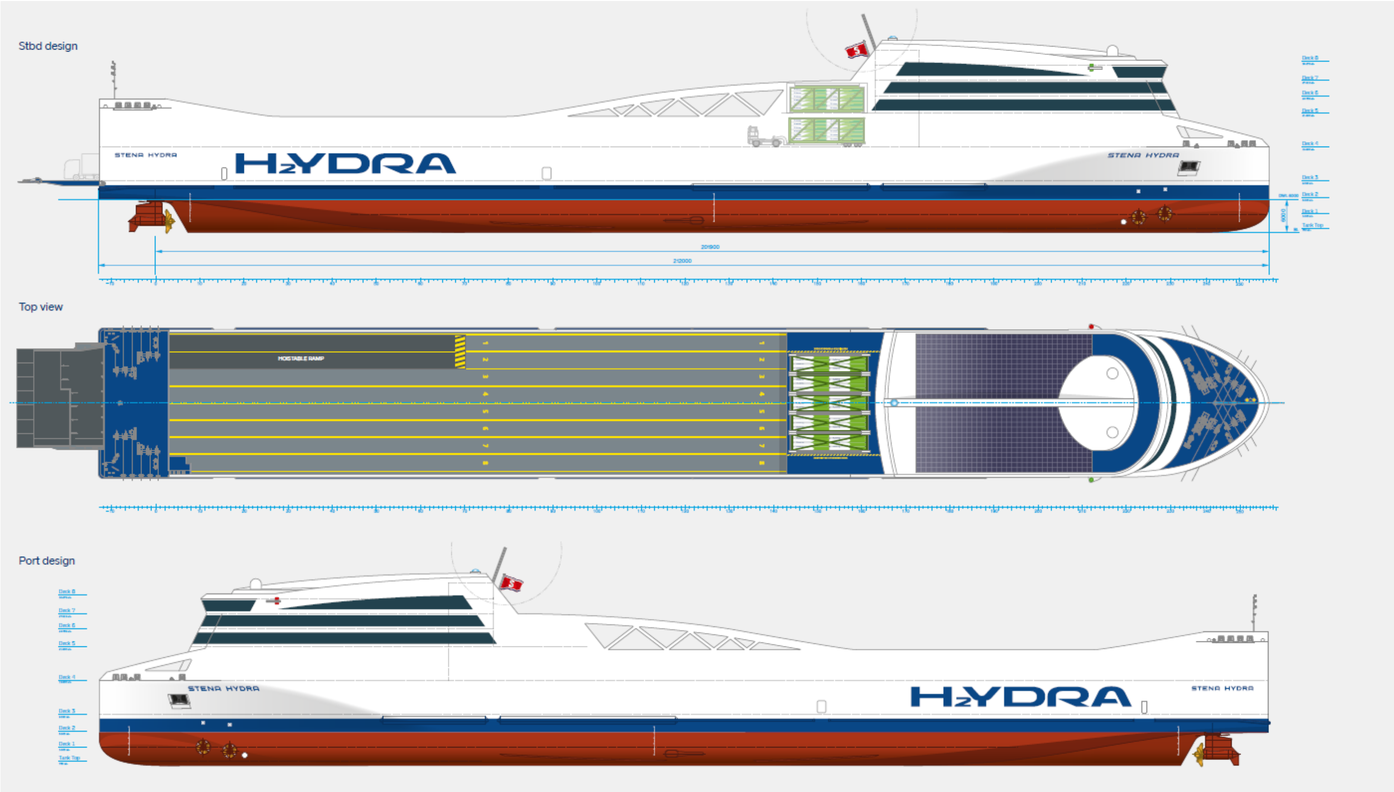

Concept design and environmental analysis of a fuel cell RoPax vessel

Report in the HOPE (Hydrogen fuel cells solutions in shipping in relation to other low carbon options) project

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Alternative marine fuels, Hydrogen propulsion, Fuel cells, PEM fuel cell, Cost, Emission, Ferry, RoPax ship

Summary

This report includes a ship concept design developed for a RoPax ship (a ferry transporting passengers and goods) with hydrogen fuel cell propulsion for intended operations on the route Frederikshavn (Denmark) to Gothenburg (Sweden). The assessments, performed within the HOPE (Hydrogen fuel cells solutions in shipping in relation to other low carbon options – a Nordic perspective) project, shows that it is technically feasible to build and operate such a ship with existing technology for the studied route between these two Nordic countries. Also, the costs of such a concept are assessed and compared to other fuel options including battery-electric propulsion, electro-ammonia, electro-methanol, biomass-based methane, or fossil liquefied natural gas (LNG), as well as conventional fossil marine gas oil (MGO).

The overall result from the comparative analysis of the estimated costs is that the hydrogen fuel cell ship, when assuming current or near future costs for the technology and the hydrogen, is estimated to be some 25 percent more expensive than a conventional fossil fuelled (MGO) RoPax ship (when including costs for emissions in the EU emission trading scheme). However, the cost developments are uncertain. In the case that fuel cell prices, and hydrogen prices, are decreasing, and todays cost levels of emission allowances in the EU emission trading scheme (ETS) increase, the hydrogen fuel cell ship could possibly be operated at lower total costs compared to the MGO fuelled ship.

A cost benefit analysis was also performed, comparing costs linked to the technical implementation of hydrogen fuel cell solutions in shipping (with a private and social perspective) to benefits in terms of reduced external costs linked to lower emissions and potential subsides. The cost benefit assessment also confirms that the investment from a private perspective is not cost effective and that additional subsidies may be needed for investments in fuel cell hydrogen technology to take place. The cost effectiveness from a social perspective is strongly dependent on values of highly uncertain parameters.

The impacts of emissions of hydrogen as fuel in a Nordic context were assessed for deployment scenarios for hydrogen and fuel cell solutions in Nordic shipping. There is a considerable potential for emission reductions both in terms of CO_2, nitrogen oxides (NO_X), sulphur dioxide (SO_2) and particulate matter (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. Considering the relatively long lifetime of vessels, investments must be made soon to enable a hydrogen powered shipping fleet in the near future. Since it is currently not economically viable with hydrogen and fuel cells vessels there is need for subsidies and investments in pilots to develop solutions and speed up the process.

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1 Introduction

The Nordic countries aim for a carbon-neutral Nordic region[1]. 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 (Hydrogen fuel cells solutions in shipping in relation to other low carbon options – a Nordic perspective) project addresses how regional shipping in the Nordic region can make 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 an operating distance of around 100 nautical miles, is designed for including operation with hydrogen as fuel and fuel cells for energy conversion.

Both the conditions for designing such a ship and the consequences are studied (Stenersen and Lundström, 2023). 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 (Latapí et al., 2023). For example, in terms of drivers, policy options needed to accelerate the uptake of hydrogen based marine solutions are assessed (Latapí et al., forthcoming). Also, the potential of producing these fuels in the Nordic region are reviewed from a shipping perspective (Stenersen and Lundström, 2023).

In this report, the overall design of the concept ship is compared with other fuel alternatives from a cost perspective. A realistic potential for uptake of these technologies/fuels by Nordic shipping are also assessed and the benefits regarding lower emissions of GHGs and air pollutants are calculated. This report summarizes the work performed on concept design and scenario and impact analysis of the HOPE project (work packages 3 and 5).

[1] Declaration on Nordic Carbon Neutrality, https://www.norden.org/en/declaration/declaration-nordic-carbon-neutrality

2 Concept design and associated assessments

Within HOPE, a concept ship has been designed for ship propulsion by a fuel cell fuelled by hydrogen. The results presented in Stenersen and Lundström (2023), 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. In addition, interactions have been close with the work conducted on laboratory tests and models of concept design of the HOPE project (Yum & Stenersen, forthcoming), from which for example energy need data have been taken and further used within the concept design studies presented here.

The ship concept design has been delivered in terms of so-called General Arrangement drawings of the ship (see Figures 1-3 and Figures A1-A3 in Appendix A), general descriptions of the propulsion system and a brief discussion in relation to some of the solutions choices. The hydrogen fuelled ship concept developed has been named *Stena H$_2$YDRA*.

The ship concept design has also been compared with selected alternative solutions for similar vessel design with other propulsion solutions such as fully battery electric, electro-ammonia, electro-methanol, liquefied biogas (LBG), fossil methane in the form om liquefied natural gas (LNG) and conventional fossil marine gas oil (MGO). The comparisons have focused on total costs of ownership, representing annual costs from operation and investment. The cost estimations also include the costs of carbon dioxide (CO_2) emissions within the EU Emission Trading System (EU ETS).

2.1 Ship concept design

The ship concept design includes assumptions on needed energy storage and the concept was made for both compressed and liquid hydrogen storage. The principal particulars and ship capacity for the concept design of the vessel Stena Hydra is listed in Table 1.

Table 1. List of the principal particulars and ship capacity for the concept design of the vessel Stena Hydra as illustrated in the General Arrangement for the ship concept design. Note that propulsion power has been varied during the latter phases in the ship concept design process.

Principal particulars		Capacities	
Length O.A. (meters)	212 000	Deadweight (metric tons)	About 6000
Length P.P (meters)	201 900	Payload (metric tons)	About 4500
Beam (meters)	26 700	Lane meters	About 2500
Design draft (meters)	6000	Passenger facilities	Day ferry
Scantling draught (meters)	6300	Crew cabins	50 single
Propulsion power	2x7.5 MW		
Net hydrogen storage (approximately)	10 tons		
Operational range	150 NM		
Speed	22 kn		

A ship design drawing of the hydrogen fuel cell concept ship Stena H2YDRA is presented in Figure 1. Figure 2 represents a General Arrangement drawing for the hydrogen fuel cell RoPax ship for the compressed hydrogen concept. Supplementary General Arrangement drawings for this concept as well as the liquid hydrogen concept version are included in Appendix A. Figure 3 includes a so-called one line diagram showing the electrical power system with compressed hydrogen storage (corresponding figure for the liquid hydrogen storage case is included in Appendix A).

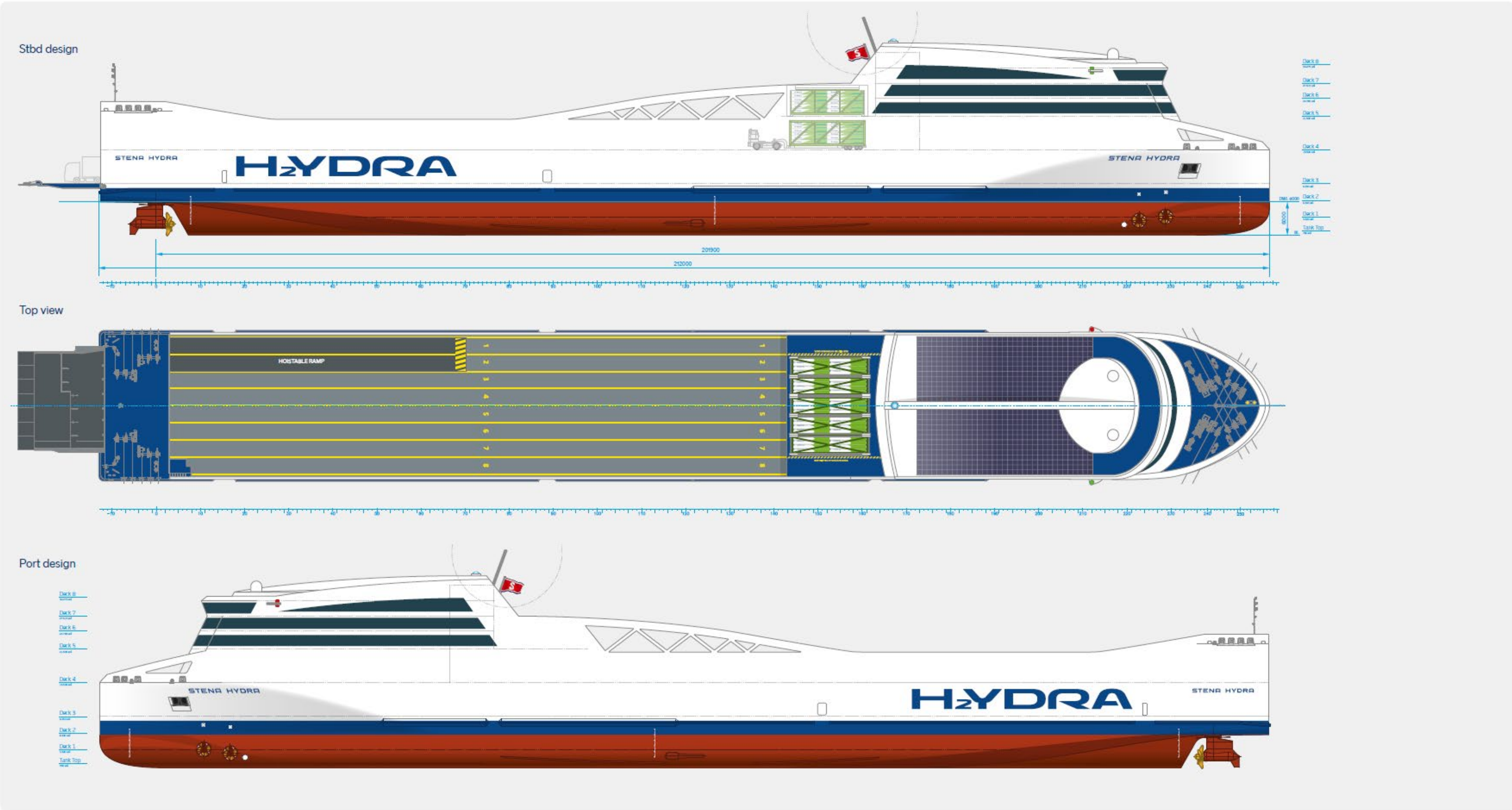

Figure 1. Ship design drawing of the hydrogen fuel cell concept ship Stena H2YDRA.

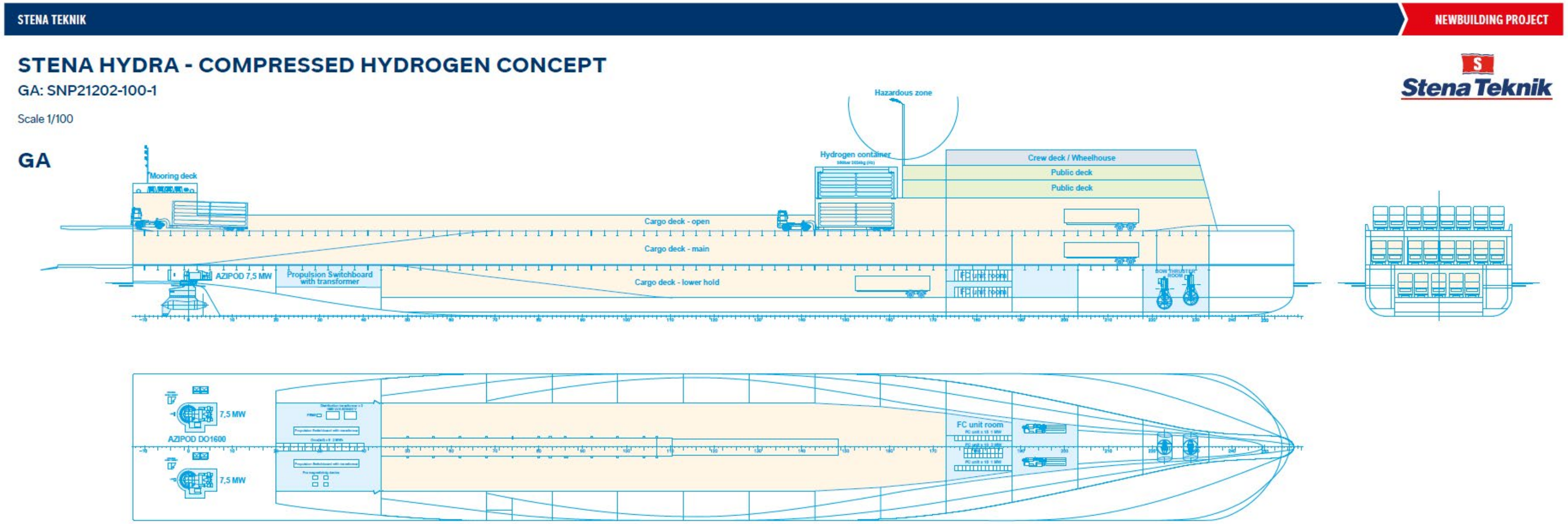

Figure 2. General Arrangement drawing of the hydrogen fuel cell concept ship Stena H_2YDRA showing cargo decks etc.

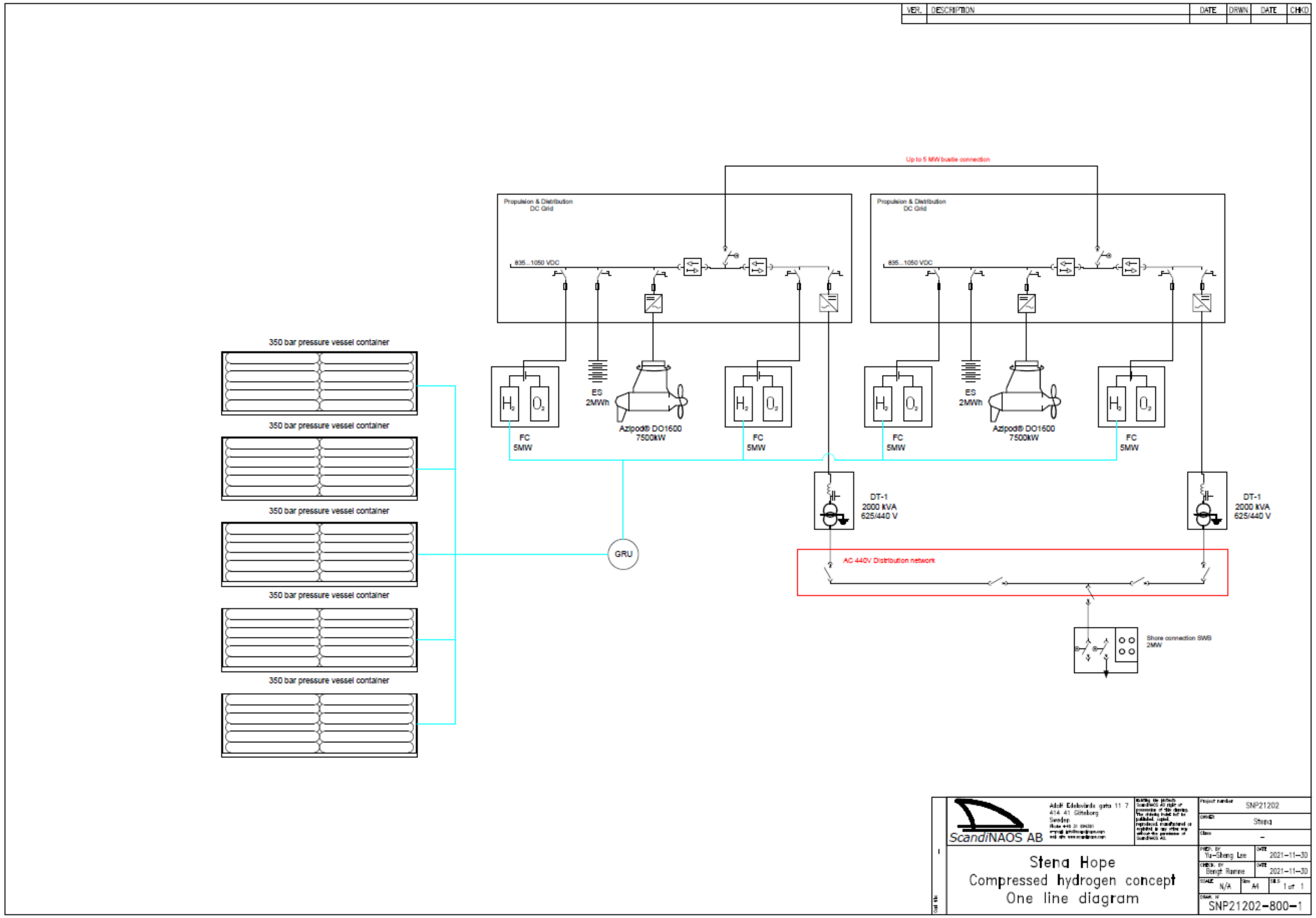

Figure 3. One line diagram showing the electrical power system for the compressed hydrogen storage concept version.

2.2 Powertrain design

The powertrains to be used are designed including fuel cells and hybrid solutions. The total power need, propulsion economy as well as route performance for the operations of the vessel in a roundtrip perspective are estimated for different installed fuel cell power capacity. The chosen capacity for the fuel cell installation is 25 MW since the lowest roundtrip propulsion costs were estimated for that size of the installation. The assumed size of the electrical engines for the propulsion is in total 20 MW. The estimated average fuel cell energy efficiency based on the assumed load profile modelled, based on fuel cell data from the manufacturer Powercell, is 52 percent and the efficiency of the electrical engine is set to 98 percent.

2.3 Hydrogen storage and handling

The requirements for storing and handling the fuel are designed. This considers the options assessed in Stenersen and Lundström (2023) as well as safety regulations. During the project, different options for storage and handling of hydrogen have been discussed and assessed. The chosen system on which the cost estimations are based is compressed hydrogen stored and handled in an ISO container where empty containers are replaced with full containers during the one-hour port stay. In total 10 containers containing about 1 ton hydrogen each are assumed to be stored at weather deck on-board. It must be noted that more detailed safety assessments, as well as ongoing development of hydrogen bunkering systems, might suggest another solution as the most overall favourable in the future. The different solutions all come with different pros and cons.

2.4 Basis for cost calculations

The basis for the cost calculations is the specific requirements for the ship type operating on the specific route for the specific fuels being analysed. Such parameters of the ships, which are influenced by the change in powertrain such as backup and auxiliary systems, are briefly described in this section together with a description of the costs calculations.

The total roundtrip consumption per one way trip including auxiliary systems and hotel load in port etc. is estimated to 2.2 ton of hydrogen (Yum & Stenersen, forthcoming).

Cost figures for the fuel cell installation is obtained from the fuel cell manufacturer Powercell and the fuel cell cost is assumed to be 1 400 EUR/kW, the installation cost is 280 EUR/kW, and the annual maintenance cost including replacement due to degradation is assumed to be 0.044 EUR/kWh. Expected lifetime and depreciation time is set to is 15 years, discount rate 7.5 percent and all annual investments costs are calculated based on constant payments over the lifetime. In addition, costs for electrical engines including maintenance as well as a redundancy/range extending auxiliary diesel engine installation of 10 MW as well as a 2 MWh battery installation is included in the total propulsion system for which capital costs and maintenance costs are added. Maintenance and operational costs for different propulsion components are estimated as an added percent on annual capital costs for the specific system based on figures from Kanchiralla et al (2022). Specific capital costs for batteries, and electrical engines are also based on Kanchiralla et al (2022).

The costs for building and operating the vessel have been outlined together with Stena Teknik who have long term experience of cost estimation for the building, manning and operation of Ropax vessels on the specific route of the case study vessel. Total operational costs estimates consist of energy costs (including propulsion, heat and electricity consumed on-board), 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 (hydrogen vessel only), electricity charging system (battery-electric ship only) and manning.

Regarding manning, only the crew running the ship, including the engine room, has been included. The fuel cell ship and the battery electric ship has been assumed to be manned with four less crew on-board (19 people versus 23 in the case of combustion engine propulsion). The reason for lower manning on-board hydrogen fuelled, and battery electric ships is mainly the lower demand of engine room maintenance with a more electrical oriented solution.

Since shipping will be included in the EU ETS, the cost for emission allowances for CO_2 emissions has also been included in the cost calculations. The price for carbon allowances within EU ETS is not fixed, instead the price will vary with supply and demand for allowances. During the period 2019-2020, the cost for emission allowances has been around 20-30 EUR/ton CO_2. In the beginning of 2021, prices for allowances started to increase and since end of 2021, the cost for emitting CO_2 has most of the time been between 70 and 100 EUR/ton CO_2. Since emission allowances, over time, will be removed to decrease total CO_2 emissions, it has been assumed that the EU ETS price will continue to be relatively high. The base case for the calculations is an EU ETS price of 100 EUR/ton CO_2. However, further price increases can also be expected, and a higher price has been used within the sensitivity analyses.

The amount of CO_2 emission allowances that the ship owners, managers, and charterers will need to purchase will be reported and verified through the existing EU MRV (Monitoring, Reporting and Verification) system. Even though the specific details are not yet revealed it is likely that the use of biofuels, renewable fuels of non-biological origin, and recycled carbon fuels fulfilling the sustainability and GHG emissions saving criteria under the EU's Renewable Energy Directive (RED) will account as zero carbon fuels. Therefore, within this study, it is assumed that no emission allowances will be needed for ships fuelled with hydrogen, electricity, electro-ammonia, electro-methane as well as biogas (LBG). Emission allowances are, on the other hand, accounted for MGO and LNG in line with the standard emission factors for these fuels within the EU MRV.

2.5 Other solutions

The analysis of a ship propelled by hydrogen and fuel cells, described as the concept design vessel has also been modified to cover other fuel-propulsion solutions. The vessel and ship performance (e.g., speed and transport work) are assumed to be the same for the different solutions being compared which represents a reasonable assumption for this overall comparison. However, there will probably be some differences in final design solutions due to the different propulsion choices such as cargo deck layout in relations to different fuel storage needs etc. which has been overlooked in this study.

The six fuel and propulsion options for the RoPax vessel that are being compared with the hydrogen fuel cell option are:

- Battery-electric propulsion where batteries are charged at the port stay with shore side electricity connection.

- Combustion of electro-ammonia in dual fuel marine diesel engines built to run on either diesel fuel or ammonia.
- Combustion of electro-methanol in dual fuel marine diesel engines built to run on either diesel fuel or methanol.
- Combustion of bio methane in dual fuel marine diesel engines built to run on either diesel fuel or methane.
- Combustion of fossil LNG in dual fuel marine diesel engines built to run on either diesel fuel or methane.
- Combustion of conventional fossil marine gas oil (MGO) in conventional marine diesel engines.

For the different solutions, the estimated output on the propeller shaft for the hydrogen fuel cell concept vessel as well as the other consumption onboard from auxiliaries etc. have been the basis for the power need. Consumption of electricity has been estimated based on energy efficiency conversion in a system perspective taken from Rise and Chalmers (2021) (87 percent electricity conversion from grid to shaft energy). Consumption of ammonia, methanol, methane and MGO has been estimated based on energy efficiency conversion in a system perspective covering the fuel efficiency for the different engine systems included in the comparison based on Kanchiralla et al. (2022). Also, the comparative basic costs for the different engines, except fuel cells, have been taken from Kanchiralla et al. (2022) but have been normalised with the capital and installation costs for conventional diesel engine propulsion system estimated in discussion with Stena Teknik, who has widespread experience of purchase of such systems. A comparison of the efficiency from fuel (or electricity from the grid) to shaft energy for the six different assessed fuels is presented in Table 2.

Table 2. Energy efficiency from fuel to shaft energy for the assessed fuel-propulsion options (from electricity for the battery electric case).

Hydrogen FC	Battery-electric	Electro-ammonia	Electro-methanol	Bio methane	LNG	MGO
50 %	87 %	44 %	48 %	48 %	48 %	48 %

Energy prices for alternative fuels (hydrogen, electricity, e-ammonia, e-methanol, biogas) are taken from Brynolf et al. (2022). The costs have been compared with future fuel costs estimates in other studies and fits reasonably well with other studies being published, see Figure 4. Please note that the cost figures represent cost estimates for 2030, that the cost assumption for methanol is based on biomass hydrogenation to methanol and that the study assess the ammonia fuel to be more costly than methanol per energy content, while the opposite relation can be found in other studies. However, future cost predictions for alternative fuels are, like fossil fuel prediction costs, contains large uncertainties. Even short-term cost predictions on energy contains large uncertainties and fuel prices also vary significantly over time.

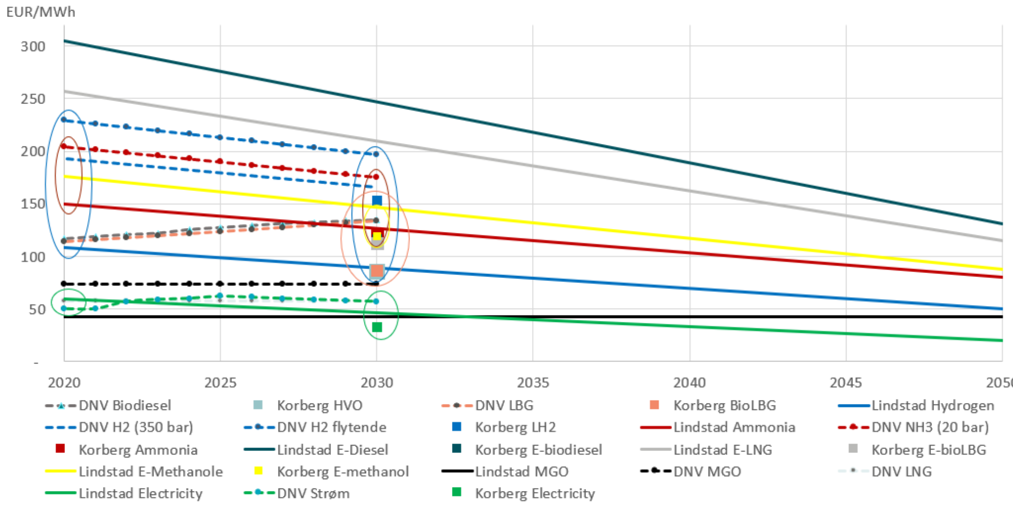

Figure 4. Comparison of fuel cost estimates from three different studies. Lindstad (2021) reports costs for 2020 and 2050, Korberg (2021) estimates costs for 2030 (shown as square dots) and DNV (2019) presents annual cost development predictions for the years 2019 until 2030. The height of the color-coded ellipses illustrates the cost spread between the studies for similar fuels. From Jivén et al., 2022.

Cost predictions for fossil fuels are based on historical costs for MGO and LNG bunkered in Rotterdam published by Ship & Bunker (2023). It has been assumed that future bunker fuel prices for MGO and LNG will be more in line with cost levels before the energy crisis due to the Russian war on Ukraine. The base case for fossil energy prices represents the approximate energy cost levels of today (and are in line with average cost levels of 2021). The fuel prices for all fuel and energy carriers used in this study are presented in Table 3.

Table 3. Energy prices used in the base case calculations for the different fuel-propulsion options.

Hydrogen	Electricity	Electro-ammonia	Electro-methanol	Bio methane	LNG	MGO	Unit
115	50	149	121	104	50	65	EUR/MWh
3 833		774	662	1 348	685	776	EUR/ton

2.6 Economic ship concept performance and comparison with alternative solutions

The main task has been to estimate the cost, as well as perform sensitivity analyses for the hydrogen fuelled fuel cell ship. However, to understand if the concept vessel performance can be seen as competitive compared to other fuel-propulsion solutions, also cost estimates for the other options have been made.

As expected, the base case cost estimation indicate that a fuel cell hydrogen RoPax ship will be more costly in a total cost of ownership perspective (annual costs) than for example running a conventional RoPax ship on MGO or LNG with conventional marine diesel engines. In total, the hydrogen fuel cell fuelled ship is estimated to be 40 percent more costly, excluding EU ETS costs and 25 percent more costly when including the estimated EU ETS costs (100 EURO/ton 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. However, in case cost linked to the EU ETS (100 EURO/ton CO_2) are included, the hydrogen fuel cell ship will increase annual costs with just over 7.5 MEUR per year compared to the conventional fossil fuelled ship, see Figure 5.

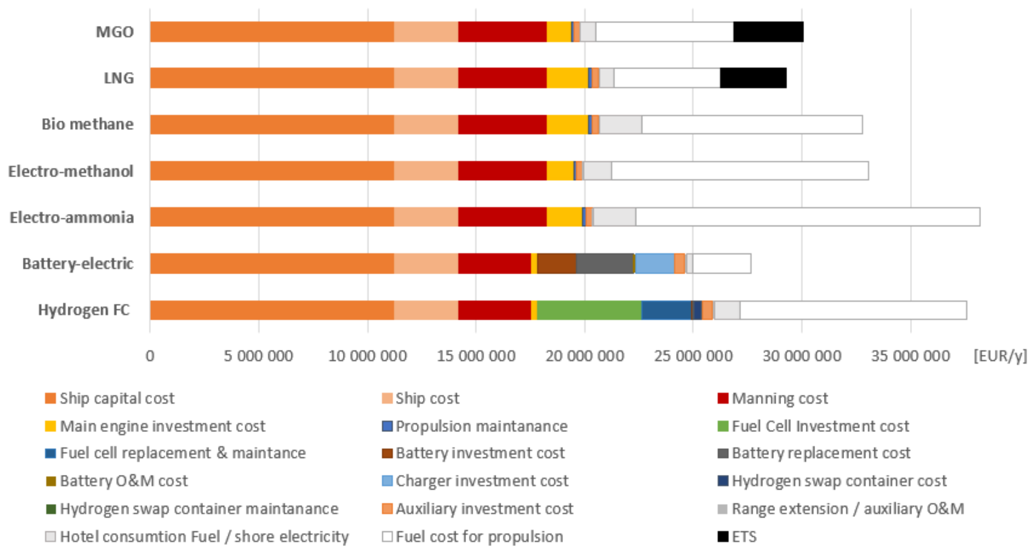

Figure 5. The total annual costs of ownership for running each of the assessed fuel-propulsion concept ships with base case assumptions. The costs are divided into investments and operational costs related to the ship construction, cost for maintenance, operations, propulsion, energy, and emission allowances within EU ETS. Note that the presented cost calculations shall be seen as an indication based on cost assumptions for each ship concept.

2.7 Sensitivity analyses of economic ship concept performance

The sensitivity analyses in relation to cost parameters focus on parameters that have a large impact on the total cost of ownership in relation to the hydrogen fuelled ship. The selected cost parameters include:

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

The cost for hydrogen in the base case is just under 4 EUR/kg (Brynolf et al., 2022) and represents the expected production cost in 2030. This cost is well below, for example, what Enova (2023) estimates that Norwegian green hydrogen projects for the marine industry can produce hydrogen at. Further, large efforts are made to support the development of hydrogen production in Europe and policy measures such as the European Hydrogen Bank (European Commission, 2023) that will support hydrogen production under the Innovation Fund umbrella can be expected to lower hydrogen production costs with 1-2 EUR/kg. Also, economy of scale, lower future electricity costs from large scale wind farms and technology development can be foreseen to further reduce the hydrogen price.

Therefore, a sensitivity analyses with a 25 percent lower hydrogen cost than the base case has been tested. The results are shown in Figure 6 which indicates that the hydrogen fuelled fuel cell ship is still some 15 percent more expensive in total cost of ownership on an annual basis, or annually 4.6 MEUR more expensive, than the MGO fuelled ship.

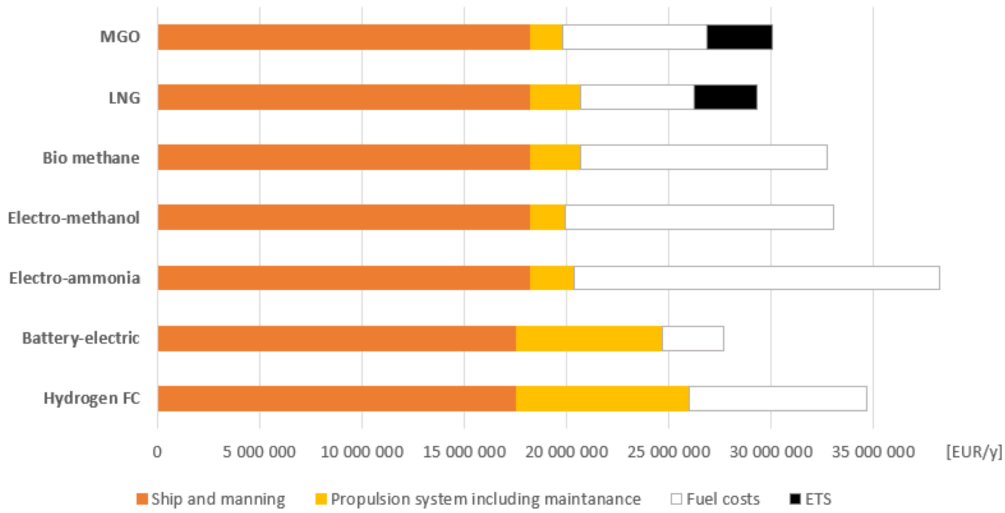

Figure 6. The total annual cost of ownership estimated for operating the studied fuel/propulsion concept ships in case the hydrogen costs represent 75 percent of the base case costs.

The base case for the hydrogen fuel cell RoPax ferry is based on cost assumptions for a pilot ferry built with mainly today's costs for the technology, which in some perspectives can be seen as mature since for example fuel cells can be purchased on the market and that earlier pilot installations have demonstrated the technology. The devices such as fuel cells are still very expensive, and with more numbers of produced units, the costs per installed unit is expected to decrease. Present costs for the PEM fuel cells of approximately 1400 EUR/kW is expected to be reduced by 50 percent in a couple of years, based on discussions with fuel cell manufacturers and other experts.

Looking at the automotive and other industries, Kampker (2023) expects costs levels of 600 EUR/kW for fuel cells to decrease towards levels of 300 EUR/kW with increased number of units being produced. The Advanced Propulsion Centre UK (2023) indicates that fuel cell systems cost for installations in large premium SUVs will decrease in total cost of ownership for a fuel cell installation from today's levels to approximately half the costs in 2030 (measured in costs per kWh). APC has earlier (2021) developed an industry consensus roadmap in which system installations costs in heavy duty vehicles have been estimated to 455 USD/kW in 2020, 195 USD/kW in 2025 and 80 USD/kW in 2035.

Therefore, a sensitivity analysis where the investment cost for fuel cells (at 1400 EUR/kW in the base case) was halved and the maintenance cost of the fuel cells (0.044 EUR/kWh in the base case) including replacement due to degradation over time was lowered to 75 percent of the base case cost, has been performed. The results are shown in Figure 7 and indicates that the hydrogen fuelled fuel cell ship is still some 15 percent more expensive in total cost of ownership on an annual basis or annually 4.6 MEUR more expensive than the MGO fuelled ship.

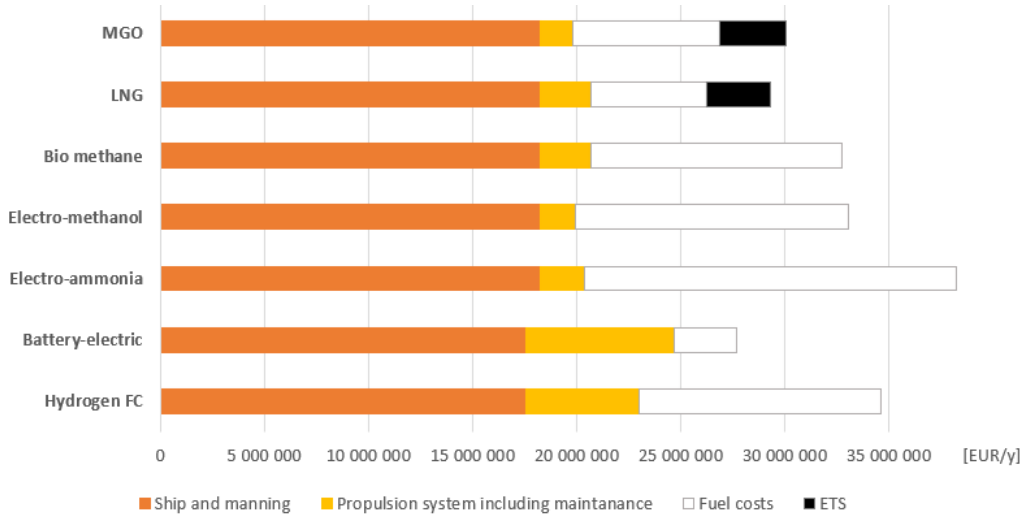

Figure 7. The total annual cost of ownership estimated for operating the assessed concept ships in case the cost of fuel cells is halved compared to base case and the cost for maintenance of the fuel cells including replacement due to degradation over time is lowered to 75 percent of the base case cost level.

The GHG emission reduction targets will decrease the total amount of GHGs that are allowed to be emitted under the ETS. This is expected to lead to higher cost for emission allowances in the system. Therefore, an EU ETS price of 200 EURO/ton CO_2 (a doubling compared to the base case) was tested in a sensitivity analysis. The results are shown in Figure 8 and indicates that the hydrogen fuelled fuel cell ship is still some 13 percent more expensive in total cost of ownership on an annual basis or 4.3 MEUR more expensive than the MGO fuelled ship.

For the case with a combination of the hydrogen costs set to 75 percent of the base case cost, halved fuel cell price (with maintenance and replacement set to 75 percent of base case cost) and doubled price for emission allowances in the EU ETS compared to base case the annual cost of ownership for the fuel cell ship is 5 percent lower than the conventional fueled MGO ship or some 1.5 MEUR lower annual costs (Figure 9). It can be noted that it is just when all the alternated costs, tested in the sensitivity analysis, are combined that the business case for the fuel cell hydrogen ship is competitive in economic terms in comparison with a conventional fossil fuel ferry operated on MGO.

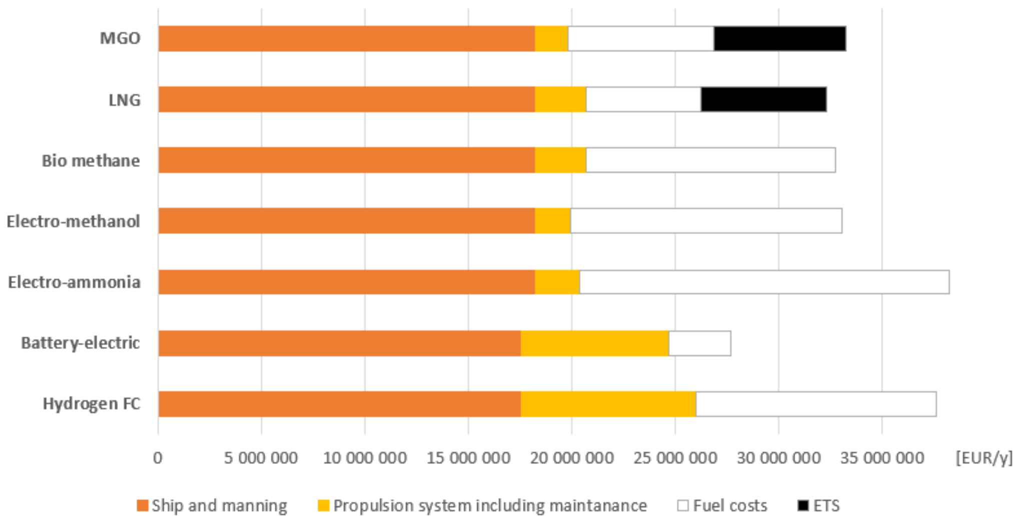

Figure 8. The total annual cost of ownership estimated for operating the studied concept ships in case the cost for carbon emission allowances in the EU ETS is doubled compared to the base case (i.e., reaches 200 EURO/ton).

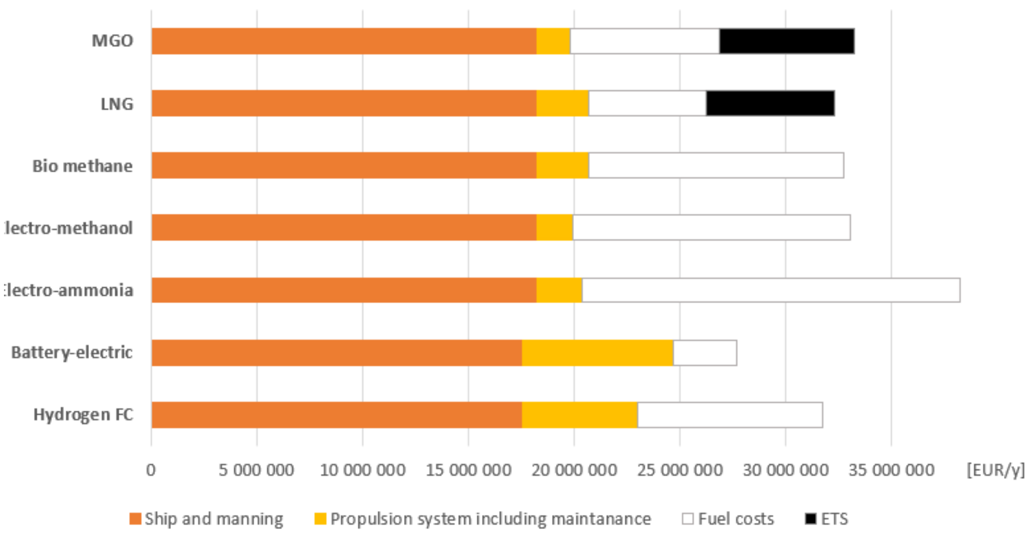

Figure 9. The total annual cost of ownership estimated for operating the studied concept ships in case the hydrogen cost is set to 75 percent of the base case costs, the fuel cell costs are halved and the cost for maintenance of the fuel cells including replacement due to degradation over time is lowered to 75 percent of the base case cost level and the cost for carbon emission allowances (EU ETS) is doubled compared to base case (i.e., reaches 200 EURO/ton).

3 Scenario and impact analysis

In WP5, 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 (see Section 3.1). Furthermore, 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 (see Section 3.2-3.5).

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 (represented by Denmark, Norway, and Sweden) when striving for low CO_2 emissions (Nordic carbon neutrality by 2050) have also been assessed using energy systems modelling, specifically the Open Nordic (ON) TIMES model (https://cleanenergyscenarios.nordicenergy.org/). This assessment is presented in Hansson and Unluturk (2023).

3.1 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 are included. 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 GHGs and air pollutants, are related to the increased costs for investments and fuel. For both cases we use the 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 Section 2.6. Also, alternative costs are used for a sensitivity analysis using the costs presented in Section 2.7.

For the private costs we assume a depreciation time of five years and an interest on the investment of 10 percent. The difference in annual costs between the FC and the MGO ship is about 10 600 kEURO of which 41 percent is for capital costs and 59 percent for fuel costs. The costs for ETS emission rights are assumed at 100 EURO per tonne CO_{2eq} and the rebate in port fairway fees is about 830 kEURO (see Parsmo et al. 2023 for a description of how this is calculated). 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-hydrogen technology to take place. However, since both the ETS cost in the future and the costs for FC technology (mainly the stacks) are highly uncertain we also made an alternative calculation using the assumptions in Section 2.7. Assuming an ETS cost of 200 EURO per tonne CO_{2eq} (i.e., a doubling compared to the base assumption), that the price for hydrogen is 25 percent lower (due to subsidies and reduced production costs) and that the price of fuel cells is half of the base assumption, 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. Assuming a depreciation time of 15 years and an interest of 3.5 percent the different annual cost between the ships amounts to 9 600 kEURO of which 35 percent is for capital costs and 65 percent for fuel costs. The annual emissions of the air pollutants nitrogen oxides (NO_X), sulphur dioxide (SO_2) and particulate matter (PM) are calculated for the FC and MGO ships using emission factors from MEPC (2014), Faber et al. (2020), MEPC (2021), Fridell (2022), and THETIS-MRV (2022). Values for external cost per mass unit of emissions for the Baltic Sea are taken from van Essen et al. (2019) and recalculated to 2020. The external cost for CO_2 used is 110 EURO per tonne. The resulting benefit to cost ratio is then 0.56 showing that with these assumptions the investment in FC-hydrogen technologies is not beneficial from a social perspective. However, the external cost for CO_2 is highly debated and may be assessed in different ways. In Rennert et al. (2022) it is argued to use a cost of 185 USD per tonne CO_2 (corresponding to 169 EURO). With this value, a 25 percent lower price for hydrogen and a 50% lower price of fuel cells, the ratio becomes 1.33. Thus, the conclusion regarding the cost effectiveness is strongly dependent on values of highly uncertain parameters.

3.2 Identification of the Nordic shipping fleet

To develop scenarios for potential deployment of hydrogen and fuel cell solutions in Nordic shipping, Nordic shipping needs to be defined. This since there is no official definition of what constitutes the Nordic shipping fleet. When reporting shipping related emissions to international conventions, nations utilize the amount of fuel sold to calculate the emissions. In Sweden, emissions are subsequently divided into domestic and international shipping based on AIS (Windmark et al. 2017). However, one challenge with relying on this approach is that the quantity of fuel sold may not necessarily reflect the amount utilized by ships calling at national ports, as ships can refuel at various locations before reaching a specific port. As it is difficult to identify the precise amount of fuel consumed in a country it is also challenging to evaluate the cost-effectiveness or benefits of introduced measures or policies. Several regulations that currently exist or are planned to be implemented provide support to individual ships (such as the NOx Fund, port or fairway discounts and European investment incentives) or regulate the total GHG emission volume (EU-ETS).

In this report, we have therefore chosen a different approach i.e., to analyze emissions linked to when a ship makes a Nordic port call by calculating emissions occurring during the transfer from the previous port to the subsequent port of each ship. This means that we include both domestic and international shipping per ship (from the previous to the subsequent port). The model employed in this project is described in equation (1) below. The model summarizes the total emissions for all ships and routes by using emissions factors.

$$Emission_{total} = \sum_{routes} \sum_{ship} Distance_{routes} \cdot Emission\ factor_{ship}$$

The *routes* encompass arrival statistics for all ships that called Nordic ports in 2018 exceeding 5 000 GT (MarineTraffic 2022). The calculations focus solely on merchant ships, thus excluding working vessels or fishing boats, for example. To assess fuel consumption from working vessels and fishing boats, it is likely more appropriate to utilize national statistics rather than specific routes. In this assessment, the distance is assumed to be the same for each voyage (Searoutes 2022). The distance between Nordic ports is set to 50% of the total distance to avoid double counting. The emission factors for CO_2 are based on emissions and fuel statistics per nautical mile (NM) as reported by shipping companies since 2018 (THETIS-MRV 2022). The fuel consumption is represented by the average reported data over a year (to account for variations in between distinct ship routes). The method diverges from the calculation in Yum and Sternersen (forthcoming), where data was generated for each individual ship route for a specific ship. The calculations in Yum and Sternersen (forthcoming) revealed that emissions for each distinct ship route can vary, not only in terms of distance (which is due to that the ship does not always follow the exact same path) but, more importantly, in speed, weather, and wind conditions, which influence the fuel consumption. However, the variation in fuel consumption is accounted for by utilizing average reported data over a year. Further description of scenarios, missing data and emission factors can be found in the sub-chapters bellow.

3.2.1 Data

In the port call statistics, a total of 524 760 arrivals and departures to and from ports in Iceland, Sweden, Denmark, Finland, and Norway were recorded in 2018 (MarineTraffic 2022). In total, 310 arrivals and 471 departures were excluded due to missing information regarding arrival/departure ports (0.3% of all data). Within this dataset, a total of 9 812 unique ship routes were identified, out of which 191 routes could not be matched to any corresponding route in the routing tool used (Searoutes 2022). These 191 routes accounted for 3 151 ship arrivals, which approximately represent 1.2% of all arrivals.

Sometimes emissions data per distance were missing in the MRV database (see next section). There could be various reasons for this, such as the absence of a requirement for Norwegian ferries to report to the MRV or potential errors in reporting. Worth noting is that 2018 marked the initial year for MRV data reporting. In certain instances, specific vessels showed unreasonably high emissions per nautical mile. This discrepancy could stem from either inaccurate emissions reporting or, more likely, errors in distance measurement. In both these cases (missing MRV data or high emissions per NM), these ships were instead assigned average data for the category to which the ship belonged.

Each ship was categorized based on its ship type and size. Ship type and other ship parameters like size were sourced from the Sea web's ship registry (IHS 2023). However, Sea web's categorization is more detailed, and thus, this data was aggregated to align with the ship categorization proposed by the International Maritime Organization's (IMO) 4th GHG report (Faber et al. 2020).

3.2.2 Emission factors

The emission factors can be divided into two distinct categories: direct emissions factors (CO_2, CH_4, N_2O, NO_X, SO_2, and PM) and upstream emissions factors (CO_2-e). The reduction potential for hydrogen for direct emissions was assumed to be 100%, given that this study has calculated emissions reduction for fuel cells. If internal combustion engines had been used for fuel, it would lead to other emissions, such as NOx.

The CO_2 emission factors per nautical mile (NM) are those reported by shipping companies in the MRV database (European Parliament 2016, THETIS-MRV 2022). The fuel consumption on which these emission factors are based is illustrated for all ships in Figure 10 (2018–2021). In the figure each point represents an individual ship. The figure indicates a variation in fuel consumption between different ship segments, but also illustrates how fuel consumption increase for larger ships. The effect of ships size seems to diminish as vessels become very large, see for example container ships and oil tankers. However, it is still important to note there are considerable variability even among ships of the same size and category. This variability is captured in this study by linking each ship to a unique emission factor through the ship's identification number, which was included in both the port call statics and the MRV data.

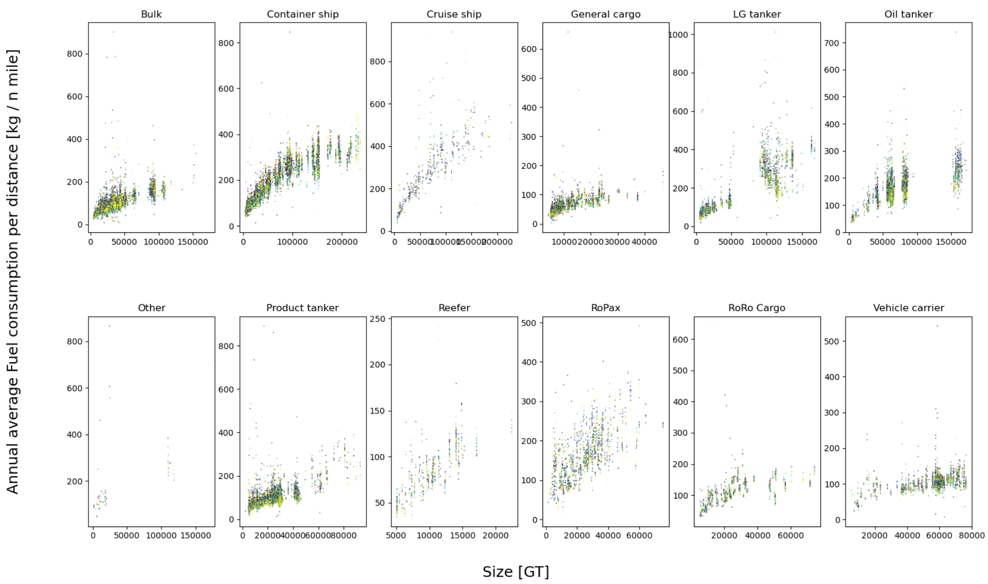

Figure 10. Reported annual average fuel consumptions per for 12 different ship categories (2018-2021). Each point represents one individual ship during on year. The different colors represent different years.

Emissions of PM, CH_4, and N_2O are based on IMO's emissions factors for the respective fuels (Faber et al. 2020). Fuel consumption was first estimated from MRV data by approximating fractions (in tons) of each fuel (residual oil - RO, marine diesel - MD, MeOH, and LNG). Unfortunately, the specific quantities for each fuel are not provided in the MRV data, resulting in a significant degree of uncertainty in this approximation. The estimated fuel fractions were then multiplied by the emissions factors for respective fuel type to determine each ship's total emissions of PM, CH_4, and NO_2 within the EU. Then, to calculate emissions per NM for pollutant X (in this case, PM, CH_4, and NO_2), the ratio between the total emissions of pollutant X and the reported CO_2 emissions was multiplied with CO_2 emission/NM for respective ship, as described in the following equation:

$$Emission\ of X\ per\ NM = \frac{Total\ emission\ of\ X}{Total\ CO_2} \cdot Emission\ of CO_2\ per\ NM$$

Conversion from CH_4 and N_2O to CO_{2e} was accomplished using conversion factors from the European Parliament and Council Directive 98/70/EC on the quality of petrol and diesel fuels (European Parliament and Council, 1998). A 100-year perspective on CO_{2e} emissions was consistently used in this study.

The emissions of SO_2 and NO_X were calculated based on the regulations specific to each emission type. These regulations depend on whether vessels operate within a designated Emission Control Area (ECA) or not. The European ECA zone, the highlighted red area in Figure 11 (VLIZ 2020), serves as an example. Different emission factors apply within and outside of ECAs. Consequently, the distances for each route (represented by the dashed lines) within each zone were estimated, resulting in a fraction as follows:

$$fraction\ in\ ECA = \frac{Distance\ in\ ECA}{Total\ distance}$$

To calculate this, the Geographic Information System (GIS) tool QGIS was used.

For SO_2 emissions, the sulfur content for each port call was calculated by first determining the average sulfur content using the following equation:

$$\overline{sulfur\ content} = sulfur\ content_{ECA} \cdot fraction_{ECA} + sulfur\ content_{No-ECA} \cdot fraction_{NO-ECA}$$

The baseline sulfur content in ECA was set to 0.1 % according to regulation while the sulfur content outside ECA was set to 2.7 % in 2018-2019 (Fridell et al. 2018), and changed to 0.5% in 2020. The fraction of fuel that consist of LNG, however, was assumed to have a lower sulfur content (approximately 0.003%). To determine the total SO_2 emissions for each port call, the sulfur content was then multiplied by a conversion factor between CO_2 and SO_2, along with the total CO_2 emissions, as described in the following equation:

$$SO_2\ emissions = \overline{sulfur\ content} \cdot\ conversion\ factor \cdot CO_2\ emissions$$

Here, the conversion factor (approximately 0.63) was depending on the difference between the molar mass of CO_2 and SO_2 and the carbon content in the fuel, according to the following equation:

$$conversion\ factor = \frac{S + 2 \cdot O}{C + 2 \cdot O} \cdot \frac{C}{S} / Carbon\ content$$

Where S (sulfur), O (oxygen) and C (carbon) are the molar mass of respective chemical element. Alternatively, the determined fuel quantity in kilograms could have been used for calculating the quantity of SO_2, removing the need for converting CO_2 emissions. Nevertheless, as noted earlier, considerable uncertainty remains regarding the specific type of fuel employed in the MRV data set. Additionally, certain ships utilize scrubbers to mitigate their emissions, thereby introducing further complexity. This estimation might be regarded as conservative in nature and as an initial attempt to estimate the emissions.

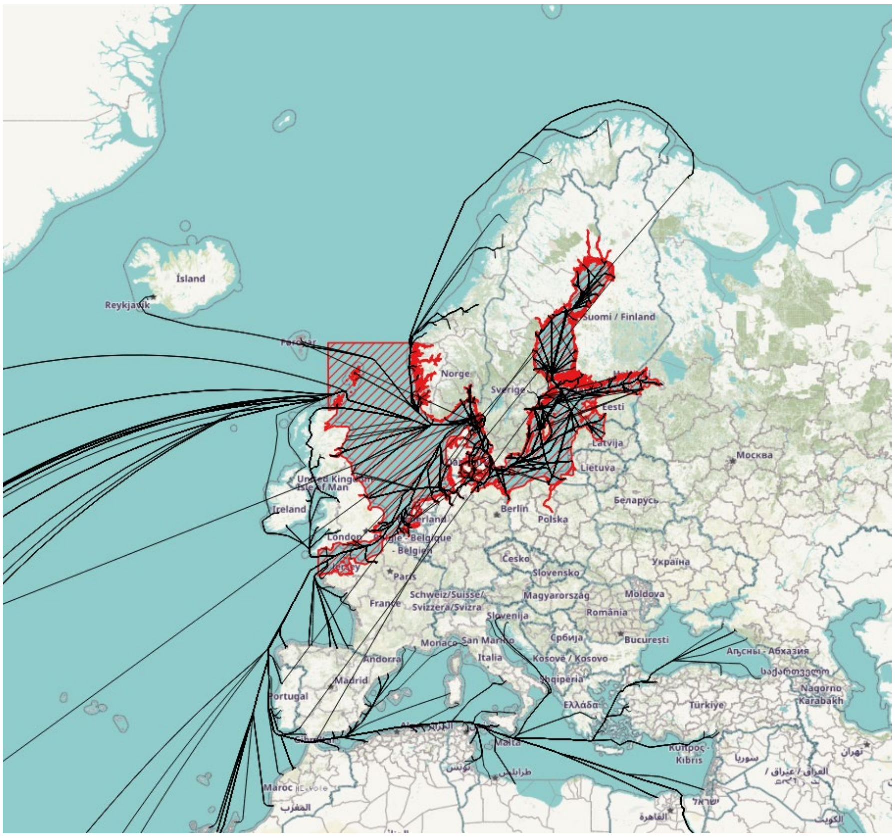

Figure 11. Illustration of the ECA-area (red) and routes to and from Sweden (used for illustraition purposes; the routes passing over countries where corrected in the calculations) (@OpenStreetMap contributors 2023, marineregions.org 2023).

The upstream emissions were calculated as the difference between producing fossil alternatives and renewable hydrogen via electrolysis. Upstream emissions for the produced hydrogen were 20.2 gCO_{2e}/kWh, based on a study conducted on life cycle emissions of renewable hydrogen in the Nordic countries by 2030 (Brynolf et al. 2023). However, no consideration was given to emissions arising from different propulsion technology. Upstream emission factors for fossil fuels were assumed to be 13.5 (RO), 14.5 (MD), and 18.5 (LNG) gCO_{2e}/MJ, relying on FuelEU Maritime (European Commission, 2021). However, the differing efficiency of the onboard engine and fuel cells system for respective fuel was considered (Kanchiralla et al. 2022) in order to obtain comparable values related to the transport work. These efficiency estimates, η_{fossil} = 42.7% and η_{H_2}= 47.2%, were only based on a single RoPax ferry. The total upstream emissions of H_2 were calculated according to the formula below:

$$Total\ CO_{2e}\ WTT\ for\ H_2 = \frac{EF_{H_2}}{EF_{fossil}} \cdot \frac{\eta_{fossil}}{\eta_{H_2}} \cdot Total\ WTT\ of\ CO_{2e} for\ fossil\ fuels$$

3.2.3 Scenario development

The scenarios developed were based on assumptions considering four factors: 1) transport development, 2) ship size, 3) energy efficiency improvements, and 4) improved utilization. Transport development involve scenarios to project trade development. The two trade scenarios used in this study, representing low and high growth, were the same as those employed by DNV (DNV GL 2020). The high trade development scenario represents a 200% rise in transportation activity by 2050 compared to 2018 (originally based on Smith et al (2014)). The alternative scenario (low growth) represents a more modest 40% expansion in transport work from 2018 to 2050.

The modeled development of transport work was complemented with assumptions regarding shifts in traffic patterns. These shifts include a progression of ship size, fuel efficiency, and cargo utilization. The ship size projections were based on DNV (2020), suggesting a 30% growth in container ship dimensions by 2050, a 40% expansion for gas tankers, and a 10% increment for bulk ships, while other ship categories kept their average sizes. All ship types were assumed to have a fuel efficiency in compliance with the EEDI regulation, a standard for new ships (IMO 2022). Throughout the modeling, aging ships were phased out and replaced by new ships, by an estimated average lifespan of 25 years across all vessel types. Furthermore, improvements in cargo utilization were considered, by assuming an enhancement of 10% by 2030 and 25% by 2050 (DNV, 2020).

The assumptions were applied on MRV data for Nordic ship traffic according to the model description in Figure 12. Development of transport work and utilization improvement are applied linearly on all ships in a certain segment, while the other parameters are applied only on new-built ships.

The baseline scenario emission was calculated with the following equation:

$$CO_{2_{scenario}} = CO_{2_{2018}} \cdot (1 + \Delta transport\ work) \cdot (1 - \Delta energy\ efficiency) \cdot (1 + \Delta ship\ size)/(1 + \Delta\ utalization)$$

The estimation of CO_2 emissions of the Nordic shipping fleet was the basis for the development of scenarios which were applied for future shipping in 2030 and 2050.

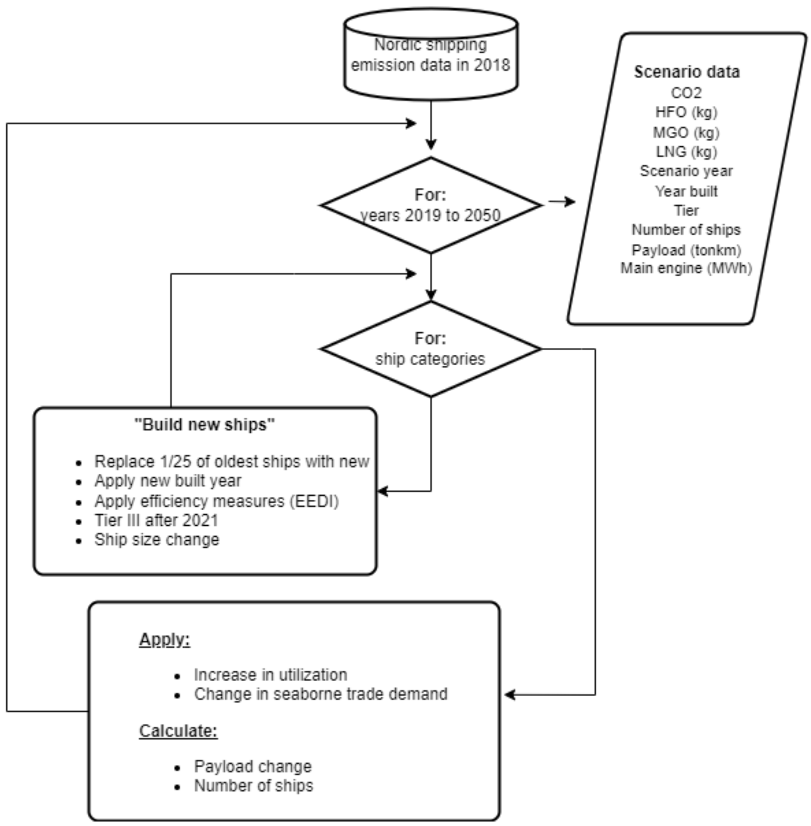

Figure 12. Overview of the model used for estimating future emissions of Nordic shipping.

3.3 Assessment of uptake in Nordic fleet and emission impacts

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. The calculated total fuel use per shipping segment in the Nordic region in 2018 is presented in Figure 13.

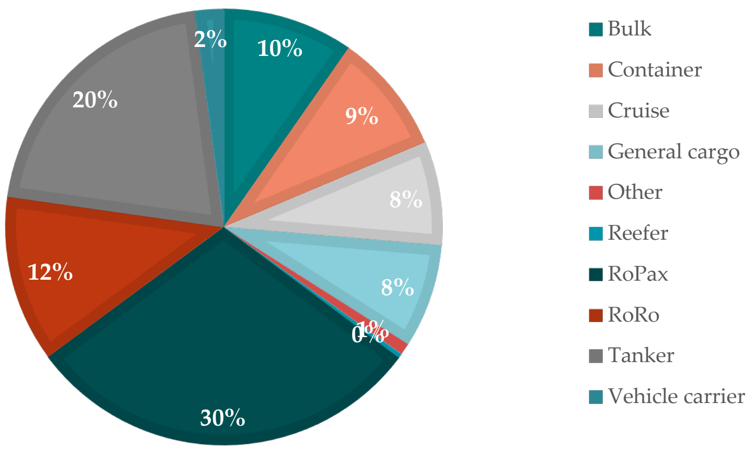

Figure 13. Calculated share of the total fuel use per shipping segment in the Nordic region in 2018.

Possible deployment trajectories for hydrogen and fuel cells in Nordic shipping has been outlined. In the first scenario it is assumed that hydrogen and fuel cells are only implemented on board the case study vessel, i.e., the RoPax ferry between Gothenburg and Fredrikshavn. In the second scenario, hydrogen and fuels cells are assumed to be implemented on board all relevant RoPax vessels (ferries) in and in between the Nordic countries. In the third scenario hydrogen and fuel cells are assumed implemented on all relevant Nordic shipping. For details see below.

For the second and third case, 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. However, hydrogen fuel cell propulsion solutions are mainly suitable for vessels travelling short to medium distances (like many RoPax vessels) due to energy density, storage capacity and bunkering issues. In addition, RoPax vessels generally travel the same routes and with predefined timetables which makes the bunkering situation easier. The assessment in this study 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. For the assessment of uptake of hydrogen and fuel cells in Nordic shipping, ships and ship categories traveling shorter distances are found most relevant. Distances up to 600 NM was used in the assessment. The limit of 600 NM was decided in dialogue with project participants and based on work by other researchers. Impacts on shipping related emissions (including GHGs, air pollutants and other impacts) in the scenarios for uptake of hydrogen and FCs in Nordic shipping are estimated. The result should be regarded as initial attempts to assess the possible impacts. Impact on the sustainable development goals (SDGs) prioritized by the Nordic governments linked to transport are also assessed.

For the case study (i.e., vessel operating between Gothenburg and Fredrikshavn), for an existing vessel (2018) the emissions of CO_2eq, well-to-wake correspond to 45 000 tonnes. The calculation is based on reported values of fuel consumption. For the theoretical fuel cell ship, the emissions of CO_2eq, 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 CO_2eq emissions.

The estimated CO_2 emissions per shipping segment that can be attributed to Nordic shipping on voyages to/from and between ports in the Nordic region per distance in 2018 is presented in Figure 14.

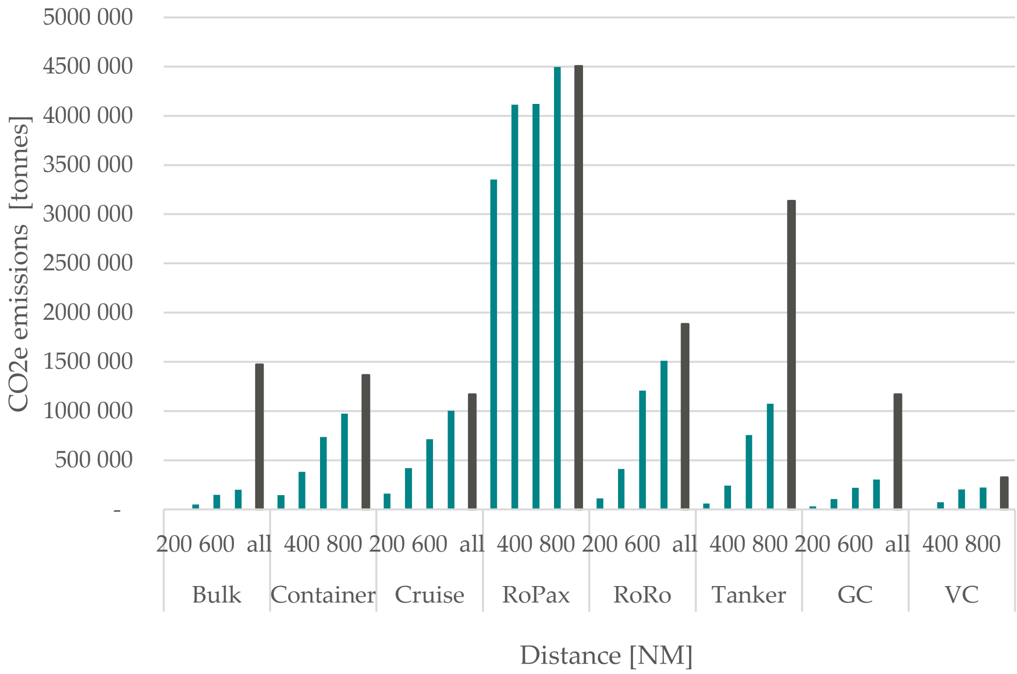

Figure 14. Calculated CO_2 emissions per shipping segment in the Nordic region per distance in 2018. The bars represent the aggregated emissions up to the marked distance (i.e., includes all voyages up to that level) and the grey bar represents all emissions for that segment.

Table 4 presents the impact on CO_{2eq}, NOx, SO_2, and PM emissions for a shift to hydrogen and fuel cells for all shipping segments travelling distances ranging from 100 to maximal 600 NM. A considerable amount of the emissions appears to be attributed to shorter distances.

In case hydrogen and fuels cells are assumed to be implemented on board all RoPax vessels (ferries) in the Nordic countries the estimated potential reduction of CO_{2e} (well-to-wake) emissions corresponds to 3.8 Mtonnes based on 2018 data, while the intra-Nordic reduction potential (i.e., ferries between the Nordic countries) corresponds to 1.52 Mtonnes CO_{2e}. In case the limit of distances up to 600 NM are used for RoPax vessels in and in between the Nordic countries (scenario 2) the estimated CO_{2e} emission reduction potential corresponds to 3.53 Mtonnes based on 2018 data. No intra-Nordic ferries travels longer than 600 NM.

In case hydrogen and fuels cells are assumed to be implemented on board all Nordic shipping the corresponding estimated potential reduction of CO_2 emissions corresponds to 14.25 Mtonnes and in case the limit of up to 600 NM are used (scenario 3) the potential emission reduction corresponds to 7.7 Mtonnes based on 2018 data, see Table 4.

Table 4. Estimated potential reduction of emissions of CO_2, NOx, SO_2 and particles from a potential implementation of hydrogen in fuel cells for all vessels with voyages up to 100 to 600 NM. Based on 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. 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.

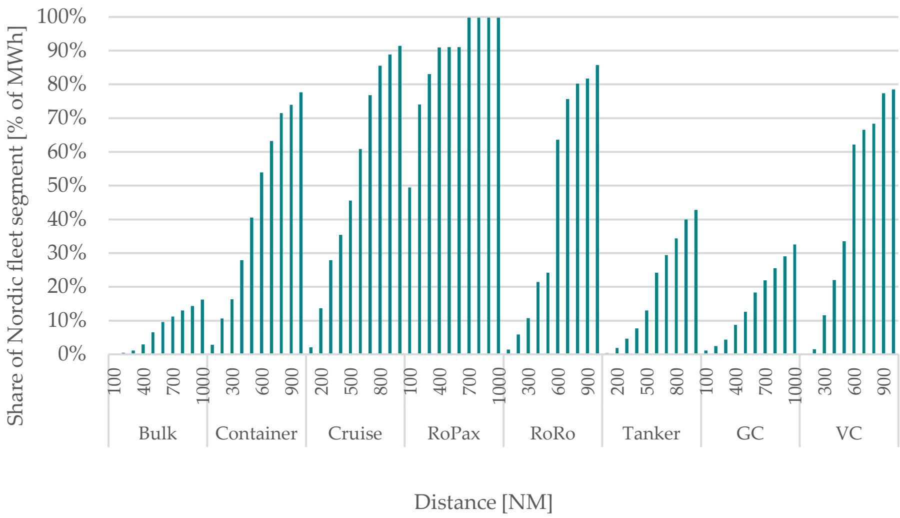

Figure 15. The share of the total fuel use per shipping segment in the Nordic region per distance in 2018. Each distances category includes all voyages up to that level (100-1 000 NM).

Figure 16 illustrates the projected total CO_2 emissions from Nordic shipping between 2018 and 2050, considering two different scenarios (high and low growth in transport demand) and assuming that no alternative fuels are implemented. Despite the assumed improvements in utilization rate and energy efficiency of ships, shipping CO_2 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 17 illustrates the projected total NOx emissions for Nordic shipping for the period 2018-2050, considering the high and low growth in transport demand scenarios and assuming no introduction of electricity or fuel cells and that ships in NECA are assumed to abate NOx if the ship is built after 2021, while ships outside NECA are not assumed to abate NOx emissions. As seen in Figure 17, the NOx emissions for Nordic shipping are expected to decrease in the future also without an introduction of hydrogen or other alternative fuels. This is due to the regulations restricting the NOx emissions from new ships.

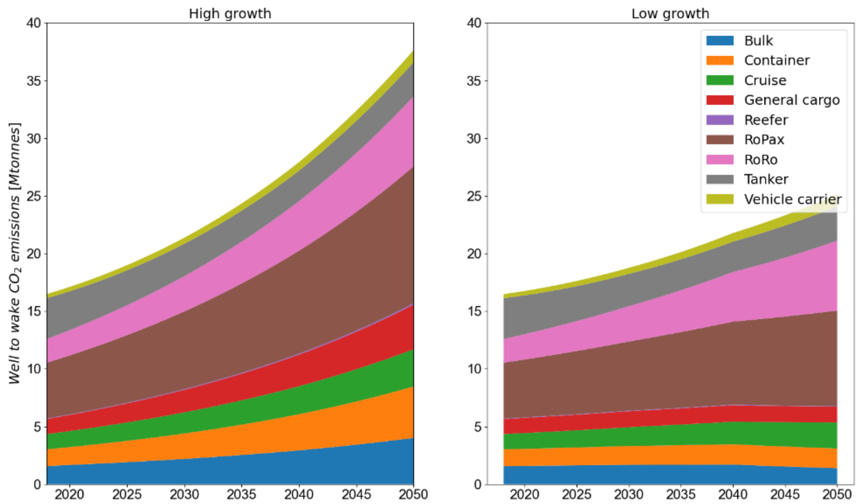

Figure 16. Modelled well-to-wake CO_2 emissions for Nordic shipping for the period 2018-2050 under the conditions of business as usual, i.e., no introduction of alternative fuels. The right graph represents high growth transport scenario while the left graph represents low growth scenario.

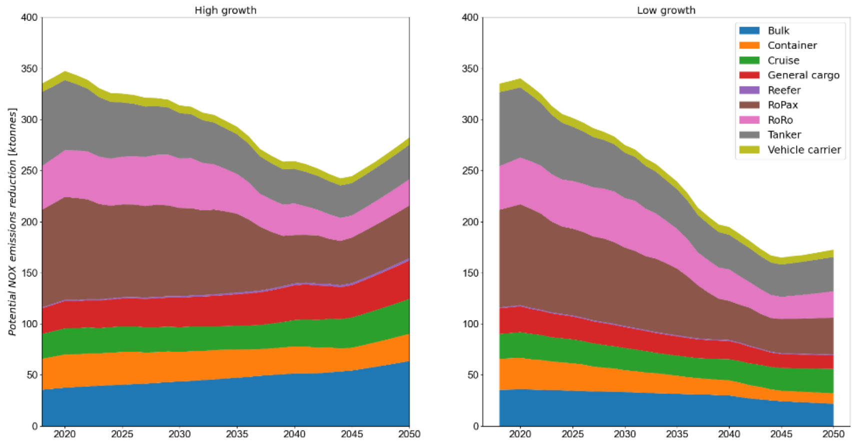

Figure 17. Modelled NOx emissions for Nordic shipping for the period 2018-2050 under the conditions of business as usual, i.e., no introduction of electricity or fuel cells. The right graph represents high growth transport scenario while the left graph represents low growth scenario. The ships that are in NECA are assumed to abate NOx if the ship is built after 2021, while ships outside NECA are not assumed to abate NOx.

Figure 18 illustrates the estimated CO_2 emissions 2018-2050 for the part of the Nordic shipping included in Scenario 3 (i.e., covering ships travelling distances >600 NM) for the high and low growth scenario, thus illustrating the CO_2 reduction potential. The size of the CO2 reduction level can be seen by comparing Figure 16 and 18. The potential reduction of CO_2 emissions for the part of the Nordic shipping included in Scenario 2 (covering RoPax/ferries travelling distances >600 NM) is also included in Figure 18 represented by the category RoPax. Figure 19 illustrates the potential reduction in NOx emissions 2018-2050 for the part of the Nordic shipping included in Scenario 3 (i.e., covering ships travelling distances >600 NM). The potential reduction of NOx emissions for the part of the Nordic shipping included in Scenario 2 (covering RoPax/ferries travelling distances >600 NM) is also included in Figure 19 represented by the category RoPax.

As can be seen in the figures there is a considerable reduction potential for both GHG emissions and NOx emissions linked to the implementation of hydrogen as fuel for shipping. The reduction potential decreases for NOx emissions due to the already implemented regulation for NOx emissions for new ships.

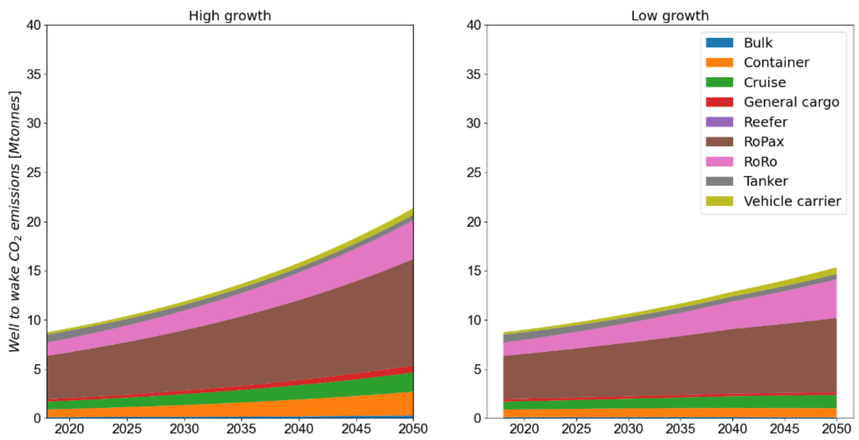

Figure 18. Modelled well-to-wake CO_2 emissions 2018-2050 for the part of the Nordic shipping included in Scenario 3 (i.e., covering ships travelling distances >600 NM). The right graph represents high growth transport scenario while the left graph represents low growth scenario. The figure also illustrates the CO_2 emissions reduction potential for the part of Nordic shipping included in Scenario 2 (covering RoPax/ferries travelling distances >600 NM, represented by the category RoPax).

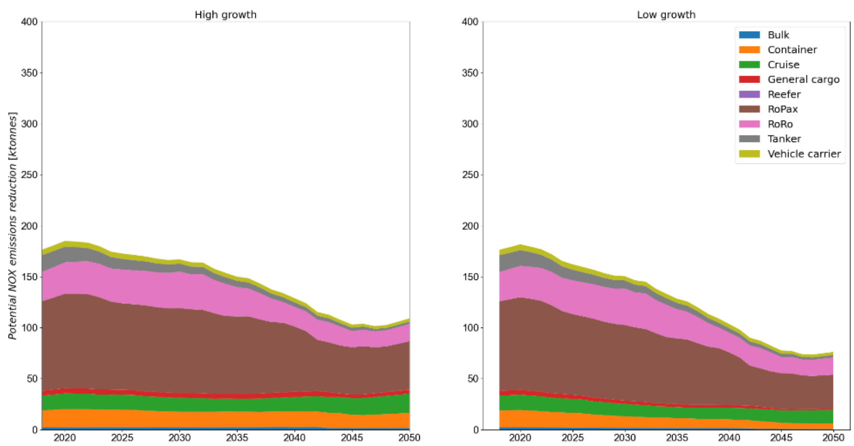

Figure 19. Modelled NOx emissions 2018-2050 for the part of the Nordic shipping included in Scenario 3 (i.e., covering ships travelling distances >600 NM). The right graph represents high growth transport scenario while the left graph represents low growth scenario. The figure also illustrates the potential NOx emissions reduction for the part of Nordic shipping included in Scenario 2 (covering RoPax/ferries travelling distances >600 NM, represented by the category RoPax).

Table 5 summarizes results for implementation scenario 2 and 3 in terms of emission reduction potential. Besides influence om GHG emissions, influence on emissions of NOx, and particulate matter (PM) are also presented in Table 5.

Table 5. Estimated potential reduction of emissions of CO_2, NOx, and particles in 2030 and 2050 from a potential implementation of hydrogen in fuel cells for the case of All ships including all vessels with voyages up to 600 NM and Only Nordic ferries including all ferries in and between the Nordic countries for a high and low growth transport scenario respectively.

Scenario	Year	Description	CO_{2eq} WTW (Mtonnes)	NOx TTW (ktonnes)	PM TTW (ktonnes)
Low	2030	Only Nordic ferries	1.9	30	2.2
		All ships	8.2	143	11.6
	2050	Only Nordic ferries	2.6	18	3.1
		All ships	10.2	65	14.4
High	2030	Only Nordic ferries	2.1	34	2.5
		All ships	9.5	167	13.8
	2050	Only Nordic ferries	3.7	26	4.4
		All ships	17.1	109	25.2

Other study on feasibility in the Nordic region

For our scenarios and assessments, we have also investigated similar work performed by others in parallel. In a report from 2022, DNV performed a feasibility study for selected alternative marine fuels by modelling Nordic emissions based on AIS data (Rivedal et al., 2022). Their feasibility analysis was divided into two steps (i) calculation of fuel consumption and energy demand for each individual voyage and (ii) calculation of the "amount" of energy carrier needed for storage. In general, the fuel system ratio (FSR) which inherently considers factors such as size was used as guide for feasibility by DNV rather than distance. A FSR of 3 was used for hydrogen. Using the FSR is a suitable ratio for some ship types but not for all as the storage capacity is not linear. For example, there is a difference in storage capacity between small and large tankers. Also, the total space needed for the propulsion and fuel should be considered. A FSR of 3 may also be slightly extreme in some cases. It was concluded by the project team to use distance in this study for transparency reason.

Other limitations

There are several aspects that have not been considered in this assessment, including e.g., hydrogen leakage and safety issues.

3.3.1 Modell discussion

For the 111 RoPax vessels that seem to have travelled mainly in or between the Nordic countries the totally reported annual emissions are 4 055 412 tonnes CO_2 according to MRV (THETIS-MRV, 2022) while the modelling result is 4 003 218 tonnes CO_2 (which represent a fairly good validation). For individual ferries, the results differ in average 13%. The modelled results should be an underestimation of real value since the distances based on sea route is somewhat shorter due to the selected route was for smaller ships.

3.3.2 Impact on sustainable development goals

In 2015, the Agenda 2030 was adopted by the United Nations (UN), envisioning a sustainable development until 2030, and replacing the previous millennium goals from 2000. Constituting 17 goals, 169 milestones and 244 indicators, the agenda covers the three dimensions of sustainability: environmental, social, and economic and governance (UN, 2023). The responsibility for implementing the Agenda 2030 and associated sustainable development goals (SDGs) lies on the governments of the UN member states. However, the goals apply to everyone and require commitment from several actors, such as civil society, municipalities, regions, researchers and finally companies.

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

- SDG 3 on health, increased road safety,
- SDG 7 on energy,
- SDG 9 on resilient infrastructure,
- SDG 13 climate action,
- SDG 14 on oceans, seas, and marine resources.

The scope of HOPE, investigating how regional shipping in the Nordic region can undergo a transition towards fossil free fuels, connects to the SDGs in Agenda 2030 and the ambitions of the Nordic governments.

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, they also state there is a lack of research on SDGs and maritime-related studies and attributes this to the International Maritime

Organization's pace of implementing SDGs. This can in turn possibly be attributed to no SDG specifically addressing the maritime sector.

The assessment in this report is based on each country's voluntary national review, official governmental sources, and a SDG impact assessment tool[2]. The tool was 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. The tool is based on self-assessment of how an activity, project or organization affects the SDGs. It contributes by providing the user with a structured way to reflect upon the SDGs in relation to the project or activity.

Each country's Voluntary National Review (VNR) was reviewed based on the key words: hydrogen, shipping, and sustainable energy. Additionally, the progress reports in the review were screened for relevant topics. The result from the assessment is summarized in Table 6. Four out of 17 SDGs were identified directly and one indirectly.

[2] https://gmv.gu.se/samverkan/sdg-impact-assessment-tool

Table 6. Overview of the assessment of SDGs influenced by hydrogen and fuel cells for shipping by based on the Nordic countries' voluntary national reviews (VNR), and self-assessment using the SDG impact assessment tool.

Goal	Sweden	Norway	Finland	Denmark	Iceland
1 NO POVERTY	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
2 ZERO HUNGER	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
3 GOOD HEALTH AND WELL-BEING	Indirect- Target 3-9. Reduce illness and death from hazardous chemicals and air, water and soil pollution and contamination	Indirect- Target 3-9. Reduce illness and death from hazardous chemicals and air, water and soil pollution and contamination	Indirect- Target 3-9. Reduce illness and death from hazardous chemicals and air, water and soil pollution and contamination	Indirect- Target 3-9. Reduce illness and death from hazardous chemicals and air, water and soil pollution and contamination	Indirect- Target 3-9. Reduce illness and death from hazardous chemicals and air, water and soil pollution and contamination
4 QUALITY EDUCATION	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
5 GENDER EQUALITY	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
6 CLEAN WATER AND SANITATION	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant

7 AFFORDABLE AND CLEAN ENERGY	7.A, 7.2 strengthen international cooperation to facilitate access to research on clean renewable energy. VNR highlights Sweden's goal of having a high share of renewable energy in the transport sector	VNR mentions the Norwegian hydrogen Strategy	Relevant for project but no mention of hydrogen in NVR	Denmark's shipping industry accounts for 42% of total use of primary energy used for the country's economic activities. No mention of hydrogen. Mentions risks of Power-to-X.	VNR mentions hydrogen as renewable fuel to transform land and sea transportation.
8 DECENT WORK AND ECONOMIC GROWTH	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Relevant for project but no mention in VNR.	VNR mentions development of new ships, hydrogen propulsion	Relevant for project but no mention in NVR. Key national policy initiative: governmental cooperation with industry to construct roadmaps to identify development paths to reduce climate emissions	NVR mentions decarbonised shipping and support of green innovations and new fuels. Zero carbon shipping and Global Maritime Forum is highlighted as examples.	Relevant for project but no mention in VNR.
10 REDUCED INEQUALITIES	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
11 SUSTAINABLE CITIES AND COMMUNITIES	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant

13 CLIMATE ACTION	Relevant goal but hydrogen is not specifically mentioned in NVR. Sweden’s long-term goal is to have zero net greenhouse gas emissions to the atmosphere by 2045. Hydrogen as fuel can be a means to get there.	Relevant goal but hydrogen is not specifically mentioned in NVR. Main challenge is to become a low-emission society. Hydrogen as fuel can be a means to get there.	Relevant goal but hydrogen is not specifically mentioned in NVR. Hydrogen as fuel can though be a contributor to reduce emissions.	Relevant goal but hydrogen is not specifically mentioned in NVR. Ambitions to reduce GHG emissions by 70% 2030.	Relevant goal but hydrogen for shipping is not mentioned in VNR. However, green incentives for hydrogen cars are brought up.
14 LIFE BELOW WATER	Relevant but VNR does not specifically mention hydrogen or shipping fuels.	Relevant but VNR does not specifically mention hydrogen or shipping fuels.	VNR- Mentions stricter IMO regulation of emissions from shipping to air and water	NVR highlights Denmark’s international work to strengthen efforts in green shipping which includes limiting emissions of harmful particles.	Relevant but VNR does not specifically mention hydrogen or shipping fuels.
15 LIFE ON LAND	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
17 PARTNERSHIPS FOR THE GOALS	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant

The potential benefits from a shift from MGO to other fuels such as methanol, ammonia or hydrogen and different propulsion technologies were investigated in Brynolf et.al. (2023). An indication of the alternative fuels impact compared to MGO are summarized in Figure 20.

Figure 20. The relative impact of fuel options on various environmental impact categories compared to MGO in four-stroke engines. Green color represents substantial decrease in impact compared to MGO, yellow represents same or almost the same impact as MGO, orange represents a clear increase in impact and red represents a considerable increase compared to MGO. Based on Brynolf et al. 2023.

Impact category	Compressed hydrogen in fuel cells	Liquified hydrogen in fuel cells
Acidification	0.1	0.1
Ecotoxicity, freshwater	1.1	1.2
Ecotoxicity, freshwater - inorganics	0.1	0.1
Ecotoxicity, freshwater - metals	1.9	2
Ecotoxicity, freshwater - organics	0	0
Eutrophication, freshwater	2.2	2.3
Eutrophication, marine	0.1	0.2
Eutrophication, terrestrial	0.1	0.2
Human toxicity, cancer	2	2.2
Human toxicity, cancer - metals	2	2.2
Human toxicity, non-cancer	1.8	2
Human toxicity, non-cancer - inorganics	1.2	1.2
Human toxicity, non-cancer - metals	2.2	2.4
Human toxicity, non-cancer - organics	0.3	0.3
Ionising radiation	7.2	7.8
Land use	5.2	5.5
Ozone depletion	0	0
Particulate matter	0.2	0.3
Photochemical ozone formation	0.1	0.1
Resource use, fossils	0.7	0.7
Resource use, minerals and metals	0.8	0.8
IPCC 2021 GWP 100	0.2	0.2
IPCC 2021 GWP 20	0.2	0.2

The two marked options to the right in the table are hydrogen in fuel cells, e-CH2 PEM FC and e-LH2 PEM FC and they are the most relevant for HOPE. Green indicates a decrease in impact on the impact categories compared to the base scenario with MGO. Yellow represents the same or similar impact as MGO, orange indicates an increased impact compared to MGO and red represents a considerable increase in impact compared to MGO. To summarize, in comparison with MGO, hydrogen in combination with fuel cells have a decrease in impact on 16 out of 23 impact categories. Only ionizing radiation and land use get a considerable negative impact. Thus, for most impact categories a decrease in impact is to be expected from a shift from MGO to hydrogen in fuel cells in shipping in the Nordic region.

Sala et al. (2020) presents a connection between impact categories and selected SDGs. By combining the information in Figure 20 and the mapping of impact categories and relevant SDGs in Sala et al. (2020) we get an overview of the expected link between impacts of hydrogen and fuel cells in shipping and the SDGs (Table 7). As SDG 7 (as well as SDG9) were not included in Sala et al. (2020) SDG 7 has been added in this report based on Brynolf et al. (2023). The comparison (see Table 7) indicates that the implementation of hydrogen fuel cells in shipping might have a positive impact on SDGs 3, 7, 13, 14 and 15. However, it may also have a negative impact on SDGs 3, 6, 7, 14 and 15.

Table 7. Link between environmental impact categories relevant for hydrogen and fuel cell implementation in shipping (based on Brynolf et al., 2023) and sustainable development targets (SDGs, based on Sala et al., 2020). Green colour represents substantial decrease in impact compared to MGO, yellow represents same or almost the same impact as MGO, orange represents a clear increase in impact compared to MGO and red represents a considerable increase compared to MGO.

Impact category	**Compressed hydrogen in fuel cells**	**Liquified hydrogen in fuel cells**	**Relevant SDG**
Acidification			SDG 7, 15
Ecotoxicity, freshwater			SDG 6, 7
Ecotoxicity, freshwater- inorganics			SDG 7
Ecotoxicity, freshwater- metals			SDG 7
Ecotoxicity, freshwater- organics			SDG 7
Eutrophication, freshwater			SDG 7, 14
Eutrophication, marine			SDG 7, 14
Eutrophication, terrestrial			SDG 7, 15
Human toxicity, cancer			SDG 7, 3
Human toxicity, cancer- metals			SDG 7
Human toxicity, non-cancer			SDG 3, 7
Human toxicity, non-cancer- inorganics			SDG 7
Human toxicity, non-cancer- metals			SDG 7
Human toxicity, non-cancer-organics			SDG 7
Ionising radiation			SDG 3, 7
Land use			SDG 7, 15
Ozone depletion			SDG 7, 13
Particulate matter			SDG 3
Photochemical ozone formation			SDG 3, 7
Resource use, fossils			SDG 7, 13
Resource use, minerals and metals			SDG 7
IPCC 2021 GWP 100			SDG 7, 13
IPCC 2021 GWP 20			SDG 7, 13

4 Main findings and recommendations

The base case estimation indicates that a hydrogen 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 for emissions allowances of 100 EURO per tonne CO_2.

However, there are large uncertainties in relation to some cost parameters e.g., linked to cost of hydrogen, price of fuel cells, and price of emission allowances within EU ETS. In case 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 100% compared to the base case (i.e., reaching 200 EURO/ton CO_2) the fuel cell ship is estimated to have a 5 percentage lower annual cost of ownership than the conventional fuelled MGO ship.

Another aspect for pilot installations that has not been analysed quantitatively within this project, is the potential for unexpected costs connected to pilot projects including technology that is less mature, and less used and widespread. This is a potential risk for the first movers which also can be 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. The different ship concepts include potential risks connected to the maturity of the technology where a methanol or biogas fuelled ship has potentially lower such risks than hydrogen and fuel cells, ammonia, or battery-electric propulsion.

In terms of impacts linked to the implementation of hydrogen and fuel cells in Nordic shipping, there is a considerable potential for emission reductions both in terms of CO_2, NOx, SO_2 and PM, 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 here and that service and fishing vessels are not included, which are relevant particularly for Norway and Iceland. The use of hydrogen also influences several SDGs.

For the case study in focus (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 ktonnes. 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 ktonnes 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 ktonnes of CO_2e emissions.

Hydrogen fuel cell propulsion solutions are mainly suitable for vessels travelling short to medium distances due to energy density and storage capacity issues. A considerable amount of the emissions from Nordic shipping appears to be attributed to shorter distances, highlighting the large potential. RoPax is one of the most relevant ship segments for future hydrogen and fuel cells propulsion in the Nordic region due to their distances travelled. However, RoPax vessels generally also travel the same routes and with predefined timetables which makes the bunkering situation easier.

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.

The potential future role of hydrogen, as well as electrofuels, and biofuels for shipping will 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.

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Appendix A – Supplementary General Arrangement drawings

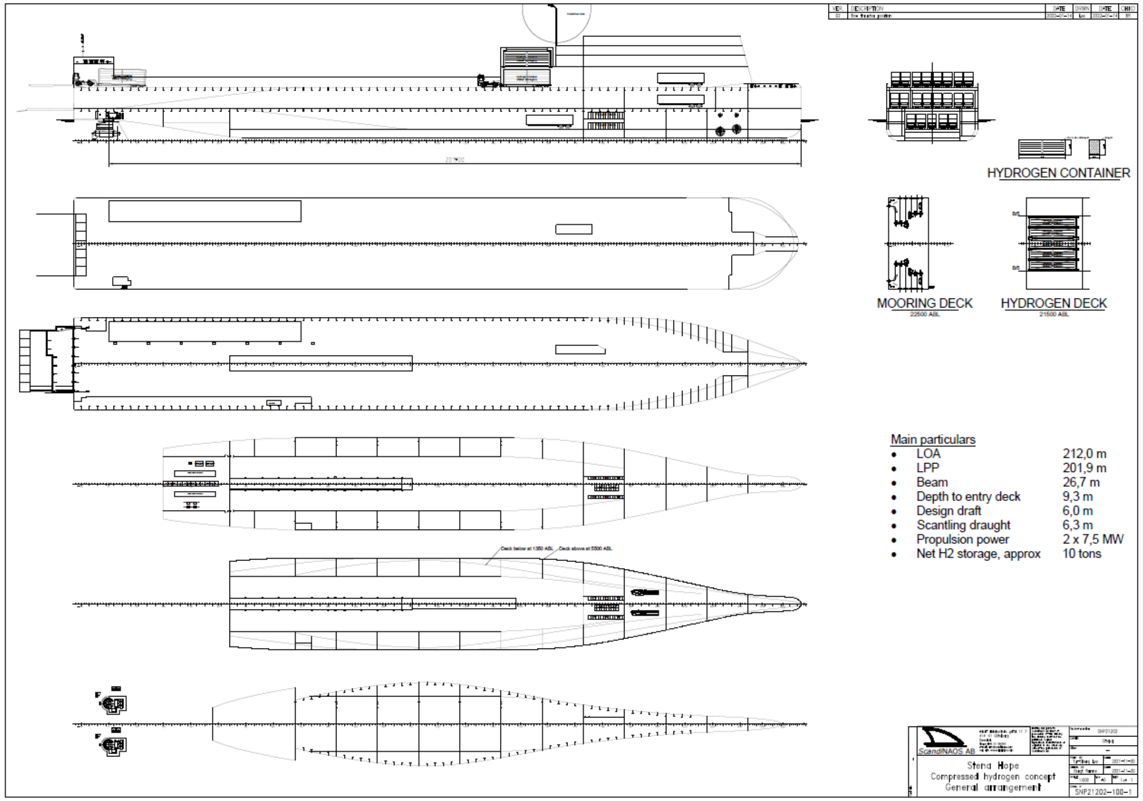

Figure A1. General arrangement drawing of the compressed hydrogen concept version.

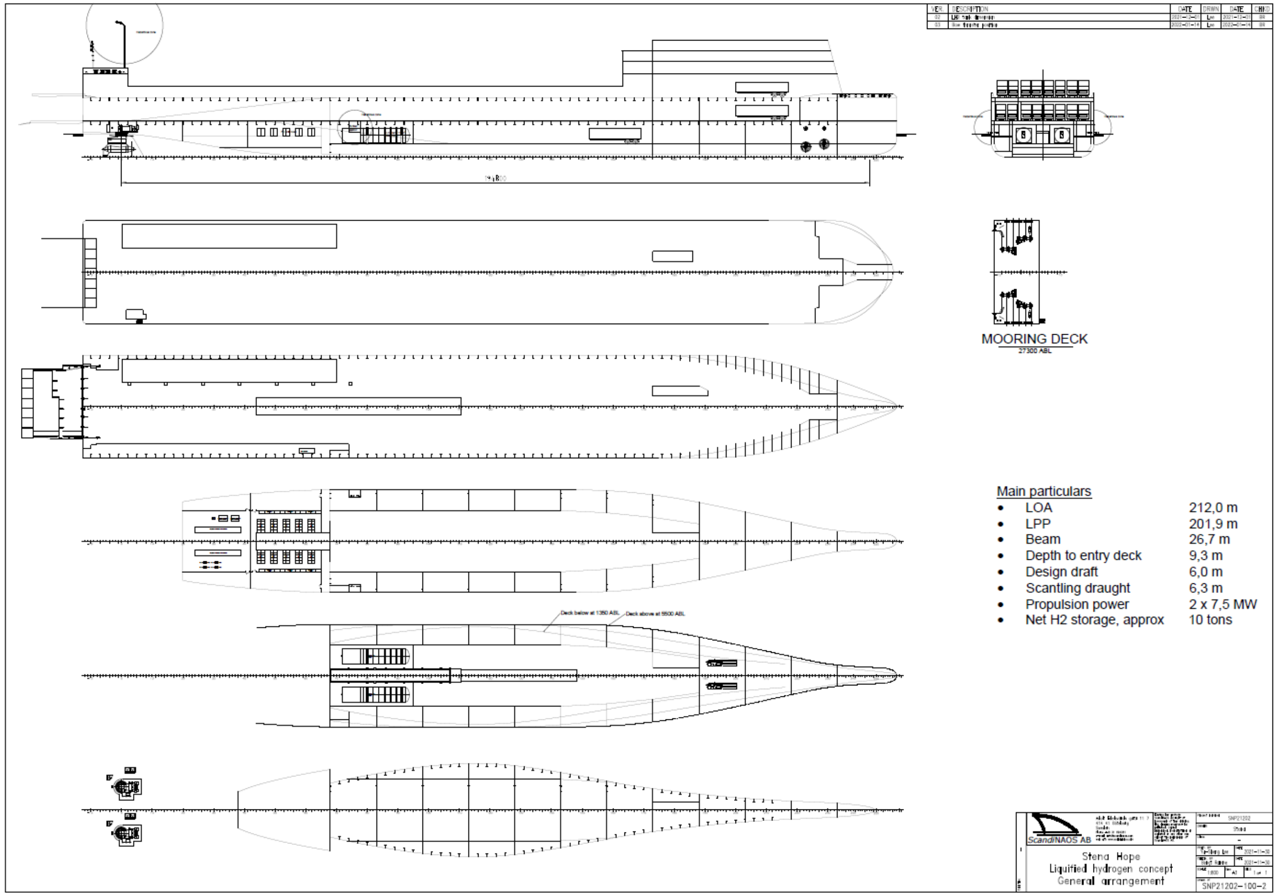

Figure A2. General arrangement drawing of the liquid hydrogen concept version.

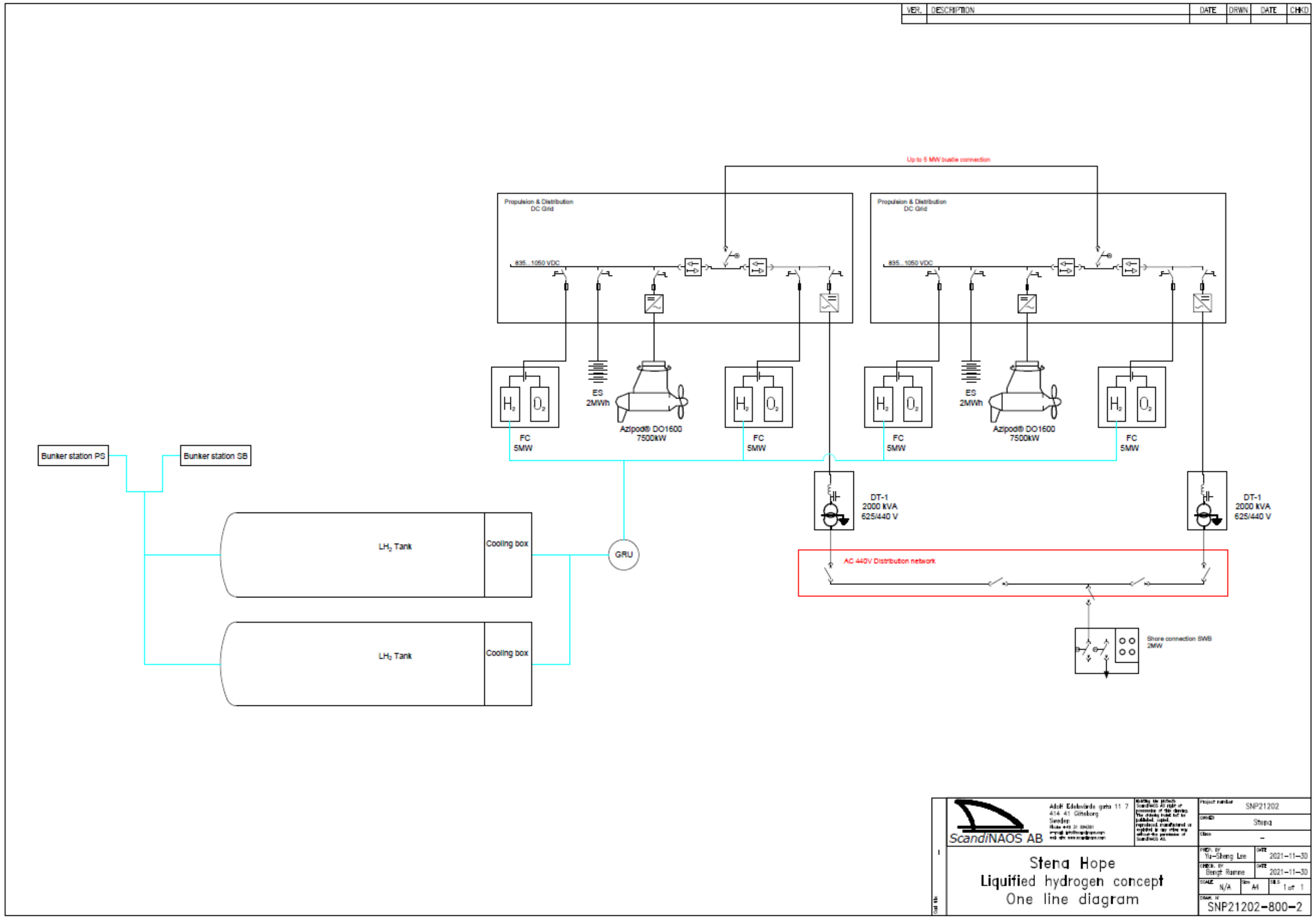

Figure A3. One line diagram showing the electrical power system for the liquid hydrogen storage concept version.

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