within the Battery Materials Research area, there has been an active collaboration with University of Uppsala, involving a visit by PhD student Elise Ramleth Østli, starting from 1st of August 2019 until February 2020. During her stay she worked with «atomic layer deposition» in order to make protective coatings for the cathode material $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO), and also characterization of the materials. Professor Daniel Brandell, UU, participated and gave a presentation on the Mozees annual meeting 2020 (21-23 September), “Polyesters as next-generation solid electrolytes for Li-and Na-batteries”.

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

SAFT

Together with SAFT, partners in MoZEES have designed a Round Robin test for electrochemical characterization of commercial electrodes supplied by SAFT. The activity will later be extended to include a larger variety of materials from MoZEES partners. All battery materials research partners are participating in the activity (IFE, NTNU, UiO, SINTEF), as well Elkem.

RWTH UNIVERSITY AACHEN

MoZEES has established a MoU with RWTH University Aachen in 2018, which enables the exchange of researchers and students. Researchers from IFE og RWTH Aachen collaborate on research topics related Li-ion batteries. Professor Egbert Figgemeier from RWTH Aachen participated in the Mozees Annual meeting in 2020 (21-23 September), and gave a presentation “State of the Art of Silicon in Commercial Lithium Ion Batteries Cells and Perspectives on Higher Silicon Loadings Enabled by Electrolyte Additives”.

HORIZON 2020 PROPOSALS

HYDRA - Hybrid power-energy electrodes for next generation litium-ion batteries, coordinated by SINTEF: https://www.sintef.no/en/projects/2020/hydra-/

Doctoral Dissertation on Battery Materials

On 21 April Ika Dewi Wijayanti successfully defended her doctoral thesis entitled "Novel Zr- based AB2 Laves type Alloys as Advanced Anodes for High Energy - High Power Metal Hydride Batteries". Ika's project has been funded by an Indonesian fellowship and is associated with MoZEES through the focus on NiMH batteries (Task 1.4).

Ika Dewi Wijayanti submitted the academic thesis as part of the doctoral work at the Norwegian University of Science (NTNU). The doctoral work has been carried out at the Department of Materials Science and Engineering, where Senior Scientist I Volodymyr Yartys (IFE) has been the candidate's supervisor.

Professor Hans Jørgen Roven (Department of Materials Science and Engineering, NTNU) and PhD Kwo Young (BASF SE) have been the candidate's co-supervisors.

The trial lecture and public defence was implemented with an online-based solution.

RA2 Hydrogen Components and Technologies

The main objective of RA2 is to enable the production of fuel cells, electrolysers and hydrogen storage tanks with lower cost and higher efficiency, and thereby contributing to reaching the 2025 targets (DOE & EU) for transportation fuel cells, hydrogen production from renewable energy sources and hydrogen storage. The work is prioritized within development of high performance electrocatalysts, low-cost bipolar plates and membranes and improvement of testing protocols for high pressure composite hydrogen pressure vessels.

Collaboration with user partners and international collaboration

The research on components for water electrolysis and fuel cells is of particular interest to the industry partners Nel, Johnson Matthey, and Teer Coatings, respectively, while the research on hydrogen storage tanks is particularly relevant for Hexagon. The competence and knowledge generated in RA2 is also interesting for other industry partners in RAs 3 and 4. Teer Coatings has provided gold- and carbon coated BPPs for PEM fuel cells in Task 2.2. They will also be involved with the post-mortem analysis of the components. Johnson Matthey has contributed with supplying cathode Pt/C catalyst and anode IrO_2 for Task 2.1. In addition to this, the collaboration with the user partners has been through discussion in the RA meetings, exemplified by the valuable input from Nel and Johnson Matthey on the in-situ testing of electrodes in alkaline electrolysers in Task 2.2.

Task 2.1 – High performance catalysts

The price and the scarcity of Ir represents a major bottleneck for a continued upscaling of the clean hydrogen production using PEM water electrolysis. Ruthenium pyrochlores have lately been reported to have high catalytic activity for oxygen evolution and higher stability than ordinary ruthenium oxides in acidic environments. We have started an activity in MoZEES to investigate this class of materials under operating conditions in single PEM electrolyser cells. During 2020, $Ru_2Y_2O_{7-d}$ electrocatalyst further improvement of the microstructure has been attempted through sieving to ensure proper microstructure for catalyst layer manufacture. A shift in spray technique required the acquirement of a hot plate with vacuum which will arrive at the end of January 2021. Due to the shift in technique and need for new equipment this activity has been delayed. The catalyst layers will be produced and tested in situ in PEM electrolyser single cell in 2021.

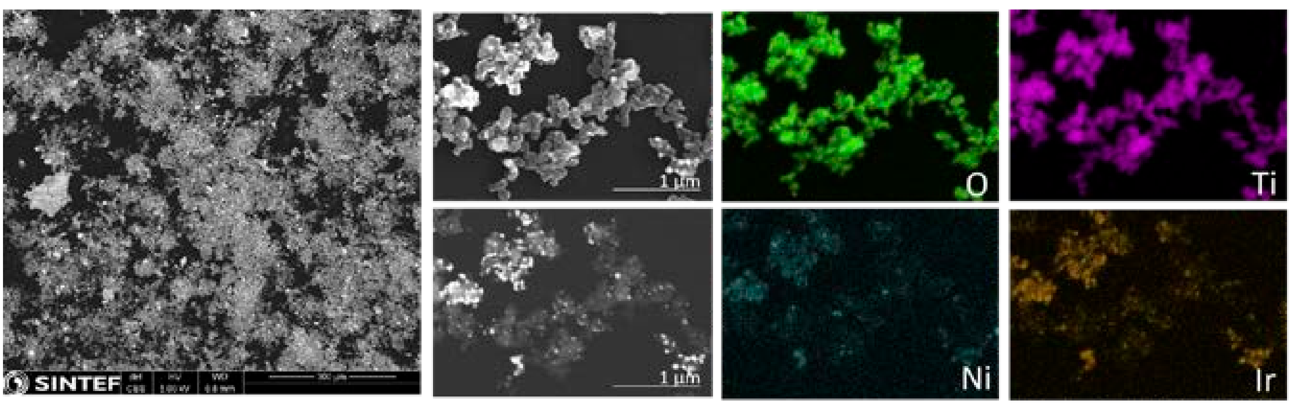


Figure 1: SEM micrograph of $Ru_2Y_2O_{7-d}$ catalyst powders (left) and SEM/EDX results of Ir on TiO_2 catalyst prepared by galvanic replacement (right).

Another direction of the task has investigated a new method combining scalable co-precipitation synthesis of $NiTiO_3$, a reducing heat treatment to produce metallic nickel and TiO_2 and galvanic replacement of Ni with Ir, making Ir supported on TiO_2. Here, powders have been prepared, successfully demonstrating the galvanic replacement (Fig.1, right). Further work will be related to optimization of the process and electrochemical validation of the performance of the catalyst. This work was summarised in deliverable T2.1-D4 in 2020.

Task 2.2 – Low cost bipolar plates

Alkaline electrolysers

Various electrode materials, such as SS304, Incoloy 800 and Inconel 718, have been activated for OER using the established activation procedure developed for SS 316. The activation procedure involves anodizing the electrode material at 1.7 V vs RHE for 18 hours in a high pH KOH electrolyte. During activation, small Ni-enriched deposits are formed at the surface depending on pH. The surface composition of Ni and Fe that is reached after activation is quite consistent and depends on the pH of the activation electrolyte. The Ni content increases with respect to Fe with increasing pH up to pH=7.5. At higher pH the composition remains the same. The low-Ni content stainless steel materials (SS316 and SS304) possess similar performance after activation, but markedly better than activated Incoloy 800, Inconel 718 and a pure nickel plate. The OER activities were correlated to the surface composition using XPS. Finally, SS316 was chosen for more in-situ analysis in a commercial Green Light alkaline electrolysis test station in the Norwegian Fuel Cell and Hydrogen Centre. This activity was performed in close collaboration with SINTEF, who leads the infrastructure and operates the electrolysis test stations. Valuable input on in-situ testing was also provided from industry partners (NEL, JM) in conjunction with project presentations. The cell with activated SS316 as anode has better performance compared to the cell with pure Ni as anode (Figure 1). The in-situ durability analysis was performed for more than 200 h at a constant operating current of 0.8 A cm^{-2} in 30% KOH at 80°C and 9 bar. The resulting chronopotentiometry curve is given in Figure 2 and shows that the activated SS316 is stable at these conditions. In fact, the performance increase over the course of the 200 h.

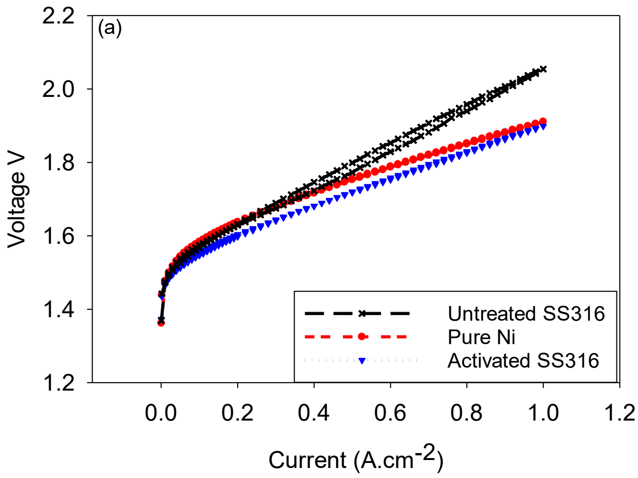


Figure 2: Steady state polarization curves for different anodes (not IR-corrected). Untreated samples are as-received samples that are polished prior to polarization.

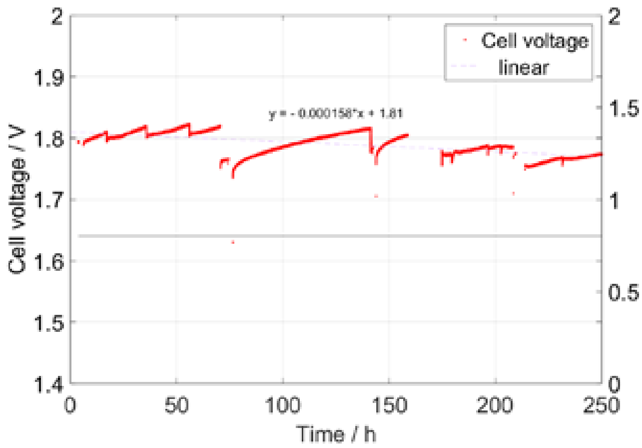


Figure 3: Chronopotentiometry at a constant current of 20 A (0.8 A cm^{-2}) at 80˚C and 9 bar for a single water electrolysis cell with activated SS316 as anode.

PEM fuel cells

In-situ testing of three different types of bipolar plate (BPP) has been completed. The lifetime of the uncoated stainless steel BPPs (350 hours) was significantly shorter than both the gold coated BPPs (450 hours) and carbon coated BPPs provided by Teer Coatings (850 hours). Over the first 150 hours of operation (Figure 1), there is a correlation between in-situ interfacial contact resistance (ICR) and performance, with the high ICR of the stainless steel BPPs leading to the lowest performance. However, the ICR increase of the stainless steel BPPs (10 mΩ cm^{-2} during the first 150 cycles) only accounts for a small portion of the total performance decrease observed at

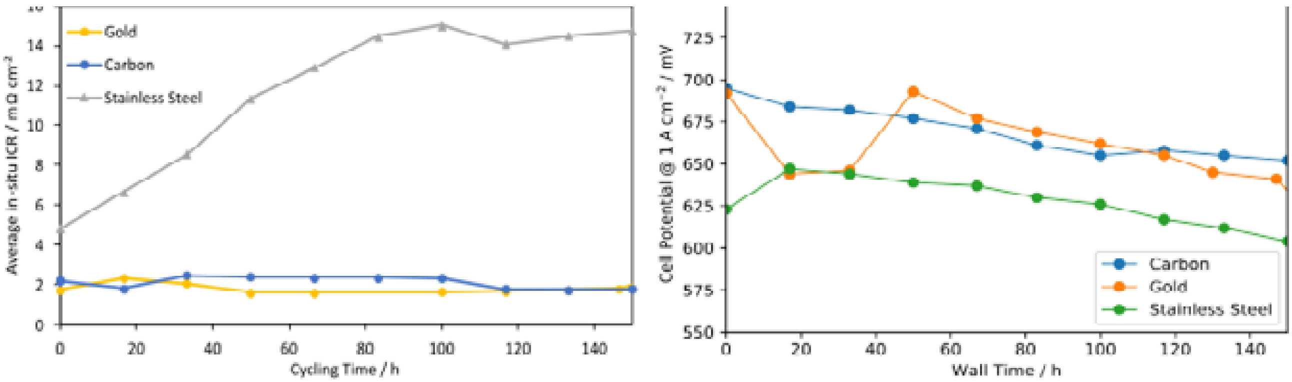


Figure 4: In-situ ICR data (left) and cell voltage data (right) recorded during the first 150 hours of operation of fuel cells assembled with gold coated, carbon coated or uncoated stainless steel bipolar plates.

1 A cm^{-2}. Similarly, the performance of the gold and carbon coated BPPs decrease despite a stable ICR, leading to the conclusion that increased ICR of the BPP is not the main performance degradation mechanism in this case.

Post-mortem analysis of the BPPs and catalyst coated membranes (CCMs) will be performed at Teer Coatings, and SINTEF, respectively, to determine whether any changes to the BPPs surface has occurred, and whether any ions leeching from the BPP have caused damage to the membrane.

Additionally, a communication outlining the in-situ ICR technique has been prepared for publication.

Task 2.3 – Improved polymer membranes

During 2020, polymer membranes based on H_3PO_4-PBI/TiO_2 composites with controlled filler contents and acid doping were synthesized. Proton conductivity measurements under controlled temperatures (RT<T<120 °C) and relative humidity (5%<RH<100%) were performed (ongoing) to evaluate and compare with literature findings, as well as theoretical models by own experiments. A few selected results are given in Fig. 1. Thermodynamic values such as activation energies and pre-exponential factors have been determined. Acid and water uptakes were also determined based on weight analysis.

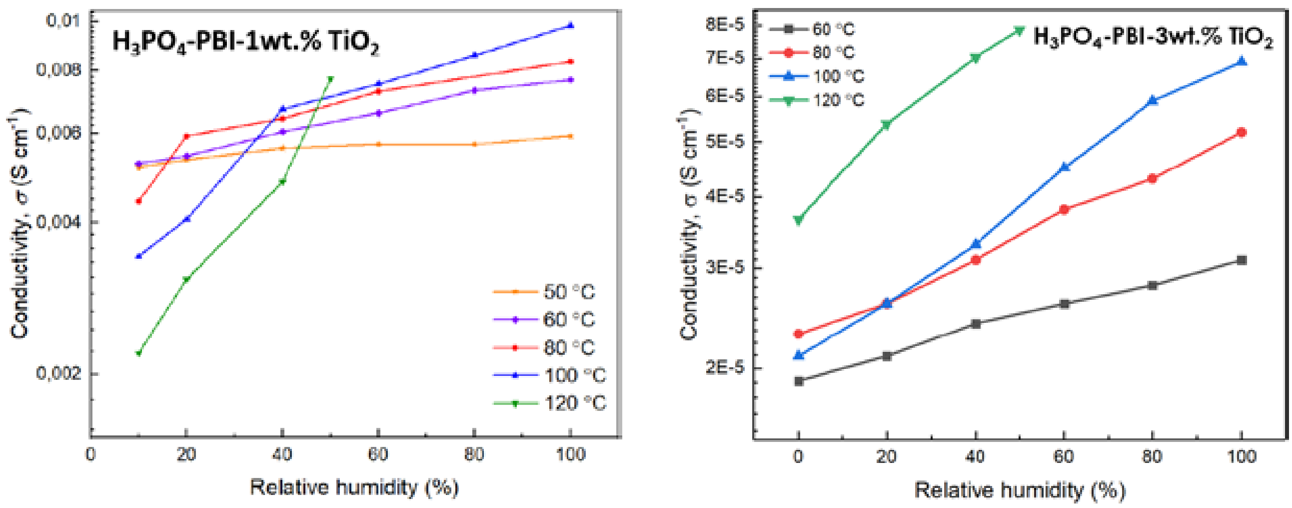


Fig.5 Proton conductivity of the H_3PO_4–PBI/TiO_2 as a function of RH measured at different temperatures

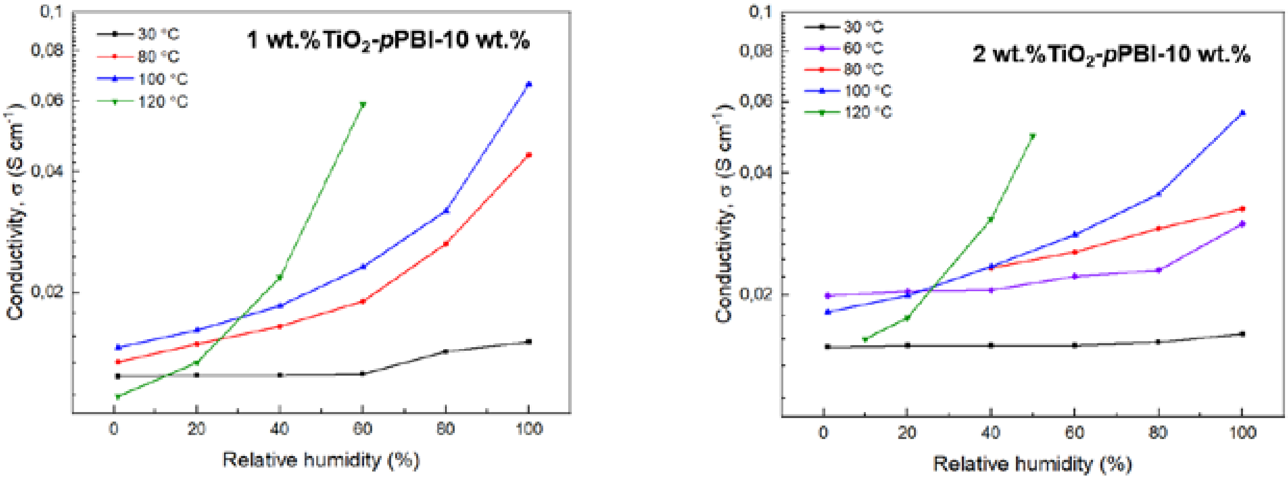


Fig.6 Proton conductivity of porous H_3PO_4-PBI/TiO_2 as a function of RH measured at the indicated temperatures

Porous H_3PO_4-PBI/TiO_2 composite membranes with variable doping and fillers have been fabricated and proton conductivity measurements of the membranes were conducted. A few selected results are given in Fig. 2. We will combine all established results to develop an appropriate proton conduction model for the composite membranes, including surface protonics. This will be pursued throughout the duration of the project.

We expect that collaborating partners such as SINTEF Oslo and Johnson Matthey Fuel Cells may fabricate membranes based on the materials we have studied and according to our specifications, for testing in UiO's labs and in the national infrastructure PEMFC test facilities in the final stage of this project.

Task 2.4 – Lifetime, durability and performance

Initial single-cell PEMFC degradation measurements have been performed, using advanced electrochemicmal characterisation techniques to extract relevant parameters as inputs for the degradation modelling activities in RA3. The initial degradation parameters were collected under steady-state operation at high current density, where significant cathode flooding was observed, and under OCV hold, where a high rate of hydroxyl radical production is expected. This data will serve to quantify the degradation rates for the lower and upper bounds of extreme operating conditions.

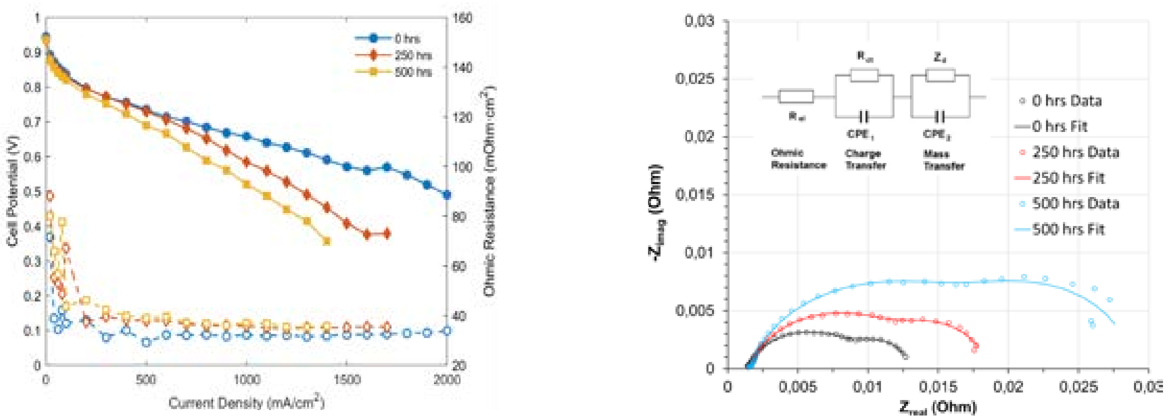


Figure 7: Polarization data (left) and Nyquist plots (right) obtained every 250 hours during long term fuel cell measurements at high current density operation. For all data collection, the fuel cell was operating at 70 C under pure hydrogen at the anode (stoichiometry of 1.5) and air at the cathode (stoichiometry of 2.5), both gas streams were humidified to 50% RH, the anode and cathode were operated with back pressures of 1.1 and 1.0 barg, respectively. The electrochemical impedance data was collected under galvanostatic conditions at a current density of 600 mA/cm² and the equivalent circuit used to determine useful electrochemical parameters is shown as the inset.

Task 2.5 – Hydrogen storage tanks

At NTNU a PhD on fatigue mechanisms in hydrogen composite cylinders is close to being completed. The work has shown that DIC (Digital Image Correlation) monitoring can be used to recognize material strains and early fatigue damage, a result highly interesting and relevant for industry partner Hexagon. The fatigue properties measured locally by DIC can also be used to better predict damage growth under fatigue around a defect. The prediction is done by novel ways to model fatigue damage growth in a finite element program. Most of the scientific work was performed prior to 2020, and the work in 2020 was focusing on exploring the results and writing papers. The PhD defence and publishing of 3 papers is planned for 2021.The first paper "Filament wound composite fatigue mechanisms investigated with full field DIC modelling" was submitted in 2020 and was accepted in January 2021.

PhD Blog: Critical Review of Composite Membranes for Polymer Fuel Cells

Can cheaper and more efficient fuel cells be developed by dispersing ceramic nanoparticles in the polymeric membrane? Several studies report on improved performances using so-called fillers, but MoZEES PhD student Xinwei Sun (supervised by Prof. Truls Norby and Dr. Athanasios Eleftherios Chatzitakis) has found few credible rationalisations of why they work.

The development of fuel cells as energy converting devices has received increasing interest over the past decades. A part of the research in MoZEES contributes towards production of fuel cells with lower cost and higher efficiency in order to meet the 2025 US DOE targets in the transport sector. The Group for Electrochemistry at University of Oslo contributes to the development of proton conducting membranes based on composites of polymers and ceramic nanoparticles for polymer electrolyte membrane fuel cells (PEMFCs) and electrolysers (PEMEs).

The pursuit of higher operating temperatures

The heart of a PEM electrochemical cell consists of a solid polymer electrolyte sandwiched between two electrodes. The electrodes are further assembled using porous gas transport layers and bipolar plates acting as current collectors and connecting cells in series. When the PEMFC is in operation (Figure 1), humidified H_2 is supplied to the anode, being oxidized into protons and electrons. The hydrated protons, namely H_3O^+ ions are transported through the electrolyte to the cathode, while the electrons must migrate there through an external circuit with the load. At the cathode, the recombination of protons and electrons occurs via reduction of O_2 to form water as the only product.

Conventional low temperature PEMFCs (LT-PEMFCs) that typically operate below 80 °C suffer from slow reaction kinetics, water flooding of the electrodes, complex heat management, gas crossover, and poisoning of the catalysts.

Most of the above-mentioned issues can be overcome by operating the PEMFCs at higher temperatures. The high temperature PEMFC, or HT-PEMFC, is very much like the traditional PEMFC, but the proton-conducting electrolyte, traditionally Nafion®, which would dehydrate above 100 °C, is modified or replaced with a high-temperature tolerant polymer or composite. Higher temperatures facilitate the electrode reaction kinetics significantly, and in turn improve the fuel cell and electrolyser performance as a whole.

Xinwei Sun (Photo: Ann Kristin Støversen)

Moreover, the waste heat released is of higher temperature and hence quality and may find broader utilization, such as producing hot water and ambient heating. Higher temperatures result in the reduction of water flooding at the electrodes and simplify the water management, as water is in vapour phase. The purity of fuel and catalyst poisoning are becoming less critical as well. The CO tolerance is increased by about three orders of magnitude if the PEMFC is operated at 160 °C.

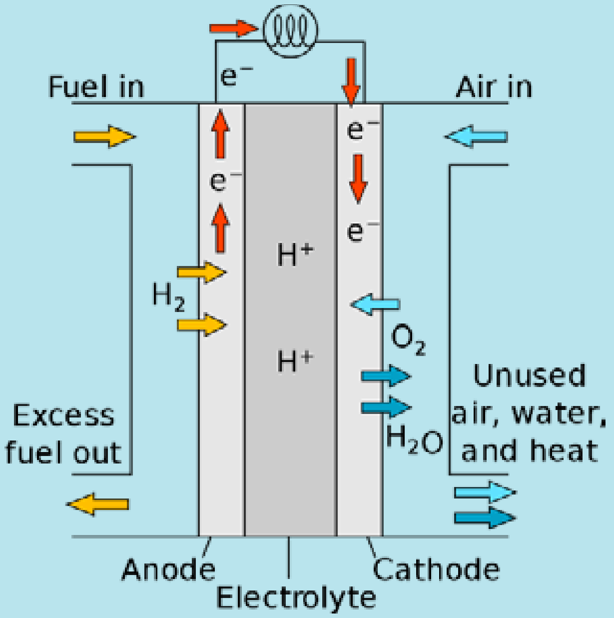


Figure 1 Schematic of a PEMFC [1]

Are ceramic fillers the answer?

The performance of the PEMFC is partly characterized by the protonic conductivity and water content of the electrolyte, which are dependent on the temperature and relative humidity (RH). Many studies attempt to improve the protonic conductivity, water content and stability of the polymer membranes at elevated temperature and lower RH through the dispersing a secondary ceramic phase (filler) so as to make a polymer-ceramic composite.

One example of such fillers is silica, SiO_2. Silica is not new to us, we find silica gel packets in all kinds of products we buy (Figure 2) – water is adsorbed on the surfaces of its millions of tiny pores and keeps the relative humidity of the surrounding air low, in order for the products to be preserved longer. For instance, silica packets in leather products limit moisture that would otherwise increase the growth of mould.

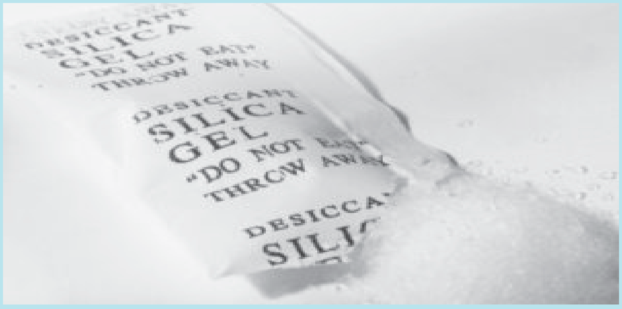


Figure 2 Silica Gel packets as desiccant [2]

Inspired by this, people have tried to prepare composite membranes by introducing nanostructured particles of silica into the polymer structure to improve the water uptake and retention. In addition to silica, the same principle is exploited with other ceramics of various kinds (metal-organic frameworks (MOFs), metal phosphates, solid acids, clays, carbon structures etc.) that are believed to strongly absorb water. Such materials have been introduced to both the traditional polymer electrolytes like Nafion®, as well as HT polymers such as polybenzimidazole (PBI) and polyether ether ketone (PEEK). Ceramic dispersions may increase the hardness and temporarily the thermal stability of the membrane, but they on the other hand also increase the brittleness of the membrane. Are they really of help in terms of water retention, hence protonic conductivity, at high temperatures? For this and other reasons, we did an extensive literature review.

Indeed, we have seen in some cases large improvements in protonic conductivity, power density, or stability operated at higher temperatures and lower RH. However, full PEMFC tests at the US DOE target temperature of 120 °C are missing from the majority of these works, and they are of paramount importance in order to assess the compatibility, stability and lifetime of such composite membranes. We have seen few credible rationalisations of why fillers work. Some refer to the use of proton conductive particles, all of which are recently understood to exhibit only protonic conduction instead in adsorbed water or acids. This encourages us to study PEM composites onwards with emphasis on well-characterised microstructures, as well as a well-founded assignment of protonic conduction appropriately to bulk solid polymer and ceramic phases and liquid phases, adsorbed water layers, and interfaces.

[1] https://en.wikipedia.org/wiki/Proton-exchange_membrane_fuel_cell. Date: 01-12-2019
[2] https://science.howstuffworks.com/innovation/science-questions/question206.htm. Date: 09-12-2019

RA3 Battery and Hydrogen Systems and Applications

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

The RA3 research objectives are:

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

Advanced fuel cell systems

In 2020, a PEM fuel cell short stack was operated with a dynamic load profile at SINTEF to determine i) how long the voltage takes to stabilize, ii) the magnitude of double layer charging, and iii) water/heat balance effects. The dynamic load profiling involved gradually larger current jumps in increments of 10 % of max current. The maximum current is the highest of the two following: the average at a cell voltage of 0.65 V from polarisation curve, as recommended by the EU harmonised test protocols, or the maximum current allowed by the stack manufacturer. To make sure that the supply of reactants was sufficient upon increasing the current, the flows were increased to the corresponding level 30 seconds prior to increasing the current. This was done to alleviate water management issues and prevent fuel starvation immediately after the current step. Similarly, the flows were decreased 30 seconds after decreasing the current. The current was held for 10 minutes at each point to allow stabilisation of temperature and RH values. The minimum relative current was 10 % to avoid prolonged periods of OCV. The total dynamic profile took approximately 18 hours to perform.

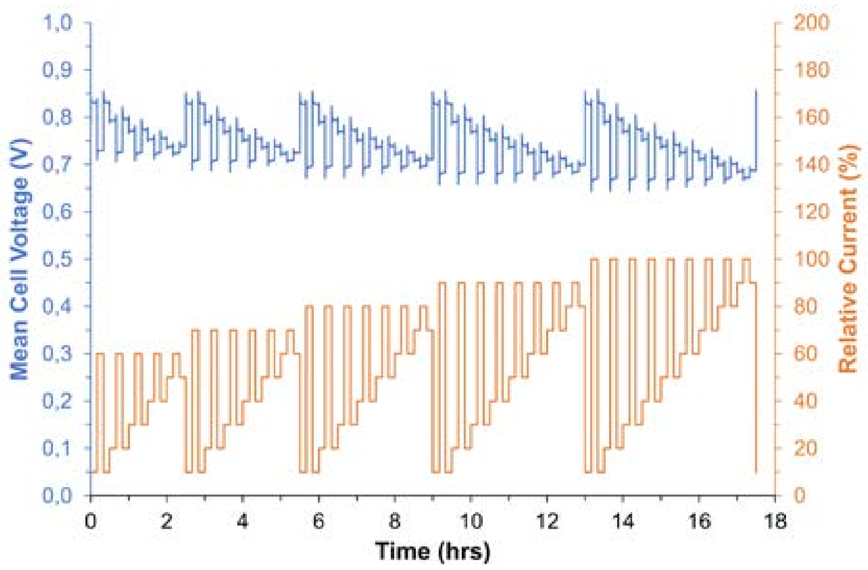


Figure 1: Dynamic load profile of PEMFC short stack

Results are given in Figure 1, showing that the stack has a good dynamic response to the current steps. The increased gas flow leads to a brief increase in stack performance before the current step. During the current step, the initial sharp transient response is attributed to capacitive charging or discharging of the electrochemical double layer, while the following equilibration and return to steady-state voltages is attributed to a combination of water and heat balance processes taking place within the cells. The stack furthermore exhibits no signs of mass transport losses up to current densities of 1,5 A/cm^2. Future work will aim to further characterize PEMFC stacks from various manufacturers, assessing their suitability for maritime transport applications.

Battery Safety

Electrification of heavy-duty vehicles requires larger and more energy-dense batteries, but this creates additional safety challenges. In MoZEES we study both the processes that can lead to fires and explosions in batteries, and the consequences of such incidents. The latter involve studies of the combustion properties of representative gas mixtures emitted from a defective lithium-ion battery. This work is carried out at USN, and in 2020 the focus has been on validating input parameters to CFD models that can be used to simulate battery explosions. The work has entailed determining the laminar burning velocity and the Markstein length for dimethyl carbonate and propane in a 20-liter explosion sphere. The laminar burning velocity has in this case been measured close to the saturation point under the initial conditions, which has not been previously reported. Figure 2 shows that the flame exhibits spherical propagation in most experiments and has a smooth surface with relatively few wrinkles. This work will be very useful for the design of safer battery systems and battery rooms, for example in ferries, and the results were recently published in an article in the Journal of Combustion, Explosion, and Shock Waves. FFI also contributes to the work related to battery safety in MoZEES, and in 2020 they completed two experimental battery test containers. These containers will be used to study the consequences of real battery fires and explosions, and to test and develop firefighting strategies.

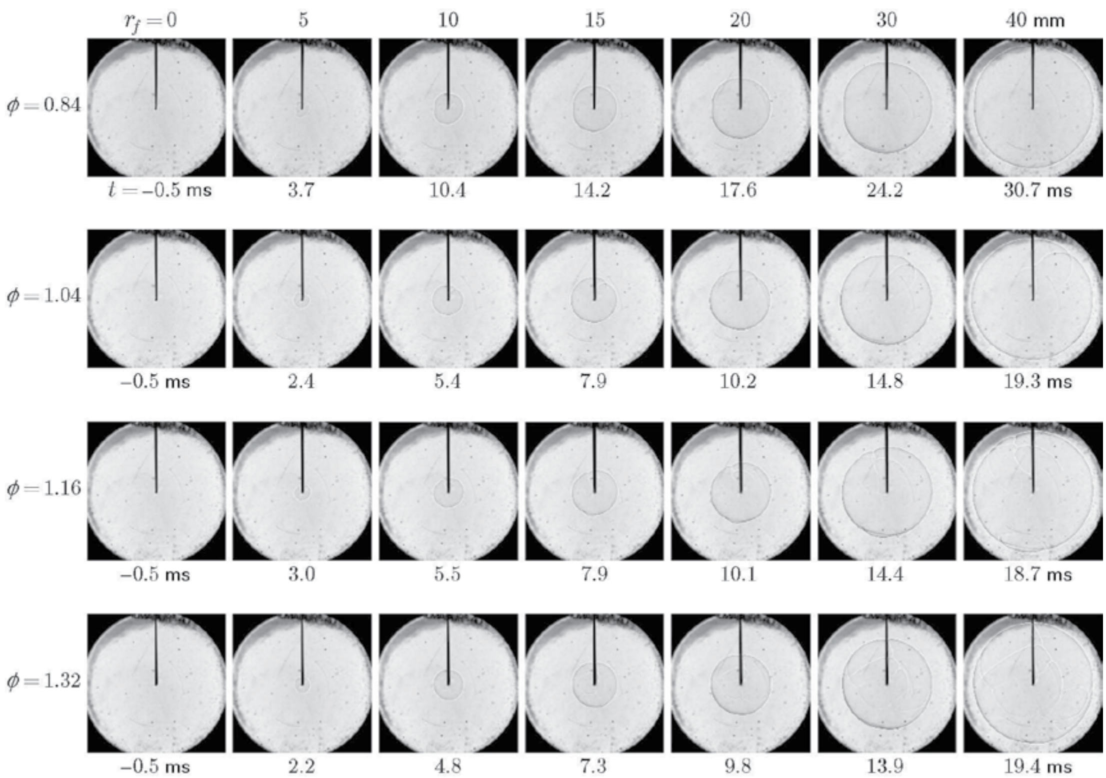


Figure 2: Shadowgraph images of dimethyl carbonate combustion

Hydrogen safety

In 2020, the research group at USN published an article documenting large-scale experiments related to the consequences of unignited hydrogen releases in confined spaces. The aim of this study was to validate a model for predicting overpressure arising from accidental hydrogen releases in areas with limited ventilation. Experiments were performed in a large-scale setup that included a steel-reinforced container of volume 14.9 m^3 and variable ventilation areas and mass flow rates. The pressure peaking phenomenon, characterized as transient overpressure with a characteristic peak in a vented enclosure, was observed during all the experiments. The model description presents the relationship between the ventilation area, mass flow rate, enclosure volume, and discharge coefficient. The experimental results were compared with two prediction models representing a perfect mix and the real mix. The perfect mix assumed that all the released hydrogen was well stirred inside the enclosure during the releases. The real mix prediction used the hydrogen concentration and temperature data measured during experiments. The prediction results with both perfect mix and real mix showed possible hazards during unignited hydrogen releases.

Hydrogen Trucks case study

As part of the case study on hydrogen trucks, a vehicle model for fuel cell electric heavy-duty vehicles was established in MATLAB Simulink in 2020. The hybrid fuel cell/battery power train was modelled using the building blocks in the QSS Library as basis and the required adaptations for a heavy-duty vehicle was documented. The model included a simple battery control strategy to determine the fuel cell and battery power output and input from regenerative breaking, and was validated using the Braunschweig driving cycle (frequently used test cycle for city buses featuring "stop-and-go" driving). This work will be continued as part of a master thesis in 2021 focusing on improving the fuel cell system model (efficiency calculations), improving the vehicle block model (incl. elevation in drive cycle) and including thermal management of fuel cell and battery.

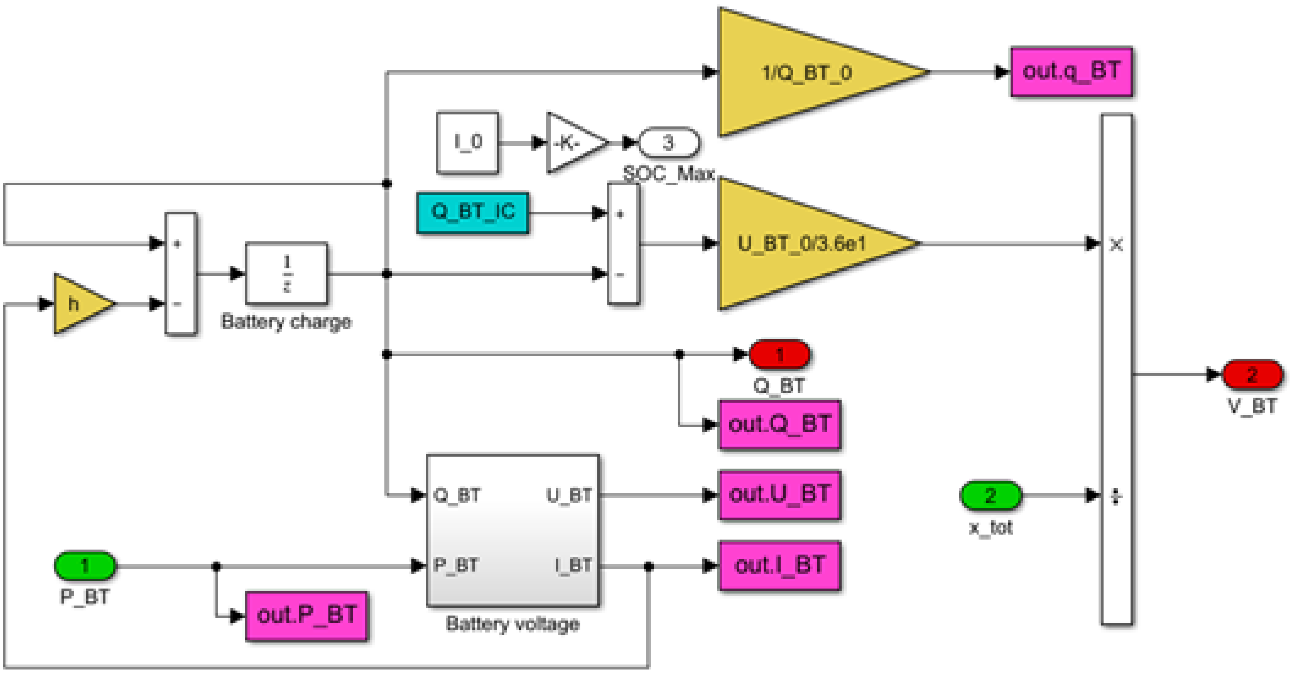


Figure 3: FCEV Bus model in MATLAB Simulink

The case study-related work in 2020 also included discussing a preliminary design for a zero-emission truck fleet management tool. The management and planning of a fleet of vehicles in goods pickup and distribution is a complex planning problem, and decision support tools based on methods from optimization and operations research have been widely used in this area to find cost efficient plans. With vehicles facing range constraints due to limited fuel, the Vehicle Routing Problem (VRP) needs to take into account charging and filling stations. Other challenges that can be imposed by fuel-cell- and battery-electric trucks are complex energy consumption models, including regeneration of (breaking) energy, dimensioning and optimising components' specifications (battery/FC) in hybrid solutions, and battery and fuel cell degradation (relevant for operational planning). To include all details and technological requirements for fuel cell and battery electric vehicles in a traditionally used central optimization model would be very demanding. As an alternative approach, a modular and service-oriented design was proposed.

At the core of such a system would be a traditional solver for VRP problems that creates a set of cost-efficient routes based on traveling distance and approximate ranges for all trucks. These routes are then forwarded to the energy consumption model that creates power load requirements and regeneration possibilities along the routes for relevant truck types and the current weather situation (e.g. considering heating needs). The routes

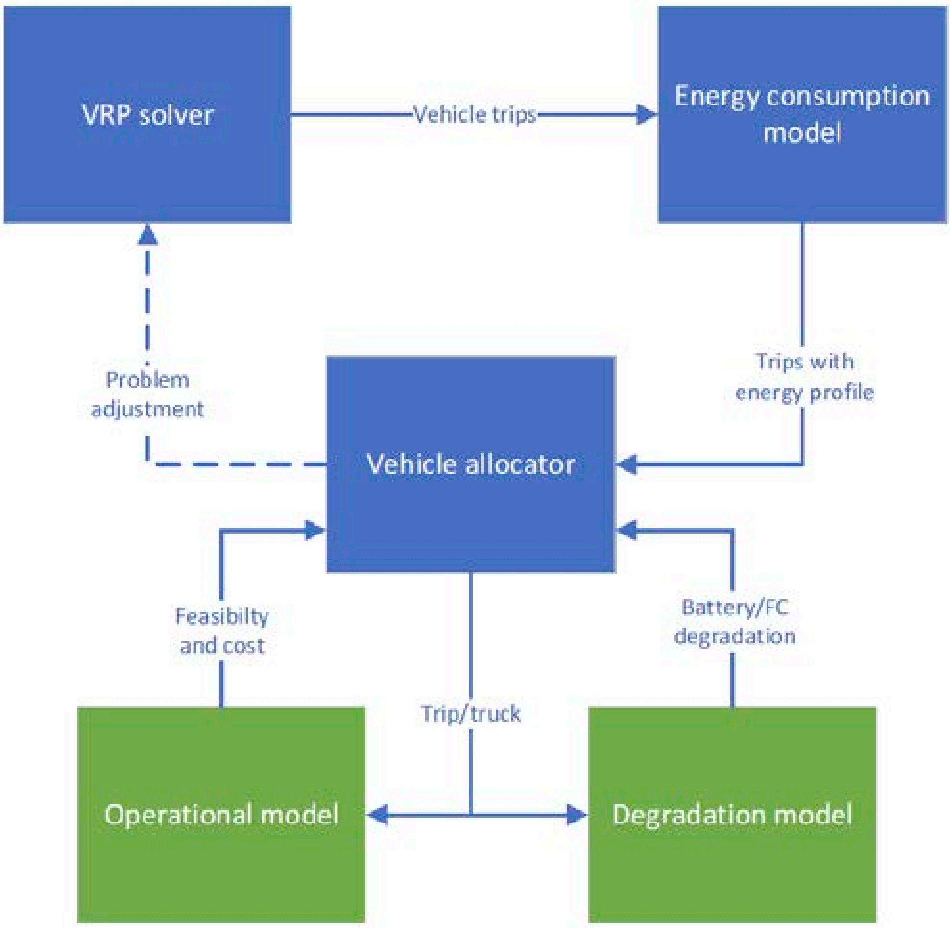


Figure 4: Overview of a modular design for a fleet management system

with the associated power usage profile are handed over to a vehicle allocation models that selects the specific truck for each route considering the state of all trucks of the fleet (e.g. battery capacity and fuel cell efficiency).

Collaboration with user partners

Hydrogen safety was a key part of the Maritime Case Study (2017-2019), and will similarly have a significant focus in the case study on hydrogen trucks (2020-2021) and trains (2022-2023). In case of a fire or a collision, hydrogen may be released from the onboard pressure vessels via a Temperature Pressure Relief (TPR) valve. Whether such a release inside a tunnel will result in flammable gas mixtures is entirely dependent on the design of the hydrogen system (the amount of hydrogen per tank, the storage pressure, the diameter of the TPR valve) and other factors such as the tunnel cross-section and travel speed. In 2020, a collaboration was therefore initiated between USN, Lloyd's Register, ASKO, the Norwegian Railway Directorate and the Norwegian Public Roads Administration to prepare a scenario matrix for hydrogen-powered trucks and trains in tunnels. Based on this matrix, Lloyd's Register will perform CFD simulations of i) TPRD releases with delayed ignition ii) catastrophic tank ruptures leading to explosions and potentially delayed explosion in the released gas. Analyzes with such systematic parameter variations will be very useful both to be able to provide design recommendations to the technology suppliers, as well as to give advice to directorates and safety authorities on the requirements to the operators.

Prototype high-pressure PEM water electrolysis stack from NEL installed in the test rig at IFE which is capable of characterizing stacks with hydrogen outlet pressures up to 200 bar. The test rig is a part of the national infrastructure Norwegian Fuel Cell and Hydrogen Centre (NFCH) and will be used in Task 3.4 in MoZEES.

International Collaboration

A PhD student from the University of Genoa (UNIGE) visited IFE in the spring of 2020 to work on modeling of fuel cell systems and the associated power electronics. She unfortunately had to end her stay earlier than planned (due to Covid-19), but wants to return to Norway when the situation allows it. The MoU established with UNIGE includes an agreement that MoZEES will get access to operational data from their new fuel cell laboratory. These data will be used to validate the fuel cell system models developed within MoZEES.

PhD Blog: Why do Lithium Ion Batteries Catch Fire or Explode?

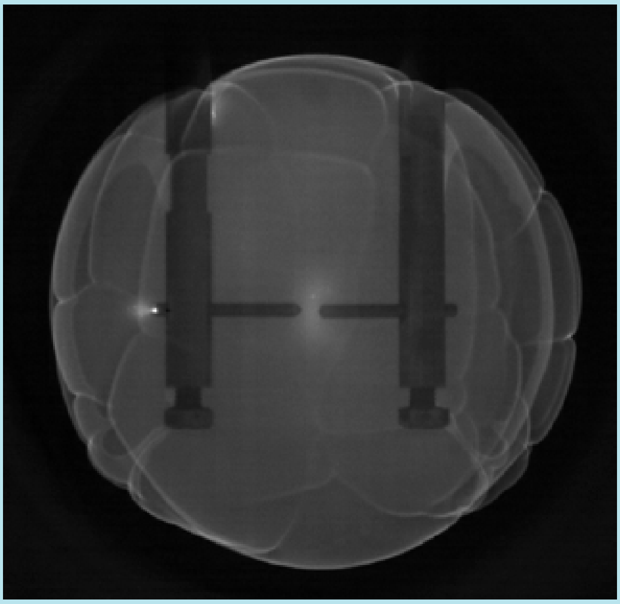
Luckily, major explosions caused by Li-ion batteries are an uncommon occurrence. If they are exposed to the wrong conditions, however, there is a slight chance of them catching fire or exploding. Mathias Henriksen's (USN) PhD project focuses on the combustible gases released from a malfunctioning Li-ion battery and the flame speed and pressure build-up of these gas mixtures. The study provides insight into what types of explosion hazards and scenarios one can expect upon a Li-ion battery failure, and may help integrate the technology more safely in their various applications.

A quick search on YouTube or Google will provide several hundred videos and images of lithium ion (Li-ion) batteries causing fires and explosions. Lithium ion batteries are used in all types of products today, perhaps most commonly in electronic devices such as laptops, cell phones, and cameras, but they are also an attractive option for large scale energy storage such as in power grid systems and electric vehicles. Unfortunately, if Li-ion batteries are exposed to the wrong conditions, there is a slight chance that a violent failure can occur. Such a failure can have severe implications for large battery systems, and research shedding light on these consequences are essential to implement better safety measures.

Li-ion batteries have all the elements needed to self-sustain a fire

To understand how a Li-ion battery can catch fire or explode, it is necessary to investigate how the battery is built. A Li-ion battery store and release its electrical energy through electrochemical reactions. When electrical energy is drawn/discharged from the battery, lithium ions move from one electrode to the other. The electrodes are submerged in a liquid called an electrolyte, which allows for the movement of ions and consists of lithium salt and organic solvents. It is these organic solvents which are the leading fire hazard in Li-ion batteries. Furthermore, the positively charged electrode (cathode) in the battery contains oxygen, which may be released if the battery is subjected to specific stresses, e.g., internal short, excessive heat, and more. This means that the Li-ion batteries have all the elements needed to self-sustain a fire.

In a powerful thermal incident, the Li-ion battery may



One image a high-speed movie of a flame in the explosion sphere.

release some of the flammable electrolyte along with various flammable/toxic gases such as hydrogen (H_2), methane (CH_4), carbon monoxide (CO) and hydrofluoric acid (HF). The amount and rate of the gas released depend on different parameters that are related to battery chemistry and the amount of electrical energy stored. A release of these flammable gases is what can cause fires and explosions.

The study of fast-moving flames and shock waves

The focus of my Ph.D. study is on the combustible gases released from a malfunctioning Li-ion battery, and the understanding of the types of explosion hazards and scenarios one can expect upon a violent failure. To assess the danger related to an explosion, I focus on the pressure build-up and on the flame speed of the combustible gas mixture. In our laboratory, we have an explosion sphere where we can study all of these explosion mechanisms for different types of flammable mixtures. By using high-speed cameras to capture movies of the moving flame inside the explosion sphere, we can study the flame in detail. We have high-tech cameras available which can film with frame rates ranging from 50 to 5 000 000 frames per second. This allows us to study even extremely fast-moving flames and shock waves. The results from these experiments will be used as inputs and for verification for a simulation tool, so predictions of potential consequences can be made. These predications may help integrate Li-ion technology more safely in their various applications.

Luckily, major explosions caused by Li-ion batteries are an uncommon occurrence. However, it is still essential to understand the potential consequences of Li-ion vapor cloud explosions. By understanding the consequences, better safety measures can be implemented. The importance of this work is that it lays the framework for an advance in safety-features that can reduce or avoid damage to materials, human life, and the environment.

For more information about the work done in this Ph.D. study, see the following publications:

- Henriksen M, Vaagsaether K, Lundberg J, Forseth S, Bjerketvedt D. Explosion characteristics for Li-ion battery electrolytes at elevated temperatures. Journal of Hazardous Materials 2019;371:1–7. https://doi.org/10.1016/j.jhazmat.2019.02.108.
- Henriksen M, Vaagsaether K, A.V: Gaataug, Lundberg J, Forseth S, Bjerketvedt D.Laminar burning velocity of the dimethyl carbonate-air mixture formed by the Li-ion electrolyte solvent. Combustion, Explosion, and Shock Waves (DOI https://doi.org/10.1134/S0010508220040024).

RA4 Policy and Techno-Economic analysis

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

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

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

Specific case studies of new concepts and business models are made based on the needs of user partners within four prioritized transportation subsystems: (1) Urban mobility and logistics, (2) Coastal line vessels and ferries, (3) Long-haul freight and passenger transport, and (4) Transportation terminals. In order to be able to define relevant concepts, business models, and values chains, RA4 collaborates closely with system experts in RA3 battery and hydrogen technology experts in RA1 and RA2 and other experts among our MoZEES industry partners.

During 2020, RA4 has developed a new method for calculating the energy consumption of high speed ferries using AIS position and speed data from the Norwegian Coastal Administration and earlier work done in MoZEES RA3. The results can be used to calculate the hydrogen need for such ferries. The model has been developed to handle data from all high speed passenger vessels with data for one full year. The vessel movements are split according to time at harbor and trips defined based on set harbor stay time-limits. The model has been used to do a feasibility study on which vessels are likely candidates for hydrogen or battery propulsion based on current movements and services using AIS data for 2018. Vessels found to cover 90 % of their movements by either battery or hydrogen were set to be likely candidate for conversion to zero emission technology. The time at harbour used to split the movements in the feasibility study was set to the time needed to either refuel or recharge the vessels based on the estimated storage capacities and assumptions on shore power or hydrogen refueling speeds. The models can hence be used to calculate the hydrogen need. and further identify the volumes of hydrogen or charging capacities needed in harbors to be able to keep current high speed passenger service. The work has been submitted as an article to Transport Research part D : Transport and Environment.

RA4 also studied the wider Economic Effects of Green Water Transport using the Regional Equilibrium Model REMES. Results largely support the notion that, with some caveats, such shift is marginally positive for the

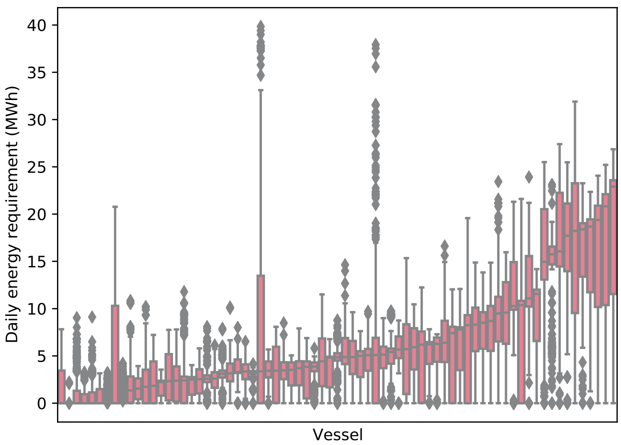


Figure 1: Daily energy requirement for all vessels included in the analysis

economy, contributing to increased total value added of varying degrees across sectors. The study considered the partial and/or total electrification and hydrogenation of several sea-transport sectors, simulating a gradual change from diesel and other fossil fuels into cleaner energy sources by 2035. The Norwegian economy seems prepared to bring down emissions in maritime transport without a large or significant sacrifice in sector-based value added, regardless of the GDP benchmark expected. While some indicators and regions will see decreases in their production, these are often in sectors whose contributions are not large and/or which are offset by other effects in other parts of the economy.

While the total expected increase in GDP was, for the most part, modest, we consider that the environmental and societal benefits from the shift, not endogenously measured by the macroeconomic model, contribute to make this shift not just economically possible, but overall desirable in the long term.

This study is expected to be followed up by a more thorough analysis which includes an updated dataset, extensions and interactions with land transport, and a more refined modelling of the technology change which goes beyond fuel substitution.

RA4 has also continued the work on the case study for buses and submitted an article on battery electric bus operation to Energy Policy. In this article it is concluded that battery electric buses can become competitive with diesel buses by 2025. To speed up phase-in, transport authorities can introduce contract change orders (emphasizing zero emission requirements) and municipal administrations can better facilitate infrastructure-establishments.

A research article on fast charging usage was published in the World Electric Vehicle Journal in 2020. The article focuses mainly on passenger vehicles, but the results related to temperature variation of fast charging is relevant for fast charging of light commercial vehicle and heavy duty vehicles. The article was published with partial MoZEES funding.

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

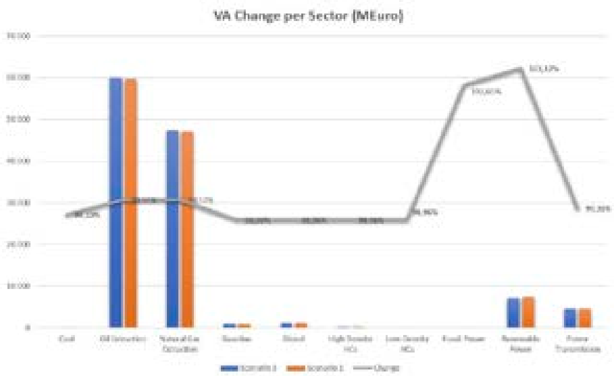


Figure 1 Value added change total and relative in the energy sectors, national, by 2035. Scenario 3 is a BAU case, whereas scenario 1 sees the most ambition introduction of electricity and hydrogen in the maritime transport industries in Norway.

MoZEES Innovation Activities

In 2020 there was established an industry driven MoZEES Innovation Forum, which will be steered by a MoZEES Innovation Committee. The main objective of the MoZEES Innovation Forum is to create a meeting place to coordinate the MoZEES research activities with national innovation activities and to create new battery and hydrogen activities (MoZEES spin-off projects) with partners in relevant industrial clusters in Norway and abroad.

In relation to the MoZEES innovation activities there was in 2020 established a set of MoZEES Roadmaps (e.g., Figures 1 and 2). A major objective with the MoZEES Roadmaps is to further strengthen and alignment between the research and innovation activities in the Center. The MoZEES Roadmaps are also intended to be used as guidelines and input to national roadmaps on batteries, hydrogen, and zero emission transport.

The MoZEES Roadmaps show that there is a special focus on R&D of zero emission solutions for heavy duty transport, particularly on the use of batteries and hydrogen in maritime applications. There is also a strong focus on battery material research that can assist the development of new industrial battery value chains in Norway and abroad. The long-term goal of MoZEES is to contribute to significant innovations in the following two key research areas:

1. Development of new battery, hydrogen, and fuel cell technology and systems for zero emission maritime applications suitable for near-coastal operations in Norway

2. Production of new and advanced Li-ion battery materials suitable for international and commercial battery value chains.

In MoZEES there has over the past 3 years been performed a so-called MoZEES Maritime Case Study on the development of new, safe, and cost-effective solutions for use of hydrogen in high-speed passenger ferries (often also referred to as high-speed crafts or HSCs). In 2020 researchers and PhD-students from IFE, SINTEF, TØI, and NTNU were engaged in joint research activities defined by MoZEES partners, including MoZEES partner Hub for Ocean, the host for Arena Ocean Hyway Cluster, a national innovation arena for hydrogen in the maritime. MoZEES contribution here is on R&D related to new solutions based on renewable energy, water electrolysis, compressed hydrogen storage, and PEM fuel cell systems, all key technologies where the MoZEES partners have substantial expertise.

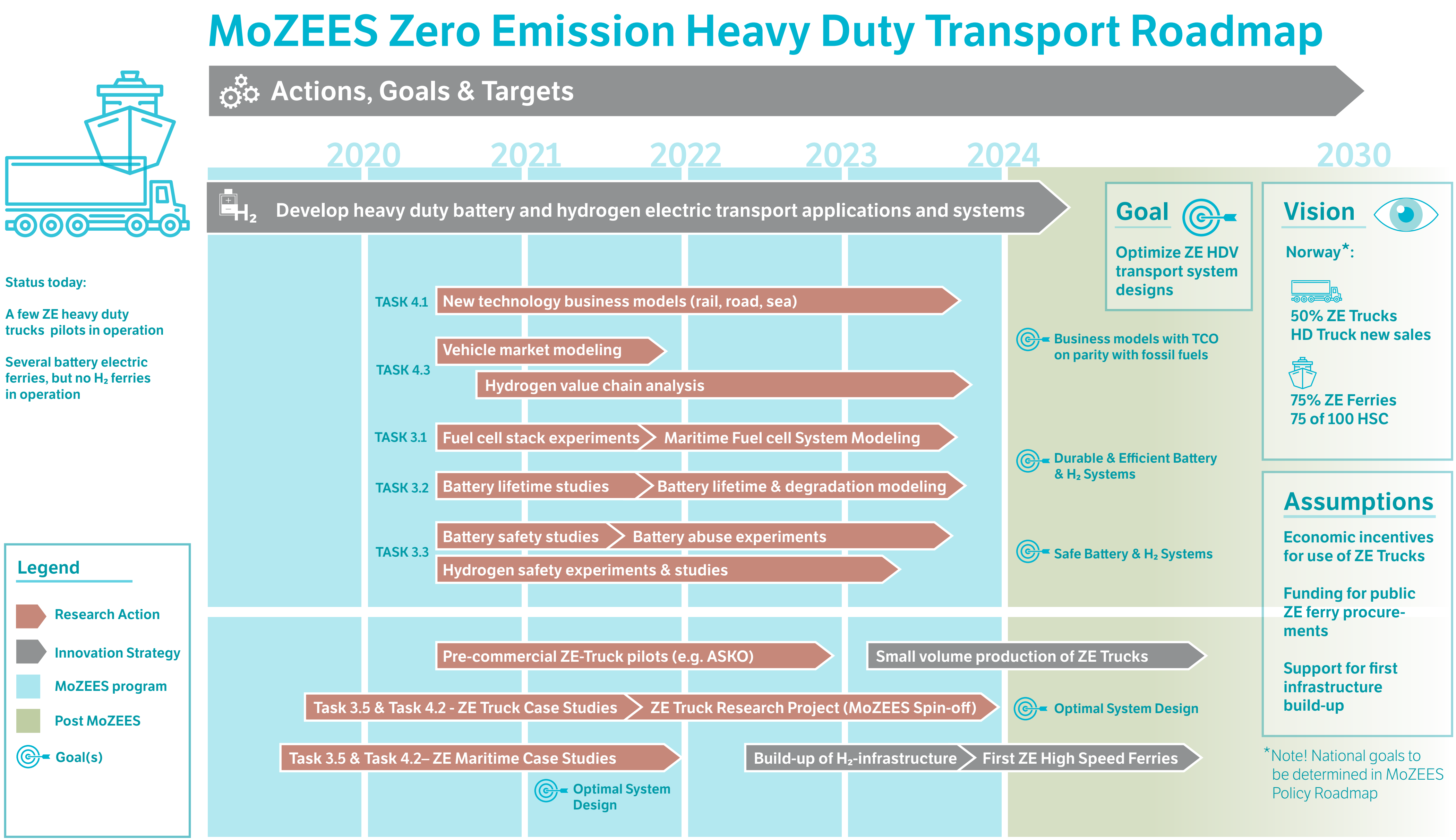
In 2020 the work on a MoZEES Heavy-Duty Truck Case Study also began to take shape and form. Several of the MoZEES partners are involved in different projects on this topic, including the hydrogen and fuel cell truck demonstration project at ASKO in Trondheim. In 2020 several key MoZEES partners were also involved in the establishment of the Arena H2Cluster, another national innovation network on hydrogen that now is supported by Innovation Norway. The plan for MoZEES is to use the H2Cluster industry network to develop new projects on hydrogen heavy duty vehicles. A MoZEES Zero Emission Heavy Duty Transport Roadmap has also been established (Figure 1).

In 2020 the Norwegian government launched a national strategy on hydrogen and is now asking for input to more specific hydrogen roadmaps. In addition, the government is prioritizing programs to develop new green maritime industries in Norway, including setting strict requirements for the use of low and zero emission ferries (from 2023) and high-speed passenger ferries (2025). The motivation to develop zero emission ferries is twofold: (1) Reduce the greenhouse gas (GHG) emissions in the maritime sector and (2) Create new maritime industries and business for the future. MoZEES is very much in line with the latest national policy, and research results from the Center is highly relevant for the further national planning on zero emission transport and the use of hydrogen in the maritime.

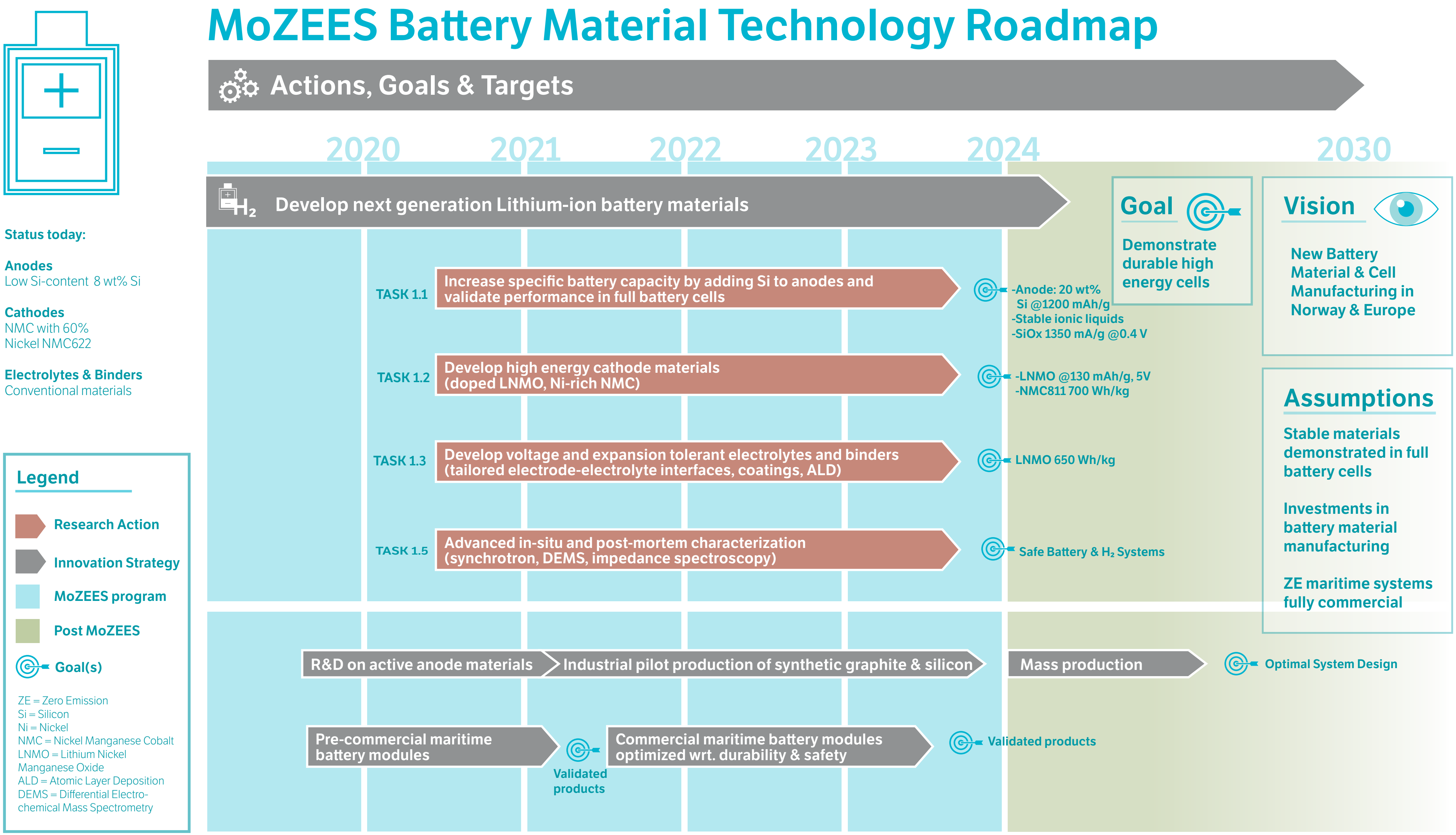
In MoZEES there are also significant research and innovation activities in on Li-ion batteries. At the MoZEES Annual Meeting 2020 there was for the first time organized a so-called MoZEES Industry & Innovation Day that specifically focused on the possibilities to establish new industrial battery value chains in Norway. Presentations made by MoZEES partners such as SAFT and Elkem (large international companies) and Cenate and Morrow (smaller Norwegian SMEs) showed that there is great interest and willingness to invest in new battery developments, both in Norway and abroad. Elkem have already established themselves in several parts of the battery value chain, while Cenate is progressing with their development and small-scale production of nanoparticles suitable for Si-based anode materials.

There is today no battery cell manufacturing in Norway, but Morrow Technologies announced towards the end of 2020 that they have clear ambitions and plans to establish a giga-size battery cell factory in the southern part of Norway. For MoZEES it is therefore very important to continue to have a close research collaboration with international battery specialist companies such as SAFT (France) that have experience in the production of battery materials, cells, and modules. In 2020 the collaboration between the MoZEES battery research and industry partners has been strengthened and there has now also been established a common MoZEES battery material technology roadmap (Figure 2).

The MoZEES battery innovation activities are also becoming more closely linked to the national Battery Norway initiative by the Norwegian Center of Excellence (NCE) Eyde Cluster, which also includes Hydro, another industrial partner in MoZEES. The goal with the Battery Norway industry network is to establish complete commercial battery value chains in Norway, including new battery cell manufacturing capabilities and advanced factories for recycling. Hydro, an industrial partner that joined MoZEES in 2019, has showed great interest in both cell manufacturing, recycling, and the reuse of key battery materials such as aluminum. Equinor joined MoZEES in 2020 and has also showed great interest for the MoZEES battery activities, particularly in the application of maritime battery systems for offshore operations. In summary, the MoZEES partners are involved in numerous hydrogen and battery innovation activities related to future zero emission transport activities (land and sea). The innovation activities within the Center are now organized by a dedicated MoZEES Innovation Committee. Several meetings with the MoZEES Innovation Forum are planned in 2021, in close collaboration with highly relevant national innovation networks such as Arena Ocean Hyway Cluster, H2Cluster, and NCE Eyde Cluster.


MoZEES Zero Emission Heavy Duty Transport Roadmap
Actions, Goals & Targets
2020
2021
2022
2023
2024
2030
H2
Develop heavy duty battery and hydrogen electric transport applications and systems
Goal
Optimize ZE HDV transport system designs
Vision
Norway*:
50% ZE Trucks
HD Truck new sales
75% ZE Ferries
75 of 100 HSC
Status today:
A few ZE heavy duty trucks pilots in operation
Several battery electric ferries, but no H2 ferries in operation
TASK 4.1
New technology business models (rail, road, sea)
TASK 4.3
Vehicle market modeling
Hydrogen value chain analysis
TASK 3.1
Fuel cell stack experiments
Maritime Fuel cell System Modeling
TASK 3.2
Battery lifetime studies
Battery lifetime & degradation modeling
TASK 3.3
Battery safety studies
Battery abuse experiments
Hydrogen safety experiments & studies
Business models with TCO on parity with fossil fuels
Durable & Efficient Battery & H2 Systems
Safe Battery & H2 Systems
Assumptions
Economic incentives for use of ZE Trucks
Funding for public ZE ferry procure-ments
Support for first infrastructure build-up
Pre-commercial ZE-Truck pilots (e.g. ASKO)
Small volume production of ZE Trucks
Task 3.5 & Task 4.2 - ZE Truck Case Studies
ZE Truck Research Project (MoZEES Spin-off)
Optimal System Design
Task 3.5 & Task 4.2– ZE Maritime Case Studies
Build-up of H2-infrastructure
First ZE High Speed Ferries
Optimal System Design
Legend
Research Action
Innovation Strategy
MoZEES program
Post MoZEES
Goal(s)
*Note! National goals to be determined in MoZEES Policy Roadmap

(Figure 1).


MoZEES Battery Material Technology Roadmap
Actions, Goals & Targets
2020
2021
2022
2023
2024
2030
Status today:
Anodes
Low Si-content 8 wt% Si
Cathodes
NMC with 60%
Nickel NMC622
Electrolytes & Binders
Conventional materials
Legend
Research Action
Innovation Strategy
MoZEES program
Post MoZEES
Goal(s)
ZE = Zero Emission
Si = Silicon
Ni = Nickel
NMC = Nickel Manganese Cobalt
LNMO = Lithium Nickel
Manganese Oxide
ALD = Atomic Layer Deposition
DEMS = Differential Electro-
chemical Mass Spectrometry
H2
Develop next generation Lithium-ion battery materials
TASK 1.1
Increase specific battery capacity by adding Si to anodes and validate performance in full battery cells
-Anode: 20 wt%
Si @1200 mAh/g
-Stable ionic liquids
-SiOx 1350 mA/g @0.4 V
TASK 1.2
Develop high energy cathode materials (doped LNMO, Ni-rich NMC)
-LNMO @130 mAh/g, 5V
-NMC811 700 Wh/kg
TASK 1.3
Develop voltage and expansion tolerant electrolytes and binders (tailored electrode-electrolyte interfaces, coatings, ALD)
LNMO 650 Wh/kg
TASK 1.5
Advanced in-situ and post-mortem characterization (synchrotron, DEMS, impedance spectroscopy)
Safe Battery & H2 Systems
Goal
Demonstrate durable high energy cells
Vision
New Battery Material & Cell Manufacturing in Norway & Europe
Assumptions
Stable materials demonstrated in full battery cells
Investments in battery material manufacturing
ZE maritime systems fully commercial
R&D on active anode materials
Industrial pilot production of synthetic graphite & silicon
Mass production
Optimal System Design
Pre-commercial maritime battery modules
Validated products
Commercial maritime battery modules optimized wrt. durability & safety
Validated products

(Figure 2).

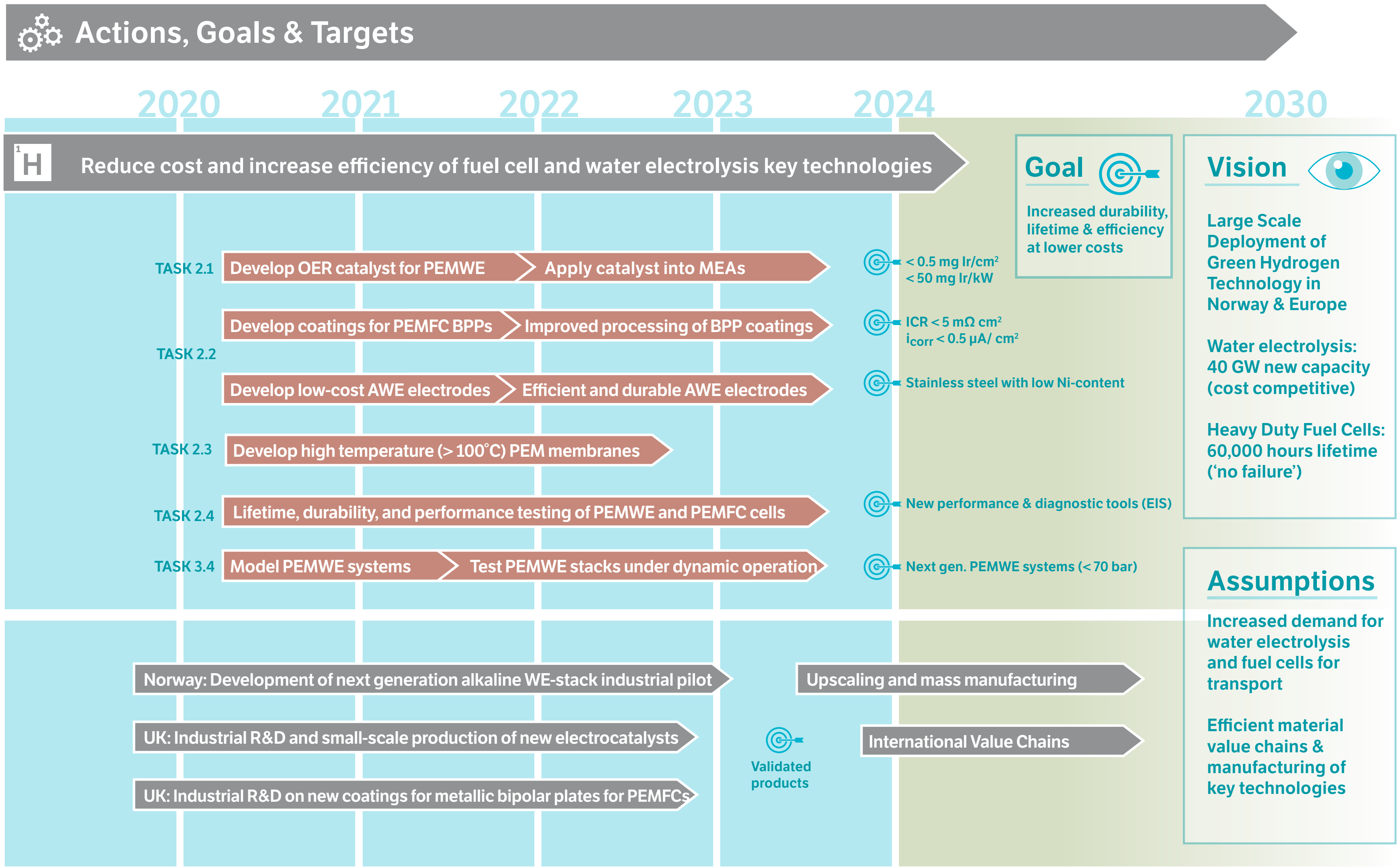
MoZEES Hydrogen Technology Roadmap

Status today:

PEM Fuel Cells
Lifetime (for Heavy Duty):
20 000 h

Alkaline Water Electrolysis
Catalysts: High Ni loading

PEM Water Electrolysis
Pressure: < 30 bar
Catalysts: 1 g/kW



Legend

- Research Action
- Innovation Strategy
- MoZEES program
- Post MoZEES
- Goal(s)

PEM = Proton Exchange Membrane
PEMFC = PEM Fuel Cell
PEMWE = PEM Water Electrolysis
AWE = Alkaline Water Electrolysis
MEA = Membrane Electrode Assembly
BPP = Bipolar Plate
OER = Oxygen Evolution Reaction
ICR = Internal Contact Resistance
EIS = Electrochemical Impedance Spectroscopy

(Figure 3).

Appendix 1: Personnel

Postdoctoral Researchers with financial support from the Center Budget						
Institution	Name	Sex M/F	Nationality	Start date	End date	Topic
UiO	Alok M. Tripathi	M	India	02.10.2018	31.03.2021	Advanced characterization of Li-ion batteries
IFE/UiO	Gaylord K. Booto	M	Congo	06.09.2018	05.03.2020	Life Cycle Analysis

PhD students with financial support from the Center Budget						
Institution	Name	Sex M/F	Nationality	Start date	End date	Topic
NTNU	Daniel Tevik Rogstad	M	Norway	01.09.2017	26.11.2020	Silicon anodes and ionic liquids
NTNU	Elise Ramleth Østli	F	Norway	21.08.2017	20.10.2021	Water-based manufaturing routes for electrodes
NTNU	Eivind Hugaas	M	Norway	01.09.2017	31.09.2020	Fatigue mechanisms of hydrogen storage tanks
NTNU	Hamid R. Zamanizadeh	M	Iran	20.09.2018	17.10.2021	Bipolar plates for alkaline water electrolysis
NTNU	Jonas Martin	M	Germany	01.08.2020	31.07.2023	Policy and techno-economic analysis
USN	Mathias Henriksen	M	Norway	15.08.2017	15.08.2021	Explosion hazards of Lithium ion batteries
UiO	Halvor Høen Hval	M	Norway	01.01.2018	15.04.2022	High voltage cathode materials for Li-ion batteries
UiO	Xinwei Sun	F	China	01.09.2018	31.08.2021	Composite Proton conducting membranes
UiO	Carina Geiss	F	Germany	21.09.2020	20.09.2023	In-operando studies of Silicon anodes

Key researchers		
Institution	Name	Main research area
NTNU	Frode Seland	Battery and electrolysis components and technology
NTNU	Andreas Echtermeyer	Hydrogen components, testing and modelling
NTNU	Asgeir Tomasgard	Policy and techno-economic analysis
NTNU	Anne Neumann	Policy and techno-economic analysis
NTNU	Peter Schutz	Policy and techno-economic analysis
UiO	Helmer Fjellvåg	Battery materials and components
UiO	Truls Norby	Fuel cell and electrolyzer materials and component
UiO	Katinka E. Grønli	Energy, Environment, Climate
UiO	Øystein Moen	Energy, Environment, Climate
USN	Dag Bjerketvedt	Hydrogen and Battery safety
USN	Joachim Lundberg	Hydrogen and Battery safety
USN	André V. Gaathaug	Hydrogen and Battery safety
USN	Knut Vågsæther	Hydrogen and Battery safety
FFI	Helge Weydahl	Battery safety, fuel cell systems
FFI	Martin Gilljam	Chemical characterization of lithium ion batteries
FFI	Torleif Lian	Thermal stability of lithium ion batteries
FFI	Sissel Forseth	Battery safety
SINTEF	Alejandro O. Barnett	PEMFC and PEMWE testing, BPP, membranes, catalysts, and AST protocols
SINTEF	Kristin Y. Bjerkan	Social scientific transport research
SINTEF	Rune Bredesen	Functional oxides, solid state diffusion/kinetics, membranes, fuel cells and electrolyzers
SINTEF	Paul Inge Dahl	Materials synthesis and processing for batteries

SINTEF	Einar Vøllestad	Functional oxides
SINTEF	Sigrid Damman	Governance, institutional drivers and barriers
SINTEF	Katie McCay	PEMFC and PEMWE testing
SINTEF	Kaushik Jayasayee	Battery testing
SINTEF	Patrick Fortin	PEMFC and PEMWE testing
SINTEF	Thulile Khoze	PEMFE and PEMWE testing
SINTEF	Solveig Meland	Social scientific transport research
SINTEF	Vibeke S. Nørstebø	Operations research, economic analysis
SINTEF	Anders Ødegård	PEMFC Bipolar plates and PEMFC systems
SINTEF	Magnus S. Thomassen	RA coordination. PEMWE/PEMFC materials and systems
SINTEF	Julian R. Tolchard	Functional oxide materials, structural characterisation
SINTEF	Werner A. Tobias	Operations research and mathematical programming, economics
SINTEF	Zenith Federico	Fuel cell control, techno-economic analyses
SINTEF	Christelle D.	Functional oxides
SINTEF	Gerardo A P.-Valdes	Operations research, economic analysis
SINTEF	Anita H. Reksten	PEMWE catalysts
SINTEF	Artur Tron	Batteries Development
SINTEF	Kyrre Sundseth	Techno-economic analyses
SINTEF	Nils P. Wagner	Li ion batterier utvikling av katoder og anoder
SINTEF	Tor O. Sunde	Catalyst development
SINTEF	Joachim G. Seland	Sample characterisation by SEM and EDS
IFE	Jan P. Mæhlen	Silicon anodes for Li-ion batteries
IFE	Preben J.S. Vie	Battery lifetime and characterization
IFE	Julia Wind	Battery modelling and characterization
IFE	Øystein Ulleberg	Hydrogen systems - fuel cells and electrolyzers
IFE	Fredrik Aarskog	Hydrogen systems - fuel cells
IFE	Ragnhild Hancke	Hydrogen systems – electrolyzers
IFE	Asbjørn Ulvestad	Silicon anodes for Li-ion batteries
IFE	Hanne F. Andersen	Silicon anodes for Li-ion batteries
IFE	Carl Erik L. Foss	Silicon anodes for Li-ion batteries
IFE	Samson Lai	Silicon anodes for Li-ion batteries
IFE	Morten Tjelta	Corrosion in alkaline media
IFE	Jon Kvarekvål	Corrosion in alkaline media
IFE	Kari Aa Espegren	Energy system modelling
IFE	Janis Danebergs	Energy System Modelling
TØI	Erik Figenbaum	Electric vehicles, environmental characteristics of vehicles, technology diffusion
TØI	Inger Beate Hovi	Vehicle and demand modelling, SCGE-modelling, cost functions, economic incentives, user needs and obstacles
TØI	Rebecca Thorne	Environment, Energy, Technology
TØI	Ingrid Sundvor	Environment, Energy, Technology
TØI	Daniel R. Pinchasik	Environment, Energy, Technology
TØI	Lasse Fridstrøm	Vehicle fleet forecasting, vehicle and demand modelling, economic incentives

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

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

Master degrees			
Institution	Name	Sex M/F	Topic
NTNU	Ingrid H. Flatebø	F	Si-anodes for Li-ion batteries – advanced characterization techniques for surface films
NTNU	Øyvind Lindgård	M	Silicon-graphite composite anodes for Li-ion batteries
NTNU	Joachim S. Bjørklund	M	Silicon Anodes for Li-ion Batteries
UiO	Hand Didrick B. Kruse	M	Layered Cathode Materials
UiO	Stian Simonsen	M	Composite Polymer Membranes
USN	Ida Hæstad	F	Modelling of hydrogen bunkering system for maritime applications
USN	Erik Nygaard	M	Hydrogen Safety, ATEX

Appendix 2: Statement of Accounts

Funding	Amount
The Research Council	13 424
The Host Institution (IFE)	1 655
Research Partners	8 318
Industry partners	5 906
Public partners	2 747
Total funding	**32 050**

Costs	Amount
The Host Institution (IFE)	5 795
Research Partners	20 277
Industry partners	3 521
Public partners	447
Equipment	2 010
Total costs	**32 050**

(All figures are given in kNOK)

Appendix 3: Publications

1. Aarskog, F.G., J. Danebergs, T. Strømgren, and Ø. Ulleberg, *Energy and cost analysis of a hydrogen driven high speed passenger ferry.* International Shipbuilding Progress, 2020. 67.
2. Aarskog, F.G., O.R. Hansen, T. Strømgren, and Ø. Ulleberg, *Concept risk assessment of a hydrogen driven high speed passenger ferry.* International Journal of Hydrogen Energy, 2019: p. 1-14.
3. Andersen, H., K. Xu, D. Malyshkin, R. Strandbakke, 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.
4. Bjerkan, K.Y., H. Karlsson, R.S. Sondell, S. Damman, et al., *Governance in Maritime Passenger Transport: Green Public Procurement of Ferry Services.* World Electric Vehicle Journal, 2019. 10(4): p. 1-15.
5. Bratland, M., D. Bjerketvedt, and K. Vågsæther, *Structural response analysis of explosions in hydrogen-air mixtures in tunnel-like geometries.* Engineering structures, 2021.
6. 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.
7. Figenbaum, E., *Can battery electric light commercial vehicles work for craftsmen and service enterprises?* Energy Policy, 2018. 120: p. 58-72.
8. Foss, C.E.L., S. Müssig, A.M. Svensson, P.J.S. Vie, 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).
9. Gaathaug, A.V. and A. Lach, *Large scale experiments and model validation of Pressure Peaking Phenomena-ignited hydrogen releases.* International Journal of Hydrogen Energy, 2021. 46(11): p. 8317-8328.
10. Gaathaug, A.V., K. Vågsæther, J. Lundberg, and D. Bjerketvedt, *Detonation Propagation in Stratified Reactant Layers.* Linköping Electronic Conference Proceedings, 2017(138): p. 162-167.
11. Halvorsen, I.J., I. Pivac, D. Bezmalinovic, F. Barbir, 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.
12. 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.
13. Henriksen, M., K. Vågsæther, A.V. Gaathaug, J. Lundberg, 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.
14. Henriksen, M., K. Vågsæther, J. Lundberg, S. Forseth, et al., *Explosion characteristics for Li-ion battery electrolytes at elevated temperatures.* Journal of Hazardous Materials, 2019. 371: p. 1-7.
15. Hovi, I.B., D.R. Pinchasik, E. Figenbaum, and R.J. Thorne, *Experiences from battery-electric truck users in Norway.* World Electric Vehicle Journal, 2020. 11(5).
16. 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.
17. Johnsplass, J.S., M. Henriksen, K. Vågsæther, J. Lundberg, 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.
18. 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.
19. Lai, S.Y., J.P. Mæhlen, T. Preston, M.O. Skare, et al., *Morphology engineering of silicon nanoparticles for better performance in Li-ion battery anodes.* Nanoscale Advances, 2020. 2(11): p. 5335-5342.
20. Lian, T., P.J.S. Vie, M. Gilljam, and S. Forseth, *Changes in Thermal Stability of Cyclic Aged Commercial Lithium-Ion Cells.* ECS Transactions, 2019. 89(1): p. 73-81.
21. Marocco, P., K. Sundseth, T.A. Aarhaug, A. Lanzini, et al., *Online measurements of fluoride ions in proton exchange membrane water electrolysis through ion chromatography.* Journal of Power Sources, 2021.
22. Richter, F., P.J.S. Vie, S.H. Kjelstrup, and O.S. Burheim, *Measurements of ageing and thermal conductivity in a secondary NMC-hard carbon Li-ion battery and the impact on internal temperature profiles.* Electrochimica Acta, 2017. 250: p. 228-237.
23. Sun, X., S.C. Simonsen, T.E. Norby, and A.E. Chatzitakis, *Composite Membranes for High Temperature PEM Fuel Cells and Electrolysers: A Critical Review.* Membranes, 2019. 9(7).
24. Sun, X., K. Xu, C. Fleischer, X. Liu, et al., *Earth-abundant electrocatalysts in proton exchange membrane electrolyzers.* Catalysts, 2018. 8:657(12): p. 1-41.
25. Tezel, A.O., S. Daniel, A. Gueguen, M. Hahlin, 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. 130504.
26. 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.
27. Ulvestad, A., H.F. Andersen, I.J.T. Jensen, T. Mongstad, et al., *Substoichiometric Silicon Nitride: An Anode Material for Li-ion Batteries Promising High Stability and High Capacity.* Scientific Reports, 2018. 8.
28. Ulvestad, A., H.F. Andersen, J.P. Mæhlen, Ø. Prytz, et al., *Long-term cyclability of substoichiometric silicon nitride thin film anodes for Li-ion batteries.* Scientific Reports, 2017. 7(1).
29. Ulvestad, A., A. Reksten, H.F. Andersen, P. Almeida Carvalho, et al., *Crystallinity of silicon nanoparticles: Direct influence on the electrochemical performance of lithium ion battery anodes.* ChemElectroChem, 2020. 7(21): p. 4349-4253.
30. Vatani, M., P.J.S. Vie, and y. Ulleberg, *Cycling Lifetime Prediction Model for Lithium-ion Batteries Based on Artificial Neural Networks.* IEEE PES Innovative Smart Grid Technologies Conference Europe, 2018.
31. Volodin, A.A., R.V. Denys, C. Wan, I.D. Wijayanti, et al., *Study of hydrogen storage and electrochemical properties of AB2-typeTi 0.15Zr0.85La0.03Ni1.2Mn0.7V0.12Fe0.12alloy.* Journal of Alloys and Compounds, 2019. 793: p. 564-575.
32. Vågsæther, K., A.V. Gaathaug, and D. Bjerketvedt, *PIV-measurements of reactant flow in hydrogen-air explosions.* International Journal of Hydrogen Energy, 2018.
33. Wan, C., R.V. Denys, M. Lelis, D. Milcius, 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.
34. Wijayanti, I.D., L. Mølmen, R.V. Denys, J. Nei, 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.
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Mobility Zero Emission Energy Systems

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