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Design Lab: a simulation-based approach for the design of sustainable maritime energy systems

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ABSTRACT

The process of achieving decarbonization in the maritime industry relies on tackling complex issues related to ship design. Designers require tools that can integrate the processes of providing relevant operational profile, configuring a target design, evaluating the design and exploring possibilities. Design Lab framework innovatively addresses this need by creating realistic operational profiles, simulating vessel performance and machinery systems, and providing comprehensive system evaluations.

The framework promotes a comprehensive design process that starts by creating an operational profile. This profile is used to simulate the vessel's propulsion power considering statistical weather conditions. Then, machinery systems are configured and simulations are performed. The performance of these systems is evaluated against key performance indicators such as total cost of ownership, carbon intensity indicator, etc., and the process is iterated with new design candidates.

A case study of a hydrogen-fueled RoPax vessel is presented to validate the framework and demonstrate its capabilities. By focusing on simulation-based predictions and performance indicators, it provides a quantitative assessment, thereby supporting the decision-making process for stakeholders.

KEY WORDS

Maritime energy system; Simulation-based design; Decarbonization; Design framework

INTRODUCTION

The shipping industry plays a crucial role in our endeavors to address climate change. It is imperative to achieve significant reductions in carbon emissions within this sector. To meet the goals set by the International Maritime Organization (IMO) IMO (2023), we must focus on two key areas: improving energy efficiency and adopting alternative technologies that produce little or no greenhouse gases. This includes a variety of strategies, such as reducing ship speed, better route planning based on weather conditions, maintaining and upgrading propellers and engines, using carbon capture and storage onboard the ships Tavakoli et al. (2023), taking care of the ship's hull Yuan et al. (2016), and using alternative low-carbon fuel.

In addition, as the regulations evolve and a broad spectrum of technological options emerge, designers need tools capable

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of incorporating future scenarios, including fuel price fluctuations and potential carbon taxes, into total cost of ownership calculations.

To explore the impact of various technologies and the effectiveness of alternative fuels on marine power systems, a framework can be established. This framework will facilitate the optimal design and operation of ship propulsion systems, providing a comprehensive assessment of their technical and economic performance. A study by Thaler et al. (2022) explored the optimal design and operation of maritime energy systems that use renewable methanol and closed carbon cycles. They focused on the integration of onboard carbon capture technologies in shipping, evaluating both pre- and post-combustion carbon capture methods. The study employs a mixed integer optimization framework to analyze the techno-economic performance of these systems on a case study of a ferry operating in the Baltic Sea. The findings reveal cost advantages and robustness against various technological and economic conditions for systems that employ closed carbon cycle strategies. Furthermore, Buonomano et al. (2023) studied a new approach to energy design for ships with the aim of reducing fuel consumption and environmental impact. They integrated two methods, Building Information Modeling (BIM) with Building Energy Modeling (BEM), to create a dynamic, 3D physics-based simulation of a ship's energy performance under real operating conditions. The case study named "Allure of the Seas", a 6000-passenger cruise ship, was used to analyze energy performance and potential waste heat recovery. Significant primary energy savings and reduced emissions are highlighted, demonstrating the effectiveness of the methods in sustainable ship design and operation.

The study by Hansson et al. (2020) investigates the viability of ammonia as a marine fuel compared to other fuel options. It combines energy systems modeling to assess cost-effectiveness in achieving climate targets and multi-criteria decision analysis (MCDA) to rank marine fuels based on various criteria including fuel performance and stakeholder preferences.

The study by Bordin and Mo (2019) optimized the battery lifetime in vessels using a developed model. The model helps to make battery investment decisions, considering factors such as battery degradation and desired lifetime. It was designed to evaluate how the different operating modes of a vessel influence investment choices in energy storage.

Moreover, Tang et al. (2018) presented an exploration of energy management in green shipping by examining the challenges posed by emission regulations that sometimes limit or even prohibit the use of diesel in ports, necessitating alternative power sources such as shore power. The study focuses on ships equipped with onboard photovoltaic (PV) systems and how the management of a hybrid energy system (HES) combining PV, battery, diesel, and cold-ironing can lead to significant electricity cost reductions.

Therefore, the design of the entire marine propulsion system plays a central role in predicting and optimizing the power requirements of maritime vessels. An integrated system design considers not only the engine's performance but also the interaction of various components such as propellers, hull shape, and energy recovery systems. This holistic approach enables accurate power predictions, essential for fuel efficiency and reducing emissions. In addition, it allows for the adaptation of innovative technologies such as hybrid power systems and alternative fuels, ultimately leading to more sustainable and cost-effective maritime operations.

The primary objective of this paper is to present the development of a comprehensive framework designed to analyze the power system of a ship power plant, focusing on its operational profile and general arrangement using a case study as a reference. Thus, in the following section, we will introduce and discuss this framework in more detail. Subsequently, the chosen case study will be described, highlighting its specific operational profile. The core aspects of the framework, which are central to our analysis, will be elaborated upon in the following. Finally, the results derived from applying this framework to the case study will be thoroughly presented and examined in the last section, providing information on the practical implications and effectiveness of the proposed system analysis.

DESIGN LAB AND PROCESSES

Design Lab is a framework developed to evaluate the performance of the vessel with realistic operational scenario and ship models that account for all relevant technical aspects of the vessel. The evaluation process is shown in Figure 1 in an iterative process for the analysis and design of a power system of a ship based on various operational parameters. The process is made of four subprocesses: defining operational profile, ship operation simulation, machinery simulation, and analysis of the design and redesign if necessary. The cycle begins with the ”Operational Profile”, which includes the route, speed profile, timetable, and weather conditions. The next phase is to run the ”Ship Operational Simulation,” using the specific ship and propulsor model from the vessel design to predict the propulsion and hotel power with the input from the operational profile. The output of the simulation is fed into the ”Machinery Simulation,” where the actual energy conversion, incorporating the machinery system model and the control strategy for the machinery system, is simulated to obtain fuel consumption and emissions. The output of the fuel consumption and emissions and the cost information from the system configuration leads to ”Analysis and Redesign,” a phase in which the total cost of ownership is considered to evaluate the economic feasibility of potential changes. This stage can influence the operational profile, signifying a feedback loop for iterative improvement and optimization of the ship's energy system design.

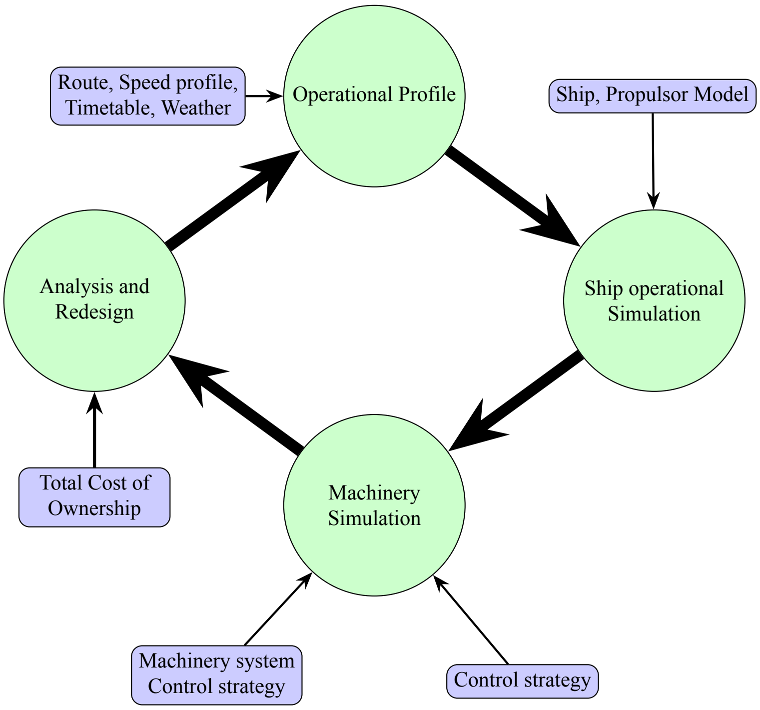

Figure 1: Design Lab process for marine propulsion systems modeling.

The framework suggests the process of the design evaluation and iteration rather than a specific implementation of the software. The framework allows designers to customize the specific models and implementation of the process fit for the purpose, providing the guidance for the implementation for defining operational profile, making ship models, performing ship and machinery performance simulation and converting the output of the simulation to KPIs. It also provides the guidance for flow of data along the design process, suggesting data interfaces between the processes. The processes should be as holistic as possible to entail all the aspects of the operation of the ship, environmental load, response of the ships, and the systems onboard as well as control strategy for the systems. At the end of the evaluation chain, the designer should define his or her own KPIs based on the output of the simulation. The most common KPI would be carbon intensity indicator and total cost of ownership or levelized cost.

For the operational profile, there are basically two ways to define it for a vessel. The first method is to define the power consumption of the vessel using the measurement data. This data can be a time series of required power or a statistical input of power vs frequencies. If such data are given, the ship performance can be skipped as the required power for the machinery system is already given. On the other hand, one can define the behavior of the vessel using its speed, route and the operation mode of the vessel. The most simple input would be to provide the design speed, length of the route and time spent in the port. Or one can define the speed profile with frequency data that provides information how much the vessel spends time with various speeds. If more information is available, one can define the route using specific way points along the path that provides spatial information for the vessel. In addition, the metocean data within the area of vessel operation can be added to the operational profile to estimate the environmental load on the ship. These information will be provided to the next step of the process, ship performance simulation.

In the ship performance simulation, the main purpose is to estimate the required power demand on the vessel, including the propulsion and hotel load. The information from the operational profile defined in the previous stage will be used as main input for the process. The hull resistance and propulsion model is created using the specific information of the design candidate such as main dimensions of the hull form and particulars of the propellers. The hull resistance and propulsor model can be as simple as a speed power curve from a model test or can be a parametric model extracted from computational fluid dynamics (CFD) models. For the propulsor model, it can be a static efficiency value, Wageningen ”B” series propeller model or a open water characteristic curve extracted from the CFD analysis. If the environmental load should be considered, added resistance due to wave and wind should be considered. One can either just add a sea margin, use an empirical model or use potential-theory-based methods to calculate the vessel response which converts to the resistance. At the end, the hull resistance and propulsor model will convert the location, heading, speed and the time of the vessel into the propulsion power. The output may be a time series, a histogram or a single value depending on the type of the input values.

In the machinery simulation, the main purpose is to calculate total fuel consumption, emissions and the degree of usage of power sources. The required power for propulsion and hotel load is the input for the simulation. A machinery system is a system that converts the energy source to usable form of energy such as shaft work or electricity and deliver them to the consumers. The machinery system can be described as a single conversion efficiency or a full blown system in which each energy converter and consumer is modeled. If various energy converters are used such as gensets, fuel cells or multiple fuels are used, there must be a control strategy for the system how the energy is shared among them. Together with the system configuration, this control strategy will affect the performance of the machinery system in terms of fuel consumption and emissions. For the purpose of calculation of fuel consumption and emissions, it is usually sufficient to use only efficiency of each component or brake specific fuel consumption to model the component. For a sophisticated system model with multiple energy convereters, the component should be described with the mode of energy sharing and whether the power source is available.

When the total fuel consumption and emissions are simulated with the machinery model, one can now calculate relevant KPIs. A common KPI is total cost of ownership (TCO). TCO must entail all the cost incurred in the lifetime of the vessel. It is usually divided into capital expenditure (CAPEX) and operational expenditure (OPEX). CAPEX comprises mainly of the cost related to build a ship, and, retrofitting cost if necessary. OPEX comprises mainly of the fuel cost traditionally, and other cost for crewing, maintenance, insurance and adminication is added. In recent development of carbon tax, pricing and penalty, additional cost for emissions may be considered. Regulaion related KPIs such as the carbon intensity indicator set by IMO can be considred for the design evaluation. Other qualitative KPIs such as safety, complexity and maturity can be considered if the design envolves nobel technolgy. At the end of the analysis, the designer makes decision if the design candiate is satisfactory to the requirements. Otherwise, the designer should create a new candiate and start a new process of evaluation. A new evaluation process can be evoked by an update of the design or when more detail information is available for more sophiscated modeling and evaluation.

CASE STUDY AND OPERATIONAL PROFILE

The case study focuses on the Stena Hydra, a conceptual ship designed to push the boundaries of marine engineering by incorporating hydrogen fuel cells.

As shown in Figure 2, the Stena Hydra design blueprint shows the integration of hydrogen fuel cell technology into its structure (light green boxes).

The main specifications of Stena Hydra, listed in Table 1, include an overall length of 212 meters and a beam of 26.7 meters, ensuring ample space for both cargo and passenger facilities.

The requirement for the design is defined as follows:

1. The ship shall travel back and forth between Göthenburg and Fredrikshaven for the given time table as of today.

2. The speed of the vessel shall be determined to meet the time table given.

3. The vessel shall be able to perform three crossings without bunkering fuel.

4. The vessel shall be able to provide at least 22 MW power for the ship to operate in the harsh weather.

5. The vessel shall be powered by hydrogen fuel cells of mature technology and achieve zero emission operation.

The use of hydrogen as the primary fuel in large ships presents a series of technological challenges.

While the core technology for such storage is readily provided by various suppliers, the maritime adaptation of this technology requires specialized systems, particularly for efficient bunkering operations within the strict time constraints specific to the type of ship in question. The low volumetric density of hydrogen makes storage a significant challenge; It requires containment in a liquid state at -252 ^{o}C or as a pressurized gas at 350$\sim$700 bar to enhance density, both of which entail substantial installation costs. Consequently, identifying the optimal storage capacity is essential to ensure the economic feasibility of the system.

Currently, Proton Exchange Membrane Fuel Cells (PEMFCs) are commercially available for maritime applications. These fuel cells (FCs) are provided as modules with a typical rated power of 200kW. Furthermore, FCs have different efficiency characteristics from diesel engines. The efficiency is typically highest in the low load range and lower as the load increases. This is almost opposite to the case for diesel engines. Therefore, fuel cell operating should be different from diesel engines, especially for determining the optimal number of modules to engage for a given load. The configuration of fuel cell modules according to the power level will affect the size of the fuel cells and the fuel consumption.

The last challenge is the cost of fuel and fuel cells. They are expected to be much higher than conventional fuel and diesel engines. The size 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 and 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 the environment conditions.

The main purpose of the design study is to size the fuel cell based power plant that provides the lowest total cost of ownership. Fuel cells will ensure that the vessel will emit no emissions for the energy conversion as long as the hydrogen is coming from green sources. One of the challenges with utilizing hydrogen fuel cell is sizing. The typical efficiency curve of a fuel cell has highest efficiency at 30% and the lowest at the rated power. The study will address the challenges mentioned to arrive at the reasonable design. The following steps will demonstrate how the design lab framework is implemented to perform such a complex design evaluation process.

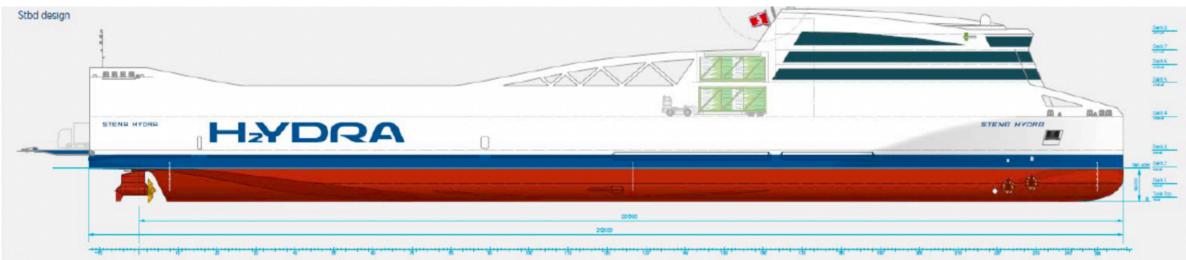

Figure 2: Ship design drawing of the hydrogen fuel cell concept named Stena H2YDRA.

Table 1: Main specification of the case study.

Item	Value
Length O.A. (meters)	212.0
Length P.P (meters)	201.9
Beam (meters)	26.7
Design Draft (meters)	6
Scantling draught (meters)	6.3
Propulsion power	15 MW
Operational range	150 NM
Speed	22 kn
Deadweight (metric tons)	6000
Payload (metric tons)	4500
Lane meters	2500
Passenger facilities	Day ferry

Definition of the operation profile

The frequency of travel and the transit time from one place to another are determined from the weekly time table of the current operation of the vessel, Stena Jutlantica. However, it doesn't provide exact way points and actual speed profile along the path including maneuvering in the confined water and transit. In order to find such detailed information, AIS data were used to create a representative operational profile. The AIS data were collected from Kystdatahuset Kystverket (2024) for Stena Jutlantica for the entire year of 2022. 339002 points were collected with many missing points in between. Figure 3 shows the spread of the points in the space with the speed of the vessel presented in a color map. The spread is rather wide, and to get the representative route of the ship, a machine learning method to find a piece-wise spline regression curve was used. The route is represented with 100 points between two ports. For the speed profile, the speeds of AIS points that are nearest to a point on the representative route are averaged and assigned to the the point. Figure 4 show the route on the map and the speed profile along distance and time.

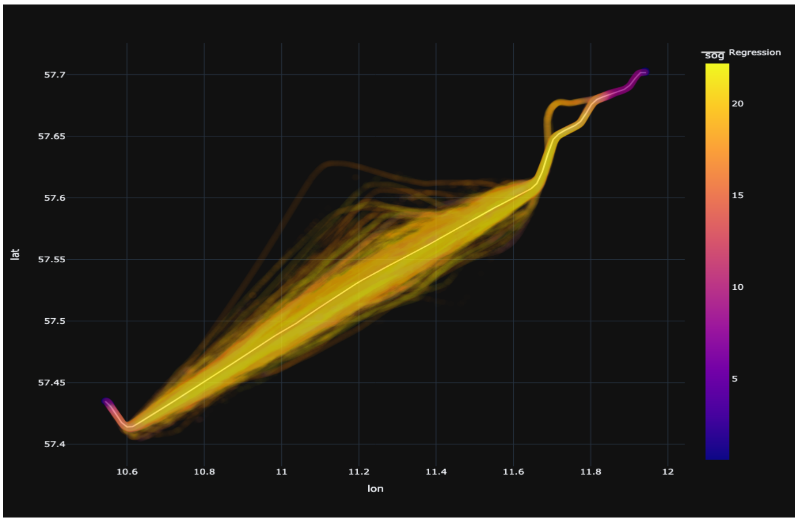

Figure 3: Actual positions and speeds of the ship on multiple voyages between Frederikshavn and Gothenburg.

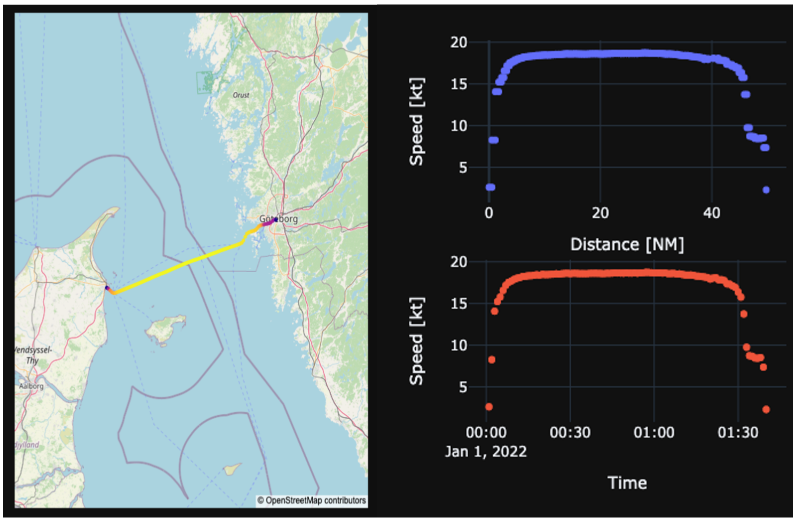

Figure 4: The representative route presented on the map and the speed profile along the length and time of the voyage

Ship Operational Simulation

With the input of the operational profile, a vessel performance simulation is performed to reproduce the propulsion power time series for entire year of 2021 and 2022. Trips are scheduled according to the weekly time table of the real operation. Each trip from one port to the other is simulated along the way points where a specific time for a way point is determined with the given the speed profile. Metocean data from the Norwegian Meteorological Institute (Institute (2023)) is used to find the wave and wind information at the way point at that specific time. The speed and the heading of the vessel together with the metocean information are provided as an input to the hull resistance model. The total resistance calculated will be converted to the shaft power using the propulsor model. In this case study, Hollenbach method is used for estimation of the calm water resistance, SNNM method by Wang et al. (2021) for added resistance due to waves, ITTC method for wind resistance and open water propeller curve for converting the required thrust to shaft power. The ship propulsion performance model is presented in Figure 5

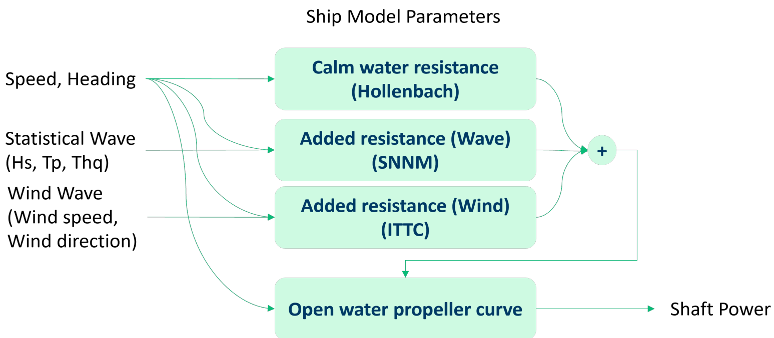

Figure 5: Components of the hull resistance models and the propulsion model used in the case study and their interfaces

The result of the ship propulsion performance simulation is shown in Figure 6. The simulation includes 2400 one-way trips from Frederikshavn to Gothenburg and vice versa throughout the year. The variation among each trip accounts for various weather conditions that the ship encounters in different time and location. There are a couple of trips where the maximum power is over 15 MW that is the maximum propulsion power of the vessel. The limitation of the simulation is that there is no involuntary speed loss due to weather condition where the speed cannot be achieved due to limitation of the installed power. However, such cases accounts less than 0.1% of the trips and, therefore, statistically.

To validate the result, the result is compared to the measured total power on the STENA Jutlandica in year 2021 and 2022 that was provided by STENA as shown in Figure 7 and 8. The results are generally in good agreement while there are some difference for high loading region. The differences are results of both model uncertainties and discrepancy in operational profile. The resistance models are based on the statistical dataset for various vessels that may lead to a certain degree of errors, and having a static speed profile may have led to inaccurate boundary conditions for the model.

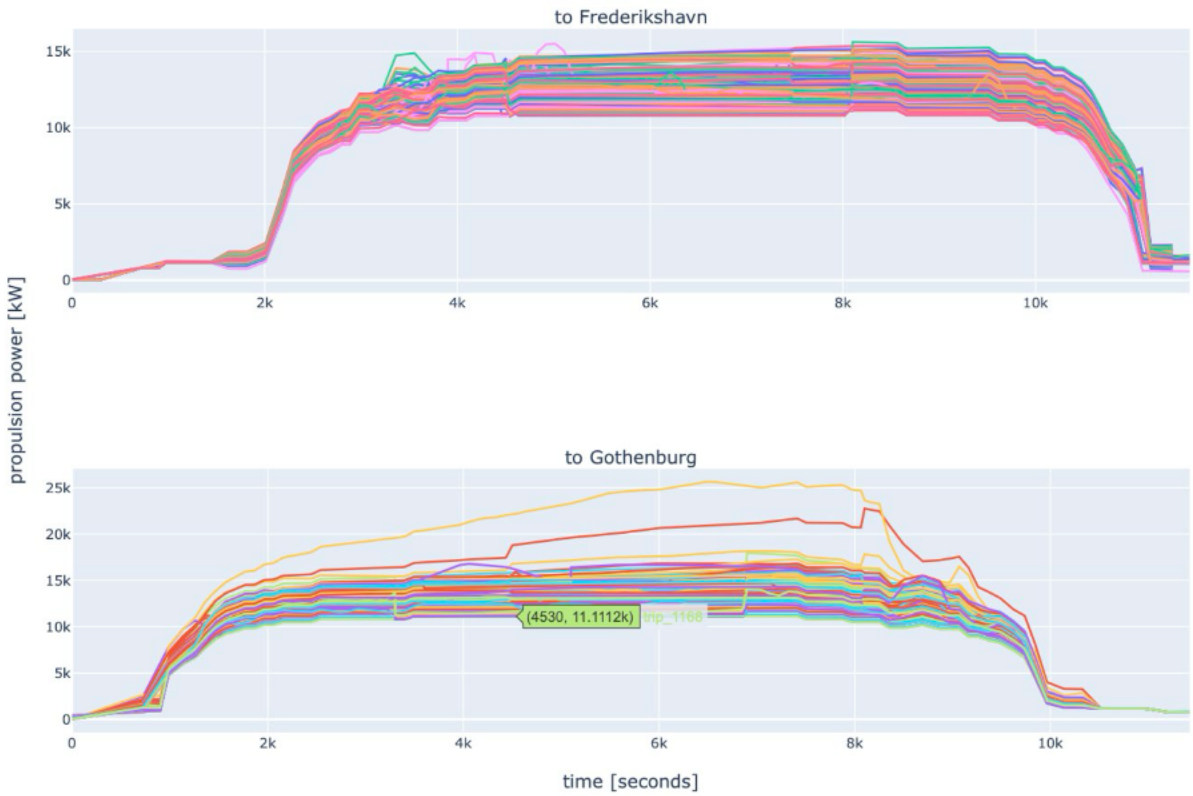

Figure 6: Prediction of the propulsion power from the simulation given as a time series for all trips in 2021 and 2022

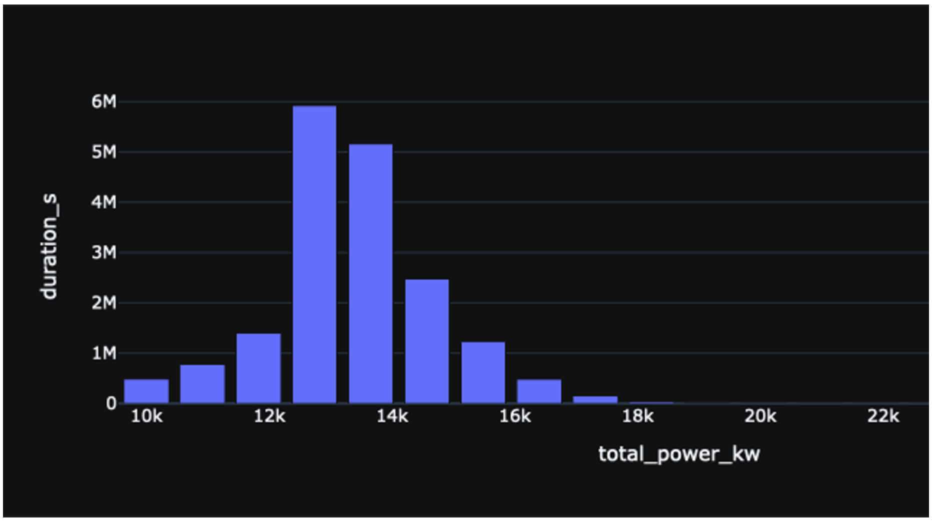

Figure 7: Histogram of the predicted propulsion power from the simulation for all trips in 2021 and 2022

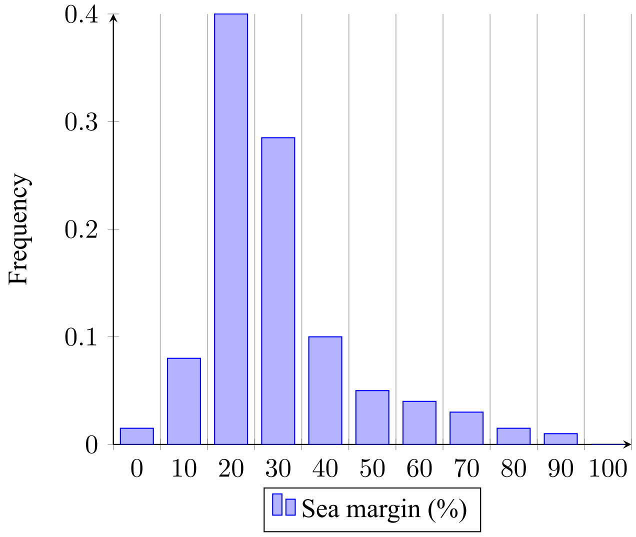

Figure 8: The histogram of the power load on gensets of STENA Jutlandica measured in 2021 and 2022.

Machinery Simulation using FEEMS

FEEMS (Fuel Energy Emissions Calculation for Machinery System) is a modeling framework designed for marine power and propulsion systems, created by the Author. It is available as a open source Python library (https://github.com/SINTEF/FEEMS/tree/main). It calculates fuel consumption, emissions, and energy balance by considering various operating modes and external power loads. The framework allows modelers to configure power systems using a component library and a single line diagram. It supports different types of power and propulsion systems, including hybrid/conventional diesel electric propulsion, hybrid propulsion with power take-in/power take-off (PTI/PTO) and mechanical propulsion with a Separate Electric Power System. The unique advantage of using FEEMS is that it will be possible to apply energy management strategy to the power sources such as load dependent start/stop of power sources, load smoothing/peak shaving operation with batteries, PTI/PTO operation, and choosing optimal power sources depending on the power demand, availability, and criticality of the operation. At the same time, FEEMS is designed to handle a large set of inputs, such as a year-long operational profile, with a short calculation time. Typically, it will give the result of calculation with over 100,000 points input within a couple of seconds. In FEEMS, a system model is created in a bottom-up approach starting with a component model to create a subsystem of components and then a system of subsystems. The system model holds both the architecture of the system and the components as objects. Typical information required to create a component model is the rated output power, the type of component in terms of functionality and power, and a load-dependent efficiency curve. For an engine component, a load-dependent brake specific fuel consumption (BSFC) curve should be given instead of the efficiency curve. For the component that converts fuel to energy, fuel information and/or emissions information should be specified as well.

When the system model is all specified, one needs to go through the following steps to arrive at the result. The first step is to define the load input for power consumers, such as propellers and auxiliary loads. Following this, it is essential to specify the operational status (either 'on' or 'off') and the load sharing mode for each power sources and energy storage units. If there are PTI/PTO machines, it is also necessary to specify the same for them as well as their PTI/PTO mode. Additionally, if the electric system includes a bus tie breaker, its status (closed or open) must be set.

Once all these settings are in place, the system model can perform a power balance calculation. This calculation is carried out for a bus and a shaft line. It involves determining the total power consumption at the switchboard or shaft line level. This process takes into account power losses in each component. The total power consumption is then distributed among power sources, energy storage units, and PTI/PTO machines. This distribution is based on their respective statuses, load-sharing modes, and PTI/PTO modes.

After completing the power balance calculation, the output power values for each power source are obtained. From these values, it is possible to calculate the fuel consumption, emissions, and running hours for the system. The final result is given as structured data that contains:

1. Duration of the operational profile input,
2. Total fuel consumption for each kind of fuel,
3. Total GHG emissions as CO2 equivalent value,
4. Running hours of power sources, PTI/PTO machines, and batteries,
5. Net energy saved in the energy storage units,
6. Total energy consumption of propulsion and auxiliary loads,
7. Above information for each power source, PTI/PTO machines and batteries.

These steps are shown in the visualization way in Figure 9.

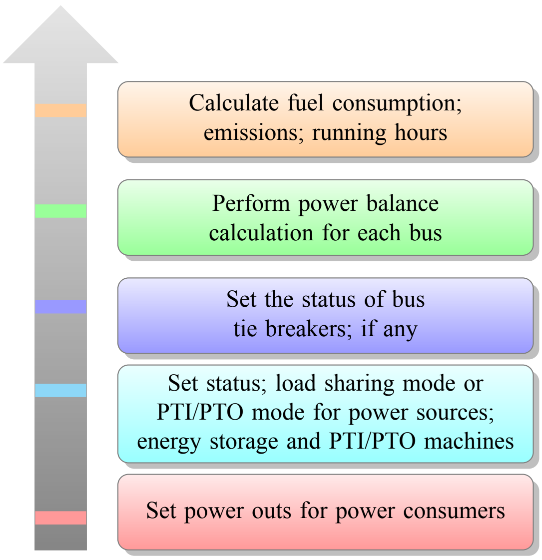

Figure 9: Procedure of calculation of the vessel's fuel consumption and corresponding emissions.

The base configuration of the machinery system has the total installation power of 20MW from fuel cells. Each fuel cell model has rated power of 200 kW. Five fuel cells are connected to a common DC link that is connected to a switchboard by a DC/DC converter. This means that there are 20 groups of fuel cell modules in total. There are two propulsion drives that are connected to each switchboard. Other load at each switchboard represents hotel and auxiliary load. The configuration is shown in Figure 10

The fuel cell group will be turned on and off depending the load level of the power sources to achieve the optimal number of fuel cells. Because the fuel cells have the best efficiency between 20% and 30% of their rated power, the number of fuel cells providing power will be determined so that the number is minimum where the power load on each fuel cell does not exceed 30%. Using this simple energy management makes sure that the plant can run at the best efficiency point depending on the load.

The fuel consumption for each trip and accumulated consumption for three consecutive trips are shown in Figure 11

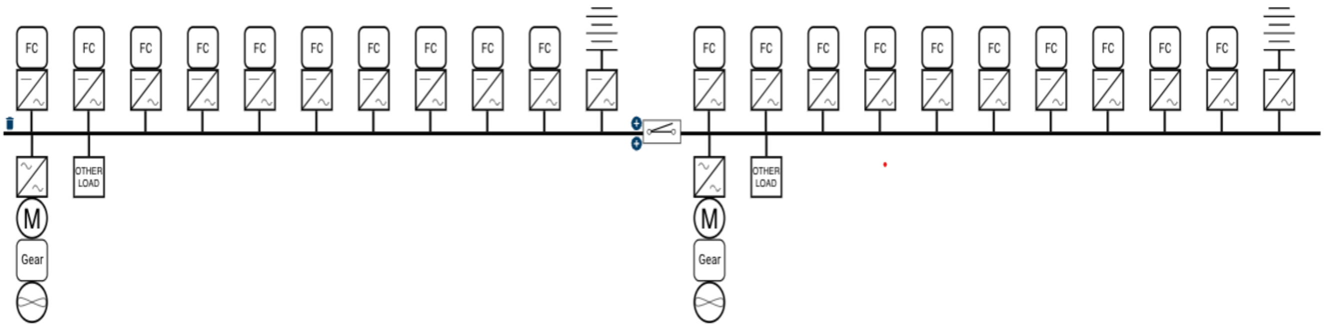

Figure 10: A machinery system with 20MW installed power from fuel cells as a base case for the design study

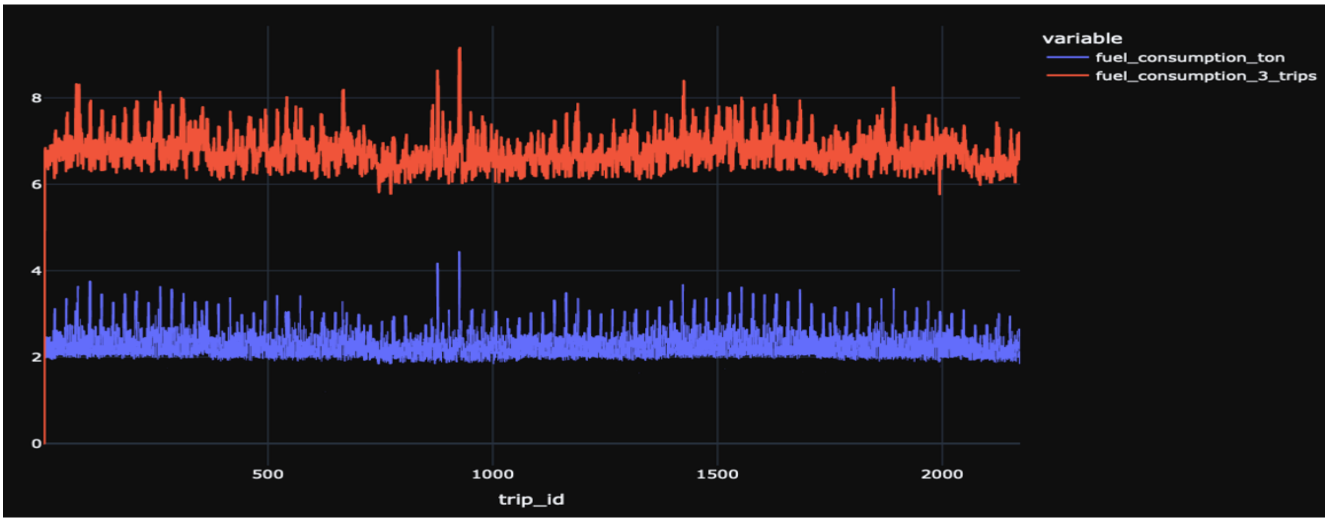

Figure 11: Fuel consumption for each trip and three consecutive trips from the machinery simulation using FEEMS

Analysis and redesigns

Among other KPIs, total cost of ownership (TCO) is a single value that expresses the system efficiency, capital cost and emissions as a single value. The calculation of TCO can be done with the input of the system configuration, fuel consumption results and running hours of fuel cells from the machinery simulation. The overall analysis is shown in Figure 12.

For hydrogen powered vessel, the cost of hydrogen storage constitutes a significant part. Deciding capacity based on the simulation results, therefore, prevent the system from over- and under-sizing of the storage. From the design requirements, the vessel must be able to make three trips without bunkering. In Figure 11, accumulated fuel consumption for three consecutive trips are presented. The maximum value is 9.2 tons. Therefore, storage capacity of 10 tons will be capable of fulfilling the design requirement while it is kept in a reasonable range.

The TCO is calculated as a levelized cost, cost per trip. The cost is calculated only for the machinery system using the following equation.

$$LC = \frac{CAPEX + \sum OPEX_i \cdot (1+r)^{-i}}{\sum n_{trip} \cdot (1+r)^{-i}}$$

$$CAPEX = 1.2 \cdot (P_{rated} \cdot C_{PS} + M_{storage} \cdot C_{storage})$$

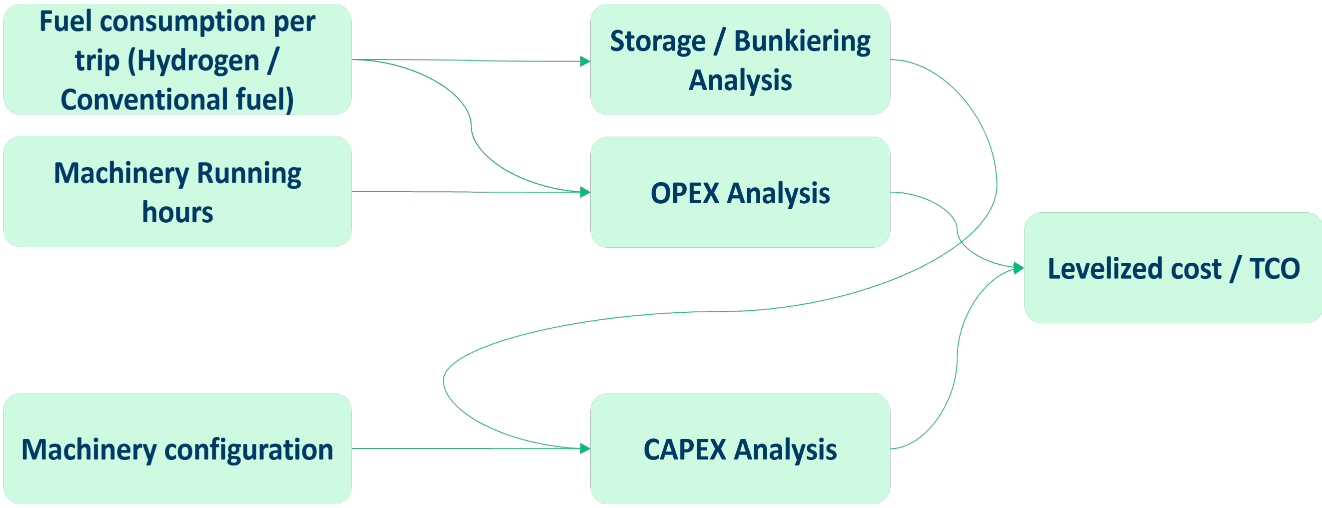

Figure 12: Analysis of the simulation results to arrive at the total cost of ownership for the design case

Table 2: Calculated TCOs for three design cases with different intalled power

	20MW	25MW	30MW
CAPEX [mEUR]	46.3	54.1	62.1
OPEX [mEUR/year]	18.308	17.497	17.008
Number of trips per year	1,353	1,353	1,353
Energy production [kWh/trip]	38,458	38,458	38,458
Fuel consumption [ton/trip]	2.36	2.241	2.168
Levelized cost [EUR/trip]	16,392	16,271	16,403

$$OPEX_i = m_{fuel} \cdot (C_{fuel} + c_{CO_2} \cdot C_{CO_2}) \cdot n_{trips} + E_{PS} \cdot C_{mt}$$

where,

r : Discount rate
n_{trip} : Number of trips per year
P_{rated} : Total installed power of power sources [kW]
C_{PS} : Unit cost for the power plant [EUR/kW]
$M_{storage}$: Storage capacity [ton]
$C_{storage}$: Unit cost for storage [EUR/ton]
m_{fuel} : Fuel consumption per trip [ton]
C_{fuel} : Fuel unit cost [EUR/ton]
c_{CO_2} : CO2 conversion factor for fuel [kg/kg]
C_{CO_2} : Cost of CO_2 emission [EUR/ton]
E_{PS} : Energy production per year [kWh]
C_{mt} : Maintenance cost [EUR/kWh]

The overall procedures are performed in three design cases: 20MW, 25MW and 30MW for total installed power. With the assumption of fuel cost of 5 EUR/kg, fuel cell cost of 1400 EUR/kW, maintenance cost of 0.045 EUR/kWh and storage cost of 1,000,000EUR/ton, the TCOs are calculated as shown in Table 2.

RESULTS AND DISCUSSION

Within the maritime industry, the transition to hydrogen fuel is based on a wide range of economic factors. Figures 13 through 16, complemented by detailed specifications based on our case study, form a comprehensive analytic structure. The Design Lab framework enables the assessment of the operational costs associated with this innovative vessel. Sensitivity analysis underscores the crucial role of hydrogen pricing, which emerges as a primary determinant of overall costs, more than the purchase of fuel cells. This paper has conducted a sensitivity analysis focusing on the three key factors:

- 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 cost analysis further suggests that hydrogen pricing provides valuable insights into determining the most suitable size of the vessel's power plant. Reduced hydrogen prices support the selection of a power plant with smaller installed capacity to reduce initial investment, whereas higher hydrogen prices may favor a larger power plant to capitalize on economies of scale. The main goal is to create maritime energy solutions that maintain environmental and economic sustainability. The Stena Hydra serves as a model or example, highlighting the necessity for strategic power configuration and smart energy management for the promotion of environmentally friendly maritime operations.

The graphical representation in Figure 13 correlates the levelized cost of maritime transport with the fluctuating prices of marine gas oil (MGO), in the context of diverse CO2 pricing under the European Union Emissions Trading System (ETS). This relationship highlights the financial consequences of carbon emissions within the maritime sphere and the requirement for shipping companies to develop strategies that can effectively address the potential effects of carbon pricing on their operational expenses. Figure 14 also shows a visualization of the effects of the MGO price on maritime transport costs per kWh, further analyzed under different ETS CO2 price scenarios. Moreover, Figure 15 represents the impact of the price of liquid hydrogen on the levelized transport costs in different vessel power capacities. The increasing prices of liquid hydrogen have a direct impact on the levelized cost, particularly for vessels that require more energy. This emphasizes the significance of taking into account fuel costs in the early stages of ship design. The diagram illustrates a comprehensive evaluation of liquid hydrogen prices and fuel cell prices, represented by the colored shapes, within the 800 to 1400 EUR/kW range. As demonstrated, the rate at which the levelized price increases is reduced as the size of the power plant increases. The reason behind this is the influence of reduced fuel usage in the larger machinery setup of the case study, despite the additional investment in the power plant, by the increased capacity of the fuel cell from 20 to 30 MW. Lastly, Figure 16 shows the assessment of levelized transport costs per kWh in the context of liquid hydrogen prices and fuel cell prices.

CONCLUSION

In summary, the Design Lab has emerged as a key tool, providing a robust and iterative framework to evaluate the designs of maritime vessels that use hydrogen fuel cells. The ability to analyze AIS data has resulted in the creation of operational profiles, which offer a comprehensive understanding of vessel behavior in real-world scenarios. These profiles serve as the basis for the design process. Furthermore, the semi-empirical approach enables the prediction of power requirements that are statistically validated, ensuring that the design of the ship is robust to the variation of maritime environments. Meanwhile, simulations conducted via FEEMS offer detailed insights into the machinery's performance, revealing system efficiency and fuel consumption patterns across a spectrum of operational loads.

Economic analysis has made it clear that while hydrogen-fueled propulsion systems currently cost more than conventional fossil-based solutions, it is possible to achieve a balance. As technological advancements continue and carbon taxation becomes a global norm, the cost of operating hydrogen-powered vessels is expected to decrease, potentially aligning with those of traditional maritime fuels. This shift would mark a significant milestone in the maritime industry's journey towards sustainability, positioning hydrogen as a viable and environmentally responsible fuel choice for the future of global shipping.

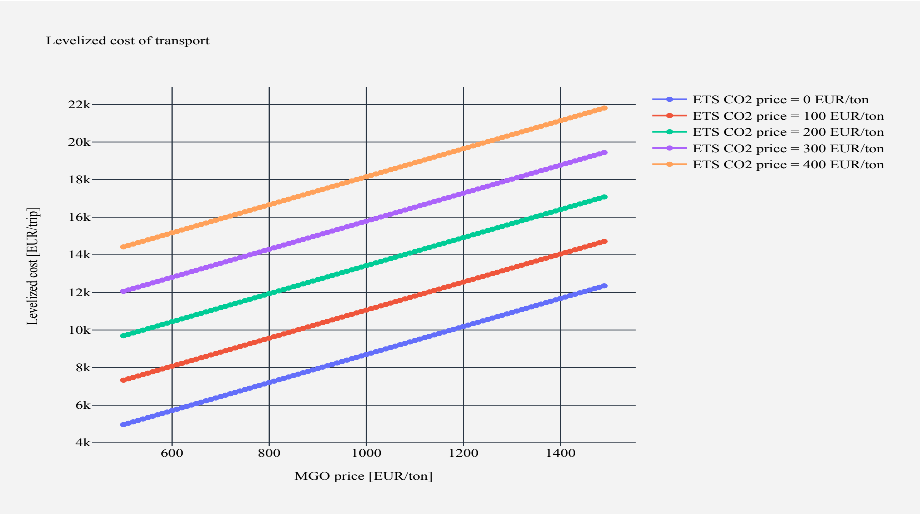

Figure 13: Levelized cost of transport regarding the marine gas oil price and the ETS.

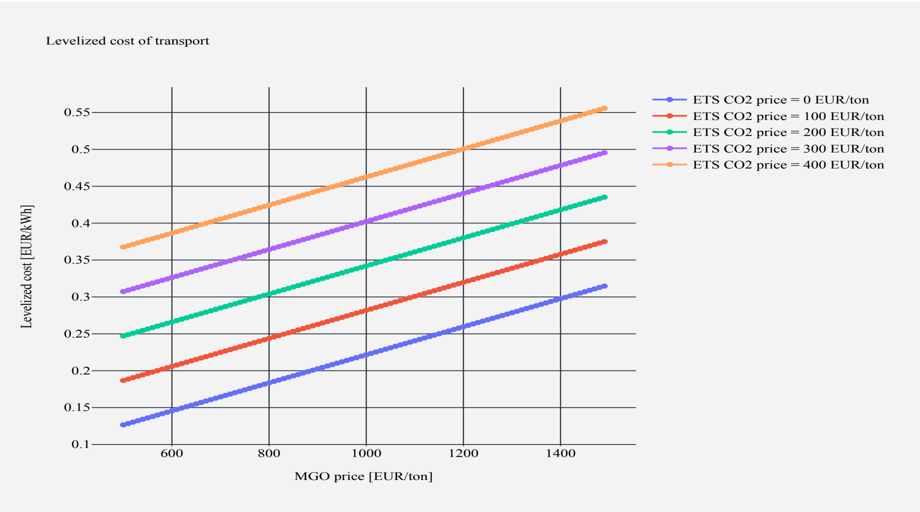

Figure 14: Levelized cost of transport per kWh regarding the marine gas oil price and the ETS.

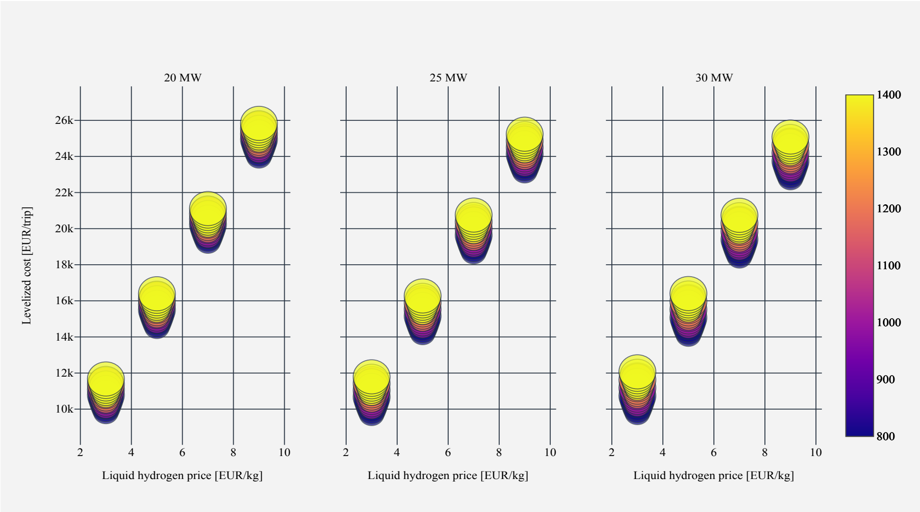

Figure 15: Levelized cost of transport based on hydrogen price.

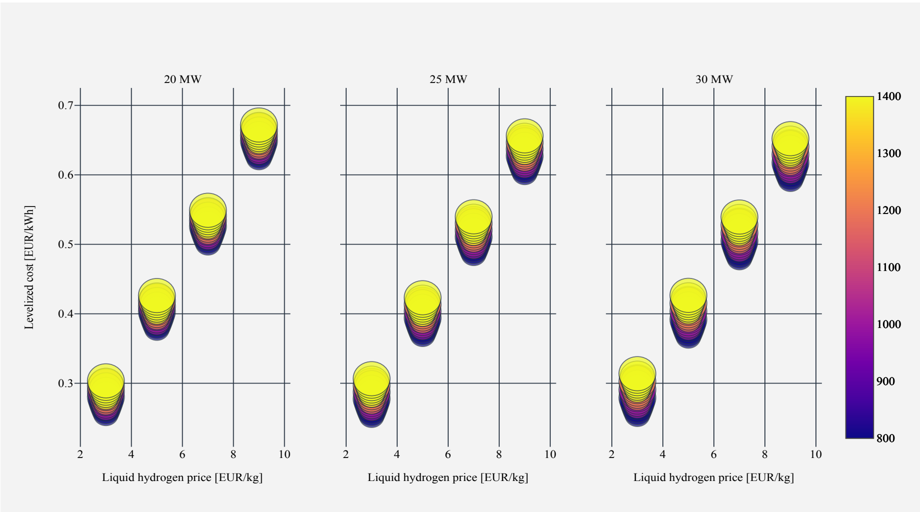

Figure 16: fig: Levelized cost of transport per kWh based on hydrogen price.

CONTRIBUTION STATEMENT

Kevin Kusup Yum Conceptualization; data Creation, methodology; writing – original draft. **Sadi Tavakoli** Conceptualization; data Creation, methodology; writing – original draft. **Torstein Aarseth Bø** writing – review and editing. **Jørgen Bremnes Nielsen** writing – review and editing. **Dag Sternesen** conceptualization; supervision; review and editing.

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