Optimization of Propulsion Layout & Energy Management System for Future Marine Powertrains using Co-Design

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Abstract

Marine energy systems are rapidly evolving, following the demand for decarbonization and increased energy efficiency. Design options are ever expanding due to an increased degree of electrification, inclusion of energy storage systems, novel energy converters such as fuel cells and dual- fuel engines, and alternative fuels such as hydrogen, methanol, or ammonia. These increasingly complex layouts also necessitate the development of accompanying energy management systems to orchestrate the operation and power split between different sources in an optimal fashion.

Design of such systems is increasingly supported by simulation and optimization methods. Optimization criteria can vary depending on the intended vessel mission and often include metrics such as; energy efficiency/range optimization, Operating/ Capital Expenditure (OPEX/CAPEX) minimization, system State-of-Health (SoH), and uptime considerations. The need for these methods is further emphasized by the characteristics of new energy converters and storage systems, considering the in-use degradation of battery and fuel cell systems, increased footprint required to place these systems, (early adopter) cost, and the reduced energy content of alternative fuels.

In the current paper benefits and challenges of applying methodology for co-design of the energy system together with the energy management in an integrated and optimal fashion are explored. The testcase considered is that of a fast ferry operating on Hydrogen (H_2) powered by a Low Temperature Proton Exchange Membrane (LT-PEM) fuel cell. The benefits are compared with traditional design approaches, in which either the system layout or energy management logic is optimized, in order to quantify the added benefit of integrated design.

While the testcase for this methodology is a commercial vessel, the methodology is designed to be generally applicable and may also strongly benefit the design of complex naval vessels. While it is unlikely that naval vessels will adopt hydrogen as a primary fuel, it can become a part of the energy sources onboard to supply smaller (unmanned) assets (UXVs) or to run fuel cells in support of low-signature operation. Using co-design to optimize towards metrics such as footprint or system health is vital to integrate these novel energy systems and guarantee their effectiveness in future marine powertrains.

Keywords: Energy Management, Marine Power Systems, Simulation, Optimization

1. Introduction:

Decarbonization and sustainability, together with digitalization and autonomy are themes that are often brought up in discussions about the future of maritime transport- operations, for commercial, private and even military applications.

Especially on the decarbonization topic, the landscape is far from clear. Multiple alternative future energy carriers, power conversion sources, technologies and propulsion layouts are being considered (Boonen 2023). These have different implications on ship design, while greatly increasing the design degrees of freedom.

The traditional powertrain design process, while straightforward for diesel-direct propulsion layouts, becomes suboptimal. Usually, the process is split in two distinct steps; the design of the physical system (i.e. the plant and its components) and the design of the control system. As the complexity of the propulsion and power generation

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Author's Biography

Nikolaos Sakellaridis completed his Mechanical Engineering studies up to PhD level in the National Technical University of Athens, Greece, on the topic of Marine Diesel Engine Simulation & Diagnosis. After working in the automotive field on 1-D/ 3-D simulations, joined Damen Research as Research Engineer. His interest include: Simulation of power/ propulsion systems, emissions reduction & energy saving technology & alternative fuels.

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system increases, the amount of design decisions and degrees of freedom to control also grows significantly. In the current approach the initial focus is on the plant design, finding the optimal sizing of the components, after which a controller is designed that keeps the plant as close as possible to its desired state. This is illustrated in Figure 1; the optimal plant is identified first without any modifications to the controller, moving from baseline 'B' to sequential step 1 'S1'. This is followed by identifying the optimal controller for the now fixed 'optimal' plant, moving from 'S1' to sequential step 2 'S2'. By sequentially executing these steps, the design space is constrained early, which helps in reducing the complexity by considering only one dimension at a time, but also ignores any design interactions between plant and controller. In co-design an integral approach is followed, keeping the development of plant and controller in parallel, aiming of solutions that are optimal on a system (i.e. ship) level (Wilkins et al., 2023). This is shown in figure 1 by moving from baseline 'B' to the co-design solution 'CD'.

Various options for co-design exist, ranging from iterative methods that alternate back and forth between plant and controller, to nested or even fully integrated optimization methods that simultaneously consider plant and controller in each step (Mylonopoulos, Polinder and Coraddu, 2023). By emphasizing optimal solutions on a system level, co-design may result in new capabilities that improve system performance that would have been disregarded if only looking at the performance of the plant decoupled from the controller. Note that the sequential solution 'S2' in Figure 1 is less optimal than the co-design solution 'CD'.

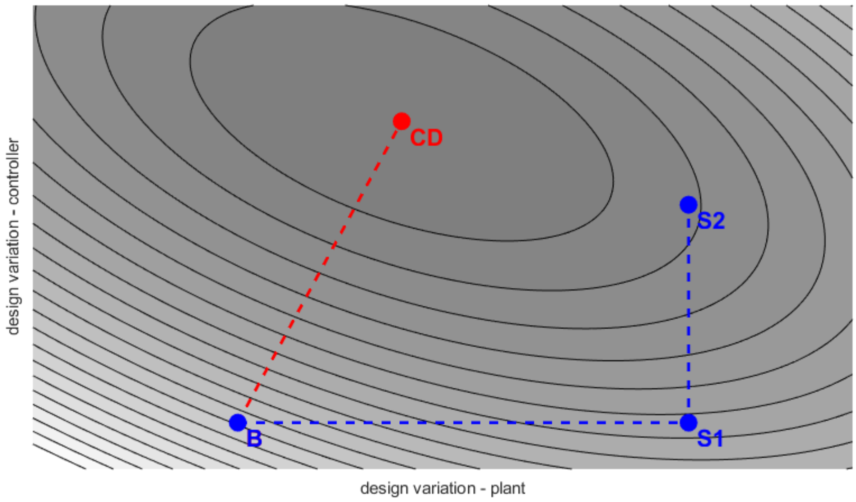

Figure 1: sequential optimization vs. co-design approach

Model Based Systems Engineering (MBSE) acts an excellent framework for experimenting with co-design, providing the methodology, the language, and an array of useful tools. By implementing both plant and controller using the MBSE process, both parts become part of a wholistic system description. Analysis, requirements, interfaces, and traceability become more consistent, which greatly simplifies the introduction of co-design. As an added benefit MBSE also encourages a data-centric approach, meaning that any iterative processes or methods can be easily accommodated.

In the paper a practical co- design application is presented using a PEM- FC powered, fast catamaran passenger ferry as a testcase to explore the requirements, applicability, and benefits of co- design in practice. The sizing of the fuel cell & battery of the hybrid system considering system health degradation, as well as rules of the Energy Management System (EMS) are optimized with respect to OPEX/ CAPEX.

The general methodology for co-design is equally valuable for naval vessels. One reason is the complexity of the power and propulsion systems found in the current and next-generation surface combatants, which include complex hybrid topologies, DC-grids, and energy storage. It very likely that traditional sequential development of plant and controller will not leverage the full capabilities of these power and propulsion systems. Co-design is needed to check the impact of early-stage cost-benefit decisions with respect to the overall system capabilities. Decisions that may be perceived as obvious and beneficial when driven by plant requirements, are in fact harmful when evaluating the integral performance of the system.

Secondly, it is expected that hydrogen will become part of the fuels carried on board of naval vessels, making parts of this work directly applicable to future product development in that market segment. Hydrogen will likely be used to (re)fuel small drones (De Wagter et al., 2021) and to feed fuel cells, needed for the reduction of emissions and/or reduction of signatures.

2. Testcase Description

The Damen Waterbus 2907 is a small, high speed catamaran ferry for inland navigation. Operating close to urban areas, it is a prime candidate for conversion to zero emission operation. This can be achieved through electrification, either as battery-electric or hybrid powertrain using H_2 fuel cells. Although an internal combustion engine (ICE) can achieve near-zero emission with appropriate aftertreatment running on alternative & renewably produced fuels, an ICE hybrid variant is not considered here.

From the two considered options, the full electric variant is the most technologically mature, using established battery technology. Complications include the need for shore-side high-power charging, while it might be necessary to alter the operation to account for battery/ charging limitations depending on the desired operation profile. Some operations are outright not possible/-practical due to current Li-Ion battery technology.

For these cases, the PEM FC hybrid configuration appears as an attractive ‘zero emission’ candidate technology. It allows operation in a more familiar way, i.e. daily bunkering and continuous operation as a direct replacement of the diesel hybrid. Of course, considerations also apply such as the relatively lower familiarity of the maritime industry with fuel cells and the limited availability of ‘green’ hydrogen. A concept of PEM-FC powered version of the Damen Waterbus 2907 is presented in Figure 2.

Fuel cell systems are often referred to as ‘high efficiency and ‘zero/low maintenance’. However, the characteristic of a fuel cell differs significantly from a combustion engine. Peak efficiency for a typical PEM fuel cell is achieved at low load factor of about 30%, with efficiency sloping downwards towards full load operation. Moreover, the auxiliary components of the fuel cell consume a significant amount of electrical energy, with main consumer being the air compressor.

In general, it can be said that a fuel cell has a very high efficiency in low part load, while net efficiency at full load is comparable to a large-scale diesel. As for the ‘zero maintenance’ part, the fuel cell stacks do degrade as a result of the operating conditions as will be described in 4.1, which needs to be accounted for in the design process.

Figure 2: Illustration of Damen Waterbus 2907 H_2 concept

3. Design Process: Baseline & Co- Design

In the current paper we explore the benefits and considerations for practical application of co-design compared with traditional design approach using a testcase of a fuel cell hybrid vessel. The design is in both cases supported by a developed simulation model of the vessel propulsion layout and energy management system, described in chapter 4.

In the baseline case definition, sizing of battery & fuel cell is defined using typical best-practice margins and considerations, while the settings of the energy management system are defined using a trial-and-error approach using the simulation model.

In the co-design case, the simulation model is coupled to an optimizer, which allows to optimize either the sizing of fuel cell and battery, EMS setpoints, or both at once. The optimization in the current work is performed with respect to OPEX and CAPEX (2 objectives), since for such a commercial application these are most important (client) considerations.

For other applications and ship types, such as naval combatants and naval auxiliary vessels, other objectives could be considered such as the endurance, power dynamics of the system (i.e. power ramp rates), or possibly even the acoustic and thermal signatures of components for any given operating point. In addition to the optimization objective, naval use cases may also introduce additional constraints. For example, with respect to required system redundancy, required degraded performance after damage, or stored energy required for vital non-propulsion and emergency loads.

More details about the baseline and co- design methodologies are given in 3.1 and 3.2 respectively.

3.1. Baseline design

The baseline design of the H_2 propulsion layout is defined using a linear process that uses the actual measured operating profile. Two full operating days are used: one referring to a high energy but average overall loading, and a second profile with less energy consumed but higher average propulsion power demands. Measured hotel load is also used as input.

The design process starts from the existing diesel hybrid version of the Waterbus 2907 and consists of the following steps:

- The diesel system including generator sets, tanks and fuel system is removed. This frees up a mass budget, that constrains the fuel cell and H_2 storage system sizing.
- 350 bar H_2 storage is chosen, considering the experience from heavy duty truck applications, and fuelling infrastructure availability, as well as a favourable footprint.
- Simple energy management system: fuel cell operates between 2 setpoints, which are determined by trial-and-error approach using the simulation model, while enforcing charge sustaining operation. The high setpoint is used as much as possible, while the low setpoint is defined to limit excessively high battery SoC condition while avoiding a start-stop of the fuel cell which is detrimental to stack lifetime.
- The battery is sized considering load-levelling operation of the fuel cell as above, incorporating margins on the maximum battery Depth-of-Discharge (DoD).
- Fuel cell size is defined such that at end-of-life (20% reduction in efficiency and power output) the output power is sufficient to cover the average load.
- The rest of the propulsion layout & vessel remain identical.

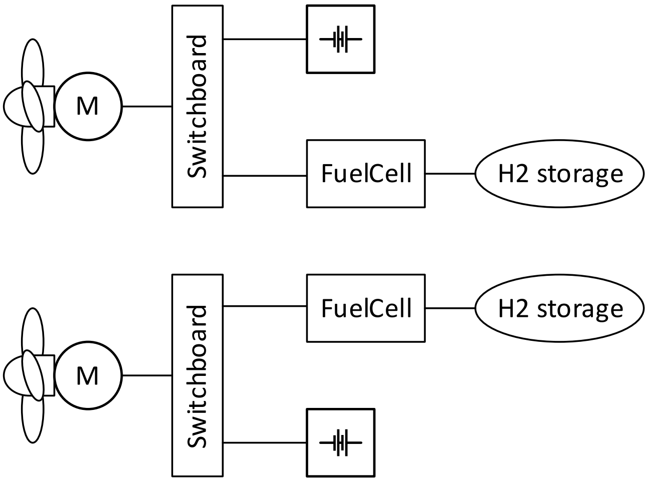

Figure 3: PEM FC propulsion layout considered.

3.2. Co-design

The simulation model is coupled to a multi- objective optimizer of using Matlab Optimization toolbox. The genetic algorithm based on NSGA-II is used for this work, given its adaptability to problems of varying complexity and global optimum estimation capability (Kalyanmoy et al., 2002).

The simulation model is coupled directly to the optimizer, with each evaluation of the objective involves a call to the model in Simulink in an inner loop. This is due to implicit coupling of the objective with the model results (e.g the H_2 storage sizing is defined by H_2 consumption result, but H_2 consumption is itself influenced by the mass of the storage).

The margins and requirements as defined in the baseline design process are introduced either as constraints of the optimization variables or as penalties to the objective functions when they are exceeded. To ensure sufficient search of the design space, a first calculation is performed with quite wide limits for the optimization variables, and based on the results, a second one is set up with narrower permissible upper and lower limits of the optimization variables.

The following calculations are performed:

- ☐ Design-of-Experiments exploration of the fuel cell-battery size design space. The results are evaluated and interpreted, showing the model's capability of capturing the essential trade-offs and system effects.
- ☐ Propulsion Layout Sizing optimization: The battery and fuel cell size are optimized in a 2-objective optimization w.r.t OPEX/ CAPEX and compared with baseline case. EMS settings are kept at the values defined in the baseline case.
- ☐ EMS settings/ rules optimization, wherein the settings of the EMS are optimized in a 2-objective optimization (OPEX/ CAPEX) while the sizing of the battery and fuel cell are kept at the values defined in the baseline design.
- ☐ Full co-design calculation, wherein the EMS settings and the sizing of fuel cell and battery are optimized within a single optimization run.

This step-by-step approach helps to quantify the added benefit of optimization,co-design and interpretation of results.

4. Simulation Model

A simulation model is constructed in Matlab Simulink using an in-house, modular propulsion system model library methodology presented in (Sakellardis, Boonen and Vink, 2022). Purpose of the model is to estimate the propulsion layout sizing and effect of energy management at initial project phase, using limited input data that is usually available at this stage. It relies on power calculation to represent the propulsion layout, and uses as input the operating profile of the vessel, the hotel load, the sizing of the fuel cell and battery, as well as setpoints of the energy management system.

Outputs of the model that are used as objectives for the optimization in this work are:

- ☐ CAPEX contribution of the propulsion system only, limited to battery, fuel cell and compressed hydrogen storage. It is assumed that battery system cost is 800 €/kWh (DNV,2024), PEM fuel cell cost is 2000 €/kW (Clean Hydrogen Joint Undertaking, 2022), and compressed hydrogen storage is 600 €/kg per kg of stored H_2 (Shin and Ha, 2023)
- ☐ OPEX, that is calculated by the daily H_2 consumption calculated at 5 €/kg (Frieden and Leker, 2024) as well as the depreciation of battery and fuel cell components. It is assumed for this work that residual value of battery at 70% SoH is zero, while that at 80% SoH the fuel cell stacks need to be replaced, with the cost of the stacks estimated as half of the total FC module cost from (Wei et al., 2014).

The basic trade-off design loops are accounted for in the model: The added mass associated with the battery, fuel cell and compressed hydrogen storage is taken implicitly into account in the propulsion power calculation. This allows the model to capture effects like, for example, diminishing returns for electric operating range when battery size increases, due to increased vessel displacement.

Other important system-level interactions that such a model must be able to account for is the trade-off between battery size and life, i.e. a smaller battery, besides the mass advantage, is also favourable regarding CAPEX. However, the battery is stressed more heavily, leading to lower lifetime and faster depreciation, therefore it is unfavourable regarding OPEX. This is compounded by higher battery temperatures due to higher C-rates, so a snowball-effect is expected at very low battery capacities.

Finally, a larger battery allows for more steady-state loading of the fuel cell, while a larger fuel cell is also expected to lead to favourable efficiency and thus H_2 consumption, subject to the same mass considerations as the battery.

The final consideration is that, as the system complexity increases, the optimal system configuration becomes less obvious. In a model-based approach, the important trade-offs must be identified in advance, and the simulation model needs to be of sufficient complexity and predictive capability to resolve these system-level effects. This needs to be balanced against the usual lack of detailed input data at initial project phase, as well as calculation cost, especially when the model is directly coupled to an optimizer, such as in the current work. Overview of the modelling approach is provided in Figure 4.

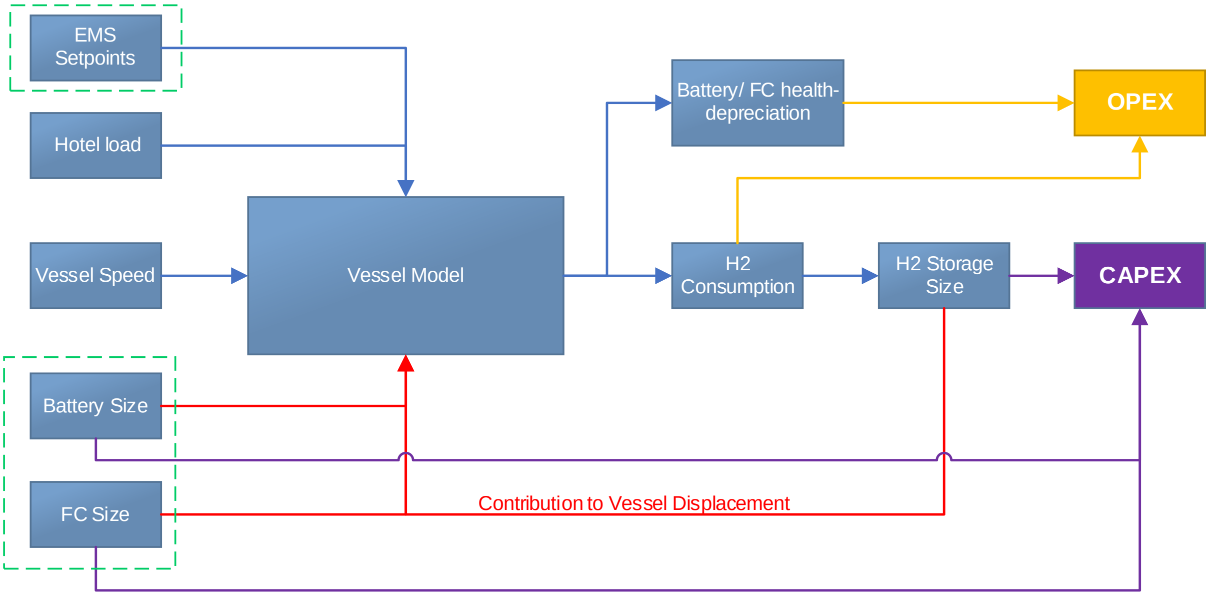

Figure 4: Overall Modelling Approach. Parameters subject to optimization within dashed green line.

4.1. Fuel Cell

The fuel cell model takes the calculated fuel cell power as input, and outputs the state of health (SoH, i.e voltage degradation) and the hydrogen consumption.

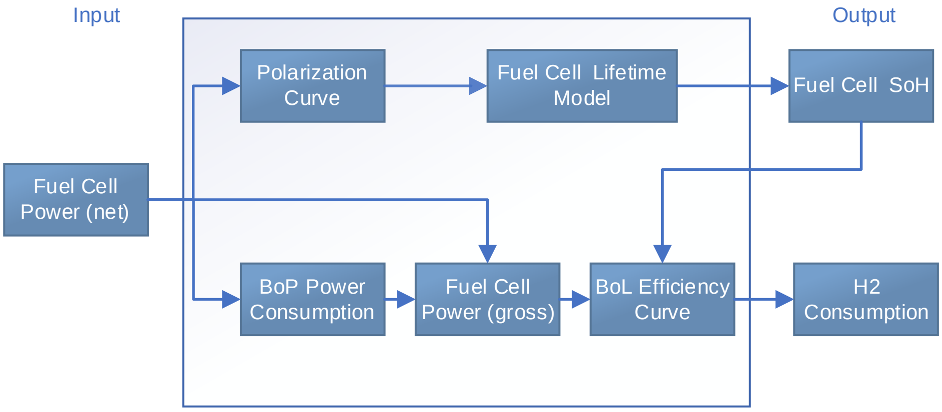

Figure 5: Fuel Cell modelling overview

The net power is model input, calculated by the vessel model, as requested by the EMS model. The consumption of the Balance-of-Plant (BoP) consumers (in practical applications this is mainly the air compressor) is calculated using in-house data of BoP load vs. load factor and assumes that this energy recirculation occurs loss-free within the module. This allows to define the total power of the fuel cell stacks and therefore the overall H_2 consumption by looking up the Beginning-of-Life (BoL) efficiency curve, corrected for current SoH

Lifetime is modelled according to (Desantes et al., 2022), in which the most important degradation mechanisms are modelled using semi empirical correlations using the voltage and current density:

- ❑ startstop
- ❑ transient operation
- ❑ operation under extreme loads (high/low- idle)
- ❑ natural degradation

The polarization curve and efficiency curve of the stack for this work is derived from (Ramírez-Cruzado, 2020). For commercial applications of the method, these values need to come from FC supplier.

4.2. *Battery*

The battery model also uses as input the energy. Starting from an initial State-of-Charge (SoC) the SoC time trace can be defined. Battery losses are calculated and used as input to a thermal model, used to define the average module temperature.

Temperature together with other stress factors such as throughput, C-rate, DoD etc. are input to a battery health/ lifetime model in order to estimate battery SoH (i.e capacity degradation). In the current work the simple model presented in (Wang et. al., 2011) for $LiFePO_4$ battery cells is used.

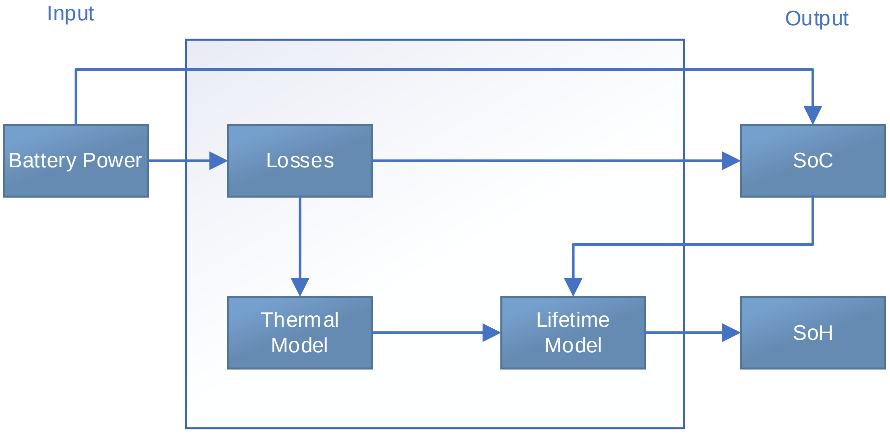

Figure 6: Battery modelling overview

The dependence of battery losses (and heat load) on the SoH has not been modelled in the current work.

5. Results & discussion

As described in section 3.2, a step-by-step approach to co-design is used in order to evaluate the added benefit vs. complexity, as well as make sure that the results are interpretable and explainable. The latter part is very important in model-based optimization, since in essence the optimizer is a black-box algorithm, and results can be affected significantly from model inaccuracies, inability to resolve trends and trade-offs that affect the real physical process, as well as model artifacts. These could be caused, for example, by model outputs under extreme input conditions, so model must be checked to behave consistently under any foreseeable input combinations during the co-design process.

Therefore, the work starts off with a Design-of-Experiments calculation and results interpretation, and proceeds with design optimization, EMS optimization and simultaneous EMS/propulsion layout co-design.

5.1. *Baseline*

Following the procedure outlined in 3.1 the baseline spec is defined, which is used as reference for comparison with the optimization results:

- ☐ Battery capacity is sized at 168 kWh and fuel cell at 438 kW. The load levelling point of the fuel cell is defined at 350kW, with power reduced as necessary to 15kW to avoid idling of the fuel cell and simultaneously keep the battery SoC within predefined limits.
- ☐ CAPEX for the fuel cell, battery and H_2 storage is estimated at 1.2 million €, with a yearly OPEX of 833,000 € assuming the vessel is utilized every single day. Almost half of the OPEX is attributed to depreciation due to fuel cell and battery aging, and the rest is defined by the fuel cost.

5.2. *Design Space Exploration: DoE*

The sizing of the battery and the fuel cell is varied between a minimum and maximum value in a full factorial calculation. Purpose is to explore the design space and assess model behaviour & robustness. Energy management philosophy is same as in the baseline case, described in 3.1. Therefore, by adjusting the fuel cell size the operational load factor changes, i.e. a small fuel cell operates closer to full load and a larger one in a lower part load condition.

Results are displayed in Figure 7. The left-hand side plot presents the H_2 consumption change vs baseline as function of the battery and fuel cell sizing. At low fuel cell capacity, the efficiency is low, together with highest parasitic consumption of BoP components. This leads to a rapid increase of fuel consumption in this region that overshadows the benefit of low fuel cell mass. This increase is compounded by the increased mass of the necessary

H_2 storage system. As expected, increase in battery size increases the fuel consumption due to increase in vessel displacement. There is an opposing trend of battery losses that tend to reduce as battery size increases, however, this effect is too minor to influence the overall result.

At higher fuel cell capacity the fuel consumption reduces, up to a point. The fuel cell average load factor is approx. 40%, even at the highest FC capacity considered, so the peak efficiency of the module has not been reached in this DoE, however the fuel efficiency of the vessel peaks around an average module load factor of 65%, due to the increased displacement that accompanies the oversized fuel cell.

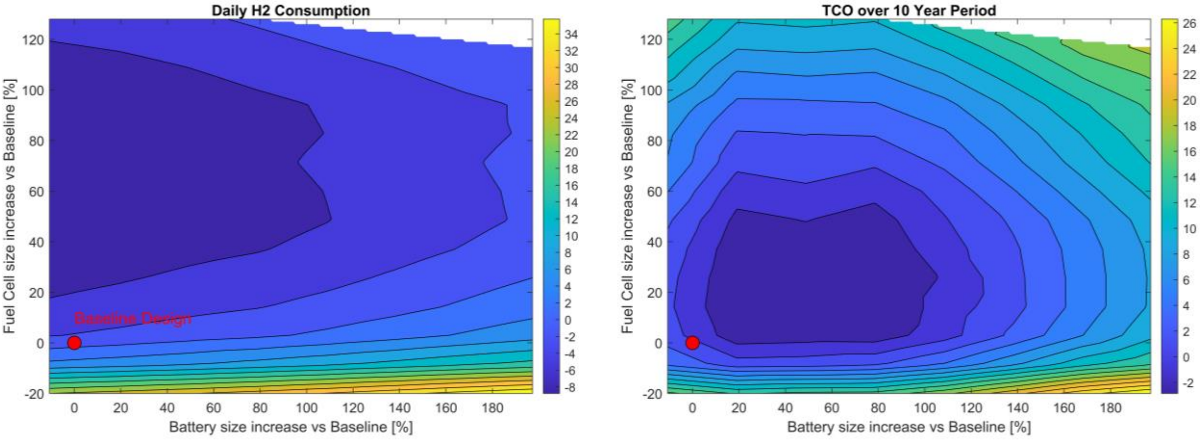

Figure 7: Daily Consumption of H_2 (left) and TCO over a 10 year period (right). Values in % change vs baseline (positive→increase, negative→decrease)

The right-hand side of Figure 7 displays the Total Cost of Ownership (TCO) associated with a 10 year period. A clear region of optimal TCO is identified, that partly overlaps with the minimum fuel consumption, but is also strongly affected with CAPEX (scaling linearly both with FC and battery unit cost). However, a smaller fuel cell operates at high load factor, which tends to reduce its lifetime, and similarly with a small battery size, that tends to have reduced lifetime due to being over-stressed and subject to higher temperatures, which from a TCO perspective tend to balance out the beneficial effect of reduced capex associated with low installed battery capacity and FC rated power.

To summarize, the baseline sizing has been achieved considering the smallest size of fuel cell and battery to fulfil the demand within the established margins and is not very far from the defined optimum of the DoE. However, there seems to be a case for some degree of battery and fuel cell over-sizing that leads to TCO reduction of about 2.5%.

5.3. Optimization: Fuel Cell & Battery Sizing

We use the optimizer as described in 3.2 to define the trade- off between OPEX and CAPEX that results when optimizing the sizing of the propulsion layout components, i.e. the fuel cell size and the battery size. In Figure 8 is presented the Pareto-front that results from the optimization calculation.

Each point represents a propulsion layout design candidate (variation of FC and battery size). Blue are the points considered by the optimization algorithm, while the pareto points (points that dominate the others, i.e. achieve the best trade off between the conflicting objectives) are shown in red. Finally, green point is the baseline design achieved with the baseline design process.

The first observation is that the baseline design is quite close to the pareto front define by the optimizer. This verifies that the traditional design approach, following best practice and expert knowledge is still effective. In this work, where the added benefits of advanced design processes are evaluated, it is important to have a best practice method that defines the baseline, or else the benefits that are observed can be attributed not to the new method, but to the fact that baseline design is largely sub-optimal and therefore there is a lot of improvement margin.

This type of analysis results in a collection of optimal solutions that one can choose from, depending on the particular requirements and/or intended function of the vessel. For example, a vessel that will be continuously operated can be designed with OPEX minimization in mind, therefore a red point to the right-hand side of the Pareto shall be chosen. Points to the right are characterized by increased battery and fuel cell size for reduction in fuel consumption and high lifetime, while points to the left represent designs with small FC- battery capacity that focus on CAPEX minimization.

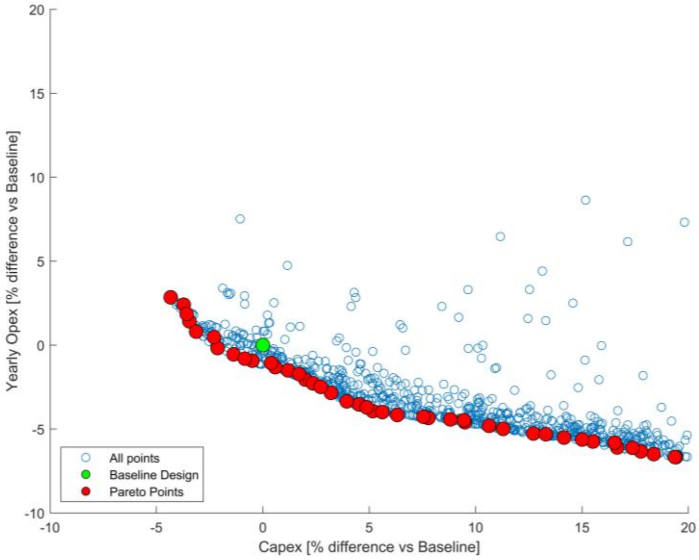

Figure 8: Optimal Solutions (pareto front) for a fuel cell-battery sizing optimization

As mentioned, the objectives and selection criteria for different application types are expected to be different. If this method would be applied to a naval combatant, a similar Pareto front could be formed, for example, one describing the trade-off between maximum endurance and maximum power dynamics. Similarly to what is shown in Figure 8, this can result in choosing an 'oversized' solution that focuses on improved power dynamics, but penalizes the efficiency and thus endurance of such a system.

5.4. Optimization: EMS setpoints

In Figure 9 the result of optimizing the EMS setpoints/ rules is shown. The simple load-levelling, rule-based EMS, as described in 3.1 is parameterized using 5 setpoints, being the high & low setpoint and corresponding SoC switching thresholds, a well as a maximum ramp-up of the fuel cell. It is interesting to note that the result consists of a very narrow pareto front, showing that the main benefit is found, as expected, in the OPEX objective, ranging from 9-10%. This improvement is attributed mainly to reduced fuel consumption in the order of 6.5 to 8.5 %, and secondly to improved FC and battery lifetime, which is improved 10-15% for both the battery and fuel cell. The CAPEX reduction is due to the slightly lower storage system needed because of H_2 consumption reduction. However EMS optimization, as expected, mostly affects OPEX.

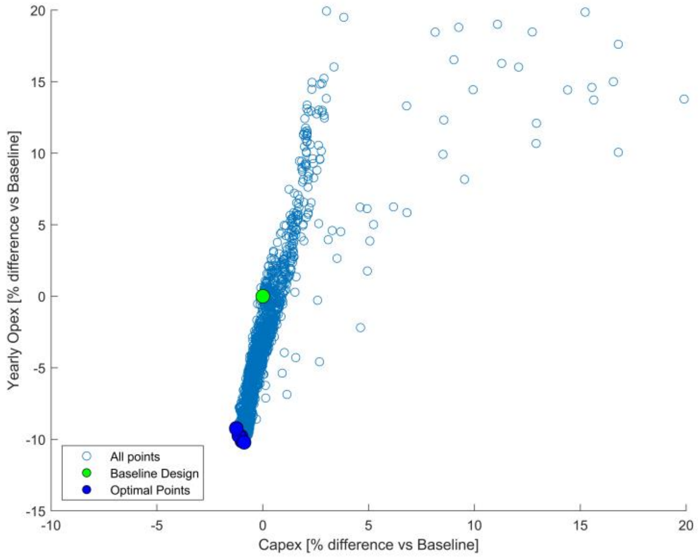

Figure 9: Optimization of EMS setpoints

5.5. *Optimization: Co-Design*

Finally, the design parameters (FC and battery sizing) as well as EMS setpoints are included in the optimization in a 1-step process (co-design of propulsion layout and tuning of the EMS) to evaluate the added benefit compared to sequential optimization (first optimizing design, then optimizing EMS for said design), with the results displayed in Figure 10.

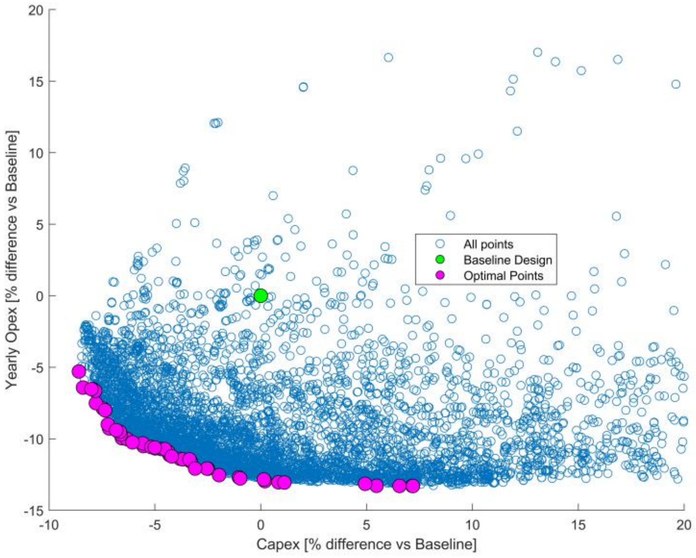

Figure 10: Co- design results

An added OPEX benefit is observed when compared to the sequential optimization of design and EMS, as well as diminishing returns in the OPEX savings by CAPEX increase (i.e. oversizing of FC and battery to achieve reduced fuel consumption and extend component lifetime).

In order to properly compare the added benefit and interpret the results, all optimal configurations are plotted on the same axes in Figure 11, resulting in a more detailed view of specific points on the Pareto-front.

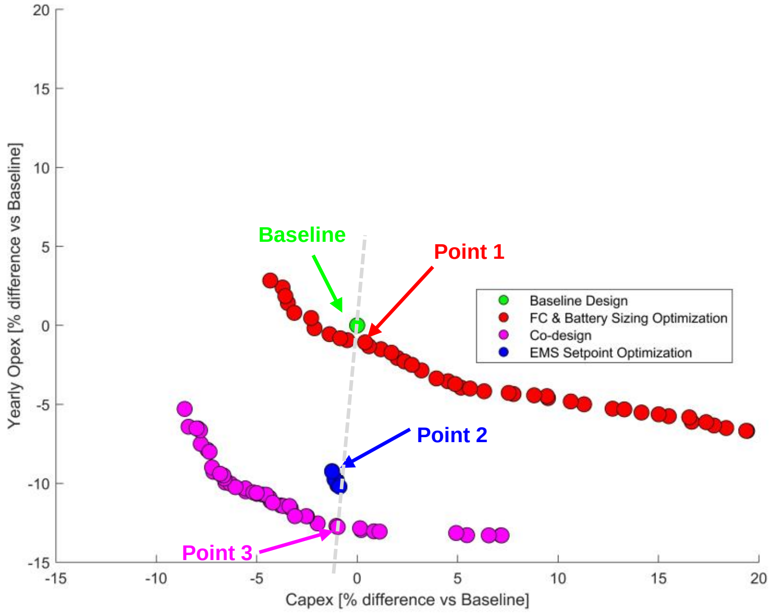

Figure 11: Comparative evaluation of results

A summary of the resulting specification of points 1 to 3, as well as the baseline, are provided in

Table 1: Summary of selected points on

	FC Size [kW]	Battery Size [kWh]	Fuel Cell Setpoint Low [kW]	Fuel Cell Setpoint High [kW]	H2 Consumption [kg/day]
Baseline	438	168	15	350	465
Point1: Design Optimization	430	189	15	350	471
Point 2: EMS Optimization	438	168	84	330	426
Point 3: Co-design	424	203	81	323	429

Point 1, which results from battery and fuel cell size optimization (i.e. system design), is very close to the baseline. Battery size is increased 11% compared to baseline with a very minor FC size reduction, that keeps CAPEX within 0.5% if the baseline. Most of the OPEX benefit is provided by 15% predicted battery lifetime increase, that overcompensates for a 1% fuel consumption increase. This shows that the marginal benefit of the size optimization is heavily influenced by the predictive capability of models used for FC and battery lifetime.

Point 2 results from optimization of the EMS parameters, with the small CAPEX improvement attributed to reduced size of H_2 storage needed on board. Leading to the conclusions that most of the 9.5% OPEX reduction is caused by fuel consumption reduction. Any remaining improvement are attributed to the slight increase in fuel cell and battery lifetime (around 10%), since the EMS setpoints tend to move towards the peak efficiency region, and both fuel cell and battery cycling reduces slightly. The ramp rate of the fuel cell also reduces compared to the baseline.

Finally, point 3 results from combined EMS and system sizing optimization, with a predicted 12.5% percent OPEX benefit and a more modest 1% CAPEX reduction. CAPEX reduction comes as a result of reduced H_2 storage requirements while a small reduction in FC size balances out a significant battery size increase (34%). The reduction in H_2 consumption is 7.8%. The fuel cost represents the larges part of OPEX improvements, at a predicted 70%, with the rest being battery and fuel cell depreciation. The remainder of the OPEX benefit is attributed to a 34% increased battery lifetime as a result of sizing increase of 20% and optimal EMS setpoints that result in reduced cycling, and secondarily to a 9% increase in fuel cell lifetime.

6. Conclusions & Next Steps

In this paper was presented a methodology for co-design and optimization of the energy system together with the energy management in an integrated fashion, and results compared with traditional design approaches or sequential system/ EMS optimization. A fuel cell- battery hybrid layout of a fast ferry was chosen as a test-case, representative of an electrified, zero emission future propulsion layout.

The conclusions of the work can be summarized as follows:

- ❑ Co-design has been successfully applied to study the propulsion layout, identifying and quantifying the benefits of co-design.
- ❑ The fidelity and complexity of the model used should be able to resolve the relevant trade offs to be usable in such a study. Therefore, the modelling approach should be considered in advance, taking into account the exact purpose, objectives, and desired outputs.
- ❑ When sized according to a traditional design process, the resulting configuration is close to optimal, when best practices and expert knowledge are employed.
- ❑ Some degree of battery capacity increase was found to be beneficial regrading lifetime extension, outweighing the negative effect of increased vessel displacement. This conclusion is specific to the testcase however, as vessels less sensitive to weight increase might further benefit from fuel cell/ battery over-sizing.

Based on the above results, it follows that practical application of the methodology is very interesting for the optimization of complex ship energy systems of the future. There is still considerable work towards generalized and robust implementation in practical applications:

- ❑ The proposed methodology should be accompanied in practice by critical evaluation of results that gives overview of the design space and model behaviour. DoE approach as described can act as a check and first step in the process.
- ❑ The robustness of the optimisation to uncertainties needs to be evaluated (e.g. OPEX & CAPEX being highly dependent on assumed costs for fuel and components, possible uncertainty in lifetime estimation of components or uncertainty in inputs such as operating profile). As a next step, robust optimization methodologies can be explored and applied, from simple repetition of the optimization under different scenarios of inputs to more complex methodologies of handling uncertainty, such as Monte Carlo analysis as per (Dall'Armi, Pivetta, and Taccani, 2022).

- ☐ Adoption is dependent on robust, well parameterized/ modularized and validated (sub)models, for both propulsion layout and EMS.
- ☐ As seen during the exercise, sometimes the calculated benefit was a result of component lifetime extension. Battery and fuel cell lifetime modelling are topics of ongoing research, with significant part of the knowledge residing with (component) suppliers. To overcome the problem of IP protection and facilitate collaboration, integration of the methodology within a co-simulation framework using Functional Mock-up Unit (FMU) ‘black box’ models is an interesting option.
- ☐ As degrees of freedom increase, so does calculation run time for reaching optimizer convergence. Proper selection of optimization algorithm & parameters (e.g. population and generation number for GA’s) is important to ensure on the one hand convergence while not leading to excessive computation times.
- ☐ In the current work a limited operation time was simulated, since the model was implemented in the optimizer loop. However, from model calculations that span over several operational years it is seen that fuel cell and battery degradation are not fully linear effects, especially when approaching end-of-life. Therefore, lengthy and extensive DoE calculation until end-of-life and using a metamodel to fit the results could be an alternative approach, with the metamodel being implemented in the optimizer loop. This helps better quantify end of life effects and apply more consistently the associated constraints, allows rapid optimization process and possibility to change objectives without repeating calculations, but some loss of accuracy is incurred during model fit.

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