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A model-based parametric study for optimal system sizing and control of a hydrogen hybrid cargo vessel

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Abstract

The current state of research in marine energy systems has concentrated on conventional diesel systems, while limited literature is available on sizing and control of alternative energy sources such as hydrogen-hybrid systems, which have attracted increasing interest recently due to the electrification trends. This paper presents a modelling and optimization study for a conceptual retrofitting of a general cargo vessel to a hydrogen-hybrid version. Generic fuel cell, battery and converter models are used, enabling easy adaptation to various powerplant sizes and ship types. The Energy Management Strategy developed herein employs the vessel's power profile to control the battery state of charge and fuel cell power output to minimize component degradations. Fuel cells and batteries are sized based on the most power and energy-intensive operating profiles of the ship. A database of fuel cells with stacks from different manufacturers has been created to test different combinations in terms of fuel consumption, cost, and weight, based on the optimization framework. Uncertainties in terms of fuel price, and capital expenses for fuel cells and batteries are presented using normal distribution graphs. The optimal sizing and control results are presented for one power profile of the vessel and for the average fuel costs obtained from the Monte Carlo simulations. It was demonstrated that with the proposed control method, the power output from the fuel cells and batteries matched the considered power profile with less than 1% error. The configuration with 8 stacks of 150 kW has the lowest total fuel cost (585.9 USD) by an average of 6.6% difference from the other solutions, but with a 1.76% higher system weight than the lightest configuration with 40 stacks of 30 kW. Overall, this study demonstrated how to size and control efficiently energy systems under uncertainties, using parametrized components.

Keywords: Cargo Vessel**,** Control, Hydrogen-hybrid Systems, Parametric Study, Sizing, Uncertainties.

1. INTRODUCTION

The shipping industry is responsible for 3% of the global Greenhouse Gas emissions. However, if no countermeasures are taken, this percentage may increase up to 17% by 2050 [1]. Thus, the International Maritime Organization has imposed stringent regulations requiring a 50% emission reduction until 2050 compared to 2008 levels [1].

One of the most promising alternative fuels for emission reduction is hydrogen which can result in zero onboard emissions if fuel cells are utilised. They are scalable power sources, with high efficiency at their rated level, and they produce power with reduced noise and vibrations compared to conventional engines, and without emitting any harmful gases. Hybrid configurations with fuel cells and batteries have attracted increasing interest in the recent years which arises from the electrification trends in the maritime industry [2]. The batteries are used to cover the peak demands and the transient loads which cannot be delivered by the fuel cells due to their limited power output and their slow response. The hydrogen hybrid configurations are more applicable for short ranges in proximity to recharging and refuelling infrastructures. Despite their higher cost and complexity compared to traditional configurations with diesel mechanical propulsion, the hydrogen-hybrid systems offer increased flexibility, energy efficiency, and reliability in case of failures [3].

Currently, most studies have focused on modelling and optimization of diesel-based (hybrid) ship systems since they have been in use for a long time, and they are well-established in the marine sector. In most cases, the objective is to increase the use of renewable sources by reducing the operation of diesel generators/engines to minimize onboard emissions. Zhu et al. [4,5] modelled and optimized the sizes of batteries, generators, and e-motors of a diesel electric vessel using the Non-dominated Sorting Genetic Algorithm to reduce emissions, lifecycle costs and diesel consumption. Vu et al. [6] proposed a Power Management Strategy using the interior point algorithm to optimally control the load splitting between the diesel generators and batteries of a hybrid tugboat. Kanellos et al. [7,8] developed models and control strategies using Particle Swarm Optimization algorithms to reduce the operational expenses and satisfy the emission requirements (operational indexes) for the case vessels. In [9,10] diesel generators, batteries and supercapacitors were modelled and sized to control optimally the highly fluctuating loads of the power profiles.

The modelling and optimization studies for hydrogen-based vessels are focused on passenger vessels (i.e., small boats, high-speed ferries, Roll-on-Roll-off vessels etc.). Since there are no emissions onboard, more focus is given on operational costs, capital expenses, and degradations. Different studies have used the generic fuel cell and battery models from Simscape library, that will also be used in this study, focusing mainly on optimal system control. Balestra et al. [11,12] modelled the powertrain of a conceptually retrofitted hydrogen-based passenger vessel using real ship data and tested the effects of component sizes on different Energy Management approaches, with focus on hydrogen cost and component degradations. Jaster et al. [13] modelled the propulsion and control systems of a hydrogen vessel and simulated them using the Hardware in the Loop method to estimate the loads and fuel consumption. Cha et al. [14] used the fmincon algorithm from MATLAB toolbox for the power management optimization to maximize the efficiency of the fuel cells while constraining the battery State of Charge (SoC). Bassam et al. [15] also used the generic Simscape fuel cell and battery components. They presented a multi-scheme Energy Management Strategy that could switch to different control approaches based on the pre-defined instructions, for varying battery SoC and operating profile, aiming to minimize the energy consumption. Bassam et al. [16] presented an improved Proportional Integral strategy for a hydrogen-hybrid tourist boat and compared the optimization results of hydrogen consumption, cost, and component stresses with three other approaches: Classical Proportional Integral, Equivalent Consumption Minimization Strategy and a rule-based method.

There are very few studies on optimal sizing and control using Simscape components that can be adjusted to different powerplant sizes for various hydrogen-based vessels. More focus has been given on optimal Energy Management approaches. In all the studies, one fuel cell stack is considered for the analysis with specifications from a specific manufacturer. All the studies for hydrogen-hybrid ships consider a passenger vessel with fixed route, schedule, and power profile for the analysis.

This study is a model-based parametric study using generic fuel cell/battery models and average converters. A diesel-based general cargo vessel will be conceptual retrofitted to a hydrogen-based version for optimal system sizing and control. The following novelties/contributions can be summarized. To the best of the authors' knowledge, this is the first such analysis for a general cargo vessel with varying and uncertain power profiles. The installed fuel cell power and battery energy capacity are estimated based on engineering judgment from a range of power profiles that were derived from real-time onboard measurements. Different combinations of fuel cells and batteries are tested in terms of fuel consumption/cost, capital expenses, weight, and component degradations with actual components from different manufacturers. The uncertainties in fuel prices and capital costs are considered for the calculations. The optimal sizing and control results are presented for one power profile of the vessel and for the average hydrogen costs obtained from the Monte Carlo simulations.

The rest of the paper is organised as follows. In section 2, the case study details are presented. The methodology framework is explained in section 3. The results from the simulations and discussions are in section 4. Finally, the concluding remarks and directions for future research are presented in section 5.

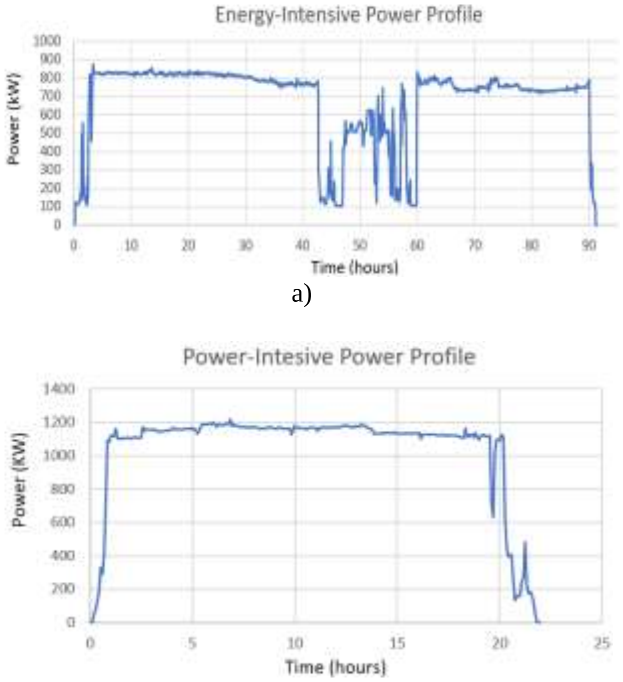
2. CASE STUDY

The general cargo vessel considered for the analysis has the following specifications that are shown in Table 1. The original version has one main diesel engine and a controllable pitch propeller.

Table 1. Case Vessel

Parameters	Values/Info
Length	89.9 m.
Width	12.5 m.
DWT	3638 t.
Year built	2007
Engine	Wartsila 9L20

The general cargo vessel does not have a fixed schedule and route. Instead, there are different operational areas and power profiles. The most energy intensive and power intensive load profiles are shown in Figure 1.



a)

b)

Figure 1: Worst case Power Profiles: a) Energy Intensive, and b) Power-Intensive

3. METHODOLOGY

3.1 Framework

A simplified diagram of the methodology that will be followed in this study is shown in Figure 2.

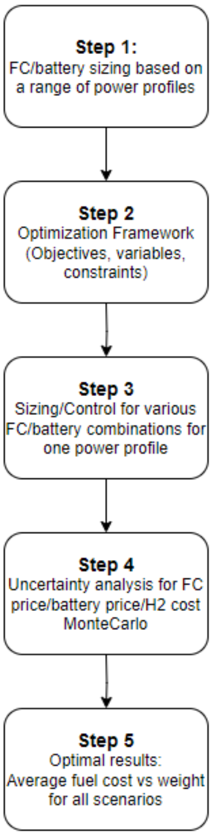


Figure 2: Simplified Methodology Framework

Data measurements have been taken for the propulsion loads from the main diesel engine of the original mechanical version of the cargo vessel with a frequency interval of 5 minutes. The power output of the engine is the propulsion power demand for the retrofitted hydrogen-hybrid version developed in this study. No auxiliary loads have been considered for the analysis since no measurements were taken.

In the hydrogen version, the fuel cells and the batteries are sized considering numerous power profiles of the vessel (step 1). The sizes of the fuel cells, which are the main power source, are such that they can cover the maximum recorded power output of 1200 kW (Figure 1b). The batteries are sized based on the most energy intensive profile of the vessel to cover the highly fluctuating loads (Figure 1a). Considering that the fuel cells provide the average power demand from 45 to 60 hours, the required battery energy is estimated to be around 1100 kWh. However, the installed battery capacity is taken as 1500 kWh to account for margins and uncertainties. An alternative weight-centred way to size the batteries would be to consider that the weight of the batteries and fuel cells combined is close to the weight of the main original diesel engine. Despite the decreased overall system weight and capital expenses, this approach was not selected as it would result in increased fuel cell usage, fuel consumption and cost, component degradations, hydrogen tank weight and volume. Hence, the powertrain components of the hydrogen-hybrid version have been selected based on power and energy requirements from the load profiles.

In step 2, the optimization framework is defined as follows:

- Objectives:
    - Fuel consumption
    - system weight
- Variables:
    - Power/efficiency of fuel cell stack
    - number of batteries
    - number of fuel cells and selection of actual components from different manufacturers.

More details about the last part (considered fuel cell database) are provided in Section 3.3.

- Constraints:
    - Power demand (t) = Power output (t)
    - DC bus voltage fluctuations +/- 5%
    - Constant FC power (min. degradation)
    - Maximum installed FC power 1.2 MW

In step 3 of the methodology, different combinations of batteries and fuel cells are tested to estimate fuel consumption, costs, degradations, weights, and optimize the voltage and power control. The analysis is conducted for a short power profile of 4.16 hours (15000 seconds) for computational reasons (Figure 3).

Figure 3: Power Profile for modelling/optimization

In step 4 of the methodology, variable and uncertain fuel cell prices, battery prices and hydrogen fuel prices are considered. The considered vessel is 16 years old, so it can be assumed it will operate for another 10 years. At certain periods in this 10-year time interval, the distribution of prices is different. With Monte Carlo simulations it is aimed to get the average total costs from the normal distributions with some interval of confidence.

Finally in step 5, the average fuel costs, calculated from step 4, are plotted against system weights for all the considered scenarios. The different scenarios for the modelling, sizing, and control analysis of the considered power profile (Figure 3) will be discussed in Section 4.

3.2 Models and control approach

A simplified diagram of the powertrain layout for ‘n’ components is shown in Figure 4.

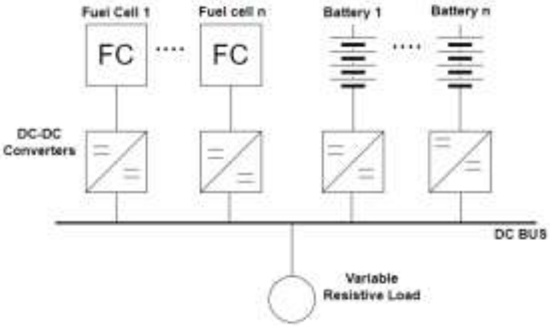


Figure 4: Powertrain configuration

Generic fuel cells and batteries from Simscape library have been used for modelling and integration of the systems to one powertrain. Average converter models have also been developed, instead of detailed converters with pulse width modulation that would significantly increase the computational time. For system-level modelling, average models are sufficiently accurate.

The fuel cells are connected to the DC bus via unidirectional DC-DC converters which increase the variable fuel cell voltage to the levels of the DC bus (1000 V). For the batteries, the bi-directional converters enable discharging or charging onboard depending on the load demand. For simplicity in this study, no shore-charging is considered. The DC bus is modelled with a single capacitance which is a summation of all the capacitances from the parallel-connected converters. The DC bus is connected to a single variable resistive load which is equal to the bus voltage divided by the load current from the power profile. The components after the DC bus including inverters, AC motors and propellers have not been modelled in this study.

The implemented Energy Management Strategy that was developed for optimal system control is shown in Figure 5.

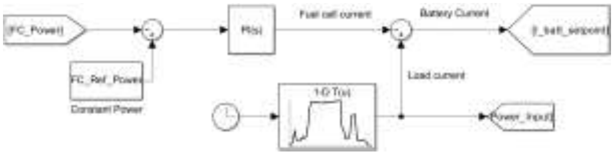


Figure 4: Energy Management Strategy

It is aimed to set the fuel cell power constant at levels below 80% of the rated power for minimum degradation according to [11]. A properly tuned PI-Controller can minimize the difference between the actual and reference fuel cell power. The DC bus voltage is also controlled with a PI-controller so that it is maintained at 1000 V. The battery reference current (setpoint) is derived by subtracting the fuel cell current from the load current. The load current is equal to the power demand in kW since the DC bus voltage is equal to 1000V. The battery setpoint is used as an input to the bi-directional converter for current control.

3.3 Database of components

For testing the different component sizes and system configurations, a database of 6 actual fuel cell components of various power levels from different manufacturers has been developed as shown in Table 2.

Table 2. Fuel cell database

Manufacturer	Rated power (kW)	Stack weight (kg)
Hydrogenics	30	61
Zepp.Solutions	50	180
Powercell	100	212
Ballard	120	250
Zepp.Solutions	150	355
Powercell	200	1070

For the batteries, a single lithium-ion module from Toshiba manufacturer has been considered for the analysis [17]. The module specifications are presented in Table 3.

Table 3. Battery Module specifications

Parameters	Values (units)
Nominal voltage	24.6 V.
Rated capacity	45 Ah.
Weight	14.6 kg.
Response time	2 sec. [11]

These modules are comprised of numerous cells, and they can be connected in series to increase the nominal voltage of the battery pack and in parallel to increase its rated capacity. The total installed energy capacity of the batteries onboard has been set equal to 1500 kWh, as it was discussed in Section 3.1. Different number of battery packs have been considered (ranging from 2 to 5 units), but the optimal configuration that gives the required capacity with the least weight, is the configuration with 2 battery packs. The parameters and values for the battery pack are presented in Table 4.

Table 4. Battery Pack specifications

Parameters	Values (units)
Nominal voltage	800 V. [11]
Rated capacity	937.5 Ah.
Weight	10.1 tons.
Number	2

4. RESULTS AND DISCUSSION

In this section, the results from the simulations are presented and discussed.

There are 6 scenarios, one for each of the stacks (Table 2). In each case, there are 2 battery packs of 750 kWh each, since this is the optimal number of battery packs that can provide the required energy with the smallest system weight. The total installed fuel cell power is limited to 1.2 MW which is the maximum power demanded from the diesel engine in the original mechanical version. Hence, for each scenario, the number of required stacks that need to be installed onboard are presented in Table 5. It is aimed to use all the fuel cells during operation in each scenario, operating near their optimal operating point to maximize fuel cell efficiency and utilization rate. This way, the 'wasted' onboard space from stacks idling for a long-time interval in case some of them were not used can be minimized. Redundancy in case of failure can be offered by the batteries which will be used only in time intervals of highly fluctuating loads (energy intensive power profiles).

Table 5. Scenarios

Scenario	Manufacturer	Rated power (kW)	Stack no.
1	Hydrogenics	30	40
2	Zepp.Solutions	50	24
3	Powercell	100	12
4	Ballard	120	10
5	Zepp.Solutions	150	8
6	Powercell	200	6

For the simulations, the fuel cells will provide power at constant levels. When the load demand is above the fuel cell level, this power will be covered by the batteries. When the load demand is below the fuel cell level, the surplus energy will be used to charge the batteries onboard.

To compare the simulation results between the cases, the total fuel cell operating power should be the same for each case, so that the initial SoC and final SoC are the same for each scenario.

The results are presented for the power profile from Figure 3, for the last scenario with 6 fuel cell stacks of 200 kW (Powercell). It has been considered that the fuel cells should be used for load levelling, i.e., provide power of 600 kW for the entire voyage. In that case, the fuel cells are used at 50% of their rated power which is close to their optimal efficiency. The obtained efficiencies for each stack at 50% operating load are presented in Table 6. These values have been validated with the manufacturer efficiency curves for each stack.

Table 6. Fuel cell operating efficiencies

Scenario	Operating power (kW)	Efficiency (%)
1	15	52.5
2	25	54
3	50	52
4	60	56
5	75	57.5
6	100	54

In Figure 5, the fuel cell power output for one stack is presented.

There are 6 stacks of 200 kW installed onboard in the last scenario, each of which operates at 50% of the rated load, so at 100 kW (10e5 W). There are no power fluctuations which indicates that the applied fuel flow rate control for the stack has been efficiently implemented.

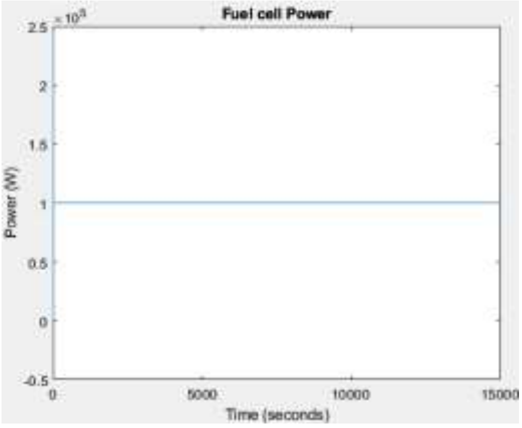


Figure 5: Fuel cell power per stack

According to [11], the degradation rate when fuel cells operate at power below 80% of their rated load, is equal to 10.17 micro-Volt/hour. Considering that the cargo vessel travels for 4.16 hours in the analysed profile, the total degradation is equal to 42.3 micro-Volt for each stack. The regulations allow a maximum of 10% voltage reduction, compared to its nominal value, before the stack needs to be replaced. This is the most efficient way to operate the stacks in terms of degradation, compared to high-power operation >80%, transient loading and start/stop cycling.

If the total fuel cell operating power was taken to be higher than 600 kW (e.g., 800-900 kW), each stack would have to operate closer to their nominal load (80% rated power), so the efficiency would drop, and the fuel consumption would increase.

On the other hand, if the total fuel cell operating power was taken to be lower than 600 kW (e.g., 500 kW), the efficiency would be increased, but a larger battery would be required to maintain the desired SoC range between 20-80%. If the battery is operated outside this range, the degradation rate is increased. Furthermore, it was observed that battery weight has a bigger impact on the overall system weight compared to fuel cells and converters. More details about the battery SoC and system weights will be provided later.

In Figure 6, the DC bus voltage is presented.

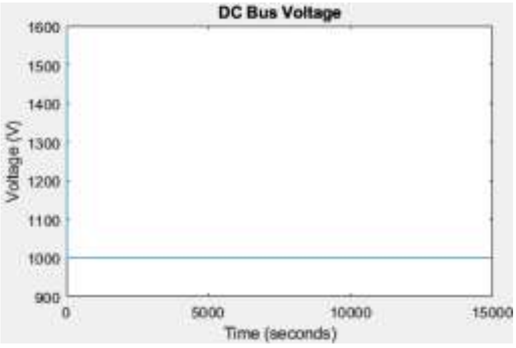


Figure 6: DC bus voltage

The P, I controller parameters have been tuned efficiently and the resulted bus voltage output is constant at 1000 V without any fluctuations. The regulations allow +/- 5% variations during steady state operation and +/-10 % variations during transient operations [11].

In Figure 7, the battery SoC is presented.

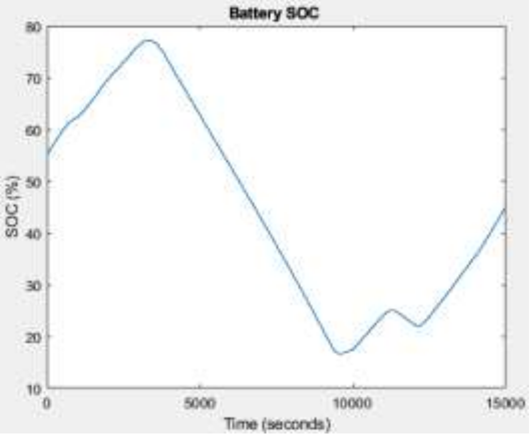


Figure 7: Battery SoC

In all cases, the initial SoC has been equal to 55%. At the beginning until around 4000 seconds, the battery is charged, with surplus energy from the fuel cells, until it reaches close to 80% SoC. Then, the battery is discharged until it reaches 18% SoC at 9500 seconds. According to [17], this battery should not be discharged below 15%. Hence, the battery SoC does not exceed the manufacturer’s recommended range 15-80%.

In Figure 8, the power profile and the power output from the fuel cells and batteries are plotted on the same graph. Since the 2 graphs almost exactly match for the entire duration with errors less than 1%, the power profile has been plotted with 3 times higher linewidth than the power output for visualisation purposes.

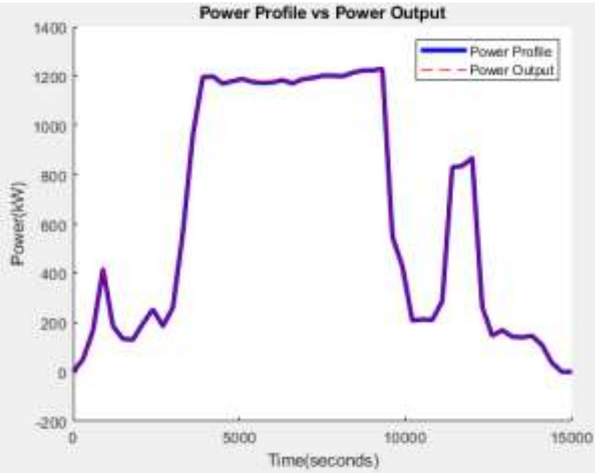


Figure 8: Power Profile vs Power output

The results for the hydrogen consumption for each of the 6 scenarios are summarized in Table 7.

Table 7. Hydrogen consumption results

Scenarios	Fuel consumption (kg)
1	142.6
2	138.7
3	144.0
4	133.7
5	130.2
6	138.7

The lowest fuel consumption (130.2 kg) is obtained from the 5th scenario with the 8 stacks of 150 kW from Zepp. Solutions. There is a 10.5 % difference with the scenario of the highest hydrogen consumption (144 kg), which corresponds to the case of 12 stacks of 100 kW from Powercell.

In Figure 9, the diesel fuel consumption (kg/hour) is plotted against the power output (kW) for the same power profile but the original mechanical propulsion system.

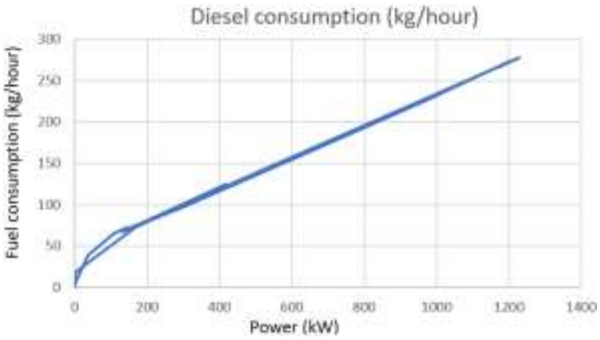


Figure 9: Original Diesel consumption

At the operating power of 600 kW, the fuel consumption is equal to 153 kg/hour, which corresponds to 639 kg of diesel required for the whole voyage of 4.16 hours. The diesel consumption is about 5 times higher than the hydrogen consumptions, which was expected due to the Low Heating Value which is 2.7 times lower for diesel, and the operating efficiency of diesel engine which was 32% at this load.

An alternative control method for the hydrogen-hybrid design is to implement the Classical Proportional Integral Energy Management Strategy [16] with a constant battery SoC at 55%. That means that the fuel cell power follows the load profile, which increases fuel cell degradation due to the transient loadings. However, it is not unreasonable to consider that all the required power comes from the fuel cells since the considered power profile is not very energy intensive. The results for the hydrogen consumption are estimated for the last scenario with the 6 fuel cells of 200 kW (Powercell) operating at 50% of their rated power.

The average fuel consumption, for scenario 6, for the entire voyage is 144.15 kg which is about 4% higher than the previously implemented control method with the constant fuel cell power (Table 7).

In Figure 10, the DC bus voltage output from the Classical Proportional Integral strategy is plotted. The values range between 1000 – 1100 V. At the steady state the DC bus voltage is exactly 1000 V but during transient loads there are deviations in the range of 5-10% which are allowable according to class limits.

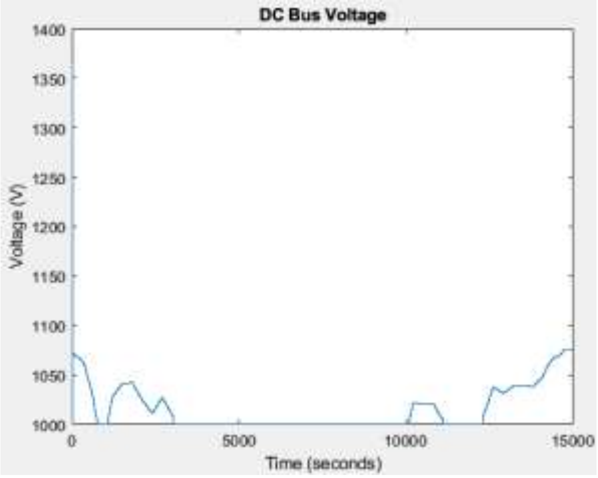


Figure 10: DC Bus Voltage with Classical Proportional Integral strategy

In Figure 11, the power profile and power output using the Classical Proportional Integral strategy are plotted on the same graph. There is a 4-8% difference at some intervals where the power output is higher than the power profile, but in the rest of the time domain the 2 plots match exactly.

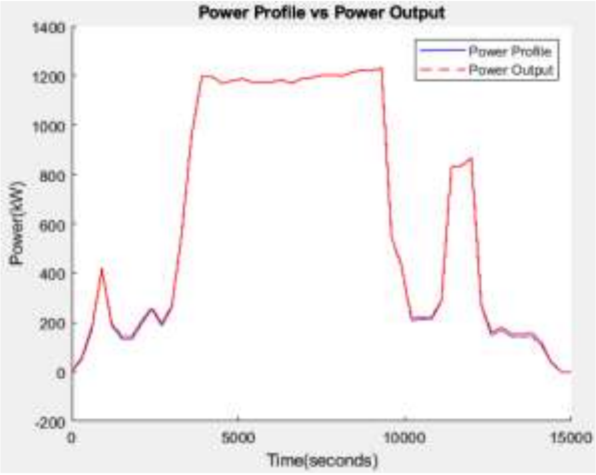
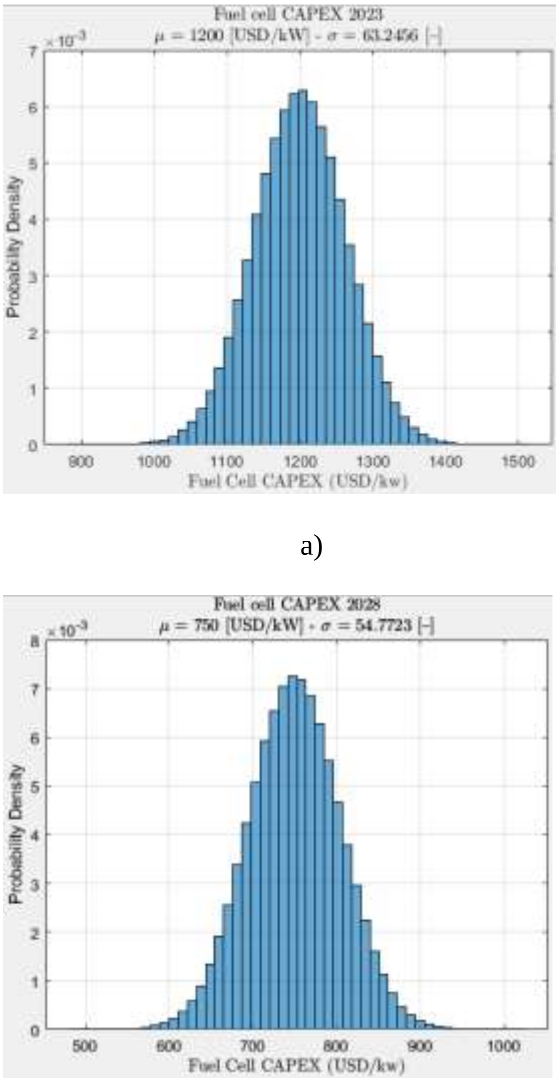


Figure 11: Power plots with Classical Proportional Integral strategy

Overall, with the Classical Proportional Integral strategy the fuel consumption is increased by 4%, there are DC bus voltage fluctuations in the range of 5-10% and 4-8% power losses during transient loads,

An uncertainty analysis has also been conducted to investigate hydrogen price variations and capital costs' variations for the batteries and fuel cells. Monte Carlo simulations are performed to obtain the average fuel costs for each case with some interval of confidence. Monte Carlo is a mathematical/statistical method that is implemented to obtain a range of outputs for uncertain, randomly generated input parameters.

In Figure 12, the fuel cell system price variations for 2023 and 2028 are presented. It is assumed that the fuel cells will need to be replaced after 5 years [18], so only once after their installation, considering that the vessel has 10 more years of operation. The graphs have been created based on price estimates from [19] and [20].



a)

b)

Figure 12: Fuel cell system price variations for: a) 2023, b) 2028

These values depend on various parameters such as material costs, area of development, production units per year, power levels etc. The prices per kW are expected to be higher for very small fuel cells < 5 kW. However, in this study the analysis has been conducted considering fuel cell systems in the range of 30 – 200 kW.

In 2023 the fuel cell prices range from 1000 to 1400 USD/kW, while in 2028 it is expected that the prices will drop in the range of 600-900 USD/kW. The average prices with the highest probability are observed at the medium point of the normal distributions at 1200 USD/kW and 750 USD/kW respectively.

In Figure 13, the battery system (lithium-ion) price variations for 2023 are presented [21]. It is assumed that the batteries will need to be replaced every 10 years based on [18]. Hence, once they are installed, they will not be removed until the end of the vessel's life.

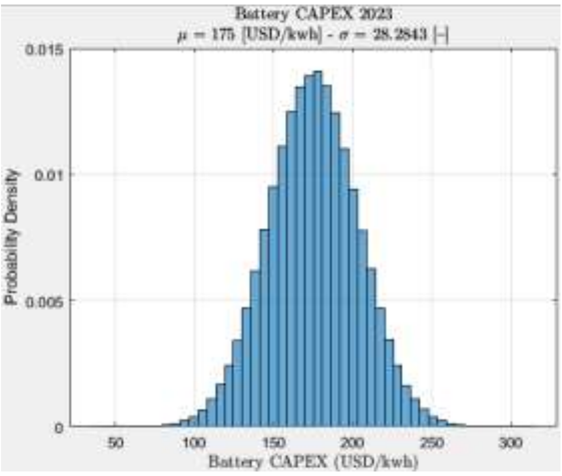
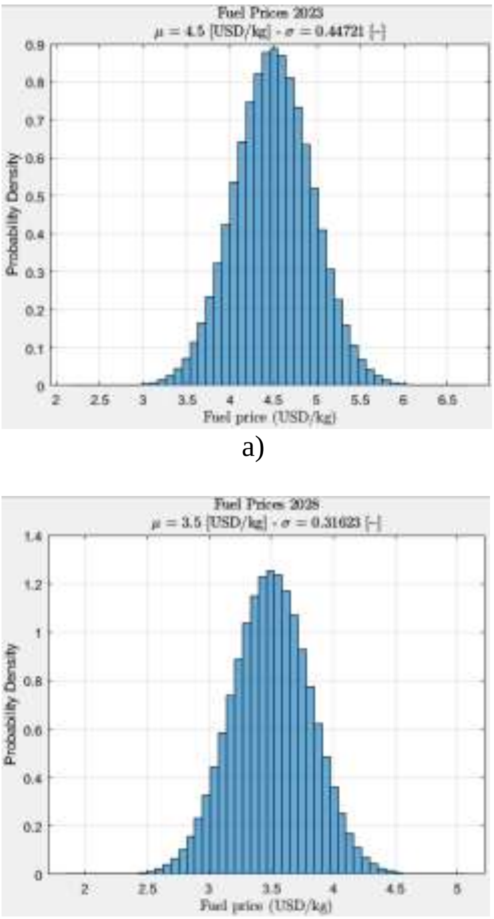


Figure 13: Battery price variations for 2023.

As for the fuel cells, the battery capital expenses include the whole system cost with prices ranging between 100-250 USD/kwh, and an average of 175 USD/kwh. The initial costs for fuel cells have much higher impact on the total cost than the capital costs of lithium-ion batteries.

Considering that the total installed fuel cell power is 1200 kW, and the total energy capacity is 1500 kWh, the total capital cost for the fuel cell and battery systems, using the average prices for 2023 from Figures 12 and 13, is 1.7 million USD.

In Figure 14, the hydrogen price variations for 2023, and 2028 are presented [22]. The vessel operates mainly in Baltic Sea and North Sea around European countries. It is important to note that these fuel prices are for green-hydrogen production costs, so that the well-to-wake emissions are minimized.



a)

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Figure 14: Hydrogen price variations for: a) 2023, and b) 2028.

In 2023, the green hydrogen prices range between 3-6 USD/kg in the operational area, while in 2028 they are expected to be reduced in the range 2.5-4.5 USD/kg. After 2028 until the end of vessel's life (2033) the prices do not change much, since the range becomes 2.75-4 USD/kg [22]. In general, the prices in the vessel's operational area are higher than in most parts of the world [22].

For the hydrogen prices in 2023, a Monte Carlo analysis is performed to estimate the total average fuel cost for each of the six scenarios with some interval of confidence. By setting the number of samples to 10000, the distribution type to normal, and by inputting the mean and the standard deviation values from Figure 14a, the simulation outputs are obtained for 10000 randomly generated input variables (fuel prices in USD/kg). The fuel cost (USD) is obtained by multiplying the fuel consumption (Table 7) with the variable fuel price. For the 6th scenario, the minimum obtained fuel cost is 375.5 USD, the maximum is 965.9 USD, and the average value is equal to 624.2 USD. Considering a confidence interval of 95%, the obtained average fuel cost will be in the range of 624.2 +/- 1.21. Increasing the interval of confidence will increase the value range. For 95% interval of confidence and a much higher number of samples (e.g., 10 million), the accuracy can be increased by a sacrifice of computational time.

The optimal solutions for the 6 scenarios in terms of weight and the average fuel cost calculated from the Monte Carlo simulations are presented in Figure 15. The ranges of fuel costs (+ or -) for 95% interval of confidence are also listed in parenthesis of each solution point in Figure 15.

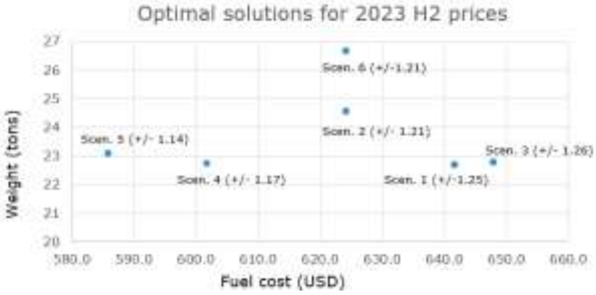

Figure 15: Weight-fuel cost solutions for each scenario for 2023 hydrogen prices

It can be observed in Figure 15 that scenario 5 with 8 stacks of 150 kW has the lowest total fuel cost (585.9 USD) by an average of 6.6% difference from the other solutions, but with a 1.76% higher system weight than the lightest configuration with 40 stacks of 30 kW.

The weight of the original diesel engine is equal to 11.6 tons. The weight of the considered fuel cells and batteries ranges between 22.6 – 26.6 tons from the 6 scenarios (Figure 15). Hence, the weight of hydrogen-hybrid version is around twice the original system's weight, without considering other auxiliary components.

5. CONCLUSIONS

In this study, a conceptual retrofitting of a diesel-based cargo vessel to a hydrogen-hybrid version was presented. The generic models for the powertrain layout and the implemented Energy Management Strategies were discussed. The developed strategy resulted in reduced fuel cell degradation, bus voltage fluctuations and power losses compared to the Classical Proportional Integral approach.

The fuel cells and batteries were sized based on the most power and energy intensive power profiles, but the modelling and optimization results were presented for a short voyage for computational requirements. A database of 6 fuel cell stacks from different manufacturers were considered for this model-based parametric study to investigate different combinations in terms of cost and weight. A Monte Carlo analysis was utilised to estimate the total average fuel costs with

95% interval of confidence for each case for randomly generated fuel prices in the range of 3-6 USD/kg in 2023. Overall, the scenario of 8 stacks/150 kW from Zepp. Solutions appeared to be the optimal solution in terms of fuel cost despite its slightly higher weight by 400 kg.

For a future work, an optimization algorithm will be implemented for the nested sizing and control problem that can be applied to numerous power profiles. The inverters, motors and propeller models will also be developed, and a lifecycle analysis will be conducted.

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