Final report

1. Project details

Project title	Ammonia electric marine power for GHG emission reduction: AEGIR
File no.	#107221 (64020-5006)
Name of the funding scheme	Nordic Energy and Transport Research Programme (NMTEP)
Project managing company / institution	Danmarks Tekniske Universitet
CVR number (central business register)	30060946
Project partners	DTU, Ballard Power Systems Europe, CoorsTek Membrane Sciences, SINTEF, Vard, VTT
Submission date	29 June 2023

2. Summary

The global introduction of green fuels and/or energy solutions is essential to achieve the overall ambitions for reducing greenhouse gas (GHG) emissions from international shipping. Ammonia is a promising fuel that has the potential to be zero-emission if produced using renewable energy sources. The AEGIR project addressed an environmentally friendly technological solution to power large marine vessels by using ammonia as primary fuel.

Specific objectives were to

- Establish a design concept for a fully electric ammonia-fuelled ship powertrain with a tank-to-electricity efficiency >60%,
- Demonstrate a reduction of GHG emissions >90% compared to current LNG (liquefied natural gas) fuelled marine engines for the design concept,
- Identify potential scale up issues for 20 MW maritime system in a concept study, and
- Experimentally validate the three key enabling technologies for the integrated concept (Solid oxide fuel cells – SOFC, Proton conducting electrochemical membrane reactor – PCEMR, and proton exchange membrane fuel cells – PCEMR).

In the AEGIR project, a system was designed with an SOFC for cracking of ammonia into H_2 & N_2 while producing electricity & heat for other system components, a PCEMR to separate H_2 at high purity from the SOFC outlet gas, which is fuelled into a PEMFC as main electricity provider. The system design was used for the following analysis showing that **efficiencies >60%** are reached when the share of SOFCs within the system is high. **90% GHG reduction** compared to LNG is reached if the fueled ammonia is produced using renewable

energy. The development of larger **modular solutions** is initiated to reach multiple megawatts of PEMFC power with one solution. AEGIR showed at single cell level that SOFC can operate stably on ammonia fuel, provided operating conditions are in a safe window; specifically the temperature needs to be ca. >750 ^{o}C. It was found that ammonia cracking occurs within the SOFC cell / stack and also when passing balance of plant components at elevated temperatures. The PCEMR can operate in presence of ammonia. With the expected selectivity of the PCEMR for hydrogen, the subsequent fuelling of the PEMFC should be feasible.

Det er nødvendigt med lav- eller bedre nul-emissionsteknologier i den maritime sektor for at sænke udledning af drivhusgasser fra international skibstransport. Ammoniak er et alternativt nul-emissionsbrændstof, hvis det bliver fremstillet ved hjælp af vedvarende energikilder. Ægir projektets overordnede mål var at undersøge en miljøvenlig teknologisk løsning til at drive store marinefartøjer med grøn ammoniak som primært brændstof.

Specifikke mål var, at

- *Designe et koncept for et elektrisk ammoniakdrevet fartøj med en virkningsgrad over 60%*
- *Demonstrere en reduktion af drivhusgasemissionerne med 90%, sammenlignet med de nuværende motorer med flydende naturgas*
- *Identificere opskaleringskoncepter og potentielle udfordringer og*
- *Validere eksperimentelt de tre nøgleteknologier for det integrerede koncept (Solid oxide fuel cells – SOFC, Proton conducting electrochemical membrane reactor – PCEMR, og proton exchange membrane fuel cells – PCEMR).*

*I Ægir-projektet blev et system designet med en SOFC som spalter ammoniak i H_2 & N_2, samt producerer strøm og varme til systemkomponenter, en PCEMR, som adskiller H_2 fra SOFC produktgas, der efterfølgende føres til en PEMFC som hovedleverandør af fartøjets elektricitet. Systemanalysen viser, at en **virkningsgrad på >60%** opnås, hvis der er en stor andel af SOFC i systemet og at en **reduktion i drivhusgasemissionen på 90%** er mulig i forhold til nuværende avancerede skibsmotorer med flydende naturgas, hvis ammoniak er fremstillet via grønne ruter. **Modulære PEMFC koncepter** er løsning for opskalering hen imod multimegawatt og udvikling er påbegyndt.*

Ægir-projektet viste, at en SOFC kan drives stabilt med ammoniak som brændstof inden for de rette driftsbetingelser, specielt temperaturer højere end ca. 750 ^{o}C. Ammoniakken spaltes i SOFC-cellen/stakken og også på varme systemkomponenter såsom rør. En PCEMR kan drives med ammoniak-holdig gas. Med den forventede brintrenhed efter PCEMR'en, skulle en PEMFC drift være muligt.

3. Project objectives

The aim of the AEGIR project was to develop, test and evaluate an environmentally friendly technological solution to power large marine vessels by using green ammonia as primary fuel. The AEGIR idea was to use a solid oxide fuel cell (SOFC) as ammonia cracker and first stage electricity production. Hydrogen in the gas outlet will be separated and cleaned through a proton conducting electrochemical membrane reactor (PCEMR) and led to a polymer exchange membrane fuel cell (PEMFC) as main electricity producer. The integration of these three technologies was expected to provide a high overall system efficiency for powering maritime transport.

The AEGIR project had four main objectives:

1) Establish a design concept for a fully electric ammonia-fuelled ship powertrain without CO_2-emissions and having a tank-to-electricity efficiency >60%

2) Demonstrate a reduction of greenhouse gas (GHG) emissions >90% compared to current State-of-the-Art (SoA) liquefied natural gas (LNG) fuelled marine engines in a well-to-tank (including emissions from electricity production and ammonia synthesis and logistics) and tank-to-propeller (including the use of the fuel on-board) analysis

3) Experimentally validate the three key enabling technologies for the integrated concept aiming at:

I. a degradation rate below 0.3%/1000 h to enable 40000 h lifetime of the SOFC system at >95% ammonia conversion,
II. a hydrogen output from the PCEMR fulfilling the ISO 14687 specifications in terms of NH_3, N_2 and O_2 concentration, and
III. a degradation rate below 0.3%/1000 h to enable 40000 h lifetime of the PEMFC system using the hydrogen purity specifications from the PCEMR.

4) Identify potential scale up issues for 20 MW maritime system in a concept study.

The main system design concept for using NH_3 in marine applications in the AEGIR project built on integrating three technologies SOFC, PCEMR, and PEMFC. The SOFC enables efficient cracking of ammonia fuel into hydrogen & nitrogen while producing electricity & heat, the PCEMR separates out H_2 at high purity and feeds it to the PEMFC, which utilizes the H_2 to produce the main part of electricity for the vessel (see Figure 1).

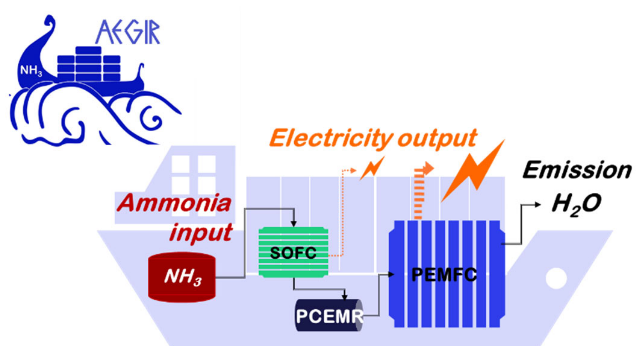

Figure 1 Illustration of the AEGIR concept

4. Project implementation

The AEGIR project was granted through the Nordic Maritime Transport and Energy Research Programme (NMTEP) with six Nordic partners in the consortium, where each partner was funded by the respective national funding body (see Table 1).

Table 1 AEGIR consortium

#	Partner		Country	National funding body
1	DTU	Technical University of Denmark	DK	EUDP (Energiteknologisk Udviklings og Demonstrations Program)
2	Ballard	Ballard Power Systems Europe	DK	EUDP (Energiteknologisk Udviklings og Demonstrations Program)
3	VTT	VTT Technical Research Centre of Finland Ltd.	F	Business Finland

4	SINTEF	Sustainable Energy Technology	NO	Norwegian Research Council (RCN)
5	CoorsTek	CoorsTek Membrane Sciences	NO	Norwegian Research Council (RCN)
6	Vard	Vard Ship Building	NO	Norwegian Research Council (RCN)

The AEGIR project was organised in five work packages (see Figure 2). Danish partners were mainly involved in WP1 (coordinator), WP2, WP4, and WP5.

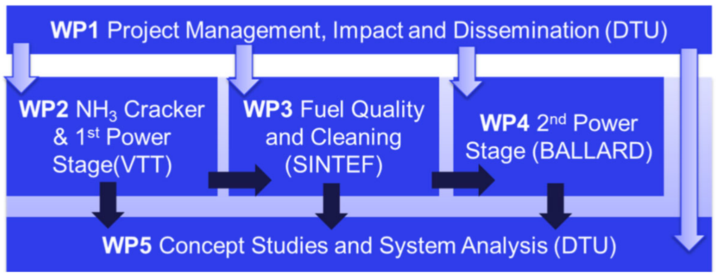

Figure 2 AEGIR project organisation

The project started 28 February 2021 and run over two years. During the project period, ten consortium meetings were held, with an additional challenge due to travel and meeting restrictions as a consequence of covid-19. In fact, only one physical Technical Workshop was possible at SINTEF (Norway) and one physical Project Meeting, which was held at Ballard (Denmark).

In addition to technical / technological risks, restrictions due to covid-19 posed additional challenges. Those were handled and solutions agreed to secure project progress.

Risks arose due to the involvement of three different technologies, both in experimental work and in design work, which required establishing mutual understanding of technology basics, operating regimes, and system boundaries and opportunities. A Technical Workshop was organised to communicate and discuss these issues across the scientific areas.

Furthermore, the ambitious project objectives and the novel character of the experimental activities created a number of risks, which were not expected from previous knowledge (see Table 2). The risks were discussed in the regular project meetings and solutions decided that should provide the best possible total output from and impact of the AEGIR project.

Table 2 List of major risks/problems encountered during the AEGIR project and how they were tackled

Topic	Related to objective #	Comment	Action
SOFC	3I	Rapid SOFC stack degradation with NH_3 fuel under AEGIR relevant conditions, which was not previously observed	Redirection of durability tests to single cell level and additional, separate study of stack interconnect durability
PCEMR	3II	NH_3 installations in the research lab strongly delayed (deliverance problems) and establishment of gas analysis failed	Concentration on durability test in presence of NH_3 without analysing the H_2 purity in the outlet
PEMFC	3III*	Implementation of NH_3 impurities in the fuel facilities for a full PEMFC system facility at Ballard not possible	Redirection of effect of NH_3 impurity tests to stack level at other partner (SINTEF)

PEMFC	3III*	Unexpected failure of the PEMFC stack test facility at SINTEF without realistic chances to re-start within a foreseen future	Use remaining resources for evaluating literature results related to the effect NH_3 impurities on PEMFC durability.

* In addition to project meetings, the partners Ballard and SINTEF had weekly meetings to track any change in progress. Outside challenges prevented most of the originally set milestones from being completed for the PEMFC related activities. While being very prepared, we were ultimately unsuccessful in completing the outlined activities. We changed our approach as the difficulties became clear and have endeavored to submit what we were able to complete.

The encountered problems made it necessary to revise and redefine the milestones of the project (Table 3).

Table 3 List of milestones and revisions due to the unexpected encountered severe problems

Milestone	Problem	Solution
PEMFC short stack operation on H_2 with purity levels from ammonia from the PCEMR	Failure of the PEMFC stack test station	• Assuming 100% selectivity of the PCEMR for hydrogen purification • Literature study about the ammonia effect on PEMFC
Ammonia conversion of >95% achieved on the SOFC stack while running part load with degradation rates below 0.3%/1000 h	Fast SOFC stack degradation at the conditions required by the stack provider	• Test at single cell level, mapping of optimum operating conditions ✓ >95% ammonia conversion reached ✓ No additional degradation observed • Separate interconnect (stack components) tests for tolerance towards ammonia
200 kW PEMFC test arrangement ready for start of tests	Facility established and ready for test with hydrogen, though not with ammonia impurities	• Test at PEMFC stack, not system level, which at the end was not feasible despite big efforts and a literature review about the topic was decided
Demonstrate > 95% extraction of hydrogen with NH_3, N_2 and O_2 concentrations according to ISO 14687 standard using a proton ceramic membrane reactor	Failure of gas analysis of the PCEMR test setup	• Durability test of the PCEMR in presence of ammonia

Finally, establishing and use of ammonia in laboratory facilities proved to be an unexpected additional challenge towards safety and handling in research environments that differs from the large-scale handling in industry (apart from unexpectedly long delivery times for relevant parts). The challenges appear over a large range, from fuelling pure ammonia up to handling of traces of ammonia and producing trustworthy and stable experimental results. The efforts for solving these issues were larger than originally expected. As ammonia receives increasing attention, a Webinar was held in order to share the gained experiences and allow research groups to learn from the first steps and to safe valuable resources for future ammonia related research. The presentations are publicly available through the AEGIR homepage (https://www.aegir-project.net/news/nyhed?id=80b58f0f-decd-4293-a622-8eb18e592f8c).

The discussion of risks and solutions and initiation of alternative activities involved also the option of applying for extension of the AEGIR project. However, it was concluded that any extension would not solve the critical problems to a degree that the originally proposed activities could be carried out and the original goals would be reached, while the selected alternative solution would provide the best output and knowledge gain.

The distribution of activities between the AEGIR partners is listed in Table 4. Apart from the main activities, there was of course an intensive exchange across the WPs with all the partners. The following report will focus on the part carried out by the Danish partners. The international partners submit the reporting to their respective national funding bodies (see Table 1). Furthermore, a summary reporting was provided to the Nordic Energy and Transport Research Programme (NMTEP).

Table 4 AEGIR partners and roles in the AEGIR project (for WP Titles see Figure 2)

#	Partner	WP	Activity
1	DTU	1	Project management (WP lead)
		2	• NH_3 cracking kinetics • SOFC single cell tests
		5	• WP lead • System evaluation and comparison with other alternative propulsion systems using techno-economic and multi-criteria decision analysis
2	Ballard	4	• WP lead • Establishment / preparation of PEMFC 200 kW system • Evaluation of scaling issues
3	VTT	2	• WP lead • SOFC stack test with NH_3 fuel • Stack interconnect tests (w/wo protective coatings) for tolerance towards NH_3
		5	• Establishment of integrated AEGIR system design (PC study) • Variation/evaluation of system sizing
4	SINTEF	3	• WP lead • Establishment of lab for NH_3 tests • Test of PCEMR in presence of NH_3
		4	• PEMFC and NH_3
5	CoorsTek	3	• PCEMR development for the testing
6	Vard	5	Provision of input to system design and interest in NH_3 results for scaling and introduction to shipping

5. Project results

Results (authors: Anke Hagen DTU, Michael B. Barfod DTU, Christina Mikkelsen Ballard Europe)

Technological results: SOFC (WP2)

The intension of using SOFC in the AEGIR concept is based on the NH_3 cracking activity of the fuel electrodes, which contain Ni in SoA fuel electrode (anode) supported cells that acts as catalyst. DTU carried out tests aiming at determining the degree of NH_3 cracking under conditions relevant for SOFC operation.

According to thermodynamic calculation, ammonia is cracked to >99% at the relevant operating temperature of an SOFC around 650-750 ^{o}C (see Figure 3a). The ammonia cracking degree was measured in the SOFC single cell test setup both in presence and absence of a cell (see Figure 3b). The cell was kept at open circuit voltage, i.e. it was not operated, to determine the purely catalytic cracking activity. In order to allow for sufficient contacting and gas distribution, Ni containing auxiliary layers are used in the setup, which would not be present in an SOFC stack. On the other hand, a stack contains metal layers as well (interconnects) and thus it is relevant to assess the ammonia cracking activity of those layers as well. The ammonia cracking is complete in presence of a SOFC, as expected from thermodynamics, in case the flow rate is low, i.e. the residence time of ammonia at the fuel electrode of the cell is sufficiently long and the temperature is above ca. 700 ^{o}C. A low flow rate is representative for operating the cell with high fuel utilization (FU) and thus a high efficiency – a preferred system operating parameter, while the high flow rate would lead to lower fuel utilization. When increasing the ammonia flow rate, the ammonia conversion decreases. This result shows that a small flow rate is recommended to reach complete ammonia conversion to hydrogen in the SOFC. The anticipated >95% ammonia conversion can easily be reached. Interestingly, there is also a significant ammonia cracking on the Ni auxiliary layers, without a cell (light green circles in Figure 3b). This can be considered a representative for an interconnect layer in a SOFC stack or the pipes for leading ammonia to the SOFC in the hot zone. This result has consequences when envisaging a stack and system, because several hot, metallic parts of the stack and hot box could potentially be active for NH_3 cracking. Furthermore, the cracking kinetics that has been studied separately at Ni/YSZ SOFC electrodes might need additional evaluation because the SOFC could account for a part of the cracking, only. This has in turn implications for the thermal conditions in the stack and the cells as the cracking is an endothermal process thereby cooling the SOFC and system components. Finally, without any cell or metal components present in the hot zone, the ammonia cracking is very small (see brown triangles in Figure 3b). This result demonstrates that the catalytic cracking requires the presence of a metal and/or SOFC.

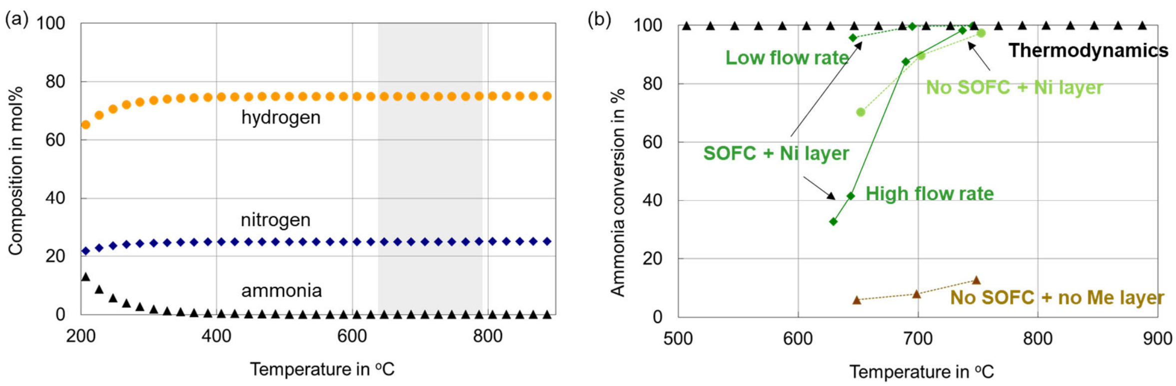

Figure 3 (a) Thermodynamics of cracking of ammonia into hydrogen and nitrogen, molar composition as function of temperature. The shaded area marks the typical operating temperature of SoA fuel electrode supported SOFCs. (b) Ammonia conversion as function of temperature according to thermodynamics (black triangles), measured in the single cell test setup with a Ni auxiliary layers (dark green rhombs, two ammonia flow rates), without a cell in presence of Ni auxiliary layers (light green circles), and without a cell and any metal auxiliary layers (brown triangles).

Previous studies carried out with NH_3 fuel at single SOFC level at 850 °C, showed that electrochemical behaviour or durability are not affected if NH_3 is used as compared to H_2/N_2 mixtures.[1] In the AEGIR project, a commercial SOFC stack was tested with NH_3 fuel by the partner VTT. In contrast to the literature studies, the used SOFC generations have a lower optimum operating temperature (below ca. 700 °C). A fast degradation of the SOFC stack was observed by VTT and related mainly to interconnect degradation. As the stacks for the project cannot be operated at higher temperatures (limit by the stack provider), it was not possible to map out potential stable operating conditions at stack level. Therefore, it was decided to test separately, the effect of NH_3 on interconnects (by VTT) and on the durability of single cells (DTU).

Figure 4 shows the results of the durability test on a single SOFC. In order to be able to assess the effect of using ammonia, a hydrogen/nitrogen fuel with the same ratio (3 to 1) was used in the first ca. 500 h (see blue curves in Figure 4). There was a certain cell degradation, expressed by the decrease of cell voltage. The magnitude of degradation is illustrated in the figure by the stippled lines. This initial degradation might be

[1] A. Hagen, H. Langnickel, X. Sun, Operation of Solid Oxide Fuel Cells with Alternative Hydrogen Carriers, Int. J. Hydrogen Energy, 44 (2019) 18382-18392.

related to conditioning processes within the electrodes of the cell. When changing to ammonia fuel (red and green curves in Figure 4), the operating temperature has a significant effect on how the degradation develops. At 700 °C, the degradation rate increases, even more when increasing the fuel utilisation (from red to green curves, which would correspond to a higher efficiency). On the other hand, the cell voltage degradation remains the same or decreases even, when operating at 750 °C (see Figure 4). This result means that using ammonia fuel at 750 °C does not increase the degradation, which is in line with the observations made at 850 °C in previous studies and with cells of different electrode compositions (ref. 1). In contrast, the degradation increases at the lower operating temperature of 700 °C. This seems counter intuitive, because degradation is typically due to thermally activated processes and thus decreases with decreases temperature. However, micro structural characterisation indicates that the degradation mechanism in this specific case is due to nitridation of nickel (both in the Ni/YSZ SOFC anode and even more the Ni auxiliary layers of the test setup). Nitridation is favoured at the lower temperature and does not occur from ca. 750 °C and above. Nitridation seems also responsible for the fast degradation of the SOFC stack that was observed in the AEGIR project by VTT, as the stack in question was operated at 650 °C, which is the target temperature of that specific stack generation.

The conclusion from these degradation studies is that SOFC can operate in ammonia fuel with no additional degradation as compared to hydrogen fuel when higher temperatures of ca. 750 °C and above are used. Otherwise, degradation due to nitridation occurs.

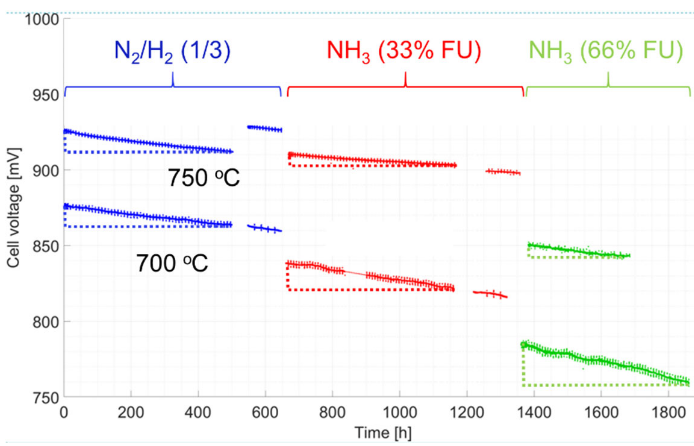

Figure 4 Durability test with hydrogen/nitrogen or ammonia fuel to the SOFC at 700 or 750 °C, cell voltage vs. time under current (0.5 A/cm^2)

Technological results PEMFC (WP4)

Ammonia has some advantages as a fuel source for PEMFCs, including its high energy density, ease of storage and transportation, and thus relatively low cost compared to hydrogen. Additionally, ammonia can be produced from renewable energy sources, such as wind or solar power, which could help reduce the carbon footprint of the fuel cell.

Several research studies have investigated the use of ammonia as a fuel source for PEMFCs. One study, published in the journal Electrochemistry Communications in 2017, reported on the use of a novel anion exchange membrane (AEM) fuel cell system that operated on ammonia. [2]The researchers found that the AEM fuel cell exhibited good performance and stability over 200 hours of continuous operation.

Another study, published in the Journal of Power Sources in 2019, investigated the performance of a PEMFC fueled by ammonia and oxygen. [3] The researchers used a platinum-ruthenium (PtRu) anode catalyst and a platinum (Pt) cathode catalyst, and found that the fuel cell had a maximum power density of 92 mW/cm^2 at 70°C.

While there have been some promising results from these studies, there are also challenges associated with using ammonia as a fuel source for PEMFCs. For example, ammonia can be toxic and corrosive, which could affect the durability and lifetime of the fuel cell. Additionally, the reaction between ammonia and oxygen can generate nitrogen oxides (NOx), which are harmful pollutants. Although these reactions are less favored at the low fuel cell operating temperatures.

Overall, the use of ammonia as a fuel source for PEMFCs is an area of ongoing research and development. While there are some challenges to overcome, the potential advantages of using ammonia, such as its high energy density and renewable production methods, make it an intriguing possibility for the future of fuel cell technology.

The key of using ammonia in SoA PEMFC technology seems to provide an efficient, cost-competitive cracking and purification solution, for example by using a PCEMR with expected ca. 100% selectivity towards hydrogen.

System evaluation results (WP5)

The partner VTT designed an integrated system combining the three technologies (SOFC, PCEMR, and PEMFC). This is the first time considering such a complex concept and there is a large range of possible combinations, sizing, and input/output media (such as hydrogen, heat, electricity). For the present project, a first selection was made for the wider impact assessment.

The wider impact assessment was performed based on the system modeling performed by VTT. In the latter, system modeling for initial optimization of the dimensions of components (SOFC, PCEMR, PEMFC) was undertaken. The modeling results were simulations of different system configurations to consider in a techno-economic analysis by estimating capital and operational expenses (CAPEX and OPEX, respectively) for the system and comparing it with other types of alternative drivetrain systems for use in the maritime sector. This captures the economic and environmental dimensions of the proposed initiatives in terms of, e.g., CO_2 reductions. Furthermore, this analysis is supplemented with an assessment including a more comprehensive set of key performance indicators relevant to determining the most attractive scenario from a business and policy perspective. In this context, stakeholder viewpoints are incorporated using multi-criteria decision analysis.

As a benchmark for the analysis, the two currently most dominant fuels for maritime propulsion, heavy fuel oil (HFO) and liquefied natural gas (LNG) are used. To these, the AEGIR system is compared. In addition, calculations have also been performed for methanol (internal combustion engine – ICE), hydrogen (fuel cell – FC), and ammonia (used in an ICE). The techno-economic analysis is based on several assumptions, as the future prices for system components and fuels are highly uncertain. However, the study has performed an extensive literature review to identify price estimates to provide a realistic economic assessment of the costs of introducing the developed AEGIR system for commercial use in 2030.

The most efficient combination of the system components suggests that the AEGIR system should consist of 2650 SOFC units, 38000 PCEMR units, and 200 PEM units. Using 2030 estimates for the costs of each unit,

[2] Qin, H., Hu, Y., Zhu, C., Chu, W., Sheng, H., Dong, Z..& Liu, J. (2017). Functionalization of polyvinyl alcohol composite membrane by CoOOH for direct borohydride fuel cells. Electrochemistry Communications, 77, 1-4.

[3] Qi, J., Zhai, Y., & St-Pierre, J. (2019). Effect of contaminant mixtures in air on proton exchange membrane fuel cell performance. J. Power Sources, 413, 86-97.

the costs are approximately 56 million Euro (MEur). In addition to this, a larger tank size is needed on the vessel due to a lower energy density of ammonia compared to HFO. This has a cost of 3.3 MEur. A cheaper solution can be obtained if the system only consists of SOFC units. In this case, the costs would only be 41 MEur. In the following, the SOFC solution without PCEMR and PEMFC will be referred to as AEGIR1. The solution consisting of the most efficient combination of the three components will be referred to as AEGIR21 (the numbers refer to the selected cases for simulations and evaluation). A sketch for the two cases is shown in Figure 5.

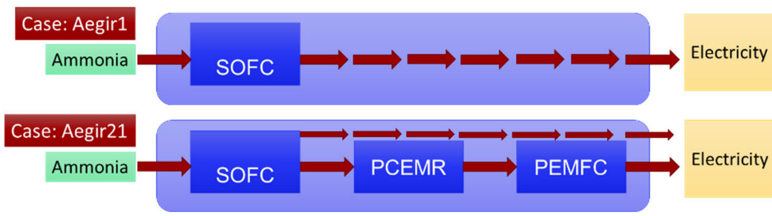

Figure 5 Illustration of two selected cases for system concepts evaluated in more detail. The detailed system includes balance-of-plant components, heat, streams, and electricity integration, and potential ammonia cracker.

For the calculation of operational expenses (OPEX), a so-called operational cycle for a containership is used to reflect a realistic performance of a ship. This cycle has been developed by Godet et al. (forthcoming)[4] and illustrates the operational profile of a containership vessel with a capacity of 5000 TEU (Twenty-foot Equivalent Units). This vessel type fits well because the AEGIR system is designed for 20 MW. According to the operational cycle, the vessel operates on sea 261 days/year with an average power output of 9.6 MW. The system is designed to work for 40000 hours. Thus, a replacement is needed every 6.4 years. The operational cycle also provides a realistic estimate of the vessel's fuel consumption.

In addition to fuel consumption and replacement costs, the OPEX also captures losses caused by reduced cargo (due to a bigger tank), extra crew to handle the fuel, and various minor expenses related to the operation. In total, the AEGIR21 system has a cost of 465 MEur over the 25-year estimated lifetime of the vessel. Table 5 shows the total costs of the alternatives examined. As can be seen, the AEGIR21 system is more than four times as expensive as HFO and LNG, which are the fossil based systems. However, it is cheaper than ICE-based methanol, which is already used today by some shipping companies and it is in the range of other “green” solutions.

Table 5 Results of the techno-economic analysis.

Alternative	Total costs (Eur)
Aegir 1	336,985,441
Aegir 21	465,232,677
HFO	102,018,461
LNG	97,715,323
Methanol (ICE)	556,281,940
Hydrogen (FC)	435,615,611
Ammonia (ICE)	373,249,435

[4] A. Godet, J.N. Nurup, J.T. Saber, G. Panagakos, M.B. Barfod, Operational cycles for maritime transportation: a benchmarking tool for ship energy efficiency, Transportation Research Part D: Transport & Environment (forthcoming – under review).

To provide a more comprehensive assessment of the different propulsion systems, a multi-criteria decision analysis (MCDA) was performed. The MCDA makes it possible to address impacts and criteria, which cannot necessarily be assigned with a monetary value and addressed in the techno-economic part. The first step of the wider impact assessment was to identify the criteria (or Key Performance Indicators) relevant to assess the characteristics of the fuels and propulsion systems. First, a long list of criteria was identified through the literature review. Afterwards, this was reduced to a set of operational criteria through discussions with the industry and academia partners. The final criteria consisted of environmental (CO_2, PM, SO_x and NO_x emissions, and aquatic risks), technological (technological matureness, regulations and guidelines), and fuel properties (bunkering availability, storage conditions, flammability, toxicity to humans, and governmental support).

A common value scale from 0-100 was defined to reflect worst and best possible performance on each criterion, and value functions were defined to measure the specific performance of the alternative options. Next, weights were elicited to reflect the relative importance of the criteria compared to each other. Table 6 presents the scores of the examined alternatives under each criterion.

Table 6 Alternatives scores under the examined criteria

	CO_2	PM	SO_x	NO_x	Aquatic risks	Technology maturity level	Regulations and guidelines	Bunkering availability	Storage conditions	Flammability	Governmental support	Toxicity to humans
Aegir 1	100	100	95	100	0	50	40	30	40	50	25	0
Aegir 21	100	100	95	100	0	40	40	30	40	50	25	0
HFO	0	0	0	0	30	100	100	100	100	100	100	50
LNG	5	38	80	33	100	100	100	80	65	30	80	80
Methanol (ICE)	100	100	90	34	60	80	80	50	80	75	50	25
Hydrogen (FC)	100	100	100	100	90	50	0	0	0	0	25	100
Ammonia (ICE)	100	100	100	10	0	50	40	30	40	50	25	0

Definition of weights that reflect the importance of each criterion is the most subjective part of the MCDA process, and the outcome of the analysis will to a great extent, depend on who defines the weights. To test the sensitivity of this, two different weight sets were defined; one reflecting an academic approach (derived through interviews with maritime experts) and one defined by industry partners (i.e., companies who are to invest in the propulsion systems). Table 7 presents the two weight sets. Note that the weights in each column sum to 1.

Table 7 Criteria weights

	Academic approach	Industry approach
CO_2	0.2500	0.2000
PM	0.0625	0.0250
SO_x	0.0625	0.0250
NO_x	0.0625	0.0250
Aquatic risks	0.0625	0.0250
Technology maturity level	0.1750	0.2500
Regulations and guidelines	0.1750	0.2500
Bunkering availability	0.0300	0.0400

Storage conditions	0.0300	0.0400
Flammability	0.0300	0.0400
Governmental support	0.0300	0.0400
Toxicity to humans	0.0300	0.0400

Clearly, academia weights the environmental criteria highest while the industry is more focused on the technological issues. Table 8 presents the aggregated results of the analysis.

Table 8 Aggregated results weight analysis

Alternatives	Total costs	Academic score	Industry score
Aegir 1	336,985,441	63.5	55.7
Aegir 21	465,232,677	61.8	53.2
HFO	102,018,461	50.4	68.8
LNG	97,715,323	62.0	70.7
Methanol (ICE)	556,281,940	**79.2**	**78.3**
Hydrogen (FC)	435,615,611	61.9	47.3
Ammonia (ICE)	373,249,435	58.2	53.6

In both cases, an ICE-based methanol system is the preferred solution. This is not surprising, as this option is the most mature technology (besides HFO and LNG) and performs the best under those criteria, which are given significant weights. The ammonia solutions are still somewhat behind, mainly due to the low technological maturity and the safety issues connected to fuel handling.

While costs and scores were determined individually in the sections above, it is interesting to set the scores in relation to the costs and examine the performance, i.e. to evaluate how big a benefit one can achieve at what extra costs (see Figure 6).

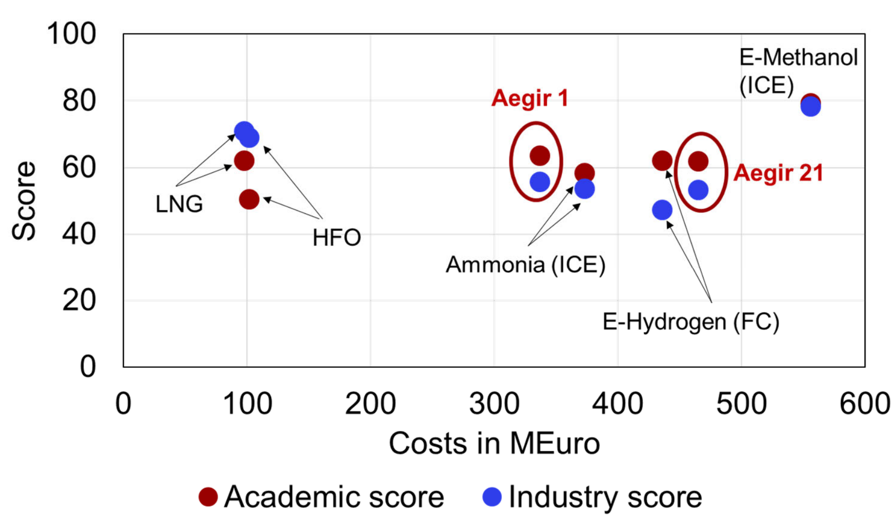

Figure 6 Scores vs. costs (academic profile: red circles, industrial profile: blue circles)

From Figure 6, it is possible to see what alternatives outperform the others by drawing a so-called efficiency frontier between the best performing in relation to their costs. In both cases, LNG outperforms HFO (a higher score is obtained at a lower price). In the industry profile, LNG outperforms all alternatives other than Methanol, thus, in principle, the choice stands between these two technologies. However, LNG and HFO are only considered in this analysis for comparison purposes and are not attractive future maritime propulsion alternatives due to their fossil origin. Therefore, the actual choice will stand between the remaining five options.

Figure 6 shows that the AEGIR1 (only SOFC) and Methanol solutions outperform the others. However, the better performance of Methanol comes at a significantly higher cost than the AEGIR solution. Moreover, it can be noted that the remaining alternatives perform with scores very similar to AEGIR, and if their prices are reduced, they could also be alternatives worth considering. Calculations show that if reducing the PEMFC and PCEMR costs by 42%, the AEGIR21 solution would have similar costs to the AEGIR1 solution (the system only consisting of SOFC). As mentioned earlier, the AEGIR solution is a long way from being technologically mature, and there are several issues regarding the handling of ammonia as a fuel that still need to be resolved. However, this analysis concludes that the AEGIR system concept shows some promising perspectives at this early stage and is worth exploring more in the future.

As a final note, the analysis has assumed that ammonia, methanol, and hydrogen are all produced green, i.e., with zero emissions in the production. This issue must also be addressed in the future, as only a tiny part of the current production is green. Worldwide ammonia production accounts for approximately 1% of global CO_2 emissions yearly. Black ammonia production (fossil fuels used) emits 90 kg of CO_2 per GJ on average. This is significantly more than the production of both HFO and LNG. If meeting the AEGIR objective of 90% CO_2 reduction compared to LNG, the ammonia produced for the system should emit at most 13.7 kg/GJ.

The evaluation provided costs for different versions of the AEGIR design as compared to SoA fossil based or other green solutions and evaluated the impact according to parameters such as technology maturity, environmental impact like emission reduction and potential risks. The results can guide decision making for further research & development and investments.

Dissemination & Communication

1) Peer reviewed articles, books, book chapters etc. published with or submitted to academic publishers
   - Plan: M.B. Barfod, J.A. Busch, J. Pennanen, Wider impact assessment of a new ammonia based fuel cell system for maritime propulsion, In preparation for Journal of Cleaner Production (will be submitted medio 2023).
   - Plan: A. Hagen, R. Caldogno, X. Sun, Ammonia fueled SOFC for shipping, In preparation for J. Power Sources (will be submitted medio 2023).
2) Non-peer reviewed publications (reports, briefs, books, articles targeting policy-makers, industry or other end users)
   - The scientific output of AEGIR was presented at the European SOFC & SOE Forum 2022, Lucerne (non-peer review proceedings), authors: A. Hagen, R. Caldogno, X. Sun.
3) Media coverage (opinion pieces or interviews/appearances in all types of mass media)

The AEGIR project has a homepage (https://www.aegir-project.net/) and a brochure presenting the overall concept. Large focus has been on the public communication, such as via LinkedIn (https://www.linkedin.com/feed/update/urn:li:activity:6866283425385517057) and articles on the homepages of the involved partners (e.g., https://www.sintef.no/siste-nytt/2021/ammoniakk-pa-skipstanken-kan-gi-stor-gevinst-ogsa-for-miljoet).

- Homepage: https://www.aegir-project.net/
- Post abut project start on LinkedIn: https://www.linkedin.com/posts/anke-hagen-035448198_aegir-project-started-to-make-international-activity-6789903960632254464--HeF
- Article posted on SINTEFs website: https://www.sintef.no/siste-nytt/2021/ammoniakk-pa-skipstanken-kan-gi-stor-gevinst-ogsa-for-miljoet/
- Article about AEGIR on a Norwegian science website: "Ammoniakk på skipstanken kan gi stor gevinst – også for miljøet", https://gemini.no/2021/04/ammoniakk-pa-skipstanken-kan-gi-stor-gevinst-ogsa-for-miljoet/
- Article in Fathomworld: " THREE NORDIC RESEARCH CONSORTIA WILL TEST THE USE OF AMMONIA AND HYDROGEN AS FUEL FOR SHIPS", https://fathom.world/three-nordic-research-consortia-will-test-the-use-of-ammonia-and-hydrogen-as-fuel-for-ships/
- Article in Safety4sea: "Norwegian project eyes cost reduction of ammonia as shipping fuel", https://safety4sea.com/norwegian-project-eyes-cost-reduction-of-ammonia-as-shipping-fuel/
- Post on the Nordic Energy Research homepage: "AEGIR in support of cutting greenhouse emissions in the maritime sector", https://www.nordicenergy.org/article/aegir-in-support-of-cutting-greenhouse-emissions-in-the-maritime-sector/
- Post on LinkedIn referring to the post on the Nordic Energy Research homepage, https://www.linkedin.com/feed/update/urn:li:activity:6866283425385517057/
- Ammonia in maritime sector: integrated in DTU PhD Course: Sustainable Fuels
- Post on LinkedIn about participation at workshop organized by the Nordic Energy Research in Malmö, involving AEGIR, CAHEMA & HIOPE https://www.linkedin.com/in/anke-hagen-035448198/recent-activity/
- Post on LinkedIn about technical presentation at Industrial Hannover Fair, Hydrogen & Fuel Cells exhibition 2022, https://www.linkedin.com/in/anke-hagen-035448198/recent-activity/
- Post on LinkedIn about the Public Forum at Industrial Hannover Fair, Hydrogen & Fuel Cells exhibition 2023,
- https://www.linkedin.com/in/anke-hagen-035448198/recent-activity/
- Post on LinkedIn about our appearance at the Nordic Mari□me Transport and Energy Research Programme Conference in Malmö 2023
- https://www.linkedin.com/in/anke-hagen-035448198/recent-activity/

4) Events targeting end users organised by the project (such as conferences, side events or workshops)

AEGIR Webinar "Ammonia in research projects - challenges and learning points from the AEGIR project", including presentations: https://www.aegir-project.net/news/nyhed?id=80b58f0f-decd-4293-a622-8eb18e592f8c

5) Presentations targeting end users given by project participants (including participation in panel debates)

Event industrial fair: AEGIR was presented by the coordinator Anke Hagen (DTU) at the Hannover Fair, which is the world's leading trade fair for industry, in the Fuel Cell and Hydrogen Exhibition at the

i. Technical Form (left picture), May/June 2022 and
ii. Public Forum (right picture), April 2023, with more than 100 attendants on site (plus streaming option).

Event workshop: Ammonia and hydrogen as maritime fuels by the Nordic Maritime Transport and Energy Research Programme, presentation by

i. Anke Hagen (DTU): Use of ammonia as fuel in fuel cells in maritime frameworks and
ii. Riccardo Caldogno: SOFC performances and durability with NH3 as fuel, Malmö, April 2022 (Colleagues Christina from Ballard Power Systems Europe and Riccardo & Anke from DTU, left picture)

Event conference: The Nordic Maritime Transport and Energy Research Programme, presentation by Anke Hagen (DTU):

i. Ammonia electric marine power for GHG emission reduction - AEGIR and
ii. Ammonia for fuel cells in the shipping sector, challenges and results of the AEGIR project, Malmö, May 2023 (Colleagues Christina from Ballard Power Systems Europe and Xiufu & Anke from DTU right picture).

Event workshop: Industry-academia follow-up workshop on green transition in ports and city-port relations by the Maritime Research Alliance, presentation by Michael Bruhn Barfod (DTU): Recent research highlights for decarbonizing shipping, Port of Aarhus, 24/5-2023.

6) Other disseminations

Student education: The AEGIR concept was integrated into formal student education by Anke Hagen (DTU), such as the

i. PhD course “Sustainable fuels and chemicals” at DTU and
ii. PhD course “Introduction to SOFC & SOEC” (in the frame of the annual, international Joint European Summer School on Fuel Cell, Electrolyser, and Battery Technology) in Greece.

6. Utilisation of project results

AEGIR investigated ammonia as source for hydrogen, which then can be used as fuel, e.g. for the shipping sector using mature PEMFC technology. Thus, the **commercial potential** is closely connected to the potential of using hydrogen.

- Clean energy production: Hydrogen is considered a clean fuel as it produces only water when burned, making it an attractive option for reducing greenhouse gas emissions. Electrolysis Assisted Hydrogen (EAH) concept can provide a means of producing hydrogen cleanly and efficiently.
- Transportation fuel: Hydrogen has the potential to power a range of vehicles, including cars, trucks, and buses. EAH concepts can produce hydrogen that can be used as a fuel for these vehicles, reducing dependence on fossil fuels and lowering emissions.
- Energy storage: Hydrogen can be used as a means of storing energy generated from renewable sources such as solar or wind power. EAH concepts can produce hydrogen that can be stored and later used to generate electricity when needed.

- Industrial applications: Hydrogen is widely used in industrial processes such as chemical manufacturing and refining. EAH concepts can provide a means of producing hydrogen for these applications in a more environmentally friendly way.

Overall, EAH concepts have the potential to contribute to a more sustainable energy future by providing a clean and versatile route to hydrogen.

The **hydrogen fuel cell market** is still in its early stages, but it is expected to grow rapidly in the coming years. Currently, there are several players operating in the market (PEMFC and SOFC), including:

1. Plug Power Inc.: A US-based company that provides hydrogen fuel cell solutions for forklifts, stationary power, and on-road applications.
2. Toyota Motor Corporation: A Japanese multinational automotive manufacturer that has invested heavily in fuel cell technology and offers the Mirai fuel cell vehicle.
3. Hyundai Motor Company: A South Korean multinational automotive manufacturer that offers the Nexo fuel cell vehicle.
4. General Motors: An American multinational corporation that is developing fuel cell technology for use in transportation and other applications.
5. BMW AG: A German multinational corporation that has developed a fuel cell vehicle, the BMW i Hydrogen NEXT.
6. Daimler AG: A German multinational automotive corporation that has developed fuel cell vehicles, including the Mercedes-Benz GLC F-CELL.
7. Honda Motor Co., Ltd.: A Japanese multinational corporation that has developed fuel cell vehicles, including the Clarity Fuel Cell.
8. Cummins Inc.: An American multinational corporation that develops and manufactures power solutions, including fuel cell systems for commercial and industrial applications.
9. Bloom Energy: A US-based company that provides solid oxide fuel cell solutions for stationary power applications.

There are also several other companies and startups that are developing fuel cell technology and products for various applications. The competitive landscape of the hydrogen fuel cell market is expected to become more crowded as more companies enter the space and existing players expand their offerings.

Ammonia-to-hydrogen projects can contribute to **energy policy objectives** in several ways:

1. Carbon Reduction: Ammonia production is currently a significant contributor to global carbon emissions. However, if ammonia can be produced using renewable energy sources such as wind or solar power, it could significantly reduce carbon emissions. Additionally, if the hydrogen produced from ammonia is used as fuel for transportation or electricity generation, it could further reduce carbon emissions.
2. Energy Storage: Hydrogen produced from ammonia can be used for energy storage. This is particularly useful for storing renewable energy, such as wind or solar power, which can be intermittent. Hydrogen can be stored and used when needed to balance the electricity grid or supply power during peak demand.
3. Transportation: Hydrogen produced from ammonia can be used as a fuel for transportation, particularly in fuel cell vehicles, shipping, etc. This could reduce reliance on fossil fuels and contribute to energy security objectives.

4. Regional Energy Security: Ammonia-to-hydrogen projects could help to increase regional energy security by reducing dependence on imported energy sources. This is particularly relevant for countries that do not have significant domestic fossil fuel resources.

In summary, ammonia-to-hydrogen projects can contribute to energy policy objectives by reducing carbon emissions, providing energy storage, enabling clean transportation, and increasing energy security.

7. Project conclusion and perspective

The AEGIR project demonstrated the large potential related to electrical efficiency and reduction of greenhouse gas emissions from the shipping sector, when using green ammonia as fuel integrated with fuel cells. System efficiencies >60% and 90% GHG emission reductions compared to SoA LNG fuel are possible.

From a technology point of view, AEGIR demonstrated that ca. 100% ammonia cracking occurs over a solid oxide fuel cell and that no additional degradation occurs at single cell level provided the optimum operating conditions are applied, more specifically, temperatures above ca. 750 ^{o}C. Increased degradation of stack components arises at too low operating temperatures below ca. 700 ^{o}C through nitridation. Thus, a safe operating window for the SOFC unit needs to be kept. For the PEMFC, an efficient cleaning of the gas and removal of traces of ammonia, for example by the highly selective PCEMR that tolerates ammonia, are critical.

AEGIR provided knowledge for future development of a ship propulsion technology based on ammonia fuel, both from a system point of view (such as costs for the system that are in the range of other green solutions for the maritime sector) and a technical point of view (such as the importance of a safe operating window).

Scaling of the technologies is a key for implementation into the shipping sector. A solution towards multi megawatts PEMFC is development of modular concepts.

8. Appendices

- Aegir homepage: https://www.aegir-project.net/
- Brochure presenting the AEGIR concept & project
- AEGIR Webinar "Ammonia in research projects - challenges and learning points from the AEGIR project", including presentations: https://www.aegir-project.net/news/nyhed?id=80b58f0f-decd-4293-a622-8eb18e592f8c
- LinkedIn post about the AEGIR project: https://www.linkedin.com/feed/update/urn:li:activity:6866283425385517057)
- LinkedIn post about the AEGIR presentation at the Hannover Fair 2022: https://www.linkedin.com/posts/anke-hagen-035448198_amazing-interest-in-ammonia-i-presented-activity-6937715118092775424-AwVs?utm_source=share&utm_medium=member_desktop
- LinkedIn post about the AEGIR Webinar "Ammonia in research projects - challenges and learning points from the AEGIR project": https://www.linkedin.com/posts/anke-hagen-035448198_ammonia-in-research-projects-challenges-activity-7034810777748303872-SgYc?utm_source=share&utm_medium=member_desktop
- Presentation "Use of ammonia as fuel in fuel cells in maritime frameworks" at the workshop "Nordic Maritime Transport and Energy Research Programme - Ammonia and Hydrogen for Ships" (A. Hagen): https://www.nordicenergy.org/wordpress/wp-content/uploads/2022/05/AEGIR.pdf

- LinkedIn post about the AEGIR presentation at the Hannover Fair 2023: (20) Activity | Anke Hagen | LinkedIn
- Presentation "Ammonia for fuel cells in the shipping sector, challenges and results of the AEGIR project" and "Ammonia electric marine power for GHG emission reduction - AEGIR" (A. Hagen) at The Nordic Maritime Transport and Energy Research Programme Conference in Malmö 2023: The Nordic Maritime Transport and Energy Research Programme Conference – Nordic Energy Research