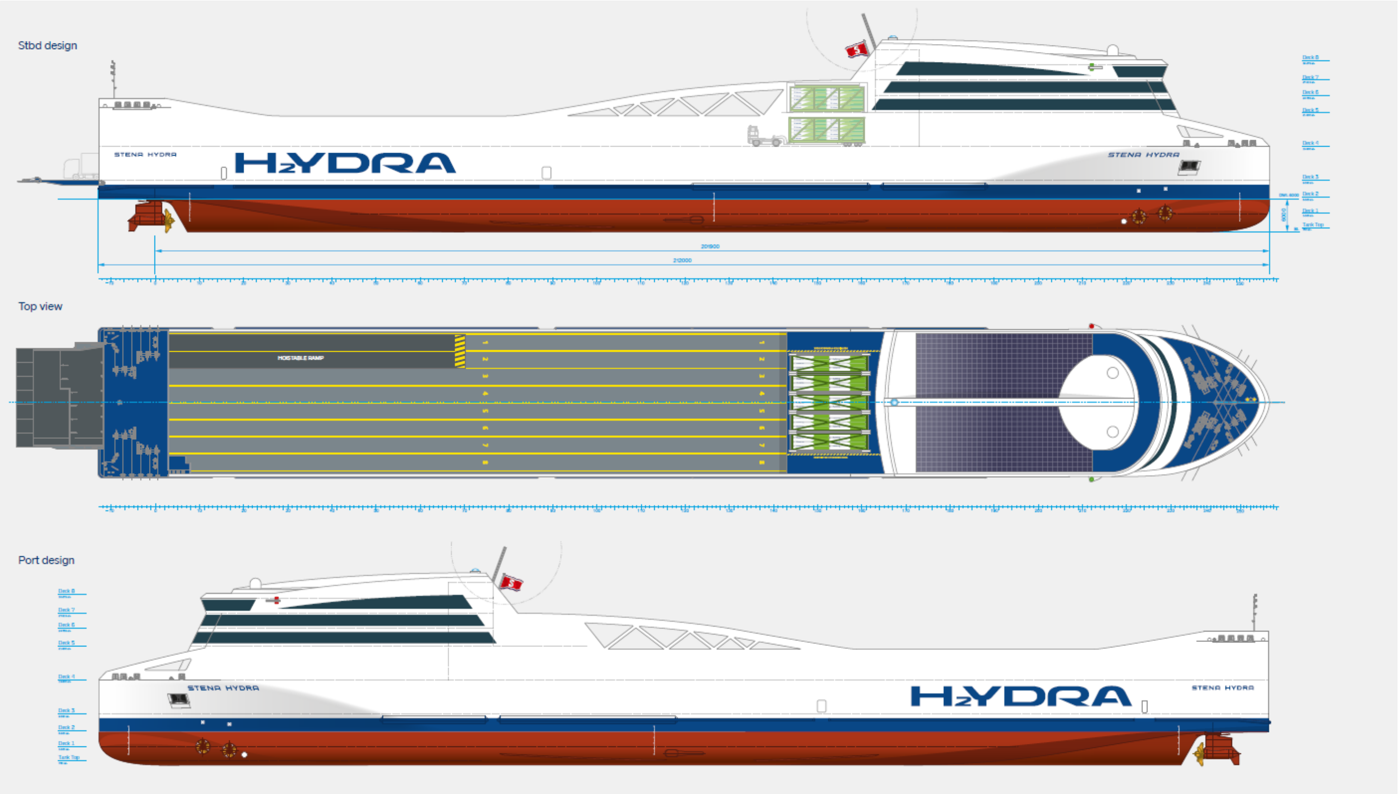

HOPE - Hydrogen fuel cells solutions in Nordic shipping

Project summary

A Nordic Maritime Transport and Energy Research Programme Project
June 2023

Swedish Environmental
Research Institute

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In cooperation with: Sintef Ocean AS, University of Iceland, Stena Rederi AB, PowerCell Sweden AB
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HOPE Key findings

To decarbonize maritime transport is one of the key issues in the Nordic region to become carbon-neutral. The introduction of alternative marine fuels is crucial for decarbonizing the Nordic shipping sector. The HOPE project has investigated different pathways with emphasis on the use of hydrogen in fuel cells. Here are some of the main findings:

- Marine biofuels (primarily biodiesel and methanol), renewable methane as well as compressed hydrogen are indicated to represent cost-effective mitigation measures in the Nordic shipping sector both in the mid (2030) and long term (2050) for different GHG reduction pathways.

- Emissions of air pollutants and greenhouse gases will decrease significantly upon an implementation of hydrogen as fuel in Nordic shipping. There is a considerable potential for emission reductions both in terms of carbon dioxide (CO_2), nitrogen oxides (NOx) and particulate matter (PM) linked to the implementation of hydrogen and fuel cells in Nordic shipping, particularly in the RoPax segment representing ferries transporting passengers and goods.

- In terms of cost, the base case estimation indicates that a hydrogen in fuel cell driven RoPax ship will be more costly in a total cost of ownership perspective than for example running a conventional RoPax ship on marine gas oil (MGO) or liquefied natural gas (LNG) with conventional marine diesel engines. The future cost of the hydrogen fuel cell options depends mainly on the cost of hydrogen, the price of fuel cells (which also will affect the cost for replacement of degraded fuel cells) and the price of emission allowances within EU ETS, which all represent uncertain parameters. There are situations where the hydrogen fuel cell option reaches lower total annual cost of ownership than the conventional MGO-fueled ship.

- The energy density of hydrogen is very low, especially when considering the bulky storage onboard. Thus, significant operational adaption is required to utilize hydrogen as fuel in a RoPax vessel. Hydrogen can be stored in gaseous form in pressure cylinders or as a liquid in cryogenic storage tanks. Ships running on hydrogen will be dedicated to defined routes with limited operational range. Bunkering of liquid hydrogen is challenging and time consuming and short turning time of ships in ports makes available bunkering time to short. Compressed hydrogen can be bunkered by swapping compressed hydrogen containers and is proposed as the potential storage solution for a case RoPax vessel studied in HOPE. Detailed solution and swapping procedures must be developed as well as the logistics of such an operation.

- Energy converters for hydrogen could be proton-exchange membrane fuel cells (PEMFCs) or internal combustion engines (ICE). Both technologies are in a demonstration phase with TRL level 5-6 for ICE and 6-7 for PEMFC. The PEMFC is offered in demonstration project in the MW range and could be scaled up to meet power demand in a RoPax vessel. Rules and regulations linked to hydrogen as marine fuels are not yet in place, and safety issues are of concern and need further clarification.

- A variety of drivers motivate shipping companies to investigate the adoption of green hydrogen and fuel cells. The most relevant include environmental commitments along with existing and upcoming policies and regulations. A variety of barriers limit the adoption of green hydrogen and fuel cells for shipping. The main barriers are the high costs of the fuel/technology, the lack of fuel infrastructure, the lack of supply of green hydrogen, and the operational challenges for handling hydrogen (mainly in storage and bunkering). The uncertainty and high risks of using this fuel and technology are also significant barriers for early movers.

The policy recommendations from the HOPE project include:

- Decarbonization of ferry routes between the Nordic countries should be promoted due to the associated benefits in terms of reduced emissions.

- A Nordic/regional approach is needed to accelerate the transition toward low and zero-emission shipping. Coordination between the countries, also in terms of policies, will be crucial to avoid fuel/technology silos. A Nordic roadmap with binding commitments for the transition toward low and zero-emission shipping would be key to guarantee that the industries of the Nordic countries move at a similar pace and to avoid delays in the transition of the Nordic shipping industry.

- Economic and regulatory policies are needed to reduce the barriers and to accelerate the adoption of hydrogen and hydrogen for fuel cells for shipping. Economic measures should include higher carbon taxes, higher taxes on fossil fuels, and the inclusion of also vessels under 5000 gross tonnages in the EU emission trading scheme (ETS). Incomes from such policies could be used to support early movers investing in renewable fuel and propulsion systems for regional shipping as in the Nordic region. Policies should also be designed with a systemic view that considers cross-sector and cross-industry factors.

- There is a need for public economic support at a sufficient level to bridge the cost difference between fossil and renewable solutions for the Nordic shipping sector. Pilot projects are needed to increase technical maturity and bring costs down. The society also need to acknowledge and handle the high risks and high costs for first mover actors in the shipping sector.

- Regulatory measures could include a ban on fossil fuels and a mandate for zero-emission vessels for specific segments (e.g., for the ferry segment).

- A promotion of renewable hydrogen-based fuels for shipping will contribute to the development of the hydrogen society in the Nordic countries.

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1 HOPE in short

The Nordic countries aim for a carbon-neutral Nordic region. Maritime transport is one of the key remaining sectors to decarbonize and is important from a Nordic perspective due to the relatively large Nordic involvement in this industry.

The HOPE project addresses how regional shipping in the Nordic region can do the transition to become fossil-free. The project aims at clarifying the potential role of hydrogen based marine solutions in reducing the Nordic greenhouse gas (GHG) emissions. In the centre of the project is a ship concept where a typical RoPax-vessel with operating distances of around 100 nautical miles is designed for including operation with hydrogen as fuel and fuel cells for energy conversion. The overall design of the concept ship is compared with selected other fuel alternatives from a cost perspective.

Further, both the conditions for designing such a ship and the consequences are studied. The conditions include technical design and costs of fuel systems and handling, powertrains etc. but also an analysis of barriers and drivers for the realisation of hydrogen solutions for shipping, such as economic, legal, and policy issues. For example, in terms of drivers, policy options needed to accelerate the uptake of hydrogen based marine solutions are assessed. Strategies and the potential of producing these fuels in the Nordic region are also reviewed from a shipping perspective. A realistic potential for uptake of these technologies/fuels by Nordic shipping are assessed and the benefits regarding lower emissions of GHGs and air pollutants are estimated.

The project partners involved in the HOPE project are:

- IVL Swedish Environmental Research Institute
- SINTEF Ocean AS
- University of Iceland
- Stena Rederi AB
- PowerCell Sweden AB

In addition, the 2030 Secretariat (2030 Sekretariatet) has supported communication activities. The work has been divided into six work packages with different but interacting tasks involving various project partners (**Figure** 1). This report summarizes the assessments made in the HOPE project including main findings. A policy brief on drivers and barriers are also included. More information regarding the HOPE project can be found at https://www.nordicenergy.org/project/hope/ or https://www.ivl.se/projektwebbar/hope.html or by contacting project manager Julia Hansson at julia.hansson@ivl.se.

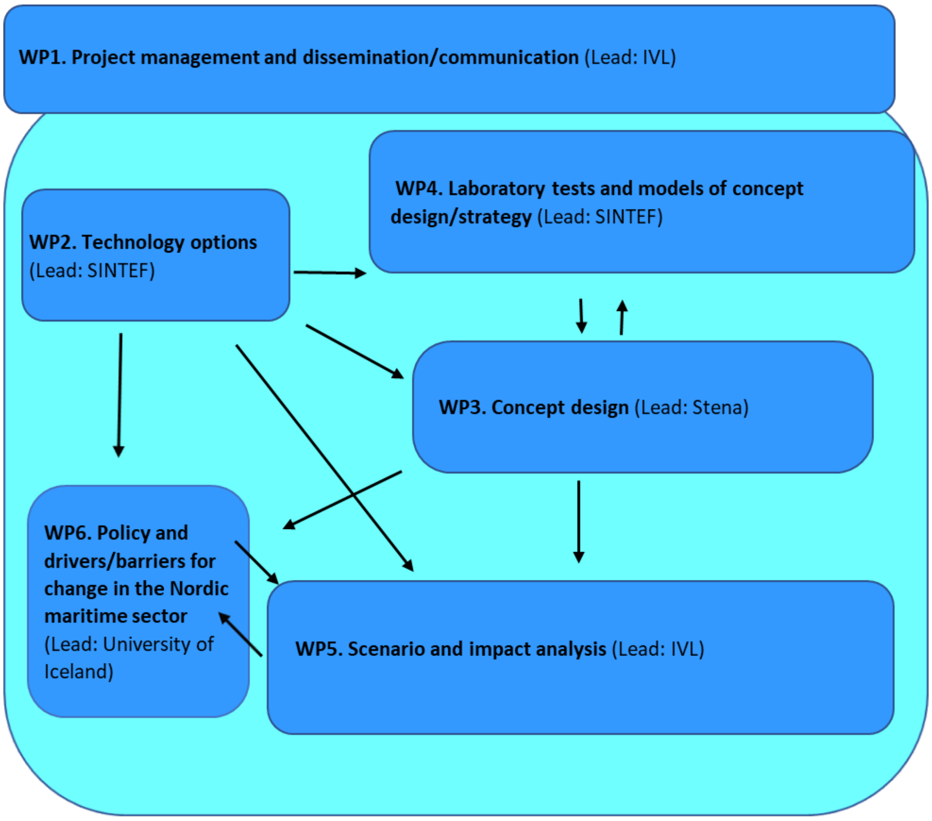


***Figure** 1. Outline of the "HOPE" project and the work packages included.*

The HOPE project is supported by Nordic Energy Research, the Norwegian Research Council, the Swedish Transport Administration, the Icelandic Research Center, BusinessFinland, the Danish Energy Agency, and in-kind contributions from companies and 2030-sekretariatet, for which we are very grateful. The opinions expressed in this report do not represent the funders official positions but are entirely attributable to the authors.

1.1 Project objectives

The overall aim of the HOPE project is to analyse options for CO_2 neutral marine fuels and powertrains/propulsion technologies from a Nordic perspective and to contribute with scientifically based decision support for the choice of low and/or zero carbon marine fuels to industry, policy makers and other actors in the Nordic region but also globally.

More specifically, HOPE assesses the potential role for hydrogen and fuel cell solutions for decarbonizing the Nordic shipping sector in relation to other low or zero carbon fuel solutions by including technology evaluation and impact assessment coveringoperational, environmental, economic and policy aspects. The main targets are to:

- Develop and assess a concept design of a ship using hydrogen and fuel cells for propulsion based on a specific case study and compare that with other low-carbon options,
- Perform modelling tests for evaluating the developed concept design/strategy,
- Assess impact and potential uptake in a Nordic perspective including scenarios, costs, and emissions, focusing on short-sea shipping between the Nordic countries,
- Assess drivers and barriers for increasing uptake of hydrogen and fuel cells in the Nordic maritime sector and assess policy options for enabling the transition.

The overall communication and dissemination aim is to contribute to strengthened cooperation and sharing of knowledge between stakeholders in the Nordic region linked to hydrogen and fuel cell solutions to further strengthen and demonstrate Nordic leadership in decarbonizing the shipping sector.

2 Marine technology options from a Nordic perspective

In WP2, fuel and propulsion technology options have been reviewed and the assessment has provided input to the other assessments in the project. Assessments of low carbon fuels, powertrains, fuel handling and storage options and fuel production from a Nordic perspective are included.

2.1 Motivation/Challenge

Decarbonizing marine transport is a huge challenge for the marine industry, and hydrogen options are under development to meet future environmental requirements. This development challenges the technology providers and commercial technologies are not in place. The fuel cell (FC) solution for marine application developed by PowerCell, and mainly in focus in this project, is at technology readiness level (TRL) 6-7 (technology being demonstrated in marine environment and concepts tested in marine operation). Other hydrogen FC solutions, e.g., solid oxide fuel cells (SOFC), for marine applications are at TRL 3-4. Hydrogen in internal combustion engines (ICEs) for marine application are around TRL 5-6 (generally not demonstrated). For ammonia in marine application development projects are under way. The TRL for ammonia fuelled FCs and ICEs is 4-5. There is a need for more knowledge on the potential for FCs and other propulsion solutions for regional shipping in the Nordic region.

2.2 Our contribution/assessments

The shipowner dilemma is illustrated in Figure 2; fuel choice, fuel availability and technology maturity. In WP2, state of the art for alternative marine fuels are outlined with focus is on hydrogen, but also other low fossil carbon fuels as ammonia, methanol and biofuels including biomethane are discussed. To evaluate hydrogen as fuel, a case ship to serve the Gothenburg – Frederikshavn route has been defined and operational requirements form the basis for evaluation of fuel storage system and power trains on board.

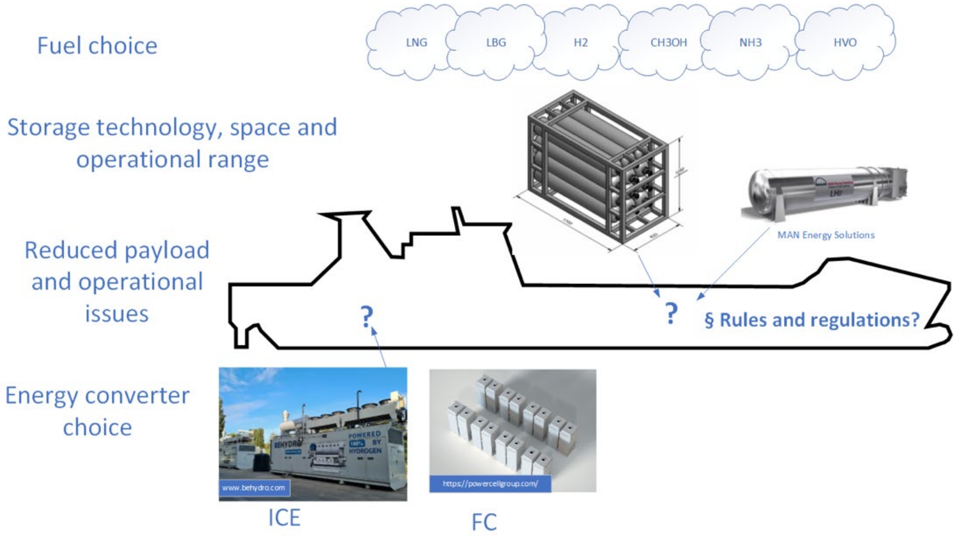


Figure 2. Shipowners' dilemma- Fuel choice and technology availability to reduce GHG emissions.

Gaseous and liquid hydrogen storage systems are benchmarked with other low carbon fuels related to storage volumes and arrangement with focus on parameters such as energy density, physical and chemical properties and safety issues and linked to operational profile and operational range of the ship (Stenersen and Lundström, 2023). Alternative power trains for hydrogen as fuel are also assessed; FC systems, conventional ICEs and marine battery systems are addressed. Special focus is on Proton-exchange membrane fuel cells (PEMFC) fuelled with hydrogen.

A separate activity has been to evaluate fuel availability from a shipping perspective and give an overview of plans for production of renewable hydrogen and ammonia in the Nordic countries (Stenersen and Lundström, 2023).

2.3 Main findings and recommendations

The energy density and chemical properties of alternative low/zero carbon fuels (Figure 3) are essential for ship design and have large influence on main dimensions, safety issues and operational aspects as fuel storage capacity and bunkering. Hydrogen as fuel is probably the most challenging of all alternatives with very low energy density when including storage system and special safety concerns which need to be handled.

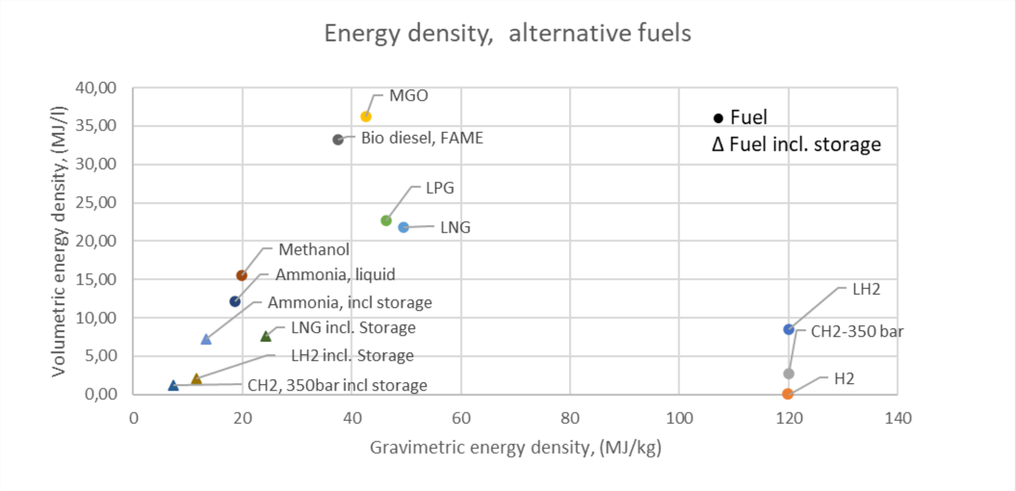


Figure 3. Energy density of alternative fuels and effects of storage tanks for cryogenic or compressed fuels.

Due to the properties of hydrogen the ship owner must accept reduced load capacity and endurance compared to traditional fuels as marine gas oil (MGO), which may be important economic factors from a ship owners' perspective.

There are several technology options to utilize hydrogen as main fuel in a large ship. Energy storage systems on board and energy converters are perhaps the most crucial. For the case ship evaluated in this project the hydrogen storage capacity was estimated to 10 tons, giving an operational range of approximately 150 nautical miles (nm). Hydrogen could be stored in compressed or liquid form. Core technology for such storage is available from several suppliers, but marinization of the technology is required including special systems for efficient bunkering within the operational time limit which apply for the ship type in concern. PEMFC and/or hydrogen fuelled ICE are the options for energy converters. PEMFC has been demonstrated in marine application for smaller ships and lower power. Typically, PEMFC modules have a power range of a few 100 kW but are scalable to the MW-range by connecting multiple single modules into a larger power system. Hydrogen fuelled ICE is planned to be demonstrated in commercial ships in 2023 and is so far offered by one supplier in a power range from 1000-2600 kW.

The technology assessment of hydrogen as fuel for larger ship with high power demand can be summarized as follows:

- Energy density of hydrogen including storage is very low. Significant operational adaption is required to utilize hydrogen as fuel in a RoPax

vessel. Hydrogen can be stored in gaseous or liquid form in pressure cylinders or cryogenic storage tanks.
- To obtain reduction in GHG emissions hydrogen needs to be produced from renewable energy and/or with carbon capture technology. Green hydrogen is not available for the shipping sector today.
- The energy demand for production of hydrogen as fuel today is significantly higher than for fossil energy sources.
- H_2/FC ships will be dedicated to defined routes with limited operational range.
- Bunkering of liquid hydrogen is challenging and time consuming. Short turning times make available bunkering time too limited for liquid hydrogen bunkering.
- Compressed hydrogen can be bunkered by swapping compressed hydrogen containers and is proposed as a potential storage solution. Detailed solutions and swapping procedures must be developed as well as the logistics of such operations.
- Energy converters could be either PEMFC or hydrogen fuelled ICE. Both technologies are in demonstration phase with TRL level 5-6 for ICE and 6-7 for PEMFC.
- PEMFC is offered in demonstration project in the MW range and could be scaled up to meet power demand in a RoPax vessel. PEMFC comes with high initial efficiency but suffer from operational degradation and FC stacks must be changed/refurnished during the lifetime of the ship. The maintenance cost is significantly higher than for ICE.
- Hydrogen fuelled ICEs are launched by one supplier and offered in demonstration projects.
- Rules and regulations are not in place, and safety issues is of concern and regulations need further development.

Economic factors are identified as one of the main barriers for adaption of hydrogen fuelled ships (see more in Section 6). This applies to investments and operational costs. Technology risk and safety issues are other important barriers which need to be resolved.

2.4 Publications

The main publication of this work package is:

Stenersen, D., Lundström, H., 2023. WP2 – Propulsion technology options for alternative marine fuels. SINTEF Ocean report OC2022-F109, D2023-03-01. Available at: https://www.ivl.se/projektwebbar/hope.html

3 Concept design of the case vessel

In WP3 a concept ship has been designed for ship propulsion by a fuel cell fuelled by hydrogen. The review and assessments in Stenersen and Lundström (2023), from WP2, have been used to design the components and features of the ship. The ship has been modelled on an earlier Stena concept design for the RoPax ship Elektra, using Rise and Chalmers (2021) as well as other internal Stena design concept studies for RoPax ships with battery electric operations. There have also been close interactions with the work conducted in WP4 which, for example, has provided energy consumption figures.

3.1 Motivation/Challenge

Hydrogen fuelled ships and fuel cells used on-board ships represent a potential zero emission technology and represent a potentially interesting concept in terms of total energy efficiency in a system perspective. The performance in terms of total costs of ownership in a long-term perspective when the technology has developed further is however uncertain. Therefore, lots of efforts is still needed and many feasibility studies, design optimisation projects and real pilot projects need to be conducted, to leverage on this potential. Therefore, this project, in line with other projects is much needed to contribute, step by step, so that hydrogen fuel cells can become an established technology, as one of many solutions, needed to achieve the targets of zero emissions from shipping in the future.

3.2 Our contribution/assessments

The ship concept design has been delivered in terms of general arrangement drawings of the ship (see Figure 4), general descriptions of propulsion systems and a brief discussion in relation to some of the technical choices. The ship concept design is based on the initial project findings and includes assumptions on needed energy storage and the concept was also developed for both compressed and liquid hydrogen storage. The chosen system on which the economical calculations has been based has been compressed hydrogen, stored, and handled in ISO container, where empty containers will be replaced with full ones during the one-hour port stay, stored on-board on weather deck.

The ship concept design has also been compared with alternative solutions for similar vessel design with other propulsion solutions such as fully battery electric, electro-ammonia, electro-methanol, biogas (LBG), fossil methane (LNG) and conventional fossil marine gas oil (MGO). The comparisons have focused on total costs of ownership, as annual costs, running the ferry operations over a lifetime. Included in the cost calculations are also the performance of the different solutions in terms of CO_2 emissions which is the basis for cost calculations for carbon emission allowances within the EU Emission Trading System EU ETS.

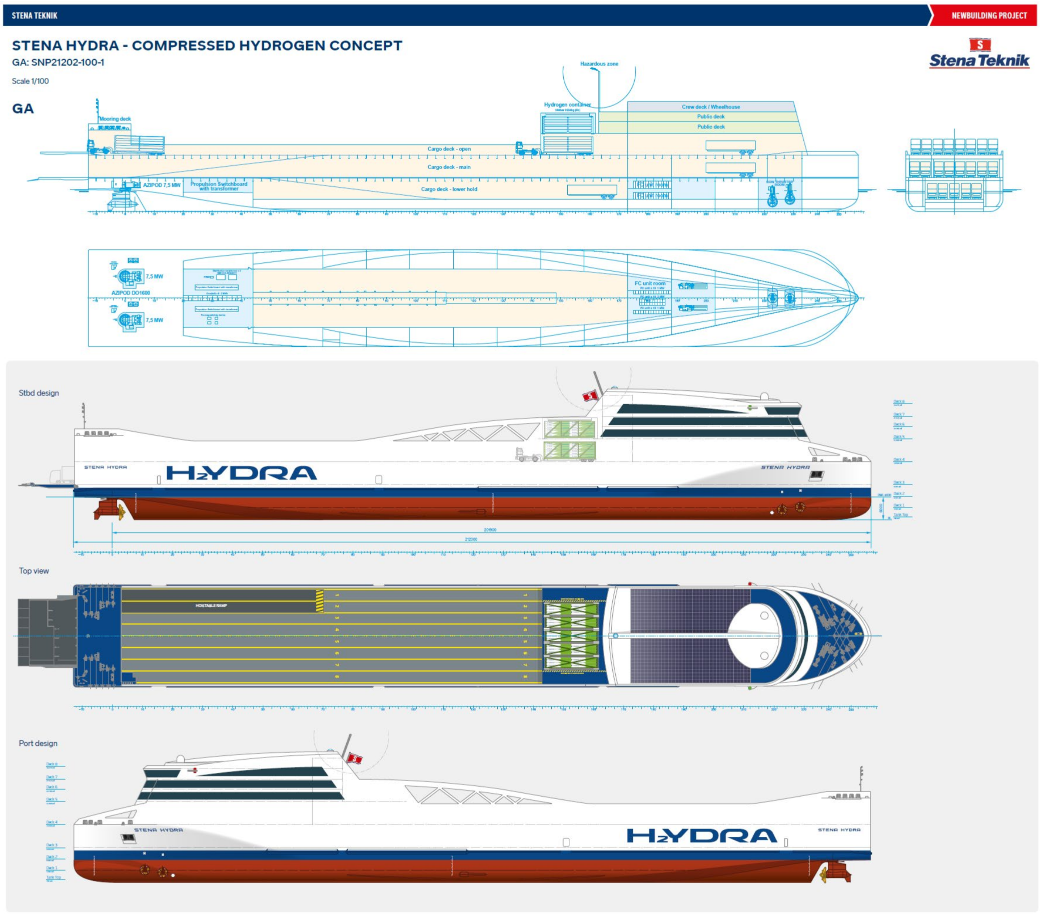


Figure 4. General arrangement drawing of the hydrogen concept Stena H2YDRA.

The total power need, propulsion economy as well as route performance for the operations of the vessel in a roundtrip perspective are estimated within WP4 of the project for different installed fuel cell capacities. The chosen capacity for fuel cell installation for the ship concept calculations has been 25 MW, hence the lowest roundtrip propulsion costs were estimated for that size of the installation. Assumed size of electrical engines for the propulsion has been in total 20 MW.

The experience of Stena Teknik, in terms of cost estimation for the building, manning and operation of RoPax vessels on the specific route, has been used for the cost estimates for building and operating the case study vessel. Total operating costs estimates consist of energy costs, ship costs excluding propulsion system, main propulsion costs, installed battery systems, installed auxiliary systems (also for the use of backup/range extension), hydrogen container swap system costs (for hydrogen vessel only), electricity charging system (for battery-electric ship only) and manning.

The focus has been on estimating and performing sensitivity analyses for the hydrogen fuelled fuel cell ship. However, to understand if the concept vessel performance can be seen as competitive towards other fuel solutions, also comparative calculations for other concepts have been made.

More detailed descriptions of the results and basis for the assessments in WP3 are available in Hansson et al. (2023), Stenersen and Lundström (2023), and Yum and Stenersen (forthcoming).

3.3 Main findings and recommendations

The base case estimation indicates that a hydrogen in fuel cell driven RoPax ship will be more costly from a total cost of ownership perspective than for example running a conventional RoPax ship on MGO or LNG with conventional marine diesel engines. In total, measured in annual costs, the hydrogen fuel cell fuelled ship is estimated to be 40 percentage more costly, excluding EU ETS costs, respectively 25 percentage more costly with EU ETS costs taken into consideration, using an expected cost of 100€ per tonne CO_2. In monetary terms, the hydrogen fuel cell ship will increase annual costs with almost 11 MEUR per year compared to the conventional fossil fuelled ship excluding EU ETS allowance costs. However, in case cost linked to the EU ETS are included, the hydrogen fuel cell ship will increase annual costs with about 7.5 MEUR per year compared to the conventional fossil fuelled ship, see Figure 5.

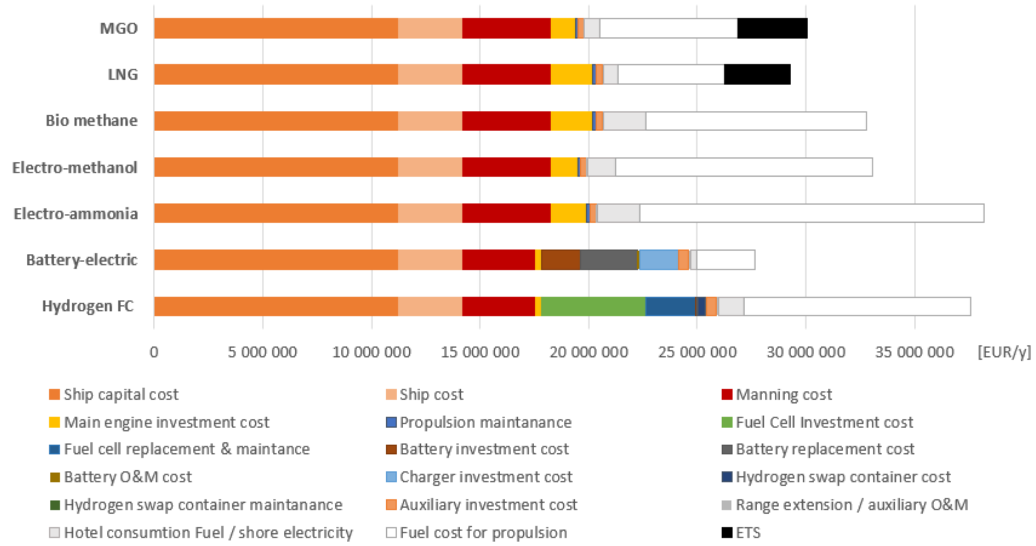


Figure 5. Estimated total annual costs for running each of the six concept ships in the base case (total cost of ownership). The costs are divided into investments and operational costs related to the ship construction, maintenance, operations, propulsion, energy, and emission allowances within EU ETS. The presented cost estimations shall be seen as an indication based on cost assumptions for each ship concept.

Due to the large uncertainties in relation to cost parameters a sensitivity analyses have been made. The focus has been on parameters that have a large impact on total cost of ownership in relation to the hydrogen fuelled ship and that is likely to develop over time including the:

- cost of hydrogen,
- price of fuel cells/capital cost (investment) which also will affect the cost for replacement of degraded fuel cells,
- price of emission allowances within EU ETS.

The results for the case where the hydrogen cost is assumed to be reduced by 25 percentage compared to the base case, the fuel cell price is assumed to be halved (with maintenance and replacement cost being reduced by 25%) and the cost for emission allowances in the EU ETS is assumed to increase by 200% compared to the base case (i.e., reaching 200 EURO/ton CO_2), are shown in Figure 6. This specific combination of potential future cost alternations results in a fuel cell ship with 5 percentage lower annual cost of ownership than the conventional fuelled MGO ship or some 1.5 MEUR lower annual costs.

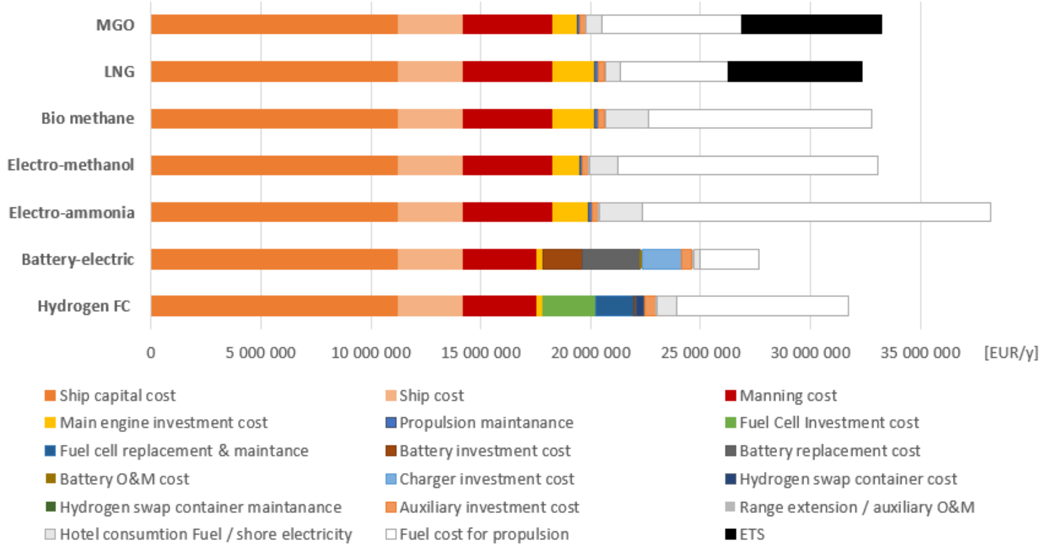


Figure 6. Estimated total annual cost of ownership for operating the six concept ships for the sensitivity analysis assuming 25% lower hydrogen cost than in the base case, halved fuel cell costs compared to the base case, 25% lower cost for maintenance of the fuel cells including replacement due to degradation over time and with 200% higher costs for carbon emission allowances in the EU ETS compared to the base case cost.

Another aspect linked to pilot installations that has not been analysed quantitatively within this project but that may be important is the risk for unexpected costs connected to first projects for technology that is less mature and not so widespread. This is a potential risk for the first movers which can represents a substantial hinder for the development. Such potential risks can be everything from delays connected to getting all permits in place, delays related to technology failures, risks for cost increases for the technology, the fuel or additional safety measures that might restrict the operations or any other obstacles that might be difficult to foresee or estimate on forehand. All the different ship concepts studied include potential risks connected to the maturity of the technology. However, methanol or biogas fuelled ships have potentially a lower such risks than hydrogen and fuel cells, ammonia, or battery-electric propulsion.

3.4 Publications

The main publication of this work package includes a project report:

Hansson J., Jivén K., Lundström H., Parsmo R., Fridell E., Wimby P., Burgren J., 2023. *Concept design and scenario and impact analysis in HOPE – Hydrogen fuel cells solutions in Nordic shipping. Report from WP3 and WP5 in the HOPE project*, Available at: https://www.ivl.se/projektwebbar/hope.html

4 Tests and models of concept design

The main objective of WP4 is to develop a methodology and models to evaluate and test the concept design of a vessel with hydrogen fuel cells as a main power source. The methodology should be holistic to entail all the operational perspectives for the vessel so that it may lead to the total cost of ownership as a key performance indicator. The method was applied using the case vessel developed in WP3 to acquire a realistic performance and fuel consumption of the vessel for one year of operation and the output is used as input in WP5.

4.1 Motivation/Challenge

Using hydrogen as fuel on a ship imposes several challenges. The first challenge is to store it onboard as it has very low volumetric density as described in Section 3. It should be stored either in a liquid from at -252 °C or in a gas from at high pressure of 250~500 bar to increase the density and storage comes with high cost of installation. It is, therefore, crucial to determine the optimal capacity of the storage to make the overall system cost viable.

Another challenge that is addressed in this work package is related to using hydrogen in fuel cells. Currently PEMFCs (Proton Exchange Membrane Fuel Cells) are commercially available for maritime applications. These FCs are provided as modules with a typical rated power of 200kW. To power the ship like the case vessel of the project, will require to install 100 to 150 modules onboard. Furthermore, FCs have different characteristics of the efficiency than the diesel engines. Efficiency is typically highest at low load range (20~30%) and lower as the load increases. This is almost opposite to the diesel engines. Therefore, operating fuel cells should be different from diesel engines especially for determining the optimal number of modules to engage for a given load. Configuration of fuel cell modules depending on the power level will affect the sizing of the fuel cells and the fuel consumptions.

The last challenge is the cost of fuel and the fuel cells. They are expected to be much higher than conventional fuel and diesel engines. The sizing of the power capacity of the power plant should be determined to minimize the total cost of ownership. To do this, a system model that simulates the power demand for the vessel, power distribution depending on the power load and fuel consumption at each fuel cell is needed. The power demand should be realistic and stochastic to reflect the real operation requirement and environment conditions.

4.2 Our contribution/assessments

4.2.1 System model for the vessel operation

Design assessment of the ship design requires a holistic approach to evaluate the performance of the ship properly. The system model is used to make sure all the technical and operational aspects of the target ship is included to evaluate the ship performance for the early design stage. The system model consists of the operation scenario, ship operation model and the ship model. The operation scenario includes the timetable of the route, speed profile, bunkering frequency, and historical weather data. The operation model includes the modes of operation. The ship model includes the technical components such as fuel storage, hull, propulsors, power system and the energy/power management system. Figure 7 depicts the structure of the system model.

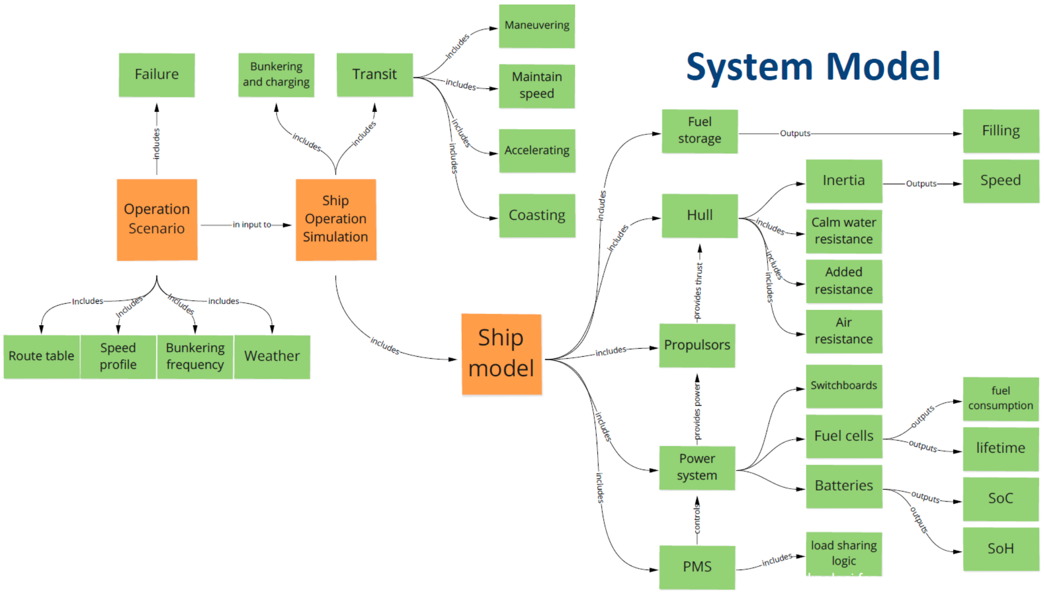
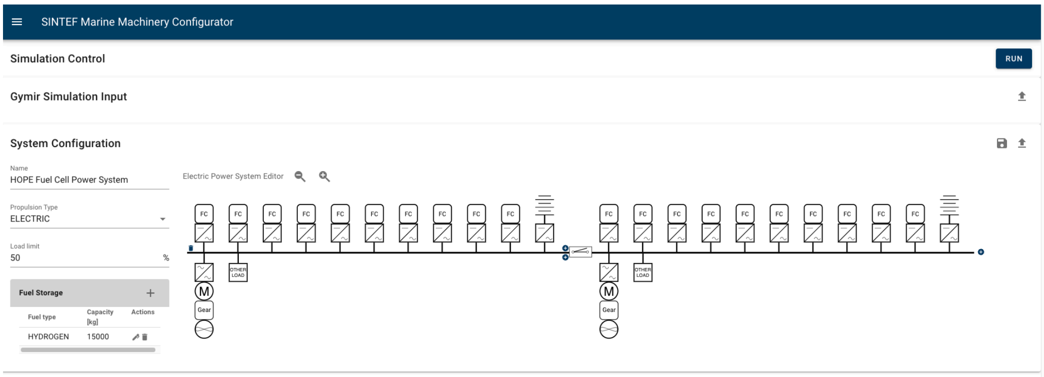


Figure 7. The structure of the system model used for the evaluation of the ship performance

The system model provides the architecture of the models that are used for the further analysis of the ship performance.

4.2.2 Machinery model/configuration software

One of the hypotheses in this work was that the system configuration and the control strategy has significant influence on the fuel consumption for the given load. To test the hypothesis, a machinery model for the power system with hydrogen fuel cells is created. In-house modeling framework, FEEMS (Fuel Emissions Energy Calculation for Machinery System) is used for modeling. The model composes of two switchboards, fuel cell group of rated power of 1MW, propulsion drives, auxiliary load, and battery packs. Each component is modeled with the efficiency that varies with the load. These efficiencies are combined to determine actual electric power consumption at the switchboards and the power loads are equally shared among the fuel cell groups that are turned on. An ideal power management system (PMS) is modeled to determine the number of fuel cell groups to be turned on for the given load and the load limit before the next fuel cell group is turned on. A Machinery Configurator software is developed so that a ship designer with little knowledge of the power system can create such a model. Figure 8 shows the snapshot of the system model created on the software.



Name
HOPE Fuel Cell Power System

Propulsion Type
ELECTRIC

Load limit
50 %

Fuel type	Capacity [kg]	Actions
HYDROGEN	15000	

Figure 8. A screen shot of the software tool for machinery configuration.

4.2.3 Design Lab framework

Design Lab is a framework developed in the project to evaluate the ship performance with realistic operational scenario and ship models that accounts all relevant technical aspects of the vessel. The evaluation process is depicted in Figure 9. The framework provides an integrated process for the holistic approach to evaluate the system so that the quick iteration of the design process is possible. It allows the designers to explore new ideas easily to arrive at the optimal design and understand the system better.

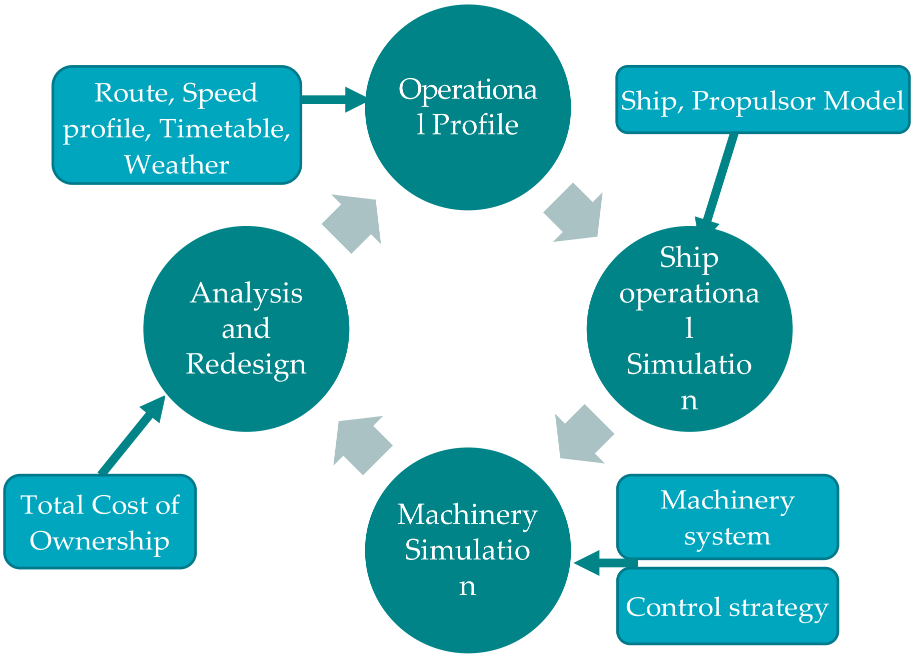


Figure 9. The iteration cycle in Design Lab framework to estimate the performance of a design candidate of a ship.

The process is made of four sub-processes: defining operational profile, ship operation simulation, machinery simulation and analysis of the design and re-design if necessary. In the operational profile, route of the ship, speed profile, timetable or frequency of the travel and weather conditions are specified. With the operational profile defined, ship operational simulation is performed using the semi-empirical model of the hull and propulsion model for the given operational profile. The simulation includes the effect of the weather conditions such as wave heights and wind speed. Typically, the simulation is run for a year or longer to get the statistically significant result. The ship operational simulation gives the time-series of propulsion power for the vessel. In the machinery simulation phase, a designer can create a machinery system and provide the control strategy. With the input of propulsion power from the ship operational simulation, one can run machinery simulation to obtain fuel consumption, emissions, energy usage and utilization of the machinery units. With these outputs, one can obtain the key performance indicators (KPIs) such as the total cost of ownership, CO_2 emissions, etc. A designer can iterate on the process if the KPIs are not satisfactory.

4.2.4 Long-term Simulation of a ferry operation

Using the framework, long-term simulation of a ferry operation was performed to support WP3 and WP5. Actual timetable for STENA Jutlandica (currently running between Fredrikshavn and Gothenburg) was used for the schedule of the vessel. The route and speed profile were modeled using the AIS data of the vessel (see Figure 10). The weather data were collected from the Norwegian Meteorological Institute database for 2021 and 2022. The hull and propeller are modeled using semi-empirical method to estimate ship resistance in sea way and propulsion power (see Figure 11). Once the propulsion power for a yearlong operation is obtained, the fuel consumption, emissions and utilization of the machinery units can be obtained using the machinery models configured from the Machinery Configurator. Power plants with total installed power of 20MW, 25MW and 30MW are modeled with maximum load limit of 30% before turning on the next fuel cell group.

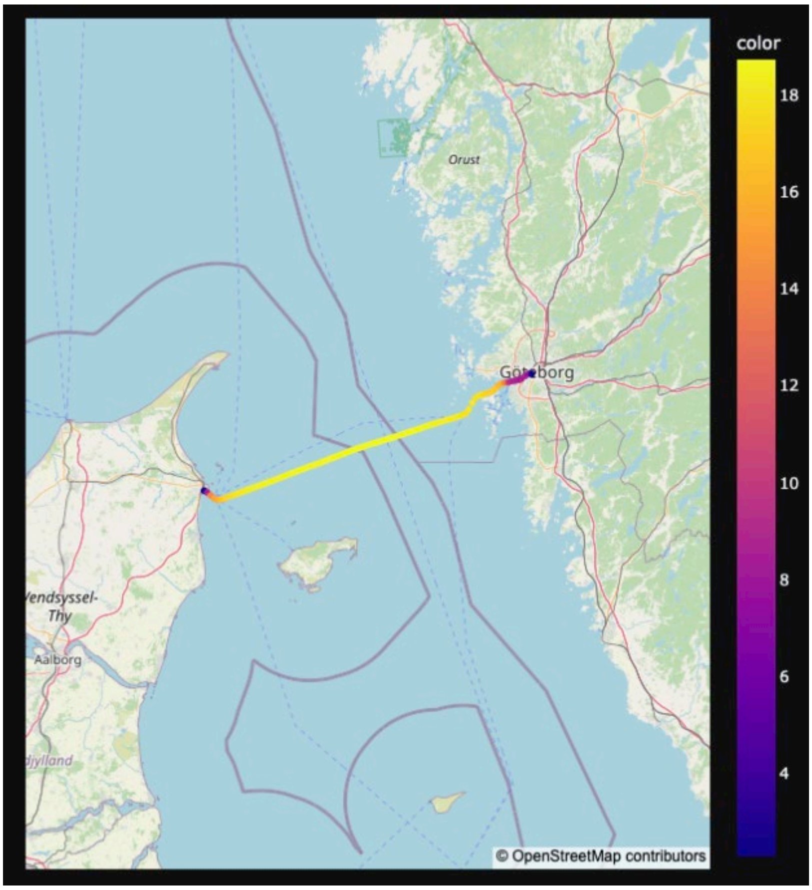


Figure 10. Route and speed profile of the target ship modelled from AIS data between 2021-2022. The color scale represents the speed of the vessel in knots.

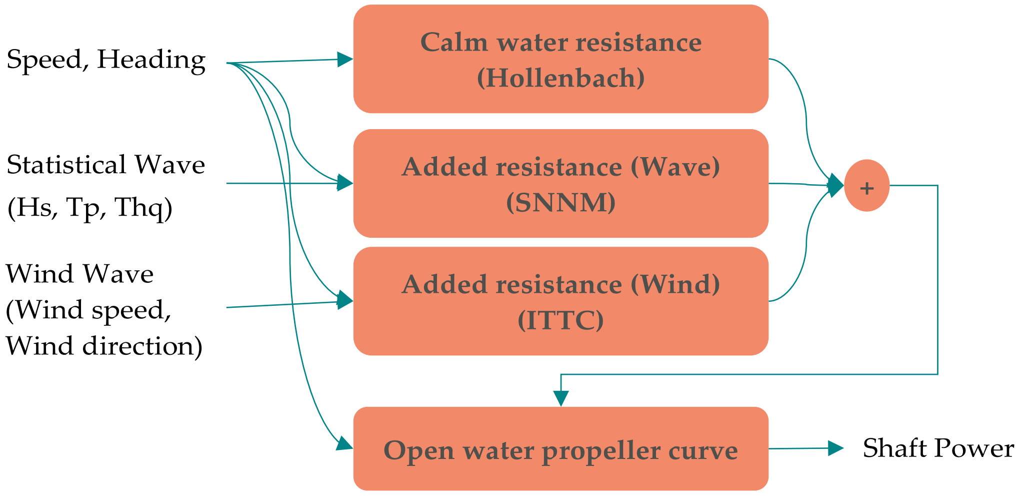


Figure 11. Hull resistance model in calm water, wave and wind and the propeller model to calculate the propulsion power from the speed, heading and weather conditions.

From the output of the machinery simulation, the two KPIs are calculated. The first one is the maximum fuel consumption for three consecutive trips and the other is the levelized cost of each trip.

4.3 Main findings and recommendations

From the initial machinery model and the operational profile input from WP3, the hypothesis that states

"The system configuration and the control strategy have significant influence on the fuel consumption for the given load."

was tested. Three systems of the total installed power of 20MW, 30MW and 40MW were modeled using the Machinery Configurator. PowerCell provided a net efficiency curve of the fuel cell module both at beginning of life (BOL) and at end of life (EOL). For the models, average of the two curves is used to account the aging of the fuel cells. The statistical power load on the power system was given by Stena from the historical onboard measurement as shown in Figure 12.

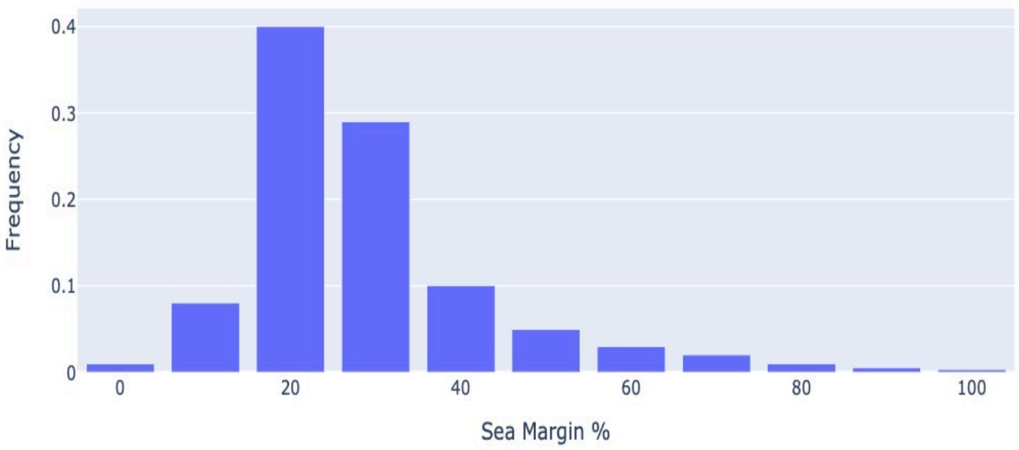


Figure 12. Histogram of the power load on the power system for the target vessel obtained from historical measurement. The x-axis represents the power load where sea margin of 0% represents 10MW and 100%, 20MW.

The power system is made of fuel cell groups of 1MW (5 modules of 200kW) which are turned on and off depending on the power load. The maximum load limit before starting a new group will determine the number of groups on for a given load. The load limit was varied from 30% to 100% with 10% increment. Fuel consumption was the main output of the simulation.

The lowest fuel consumption was obtained for the 40MW power plant with the load limit of 30%. This was expected for the given efficiency curve of the fuel cells where it has a peat at 30% of the rated power. The power plant with higher installed power will have lower loading on each fuel cell in average. The same applies for the maximum load limit where fuel cells will be less loaded with lower load limit in average. However, the higher capacity comes with higher CAPEX.

The long-term ship operational simulation provided the propulsion power for 2200 trips. The time-series of the propulsion power and the histogram are shown in Figure 13 There is large variation in the power due to the variation in the weather condition throughout the year. The shape of the histogram resembles the operational profile given by Stena from an actual ship. The simulation model predicts the performance in real-world conditions qualitatively well.

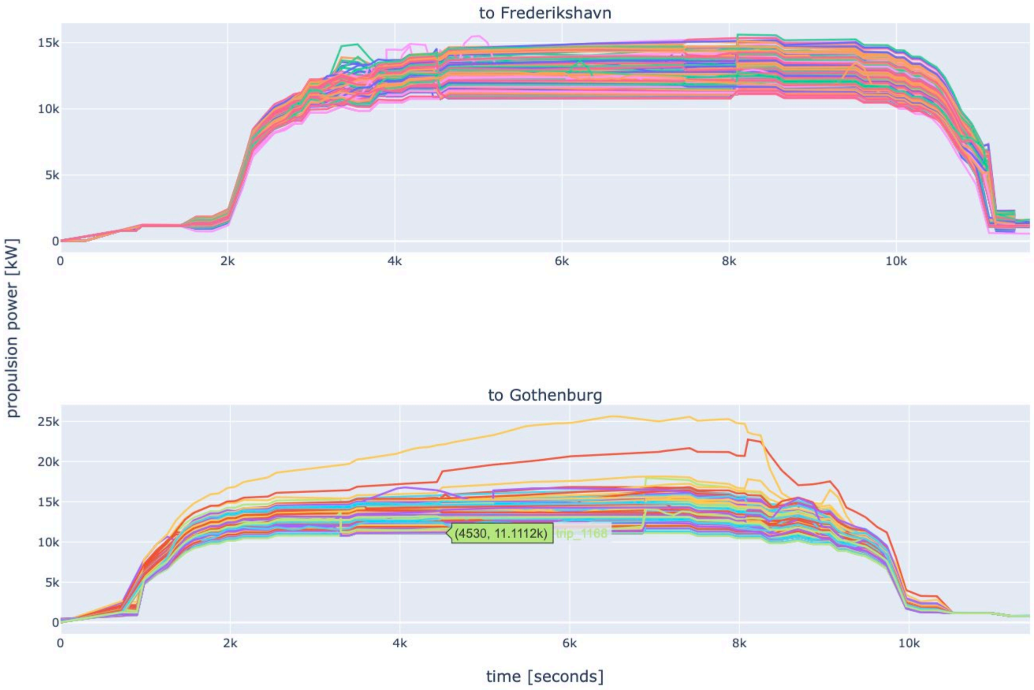


Figure 13. Propulsion power of the target vessel for the trips between Frederikshavn and Gothenburg. The x-axis represents time elapsed after the departer of the port.

The main key performance indicators (KPIs) of the analysis were the maximum hydrogen consumption for three consecutive trips and the levelized cost of the trip. The fuel consumption is 9.2 tons at the peak and 7 tons in average. Therefore, sizing the storage 10 tons will provide a good margin in normal operation and allows vessel to sail even in the most extreme weathers.

The levelized cost highly depends on other parameters such as purchase and maintenance cost of fuel cells and hydrogen cost. Sensitivity analysis was performed with the following parameters:

- Fuel cell unit cost: 800 – 1400 EUR/kW
- Fuel cell maintenance cost: 0.02 – 0.045 EUR/kWh
- Hydrogen cost: 3-9 EUR/kg

The hydrogen cost contributes most to the total cost whereas the two fuel cell cost factors have minor contribution in the variation. This suggests that the viability of the hydrogen as maritime fuel highly depends on the price of the fuel. For sizing of the power plant, the lower hydrogen price favors the power plant with lower installed power and vice versa.

Some of the findings from the tests and models of the concept ship design include:

- Design Lab provides a framework for a fast iterative method to evaluate the design of a fuel cell with hydrogen.
- AIS data processed by a machine learning method can provide a representative operation profile.
- Ship performance simulation with weather data history by semi-empirical method can provide a statistically valid power requirements for the ship.
- Machinery simulation by Fuel Emissions Energy Calculation for Machinery System (FEEMS) can give a system efficiency and fuel consumption on various loads.
- Cost of hydrogen fueled propulsion will be significantly higher than fossil-based solution but can be equivalent with further development and carbon tax in place.

4.4 Publications

The main publication of this work package includes a scientific article:

Yum, K., Stenersen, D., forthcoming. Design Study for a Ro-Pax Ferry with Hydrogen Fuel Cells using Design Lab Framework. Journal Manuscript submitted for review in scientific journal.

5 Scenario and impact analysis

In WP5, scenarios for potential deployment of hydrogen and fuel cell solutions in Nordic shipping has been developed. The scenarios were then used for assessing effects and impacts of hydrogen as fuel in a Nordic context. Furthermore, a cost benefit analysis was performed, investigating costs linked to the technical implementation of hydrogen fuel cell solutions in shipping. These costs were then compared to benefits in terms of external costs linked to reduced emissions and potential subsides.

5.1 Motivation/Challenge

One way of reducing harmful emissions from ships and at the same time reduce GHG emissions is to utilize alternative fuels such as hydrogen. There is a need for a deeper understanding of the potential for hydrogen and fuel cells for Nordic shipping as well as for the potential effects of using hydrogen as marine fuel in this region. Different fuels have different suitability for different shipping segments and vessel types. The impact assessment in the HOPE project, which is estimating the influence of fuel-propulsion shift to hydrogen and fuel cells on selected emissions, is interesting since it adds knowledge regarding which type of Nordic shipping that is most suitable for hydrogen and fuel cells and contributes to determine its merits and viability.

Estimations of the potential emission reduction linked to a shift from conventional maritime fuels to hydrogen as well as associated cost benefit assessment also provides insights that can be useful for the design of future policy instruments, including Nordic specific policies. An advantage of the HOPE project’s Nordic context is the knowledge in this field being built locally amongst Nordic actors and the knowledge exchange enables a continued development towards a more sustainable shipping industry.

5.2 Our contribution/assessments

The major assessments performed in WP5 are described in the following sections.

5.2.1 Cost-benefit analysis

Costs linked to the technical implementation of hydrogen and FC solutions in shipping has been compared to benefits in terms of external costs linked to reduced emissions and potential subsides. The analysis is done from two perspectives, private and social, differencing in the assumed depreciation time and interest rate for the investments as well as in what parameters that enters the equation. For the private perspective the benefits in form of lower costs for ETS emission rights, fairway and port fees are related to the annual increase in costs for the investments in power train and fuel system and the increased annual fuel cost. For the social perspective reduced external costs due to reduced emission of greenhouse gases and air pollutants, are related to the increased costs for investments and fuel. For both cases we use increase in costs for the FC ship using hydrogen to a modern ship with the same capacity that uses MGO. The costs for the ships are taken from WP3.

For the private costs the resulting benefit-to-cost ratio for the shipowner is 0.33 showing that the investment is far from cost effective and that additional subsidies may be needed for investments in FC/H_2 technology to take place. However, since both the ETS cost in the future and the technical costs are highly uncertain we also made an alternative calculation using the assumptions in Section **Error! Reference source not found.**, where the ratio becomes 1.03 showing that it is not impossible to make a good business case.

For the social case the costs are calculated from a societal perspective assuming longer investment times and lower interest rate. The benefit is the reduced external costs for a fuel cell ship compared to a traditional ship due to lower emissions of air pollutants and greenhouse gases. The resulting benefit to cost ratio is then 0.56 showing that with these assumptions the investment in FC/H_2 technologies is not beneficial from a social perspective. However, the external cost for CO_2 is highly debated and with a higher value combined with lower costs for the fuel cell technology the ratio becomes 1.33. Thus, the conclusion regarding the cost effectiveness is strongly dependent on values of highly uncertain parameters.

5.2.2 Emission impacts in scenarios for potential uptake in Nordic fleet

Scenarios for possible deployment trajectories for hydrogen and fuel cells in the Nordic region were developed. The potential emission reduction of specific ship segments on a variety of distances was mapped. The feasibility for hydrogen in fuel cells for propulsion is difficult to generalize. The assessment here represents a what if approach including a range for the potential effect. Detailed ship specific assessments are needed to confirm the suitability on specific vessels.

CO_2 emissions of the Nordic shipping fleet has been investigated. Firstly, the Nordic shipping fleet was investigated starting by identification of vessel movement patterns in the Nordic region using historical port call data from Marine Traffic. This was followed by a mapping of the distance, sea routes, between Nordic ports using statistics from Sea routes. Vessels were selected based on type/application and size. Vessels below 5 000 (gross tonnage) GT and fishing and service vessels were excluded from the data. Second, official data reported to European Union via the the Monitoring, Reporting and Verification (MRV) system was used to compile average fuel consumption for each individual ship and CO_2-emissions per nautical mile. This data was the basis for the development of scenarios which were applied for future shipping in 2030 and 2050. The output from this work is estimations of the CO_2 emissions that can be attributed to Nordic shipping on voyages to/from and between ports in the Nordic region.

Besides influence of GHG emissions, influence on emissions of NOx, and particulate matter (PM) are assessed. Moreover, in addition to assessing the impact on emissions for the case study vessel, the assessment also includes estimations of the impact on emissions for fuel and propulsion shift to hydrogen and fuel cells at ferries in the Nordic region and for all shipping segments.

5.2.3 Impact on sustainable development goals

The scope of the HOPE project, investigating how regional shipping in the Nordic region can undergo a transition towards fossil free fuels focusing on hydrogen-based fuels, connects to the sustainable development goals in Agenda 2030 and the ambitions of the Nordic governments. The impact on the sustainable development goals (SDGs) prioritized by the Nordic governments linked to transport was assessed

Several of the sustainable development goals are closely linked to transportation in some way. The following SDGs are highlighted on the knowledge platform at the United Nations webpage for the sustainable development goals:

- SDG 3 on health, increased road safety,
- SDG 7 on energy,

- SDG 8 on decent work and economic growth,
- SDG 9 on resilient infrastructure,
- SDG 12 on sustainable consumption and production, ending fossil fuel subsidies,
- SDG 13 on climate action, and
- SDG 14 on oceans, seas, and marine resources.

The assessment was based on each country's voluntary national review, official governmental sources and an SGD impact assessment tool developed by Gothenburg Centre for Sustainable Development, at Chalmers University of Technology and the University of Gothenburg in collaboration with SDSN Northern Europe and Mistra Carbon Exit.

By combining the sources above and the work of Sala et al. (2020), Brynolf et al. (2023) the following SDGs are found to be connected to HOPE:

- SDG 3 Good health and well-being
- SDG 6 Clean water and sanitation
- SDG 7 Affordable and clean energy
- SDG 9 Industry, innovation, and infrastructure
- SDG 13 Climate action
- SDG 14 Life below water
- SDG 15 Life on land

However, according to Wang et.al (2020), who investigated how the maritime industry can meet the sustainability goals, the maritime industry is associated with all SDGs in some way. However, there are no SDG specifically addressing the maritime sector. There is a lack of research on SDGs and maritime-related studies.

5.2.4 Cost-effective fuel and propulsion technologies - Times-Nordic modelling

The potential future role and cost-effectiveness of various marine fuel options, focusing on the potential role of hydrogen-based fuels in the Nordic countries when striving for low CO_2 emissions (Nordic carbon neutrality by 2050) has been assessed using energy systems modelling, specifically the Open Nordic (ON) TIMES model (https://cleanenergyscenarios.nordicenergy.org/) (see more in Hansson and Unluturk, 2023). The focus is on the possible development of different marine fuel options in the Nordic countries Denmark, Norway, and Sweden up until 2050.

The data used for the ON TIMES model in the Nordic Clean Energy Scenario 2020 project and the carbon neutral Nordic (CNN) scenario (NER, 2021, representing a scenario that seeks the least-cost pathway for meeting the Nordic carbon neutrality target considering current national plans, and targets) has been used as basis for this assessment. However, most of the shipping related data in the ON TIMES model has been updated. This include the demand for shipping and the performance for marine fuels, propulsion and vessels that has been updated in terms of investment cost, operation and maintenance cost, tons per vessel and utilization factor (maximal km/year/vessel). Selected policies aimed at promoting renewable fuels in the shipping sector such as a tax on fossil marine fuels and a blending requirement for alternative marine fuels are also added in additional scenarios.

5.3 Main findings and recommendations

Several emissions (including besides GHG also NOx and PM) and SDGs are influenced by an implementation of hydrogen as fuel in Nordic shipping. In terms of potential uptake in Nordic fleet and emission impacts our main findings are summarized below.

In total approximately 3 000 vessels were included in the mapping of the Nordic fleet. The sailed distance was 43 000 000 NM, 300 000 voyages and an energy consumption of 4.3 Mtoe. For the case study (i.e., vessel operating between Gothenburg and Fredrikshavn), for an existing vessel the emissions of CO_2e, well-to-wheel, for fuel consumption in 2018 are calculated to 45 000 tonnes. The calculation is based on reported values of fuel consumption. For the theoretical fuel cell ship, the emissions of CO_2e, well-to-wheel, amount to 4 000 tonnes and are thus significantly lower compared to the case study vessel. For comparison, a new vessel updated with the latest technology fueled by MGO is calculated to generate 32 000 tonnes of CO2e emissions. Figure 14 illustrates the projected total CO_2 emissions from Nordic shipping between 2018 and 2050, considering two different scenarios. These scenarios represent varying degrees of growth in transport work: one indicating a high increase and the other a low increase. It is important to note that these emissions projections describe the situation where no alternative fuels are implemented. Despite the assumed improvements in utilization rate and energy efficiency of ships (following the EEDI regulation), shipping emissions in the Nordics are expected to rise in the forthcoming years. This upward trajectory thereby highlighting the pressing need for alternative fuel solutions in the Nordic maritime sector.

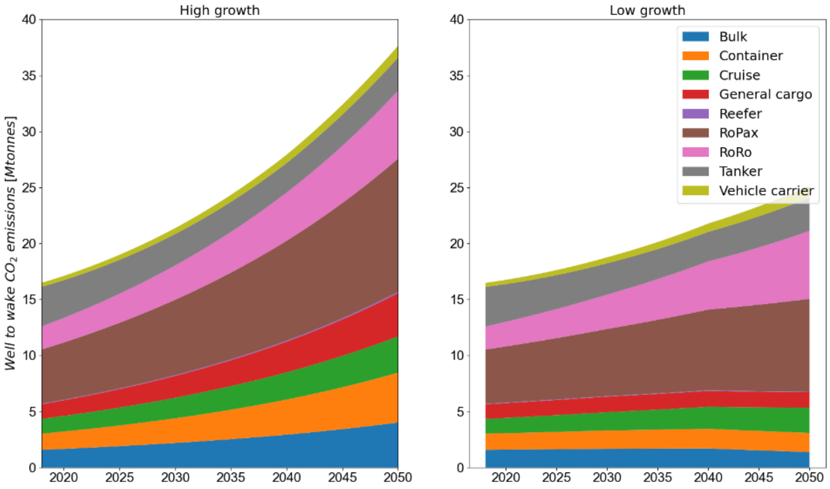


Figure 14. Modelled well-to-wake CO2 emissions for the Nordic Fleet for the period 2018-2050 under the conditions of business as usual, i.e., assuming no introduction of alternative fuels. The left graph represents high growth transport scenario while the right graph represents low growth scenario.

Hydrogen fuel cell propulsion solutions are mainly suitable for vessels travelling short to medium distances due to energy density and storage capacity issues. Table 1 below presents the impact on CO_2, NOx, and PM emissions for a shift to hydrogen and fuel cells for all shipping segments travelling distances ranging from maximal 100 to maximal 500 NM. A considerable amount of the emissions appears to be attributed to shorter distances.

Table 1. Estimated potential reduction of emissions of CO2, NOx, and particles from a potential implementation of hydrogen in fuel cells for all vessels with voyages up to 100 to 600 NM. Based on to 2018 years data.

Including voyages up to	CO2eq (WTW, tonnes]	NOx (tonnes)	PM (tonnes)	SO_2 (tonnes)	Final Energy use at sea (MWh)
100 NM	2 290 000	58 000	2 800	5 700	3 290 000
200 NM	3 680 000	93 000	4 600	8 600	5 240 000
300 NM	4 550 000	115 000	5 800	10 600	6 490 000
400 NM	5 500 000	139 000	7 300	12 500	7 910 000
500 NM	6 130 000	155 000	8 100	13 700	8 820 000
600 NM	7 700 000	197 000	10 700	15 900	11 150 000
Nordic fleet all voyages 2018	**14 250 000**	**369 000**	**21 300**	**68 000**	**20 940 000**

In Figure 15, the share of each ship segment, in terms of total fuel use, that represent voyages with different distances are presented. Each distance category includes all voyages up to that specific distance, e.g., the distance category *100 NM* include all voyages between 0 and 100 NM, *200 NM* include all voyages from 0 up to 200 NM and so forth.

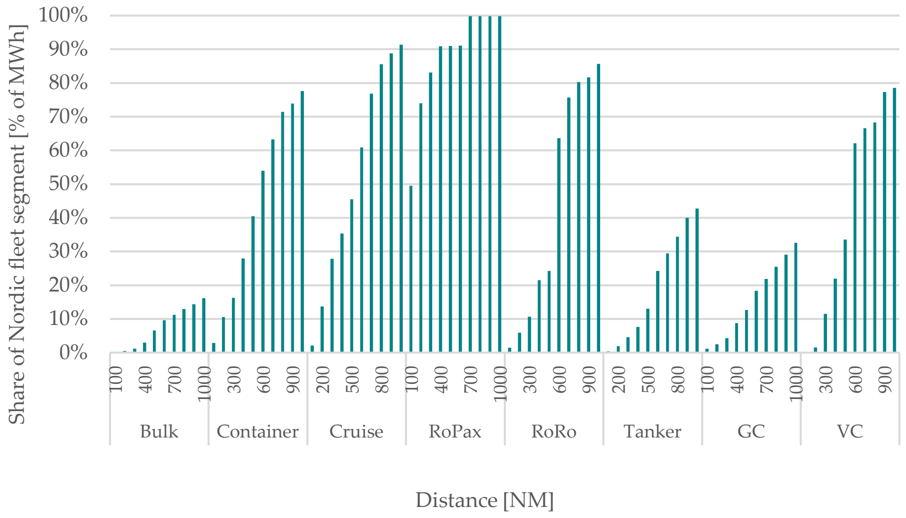


Figure 15. The share of the total fuel use per shipping segment in the Nordic region per distance in 2018. Each distances category includes all voyages up to that level (100-1 000 NM).

As can be seen in Figure 15 RoPax is one of the most relevant ship segments for future hydrogen and fuel cells propulsion as 91% of voyages are less than 400 NM and almost all routes are less than 700 NM. It is the requirements of storage and bunkering of hydrogen and fuel cells that make the technology suitable for ships travelling shorter distances compared to long distance voyages with bulk or tanker ships. In addition, RoPax vessels generally travel the same routes and with predefined timetables which makes the bunkering situation easier.

There is a considerable potential for emission reductions both in terms of CO_2, NOx and PM linked to the implementation of hydrogen and fuel cells in Nordic shipping, particularly in the RoPax segment, representing 30% of total CO_2 emissions in 2018. Remember though that only vessels larger than 5000 GT are included and that service and fishing vessels are not included, which are relevant particularly for Norway and Iceland. Considering the relatively long lifetime of vessels, investments must be made soon to enable a hydrogen powered shipping fleet in the future. Currently, it is not economically viable with hydrogen and fuel cells vessels thus calling for subsidies and investments in pilot studies to identify issues and develop solutions.

Cost-effective fuel and propulsion technologies

Our findings in terms of the cost-effectiveness of marine fuels in Denmark, Norway and Sweden for the assessed scenarios using the ON TIMES model are presented in Figure 16. This modelling is not based on the same statistics for Nordic shipping as the estimate above as it was performed in parallel. The modelling analyses show that it, by introducing renewable marine fuels, is possible to drastically reduce the CO_2 emissions from Nordic shipping to 2030 and 2050. Thus, introducing alternative marine fuels may be crucial for decarbonizing the shipping sector in the Nordic region. More specifically the analyses indicate that marine biofuels, primarily in the form of biodiesel and methanol, and compressed hydrogen represent cost-effective mitigation options in the shipping sector in the Nordic countries both in the mid (2030) to long term (2050) perspective for the assessed scenarios. In the case of more stringent CO_2 targets, synthetic natural gas i.e., renewable methane is also found to be a cost-effective option.

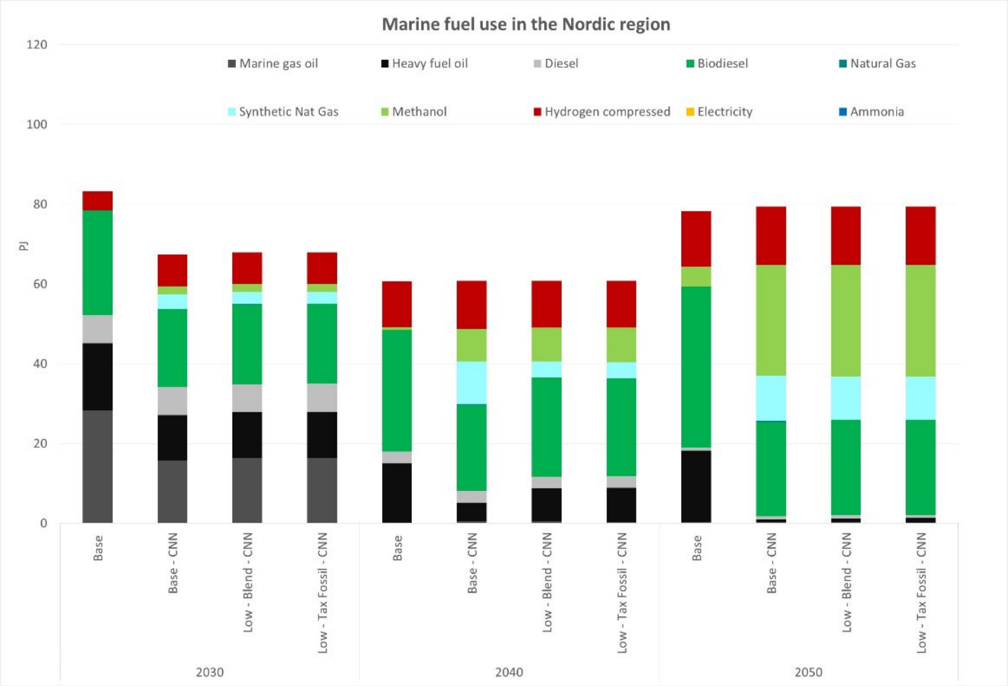


Figure 16. Fuel use in the future Nordic shipping sector (covering Denmark, Norway, and Sweden) for four different scenarios; Base scenario with moderate GHG emission reduction targets, Base carbon neutral Nordic (CNN) CNN with more stringent GHG reduction targets reaching carbon neutrality by 2050, Low Blend CNN with also blending mandate for renewable marine fuels and Low Tax Fossil CNN with CNN assumptions plus tax on fossil marine fuels.

When testing the same policies as evaluated in the modelling work in Section 6, including the promotion of renewable fuels for shipping via a tax on fossil marine fuels and a blending requirement the impact on the cost-effectiveness of marine fuels options in the Nordic countries is minor. Thus, the CO_2 reduction target in the so-called CNN scenario (corresponding to carbon neutrality by 2050) already leads to a significant introduction of renewable marine fuels.

However, the potential future role of hydrogen, electrofuels, and biofuels for shipping may in reality depend on the design and details of the policies introduced for promoting alternative marine fuels, as these may promote different fuels to different extent. Many of the fuel options are still under development, which means that cost and GHG performance may still develop considerably. Thus, updated assessments of the potential future role of different marine fuels is still needed.

5.4 Publications

The main publications of this work package include two scientific articles, one book chapter, one policy brief, one conference paper and one report:

Brynolf, S., Hansson, J., Anderson, J.E., Ridjan Skov, I., Wallington, T.J., Grahn, M., Korberg, A.D., Malmgren E., Taljegård, M., 2022. *Review of electrofuel feasibility - Prospects for road, ocean, and air transport*. Progress in Energy, 4, 042007; https://doi.org/10.1088/2516-1083/ac8097.

Brynolf, S., Grahn, M., Hansson, J., Korberg, A.D., Malmgren E., 2022. *Chapter 9 Sustainable fuels for shipping. Sustainable energy systems on ships: Novel technologies for low carbon shipping.* Editors: F. Baldi, M. E. M. Montagud and A. Coraddu, Elsevier. https://doi.org/10.1016/B978-0-12-824471-5.00017-7

Hansson, J., Unluturk, B., 2023. *Cost-effective marine fuels and propulsion technologies for Nordic shipping – the role of hydrogen versus biofuels.* Proceedings of the EUBCE 2023 31st European Biomass Conference and Exhibition, 5-8 June, 2023, Bologna, Italy.

Hansson J., Jivén K., Lundström H., Parsmo R., Fridell E., Wimby P., Burgren J., 2023. *Concept design and scenario and impact analysis in HOPE – Hydrogen fuel cells solutions in Nordic shipping. Report from WP3 and WP5 in the HOPE project*, Available at: https://www.ivl.se/projektwebbar/hope.html

Kanchiralla, F.M., Brynolf, S., Malmgren E., Hansson, J., Grahn, M., (2022). *Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping*. Environmental Science & Technology, 56 (17) https://pubs.acs.org/doi/10.1021/acs.est.2c03016. Joint publication with another project

Hansson, J., Fridell, E., Burgren, J., Davíðsdóttir, B., Goldmann, M., Jivén, K., Koosup Yum, K., Latapí, M., Lundström, H., Parsmo, R., Stenersen, D., Wimby, P., Cook, D, forthcoming. *Hydrogen HOPE for the Nordics: Shipping as a frontrunner. Policy brief article submitted for publication in the Fast Track to Vision 2030* publication by Nordforsk.

An additional article, written jointly with another project, is under preparation and will be submitted to an academic journal later.

6 Policy and drivers/barriers for change in the Nordic maritime sector

The main objective of WP6 was to identify what drivers need to be enhanced, what barriers should be tackled, and which additional policy options are needed to enhance the Nordic uptake of hydrogen fuel cells (HFCs) in Nordic shipping. To do so, the first part of WP6 was based on an extensive literature review and interviews with key stakeholders while the second part of the work package focused on identifying and assessing policy options to address the drivers and barriers. Three policy packages were proposed based on the literature review and a stakeholder workshop and the likely effectiveness of the proposed policies was evaluated using the TIMES-NEU model.

6.1 Motivation/Challenge

The main motivation for conducting this work package and research lies in the novelty of using the HFCs in the shipping industry and its ability to mitigate GHG emissions. This translates into a series of drivers for shipping companies to look into adopting this technology. However, the decision to do so is hindered by a variety of barriers for their adoption. Therefore, mapping the drivers and barriers that are expected to affect the energy innovation chain for HFCs from commercialization to adoption to the Nordic shipping industry helps get a better understanding of the measures needed to increase their uptake. Furthermore, the existing policy and regulatory framework for shipping does not fully consider the use of HFCs. It was only until 2022 that the first international policy instrument for their use was adopted (The “Draft interim guidelines for ships using fuel cells” were approved by IMO in 2022). While this is a significant first step, it also means that existing and upcoming policies need to be evaluated to understand their potential effectiveness.

6.2 Our contribution/assessments

This work package contributes to the HOPE project in a variety of ways. First, it identifies the drivers and barriers to the adoption of HFCs for Nordic shipping through a desktop study and semi-structured interviews. Existing and desired policy instruments were also reviewed and included regulatory, market based, and information focused instruments. Second, key stakeholders along the energy innovation chain in all five Nordic countries were interviewed using semi-structured interviews to capture stakeholder views on the case specific relevant drivers and barriers. Concerns, barriers, and drivers were explored with the interviews, and current policies and possible additional policy interventions were identified at the local, national, and regional levels. A stakeholder workshop was held in May 2022 with the aim of identifying policy interventions needed at national and regional levels. This allowed to identify additional measures needed to facilitate faster commercialization and deployment, including large-scale adoption.

The impact of the identified policy instruments on the competitiveness of low-carbon solutions in the shipping industry was then assessed with the second part of the work package. The drivers and barriers identified were matched to the relevant policies, creating policy packages of relevant current and additional policy instruments. The comparative cost effectiveness of different low-carbon options without policies and measures, and with proposed and current policies and measures was evaluated using the information from the review of different options and through TIMES-NEU modelling. Finally, the impact of additional policies and measures on competitiveness was identified and the findings were translated into recommendations to Nordic policymakers.

6.3 Main findings and recommendations

The findings of this work package indicate that a variety of drivers and barriers influence the decision of shipping companies to adopt HFCs. The findings suggest that shipping companies are driven toward the adoption of HFCs by internal, connecting, and external factors and they face behavioral, economic, organizational, and operational barriers (see Figure 17).

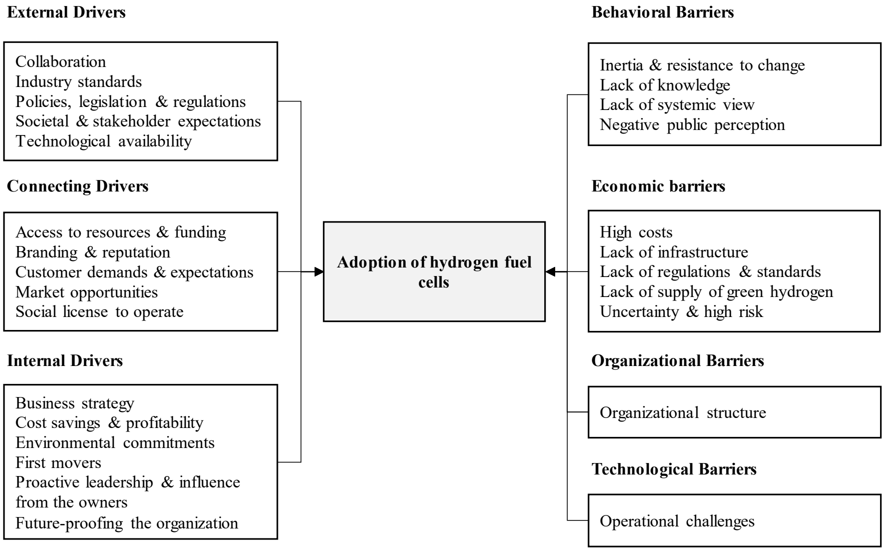


Figure 17. Drivers and barriers for the adoption of Hydrogen Fuel Cells for Nordic shipping (Latapí et al., 2023).

The findings from the interviews suggest that the most relevant barriers are the comparatively high costs associated with the adoption of HFCs as well as operational challenges such as the bunkering, storage, and handling of hydrogen (see Figure 18).

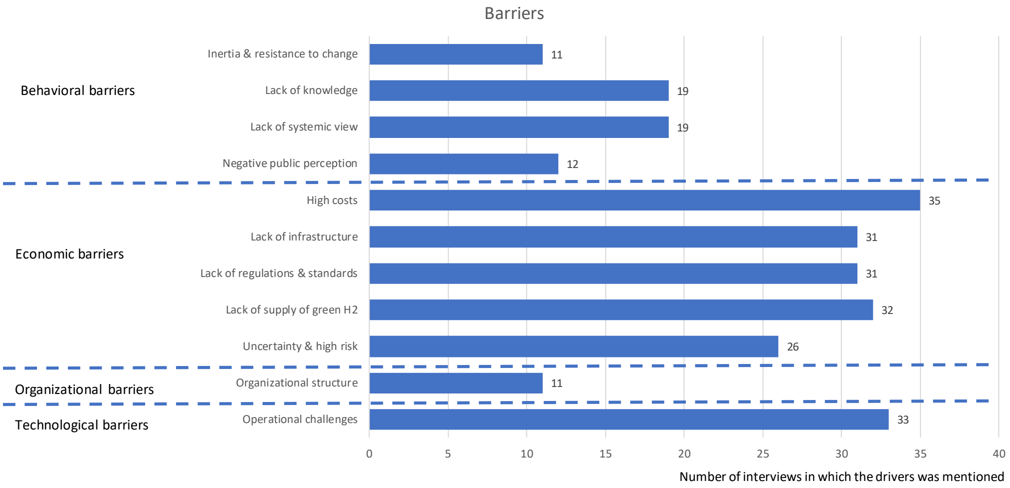


Figure 18. Behavioral, economic, organizational, and technological barriers from interviews (Latapí et al., 2023).

The second part of the research consisted of a desk study including a systematic literature review, a stakeholder workshop and an evaluation of policy effectiveness using the TIMES-NEU model. The literature review and the stakeholder workshop helped identify existing, proposed and desired policies at the international, national, and regional level that could help leverage the adoption of HFCs. The findings from the workshop indicate that the participants consider the following policies and measures as the most relevant: 1) *Economic measures*: funding and direct investments for developing the hydrogen value chain, for upscaling the production of green hydrogen, and for upscaling the pilot and demonstration projects for shipping. Also, higher effective carbon pricing through the inclusion of shipping into the EU ETS along with higher carbon taxes and other taxes on fossil fuels. 2) *Regulatory measures*: creation of a regulatory framework for the hydrogen value chain, definition of a timeline for a ban on fossil fuels, and GHG emissions reduction targets for the shipping industry. 3) Additional measures proposed included the creation of green shipping corridors as well as the creation of roadmaps for the hydrogen value chain and for the shipping industry. Three policy packages (1-3) were proposed based on the analysis of current, proposed, and upcoming policies where each package included higher effective carbon pricing and a gradual ban on fossil fuels. Each package represented a different level of ambition and were evaluated with the TIMES-NEU model. The findings indicate that the economic measures proposed have an impact on fuel consumption as early as 2025. The measures of the three policy packages are enough to drive the fuel consumption away from heavy fuel oil and marine gas oil and towards methanol and ammonia. However, HFCs do not emerge as a dominant technology due to comparatively high cost (see Figure 19). This suggests that additional policy efforts are required earlier in the HFC energy innovation chain to facilitate faster cost-effective commercialization along the value chain.

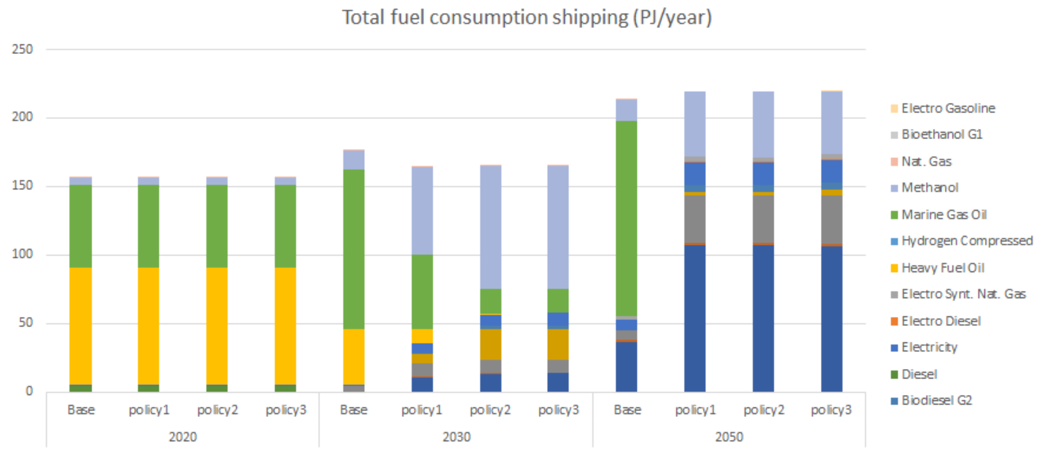


Figure 19. Estimated total fuel consumption in PJ/year. The three policy packages (policy 1-3) include higher effective carbon pricing and a gradual ban on fossil fuels but representing different level of ambitions from low (policy 1) to high (policy 3).

As a summary, the key findings from this work package are:

- A variety of drivers motivate shipping companies to look into the adoption of green hydrogen and HFCs. The most relevant include environmental commitments along with existing and upcoming policies and regulations.
- A variety of barriers limit the adoption of green hydrogen and HFCs for shipping. The main barriers are the high costs of the fuel/technology, the lack of infrastructure, the lack of supply of green hydrogen, and the operational challenges for handling hydrogen (mainly in storage and bunkering). The uncertainty and high risks of using this fuel and technology are also significant barriers for early movers.
- Economic and regulatory policies are needed for reducing the barriers and for accelerating the adoption of hydrogen and HFCs for shipping.
- Economic measures should include higher effective carbon prices, including higher carbon taxes, higher taxes on fossil fuels, and the inclusion of shipping to the EU ETS (also considering the fleet that is not currently covered, i.e., vessels under 5,000 gross tons).
- Regulatory measures should include the ban on fossil fuels and a mandate for zero-emission vessels for specific segments (e.g., for the ferry segment).
- Fuel/technology silos must be avoided. To do so, coordinated regional policies are needed to reduce the risks for early adopters.

Key recommendations:

- A Nordic/regional approach is needed to accelerate the transition toward low and zero-emission shipping. Coordination between countries will be key to avoid fuel/technology silos.
- A Nordic roadmap with binding commitments for the transition toward low and zero-emission shipping would be key to guarantee that the industries of the Nordic countries move at a similar pace and to avoid delays in the transition of the Nordic shipping industry.
- The policies should be designed with a systemic view that considers cross-sector and cross-industry factors.

6.4 Publications

The main publications of this work package include two scientific articles, one policy brief and one book chapter:

Latapí, M., Davíðsdóttir, B., & Jóhannsdóttir, L. (2023). Drivers and barriers for the large-scale adoption of hydrogen fuel cells by Nordic shipping companies. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2022.11.108

Latapí, M., Davíðsdóttir, B., Jóhannsdóttir, L., & Cook, D. (2022). Understanding the barriers for using green hydrogen-based fuels in Nordic shipping with a focus on ferries. Available at: https://www.ivl.se/projektwebbar/hope.html but also included in the end of this report.

Latapí, M., Jóhannsdóttir, L., Davíðsdóttir, B., 2023. "Benefits and Opportunities of Zero-Emission Shipping in the Arctic" within the book "Towards a Sustainable Arctic: International Security, Climate Change and Green Shipping", edited by Michael Goodsite (University of Adelaide, Australia) and Niklas Swanström (Institute for Security and Development Policy, Sweden). Published May 2023. https://www.worldscientific.com/worldscibooks/10.1142/q0390#t=toc

An additional article is under preparation and will be submitted to an academic journal later in 2023.

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Hansson, J., Unluturk, B., 2023. *Cost-effective marine fuels and propulsion technologies for Nordic shipping – the role of hydrogen versus biofuels.* Proceedings of the EUBCE 2023 31st European Biomass Conference and Exhibition, 5-8 June, 2023, Bologna, Italy.

Latapí, M., Davíðsdóttir, B., & Jóhannsdóttir, L., 2023. *Drivers and barriers for the large-scale adoption of hydrogen fuel cells by Nordic shipping companies*. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2022.11.108

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Yum, K., Stenersen, D., forthcoming. *Design Study for a Ro-Pax Ferry with Hydrogen Fuel Cells using Design Lab Framework*. Journal Manuscript submitted for review in scientific journal.

Policy brief on barriers and drivers

Understanding the barriers for using green hydrogen-based fuels in Nordic shipping with a focus on ferries

Authors: Mauricio Latapí, Brynhildur Davíðsdóttir, Lára Jóhannsdóttir and David Cook, University of Iceland, Environment and Natural Resources Programme

Key messages

- The Nordic Ministers of Environment and Climate have agreed to develop zero-emission ferry routes between the Nordic countries.
- A promising option to consider is the use of green hydrogen and green hydrogen-based fuels.
- Policy interventions would be needed to facilitate the adoption of these fuels and to address the barriers associated with their use.
- Policymakers would need to prioritize addressing the high costs and lack of supply of these fuels, the lack of infrastructure for their use, and the uncertainty and high risks for early adopters.

Introduction

In May 2022, the Ministers of Environment and Climate from Denmark, Finland, Iceland, Norway, Sweden, Faroe Islands, Greenland, and Åland signed a joint Declaration for the creation of zero-emission ferry routes between the Nordic countries (NORDEN, 2022). The overall aim of the Declaration is to help the Nordic shipping industry accelerate its transition towards new fuels and propulsion technologies that have low emissions throughout their value chain from production to end-use. To support the transition, the Ministers agreed to focus on the ferry segment and to promote the creation of zero-emission ferry routes between Nordic countries. This would allow key stakeholders to gain experience and test new fuels and technologies in pilot projects involving short ferry routes. However, currently only a limited number of fuels and technologies have the potential to deliver zero-emissions throughout their lifecycle, and most are not immediately available for the Nordic context.

Besides battery-electric ferries, a promising option for the ferry segment is the adoption of green hydrogen and green hydrogen-based fuels such as ammonia, methanol, and liquid organic hydrogen carriers (LOHC) (see: DNV, 2022; IRENA, 2021b). Using these fuels could result in significant environmental benefits, mostly from reducing emissions of greenhouse gases (GHG) and air pollutants in different stages of the value chain. These benefits are mainly expected at the production, processing, and end-use of the fuels. While the environmental benefits of transitioning to these fuels are easily identifiable, there are relevant challenges that need to be considered for upscaling their use, including those associated with a higher demand for renewable electricity. Identifying and understanding the barriers can help Nordic policymakers define the actions needed to establish zero-emission ferry routes. Policy makers would also need to consider that policy intervention would be required at different stages of the hydrogen value chain and across several industries.

To help decision makers, this brief identifies and explores the key barriers that need to be prioritized to facilitate the adoption of green hydrogen and green hydrogen-based fuels in zero-emission ferry routes. The insights presented are based on research conducted by the University of Iceland within the HOPE project (Hydrogen fuel cells solutions in shipping in relation to other low carbon options – a Nordic perspective) during the years

2021 and 2022. The research included an extensive analysis of the literature as well as a workshop and interviews with key stakeholders from the Nordic shipping industry and the Nordic hydrogen value chain.

Green hydrogen-based fuels

A color designation is given to hydrogen based on the way in which it was produced. The color depends on the process, feedstock, and energy sources used to produce it. In the case of green hydrogen, the color means that it was produced by a process called electrolysis using water and renewable electricity. The resulting product (green hydrogen) can then be used directly, or it can undergo additional processes to convert it into another fuel. Depending on the process used, green hydrogen can be converted into ammonia, methanol, or liquid organic hydrogen carriers (LOHC).

Key barriers for the adoption of green hydrogen and green hydrogen-based fuels

A variety of barriers can limit the adoption of green hydrogen and green hydrogen-based fuels for their use in zero-emission ferry routes in the Nordic countries. The main barriers that need to be prioritized are:

- **High comparative costs**: Transitioning from fossil fuels to green hydrogen-based fuels represents significant challenges. Perhaps the most relevant is to make them cost-competitive and attractive for end-users, mainly ferry owners and operators. To do so, two things need to happen: 1) The cost of fossil fuels needs to increase. The current prices of fossil fuels used in shipping, such as heavy fuel oil (HFO), marine diesel oil (MDO), and liquified natural gas (LNG), do not incorporate all the external costs to society from their production and consumption. In the field of environmental economics, these are called negative externalities and include aspects such as the costs associated with air pollution, GHG emissions, oil spills, underwater noise and vibrations, biodiversity loss, among others. 2) The costs of green hydrogen-based fuels need to decline. To do so, costs must be reduced in all stages of the value chain from their production to their delivery and bunkering to the vessels.

- **Lack of supply of green hydrogen**: Besides costs, an immediate techno-economic challenge is the availability and supply of green hydrogen that can be purchased and delivered to Nordic ports. A limiting factor for producing it at a large scale has been the price of renewable electricity, which until recently had been too expensive compared to fossil fuels. However, the price of renewable electricity has declined significantly (mainly from wind and solar) and green hydrogen is now expected to become cost-competitive by 2030 in some regions (see: IRENA, 2021b; IRENA, 2022a). While a low price of renewable electricity is fundamental for increasing green hydrogen production, there are other relevant aspects to consider for the Nordic region: 1) Producing green hydrogen requires large amounts of water and renewable electricity . This means that policy makers will need to prioritize the supply of these commodities. While the Nordic countries already have a high supply of renewable electricity in their energy mix (see: IRENA, 2022b), the production of green hydrogen at a large scale would represent a significant extra demand for renewable electricity. This means that investments would be needed to increase the capacity for producing renewable electricity and doing so could take several years in the design, planning, and construction of new infrastructure. Using large quantities of water for industrial use can be limited by its physical availability but also by regulations. For the Nordic countries this could represent a competitive advantage for producing green hydrogen since they have a higher availability of fresh water in comparison to most of the European countries (see: European Commission, 2022). 2) The historical demand for hydrogen in the Nordic region has been mostly limited to the petrochemical industry in small quantities and most of it has been with production and use on-site. As a result, the infrastructure in the Nordic countries for the hydrogen value chain associated with shipping is not readily available which means that new infrastructure would need to be developed to support an increased supply.

- **Lack of infrastructure**: The lack of supply of green hydrogen is in part linked to the lack of infrastructure. While the Nordic ferry segment has been a frontrunner in the use of alternative fuels, mainly through the early adoption of LNG and most recently with battery-electric ferries, its infrastructure is mostly designed for fossil fuels. Three aspects should be taken into consideration: 1) The hydrogen value chain can benefit from some of the existing infrastructure used by other industries. For example, most hydrogen-based fuels can be transported through existing pipelines for natural gas. A starting point would be through blending which means that hydrogen-based fuels are mixed (in a small percentage) with the blend flowing through the pipeline (see: International Energy Agency, 2019). In the Nordic context, the hydrogen value chain could benefit from using existing infrastructure such as the Norwegian oil and gas pipelines. 2) New infrastructure for the hydrogen value chain will, however, also need to be developed. For instance, ports will require on-site or nearby storage and bunkering facilities to attend vessels using green hydrogen-based fuels. 3) New infrastructure the production, transmission, and distribution of renewable electricity will be required. This is particularly relevant considering that green hydrogen-production will compete for the use of renewable electricity with other industries and consumers in the Nordic region such as energy intensive industries (e.g., aluminum smelters and iron production) and in the electrification of transportation systems.

- **Uncertainty and high risk**: The lack of availability and supply of green hydrogen along with the lack of infrastructure means that it cannot be purchased and delivered with the same guarantees as fossil fuels being used today in the Nordic region. This results in a high level of uncertainty for stakeholders and potential users. Another aspect to consider is that green hydrogen and hydrogen-based fuels are still being tested for shipping. This means that these fuels have not reached commercial maturity and therefore early adopters are expected to face high risks, mainly financial and operational, which in turn translate into high initial investments and costs.

- **Additional barriers**: Policy makers should keep in mind that additional barriers will need to be addressed. The three most relevant for the creation of zero-emission ferry routes between Nordic countries are: 1) Lack of knowledge regarding new fuels, their characteristics, and how to operate them safely. This includes the need for trained crew and specialized maintenance staff; 2) Lack of regulations and standards for the adoption of green hydrogen-based fuels for their use in shipping. This includes aspects related to the bunkering and storage of the fuels; 3) Operational challenges, mainly in relation to onshore and on-board storage as well as bunkering.

Conclusions

This policy brief discussed the main barriers that would need to be prioritized to facilitate the adoption of green hydrogen and green hydrogen-based fuels in zero-emission ferry routes between Nordic countries. The insights presented can help policy makers recognize and understand the challenges for establishing zero-emission ferry routes and can help prioritize the actions needed. The findings suggest that policy intervention will be required at different stages of the hydrogen value chain and across different industries. Therefore, a holistic and systemic perspective and a close collaboration between stakeholders will be required to establish zero-emission ferry routes between the Nordic countries. The key aspects to be considered are:

- Addressing the barriers will require close coordination and collaboration between Nordic authorities and stakeholders. An initial step could be the creation of working groups which could begin by defining a clear strategy with specific deliverables. That the barriers may be addressed through European instruments such as the Emissions Trading System (ETS) should be considered.

- Policy makers will need to evaluate the cost-effective potential of each fuel for different ferry routes. They will also need to consider optimal ways for introducing the fuels and identify how and when subsidies and policy intervention will be required in the different stages of the hydrogen value chain. This should be done considering the wider context of the Nordic region and not limited to the routes and fuels. The cost-effective analysis should follow a life-cycle perspective of the fuel from production to end-use. This, among other parameters (e.g. energy security), would help determine to what extent the production of green hydrogen-based fuels should be done within the Nordic region or imported from other regions.

- Policy packages should be prioritized over focalized policies for the establishment of zero-emission ferry routes. This requires a cross-industry and transnational approach in which Nordic collaboration will be essential. The policy packages should consider ways for mitigating risks for early adopters, the establishment of new projects, and the development of infrastructure.

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