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Design and optimized control of hybrid propulsion systems based on a modular simulation kit

System Integration & Hybridization

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ABSTRACT

To tackle climate change a strong reduction in greenhouse gas emissions is required, which also affects the shipping industry. The EU regulations introduced for shipping as part of the Green Deal are already taking effect today and will be fully applied by 2026. Both ships and ports are affected by this, e.g., through the obligation to supply shore power. Hybrid drives in ships are a promising way of making energy consumption more efficient and reducing emissions. At the same time, there is a wide range of variations in hybrid drives and they lead to an enormous increase in system complexity. In this paper, we will show how this complexity can be mastered with the help of virtual propulsion and energy systems. We present how the use of a modular and manufacturer-independent simulation platform can optimize the design according to individual ship requirements based on routes, load profiles, areas of application and other boundary conditions. Based on this, the simulation platform serves as a development basis for intelligent operational control and energy management, which includes all energy components for the drive and for the hotel load. We will also demonstrate the combined use of the virtual ship and the port's Digital Energy Twin (*). This is a very important aspect when considering the potential of energy storage on the ship for optimized energy management and its impact on port infrastructure. In this work, we focus on ferries and tugs that operate in nearshore waters and can therefore make intensive use of the opportunity of shore-side power supply. Using the example of a ferry, we will analyze different drive topologies and the energy requirements for propulsion and the hotel load with the simulation platform and present an optimal design and energy management. The modular, manufacturer-independent approach requires a clear definition of the components of the drive and energy system as well as the parameter sets for defining these components and the information and data flows exchanged between them. In addition to the application shown, the paper analyzes the topic of ontology and modeling methodology with the aim of maximum flexibility regarding the selection and configurability of the components and the optimization goals.

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1 INTRODUCTION

This article presents a simulation-based, optimized design approach for hybrid propulsion systems that integrate various energy sources, including diesel engines, fuel cells, batteries, and photovoltaics (PV), with a specific focus on ferries. The complexities associated with hybrid propulsion design are examined, along with optimization strategies aimed at minimizing costs and emissions, and the integration of fuel cells and PV systems. The open energy modelling framework (OEMOF) [1] serves as the modeling and optimization environment for this study. The deterministic approach, as outlined in "Design of sustainable integrated energy systems for green ports - selection and sizing" [2], is adapted for the design of ship propulsion systems. Optimization inputs include load profiles, component data (including costs), available space, and the specific characteristics of each component, such as the diesel engine, fuel cell, electric motor, PV array, battery, diesel and hydrogen tanks, as well as power electronic component.

1.1 State of the Art in Electrical Hybrid Propulsion System Design: Sizing and Optimization

The modeling and optimization of hybrid ship propulsion systems represents an active area of research. The work titled "Design and control of hybrid power and propulsion systems for smart ships: A review of developments" [3] provides a comprehensive overview and classifies various drive architectures (mechanical, electrical, hybrid) and energy supply systems, highlighting their respective advantages and disadvantages.

Common hybrid drive architectures include serial, parallel, and serial-parallel configurations, each differing in their coupling mechanisms and resulting properties. The selection of an appropriate architecture depends on the operating profile, costs, complexity, performance, and emissions requirements. For ferries, which frequently operate in the partial load range, electric or hybrid architectures are preferred to maximize efficiency and minimize emissions. The serial hybrid configuration offers advantages for highly variable load profiles, as it allows for optimal operation of the combustion engine and facilitates the flexible integration of different energy sources. In contrast, the parallel hybrid configuration features a less complex system where the electric motor can assume the boost function, but the combustion engine may not always operate within its optimal range. The serial-parallel hybrid configuration combines elements of the first two variants but is not considered suitable for ferries due to its complexity and high costs.

The integration of fuel cells, energy generation and storage technologies, along with their optimal operation, is discussed in "Hybrid power and propulsion systems for ships: Current status and future challenges" [4]. This paper identifies several challenges, including the complexity of the design process, which can be addressed through the proposed approach in this study and will be analyzed in subsequent sections. Fuel cells exhibit a higher efficiency than combustion engines but respond slowly to load changes, requiring intelligent control strategies. The selection and sizing of the energy storage (e.g., batteries, supercapacitors) are crucial for overall system performance and cost-effectiveness. Both factors must be incorporated into the optimization process, as discussed in "Review on the challenges of hybrid propulsion system in marine transport system" [5], which focuses on the challenges associated with battery energy storage system (BESS) sizing and their impact on costs and service life.

1.2 Methods utilized in Hybrid Propulsion System Design

Various methods are employed for the optimization of hybrid drives, including rule-based strategies, dynamic programming, model predictive control (MPC), equivalent consumption minimization strategy (ECMS) and metaheuristic optimization algorithms such as genetic algorithms and particle swarm optimization [3]. These methods vary in complexity, computational effort, and the quality of the solutions achieved.

Rule-based strategies are easy to implement but often deliver sub-optimal results. Dynamic programming can identify globally optimal solutions; however, it is computationally intensive for complex systems with numerous degrees of freedom. MPC optimizes over a limited time horizon, making it suitable for real-time applications, yet it may be suboptimal for longer time horizons. ECMS simplifies the problem by mapping battery consumption to equivalent fuel consumption but neglects the dynamics of the energy storage system. Metaheuristic algorithms can produce satisfactory solutions but do not guarantee optimality and often require complex parameter optimization.

In contrast, Linear Programming (LP), as utilized in the deterministic approach outlined in [2], offers significant advantages for overall system optimization. LP algorithms are generally efficient and capable of solving large optimization problems within acceptable time frames. This efficiency is particularly crucial for a holistic view of the system, where numerous components and boundary conditions must be considered. Additionally, LP

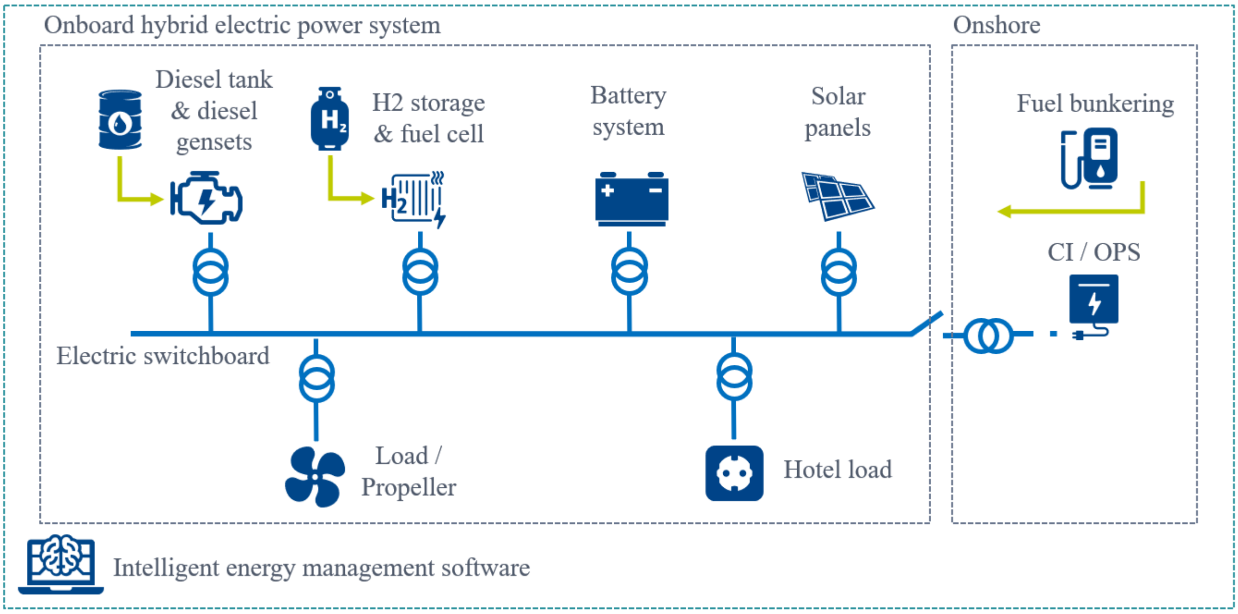

Figure 1: Setup of the onboard propulsion system and the onshore infrastructure for onshore power supply (OPS) or cold ironing (CI) and fuel bunkering as well as intelligent energy management software.

guarantees the optimality of the solutions obtained and provides transparency and scalability. For the holistic optimization of hybrid marine propulsion systems with multiple energy sources and components, LP emerges as a suitable method. OEMOF supports the implementation and solution of LP models.

1.3 Contribution

This paper presents an optimization of the design and dimensioning of components, as well as the operating strategy for hybrid ferry drives within OEMOF. A deterministic approach, based on the methodology outlined in [2], is employed with the objective of reducing costs and emissions while considering installation space and the specific characteristics of the components. The input data include load profiles, component specifications (including costs), available installation space, and the properties of diesel engines, fuel cells, electric motors, PV arrays, batteries, and diesel and hydrogen tanks. This work combines the holistic system perspective from [3] with the optimization framework from [2], explicitly incorporating considerations for fuel cell and PV systems.

2 METHODOLOGY

The methodology employed is based on modeling the target system, which serves as the basis for simulation and optimization. The models represent the system components and constraints relevant to the objectives. To conduct simulations and optimizations, clear definitions of optimization goals and boundary conditions are essential.

2.1 System Representation and System Boundaries

The system utilized for simulation is illustrated in Figure 1 and consists of the following components:

- Diesel generator and diesel tank
- Fuel cells and hydrogen tank
- PV system
- Battery storage system
- Electric motors as drive loads
- A representative hotel load

Fuel stations and charging stations are assumed to serve as onshore energy sources. The components are characterized by their relevant attributes for the simulation.

2.2 The modeling and optimization environment

OEMOF is a powerful software ecosystem supported by an active scientific community. Input is provided by energy sources and sinks as seen in the base system. The energy demand, represented by the alternating current (AC) electricity demand, is typically specified alongside a predetermined time-dependent load profile. For components that transform energy forms, such as fuel cells or internal combustion engines, their technical specification are defined. Each component can be associated with various costs, including monetary costs, emissions, and space requirements.

Typically, monetary costs are minimized:

- satisfying the specified demands,
- while adhering specific constraints, such as zero carbon emissions and limited space on a vessel,
- among all potential component choices and sizes, including considerations of whether to incorporate a fuel cell and, if so, its optimal size,
- alongside the dispatching strategy, which determines the load conditions under which the diesel generator set should be activated.

OEMOF converts these optimization problems into a linear programming format, which is then processed by an external solver to handle the output. This approach facilitates the evaluation of key performance indicators (KPIs) such as capital expenditures (CAPEX), operational expenditures (OPEX), and levelized cost of energy (LCOE).

3 CASE STUDY – SHIP EXAMPLE

3.1 Case Study Ship and Model Input Definition

Table 1: Characteristics, limitations, costs and efficiencies of the case study.

Characteristics	All Cases
Total load demand	6255 kWh
Peak load demand	4808 kW
Battery capacity limit	500 kWh
Diesel generator set costs[1]	32 €/kW
Diesel tank costs[1]	0.5 €/kWh
Fuel cell costs[1]	202 €/kW
Hydrogen tank costs[1]	3.6 €/kWh
Battery costs[1]	42 €/kWh
PV costs[1]	45 €/kWp
Power electronic costs[1]	6.4-9.6 €/kW
Diesel oil	0.049 €/kWh
Hydrogen	0.24 €/kWh
CO2 emission costs	300 €/t
Battery energy density	130 kWh/m³
Power electronic density	120 kW/m³
Fuel cell power density	102 kWh/m³
Diesel generator set power density	63 kWh/m³
Diesel oil density	10008 kWh/m³
Hydrogen density	1333 kWh/m³
Battery efficiency	97.5-98.5 %
Diesel generator efficiency	18-38 %
Fuel cell efficiency	40-60 %

[1]the costs are annual costs including investment and fix maintenance costs as well as lifetime and interest rates.

In this paper, we examine a medium-sized ferry operating in the Baltic Sea, specifically designed for car and passenger transport. This ferry exemplifies efficient maritime operations. It serves routes with easily accessible berthing facilities, ensuring a seamless transition for vehicles and passengers alike.

As previously mentioned, this work focuses on the design of a ferry. The energy demand for this example ferry is presented in Table *1*. The load profile depicted in Figure *2* illustrates the typical journey of the ferry from the departure port to the destination port over a duration of approximately two hours. Additionally, Table *1* provides the fixed input values for the optimization, including component properties, costs, and dimensional constraints. To maintain a realistic proportion of the overall space required for the tanks in relation to the space needed for the energy converters, such as fuel cells or diesel generators, it is assumed that the journey can be completed ten times before refueling. Consequently, the costs associated with the tanks are scaled down to reflect the range of a single journey. This assumption allows for a more accurate representation of space allocation in the design.

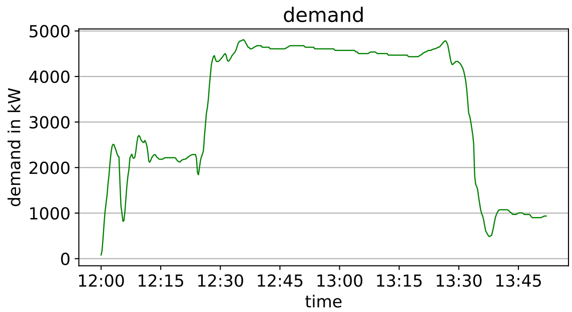

Figure 2: Load profile of the ferry for the presented case study.

This study addresses two essential aspects. First the influence of space limitations on the selection of components is investigated. In addition to costs, these limitations are often regarded as constraints in the context of complex hybrid drives that incorporate a variety of components. Second, the differences in optimization results arising from a simplified sequential optimization method compared to a more complex simultaneous optimization method is examined. The sequential approach consists of two consecutive optimization cycles. In the first cycle, components are dimensioned using constant efficiencies for diesel generators and fuel cells, without considering partial load limitations. For simplification, these constant efficiencies are assumed to equal the maximum efficiencies. The optimization of component disposition regarding load-dependent efficiencies and minimum operating loads occurs only in the second cycle.

In contrast, the simultaneous optimization approach integrates the dimensioning of components and the distribution of load across these components in a single step. This results in a significantly larger equation system, as the optimal power distribution with load-dependent efficiencies must be computed for each time step, while the dimensioning of the components remains variable and is part of the optimization problem itself. Consequently, the solution space expands, leading to increased computation time.

3.2 Results and Discussions

This chapter examines two optimization approaches for maritime energy systems: the Sequential Approach and the Simultaneous Approach. While the Sequential Approach is commonly used due to its simplicity, it often relies on constant efficiencies, leading to inefficiencies and suboptimal performance under varying load conditions. In contrast, the Simultaneous Approach incorporates load-dependent efficiencies into the optimization process, allowing for a more comprehensive understanding of component interactions and resource allocation. This chapter will highlight the strengths and weaknesses of both methods, demonstrating how the Simultaneous Approach offers a more effective solution for modern hybrid propulsion systems.

3.2.1 Sequential Approach

With the defined set of parameters for monetary costs, maximum efficiencies, space requirements, and emissions, the diesel generator set emerges as the preferred technology compared to fuel cells and hydrogen tanks. It is important to note this conclusion is valid only for the first optimization cycle, under the assumption that maximum efficiency can be applied across the entire engine map without limitations. The parameters computed from the first optimization cycle are presented in Table *2* (System A1 cycle 1). The computed parameters for the second cycle are also shown in Table *2*, but will be discussed later.

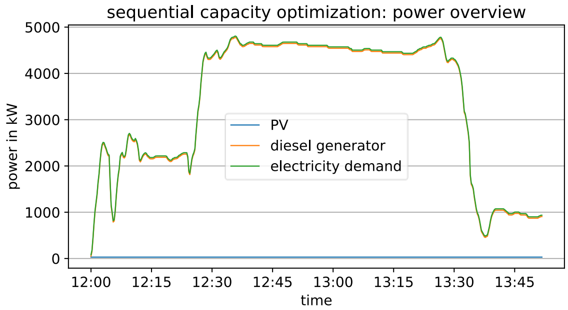

Figure 3: Power feed and consumption - sequential optimization cycle 1.

As shown in Figure *3*, the diesel generator aligns with the demand profile, while the power generated by the available PV system is minimal. The installation space on deck is limited, and the simulation considers only electricity generation during the journey. Although PV is included in the energy system, its role is minor.

Table 2: Results of the sequential approach of the first and second optimization cycle.

Characteristics	System A1 cycle 1	System A1 cycle 2
Propulsion space limit	150 m³	150 m³
LCOE	38.85 ct/kWh	43.05 ct/kWh
Emissions	4405.63 kg CO2	4916.80 kg CO2
Diesel Genset	4778 kW	4778 kW
Diesel tank	16317 kWh	18210 kWh
Fuel cell	0 kW	0 kW
Hydrogen tank	0 kWh	0 kWh
Battery	0 kWh	491 kWh
PV	30 kWp	30 kWp
Inverter	30 kW	521 kW
Rectifier	0 kW	422 kW

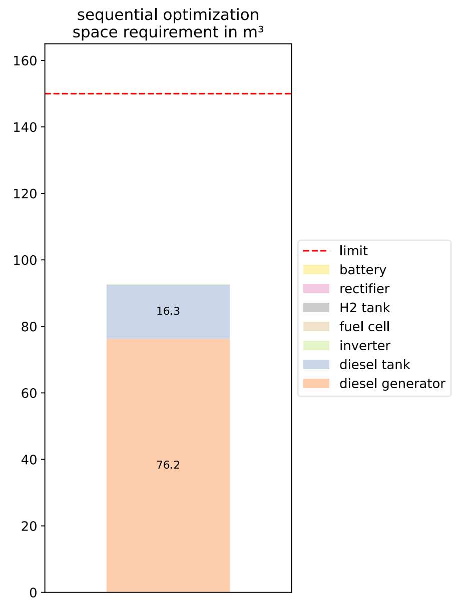

Figure 4: Use of the installation space after the first optimization cycle - sequential optimization.

Figure *4* illustrates the necessary installation space. The specified space limit of 150 m³ is not reached, indicating that it does not affect the cost-optimal solution. Figure *5* displays the distribution of power generation from the diesel generator. The red lines indicate the possible load range introduced for the second optimization cycle. Each marker represents a single operating point. Apparently, the diesel generator operates in the non-operable area below the lower load limit. This indicates that the system cannot meet stricter requirements and must be adjusted in the second optimization cycle. At this point, it becomes evident that the conventional procedure of optimization under the assumption of constant efficiencies without constraints has significant weaknesses.

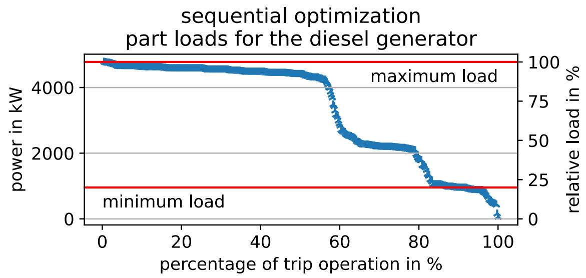

Figure 5: The distribution of power generation of the diesel generator according to the amount of energy generated – sequential optimization step 1.

In the second cycle, load limits and load-dependent efficiencies are introduced and linked to the installed capacities computed in the first cycle. This results in a shift in the distribution of operation loads as illustrated in Figure *6*. Under these new conditions, the diesel generator operates in less favorable load conditions, which reduces overall efficiency, requiring the use of a battery to meet the demand when the load drops below the lower load limit.

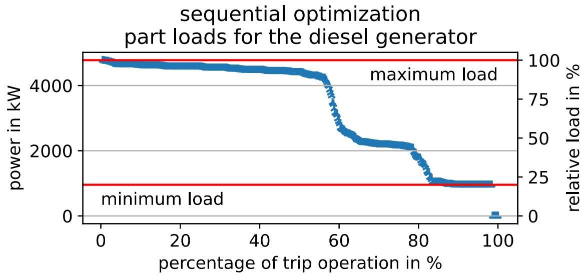

Figure 6: The distribution of power generation of the diesel generator according to the amount of energy generated – sequential optimization step 2.

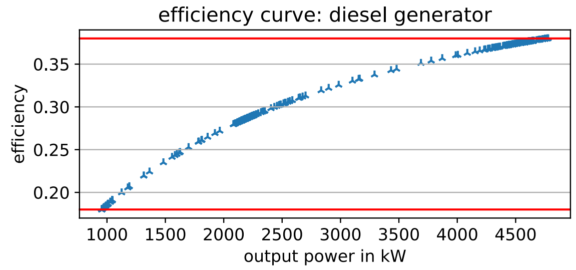

Figure 7: Efficiency curve of the diesel generator - sequential optimization.

Each marker in Figure *7* is lying on the efficiency curve of the diesel generator and represents an occurring operational point. The efficiency decreases as the load decreases. The additional fuel consumption is reduced by the battery, which helps maintain the diesel generator in a more favorable operating condition. However, the size of the diesel tank increases. The battery is charged during periods of lower demand and provides support during higher demand or outside the diesel operating range, as shown in Figure *8*.

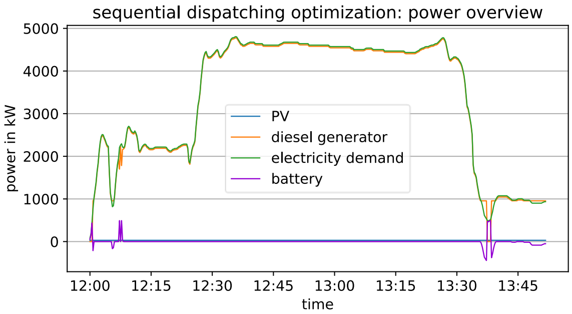

Figure 8: Power feed and consumption - sequential optimization cycle 2.

Table *2* represents also the dimensioning of the components resulting from the second cycle of the sequential optimization (System A1 cycle 2). Due to the simplified assumption of constant efficiency in the first optimization step, the fuel cell and hydrogen tank were excluded from the system, preventing their use in the second optimization step. The decrease in system efficiency leads to a larger diesel tank, and the inclusion of the battery requires larger power electronics and space requirements compared to System A1 cycle 1. But the space limitation of 150 m³ is still not violated.

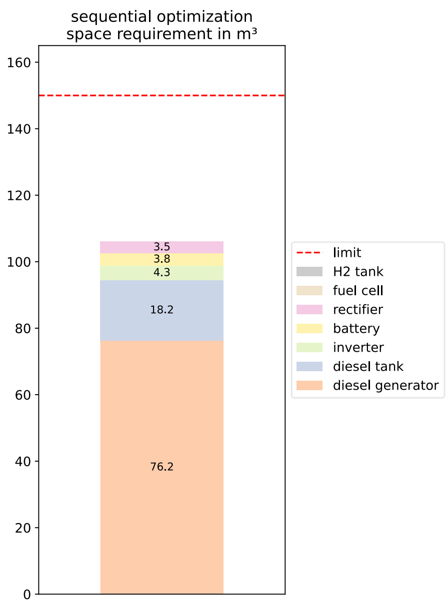

Figure 9: Use of the installation space after the second optimization cycle - sequential optimization.

The detailed utilization of installation space is shown in Figure *9*. The increase in installation space during the second optimization cycle highlights another drawback of the sequential approach. If space limitations are close to or affect the optimal solution of the first cycle, it may result in the absence of a feasible solution in the second optimization cycle with the chosen capacities. For instance, with a space limit of 100 m³, the solution from the first optimization cycle requires approximately 92.5 m³, similar to the optimization run with a 150 m³ limit. However, the best solution identified in the second cycle requires 106 m³. Clearly, with the given capacities, no solution exists that requires less than 100 m³ of installation space.

3.2.2 Simultaneous Approach

As previously described, the load-dependent efficiencies of the drive components are directly incorporated into the simultaneous optimization. The resulting system for the space limit of 150 m³ is named B1 and the system for the limit of 100 m³ is labelled B2. The relationship between operating mode and efficiency can significantly influence both the dimensioning of the components and the load distribution. Consequently, the battery is utilized to enhance the operating loads of the converters. The diesel generator is optimized for high loads, while the fuel cell operates more efficiently at partial loads.

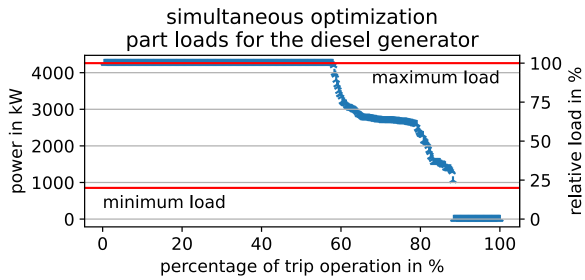

Figure 10: The distribution of power generation of the diesel generator according to the amount of energy generated – simultaneous optimization system B1.

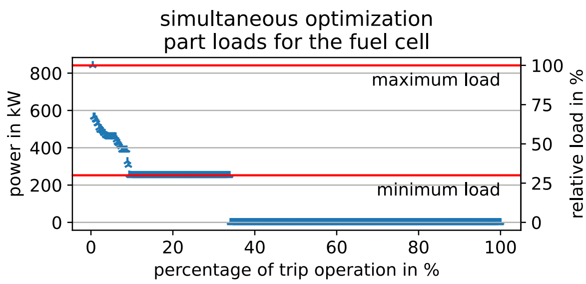

Figure 11: The distribution of power generation of the fuel cell according to the amount of energy generated – simultaneous optimization system B1.

Figure *10* and Figure *11* illustrate that the distribution of energy production aligns with these operational preferences. The diesel generator accounts for 60% of energy generation in full load ranges, approximately 20% in partial load conditions, and is switched off during the remaining 20%. In contrast, the fuel cell primarily operates in low load ranges, thereby avoiding inefficient operating points.

The efficiency curve of the diesel generator, as shown in Figure *12*, indicates an improvement in the distribution of the operating points for this optimization run, with the lowest efficiency value now is 20%, compared to 18% in the sequential optimization.

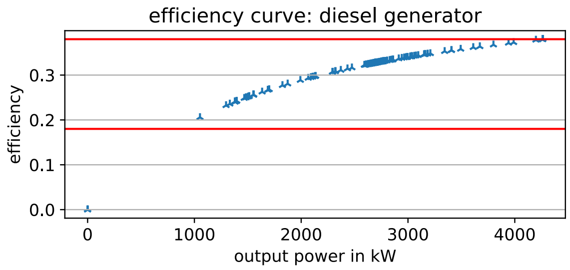

Figure 12: Efficiency curve of the diesel generator - simultaneous optimization system B1.

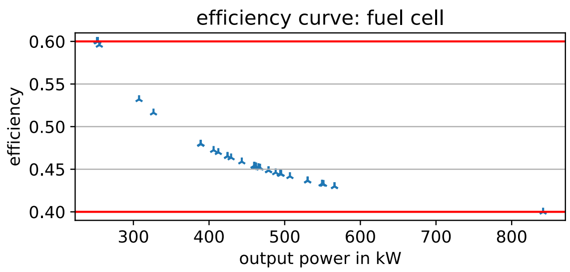

Figure 13: Efficiency curve of the fuel cell -simultaneous optimization system B1.

The distribution of operating points on the efficiency curve of the fuel cell, depicted in Figure *13*, demonstrates good efficiency at low loads, while also being utilized at medium loads. This occurs when the diesel generator is switched off and the battery is unable to meet the entire demand, as shown in Figure *14*.

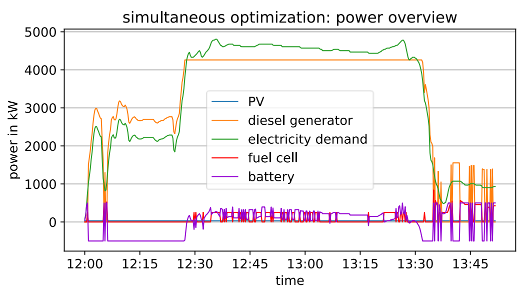

Figure 14: Power feed and consumption - simultaneous optimization system B1.

Table *3* presents the dimensioning of the components resulting from the simultaneous optimization. The simultaneous optimization was conducted with two different values for the installation space, initially assuming a construction space limitation of 150 m³. The results in Figure *15* indicate that this limitation was not fully utilized, thus having no impact on the solution.

Table 3: Results of the simultaneous approach for the optimized propulsion system design.

Characteristics	System B1	System B2
Propulsion space limit	150 m³	100 m³
LCOE	41.46 cent/kWh	41.52 cent/kWh
Emissions	4479.72 kg CO2	4727.70 kg CO2
Diesel generator	4261 kW	4277 kW
Diesel tank	16592 kWh	17510 kWh
Fuel cell	842 kW	83kW
Hydrogen tank	2104 kWh	207 kWh
Battery	500 kWh	500 kWh
PV	30 kWp	30 kWp
Inverter	1372 kW	613 kW
Rectifier	480 kW	349 kW

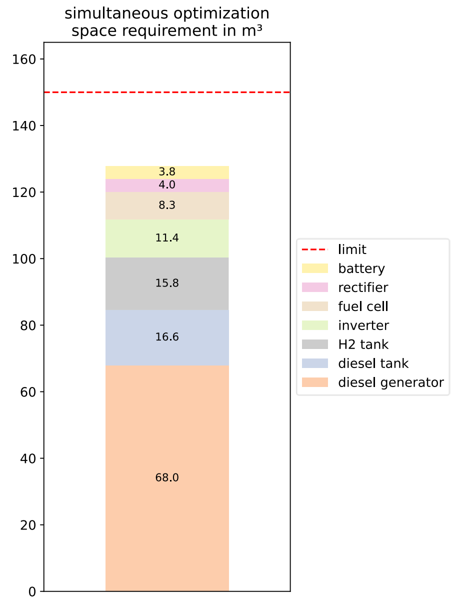

Figure 15: Use of the installation space - simultaneous optimization system B1.

In a second run of simultaneous optimization, the installation space was restricted to 100 m³, resulting in a reduction of the fuel cell size. The results are detailed in Table *3* as Systems B1 and B2 and illustrated in Figure *19*.

Figure *16* and Figure *17* show the altered distribution of energy generation from the smaller fuel cell. With the reduction in fuel cell capacity, the diesel generator is utilized nearly the whole time and operates more frequently at lower loads. The fuel cell is now used at three specific loads. The primary objective is to bridge the gap between power demand and the nominal power of the battery when the diesel engine is switched off due to falling below the lower load limit around 13:37. Figure *18* illustrates that the maximum battery power is reached at this time, with the fuel cell providing support for the load demand.

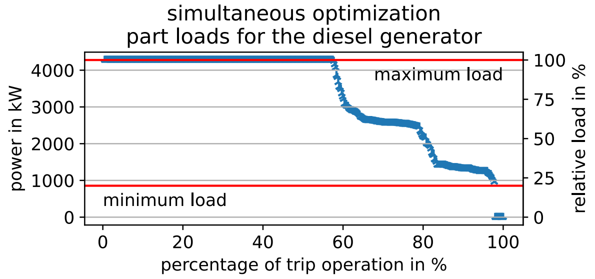

Figure 16: The distribution of power generation of the diesel generator according to the amount of energy generated – simultaneous optimization system B2.

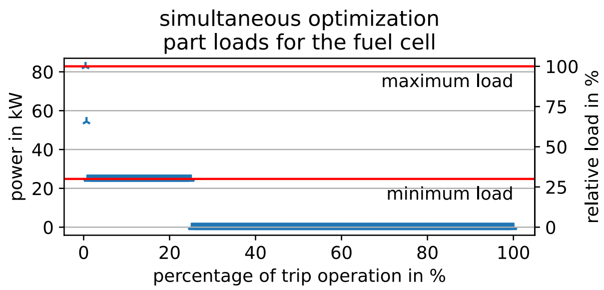

Figure 17: The distribution of power generation of the fuel cell according to the amount of energy generated – simultaneous optimization system B2.

Due to the compact design of the fuel cell within the system, its total contribution is minimal as shown in Figure *18*.

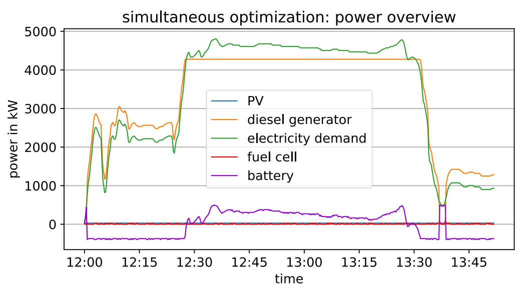

Figure 18: Power feed and consumption - simultaneous optimization system B2.

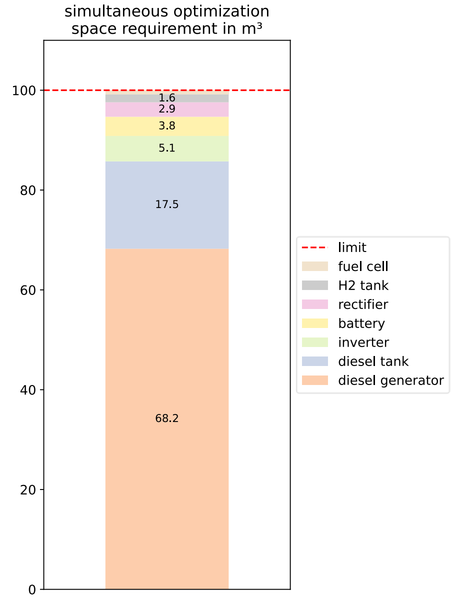

Figure *19:* Use of the installation space - simultaneous optimization system B2.

With the simultaneous approach it is possible to set up a hybrid propulsion system within the installation space limited to 100 m³, as shown in Figure *19*. The according parameters for the propulsion system design are stated in Table *3* labelled as System B2.

4 CONCLUSIONS

In this paper a methodology is developed for the design, sizing and cost implications of electrical hybrid ship propulsion systems that incorporate battery energy storage systems and renewable energy sources, such as fuel cells. The proposed deterministic approach is utilized to evaluate costs, providing optimal solutions for the propulsion configurations and their impacts on the levelized costs of energy and installation space.

The findings of this study reveal several important insights regarding the optimization of drive design. A significant effect is observed when comparing sequential and simultaneous optimization approaches. The simplified assumption of constant efficiency for energy components restricts the selection and dimensioning of these components, resulting in the loss of critical distribution options in the second optimization step and ultimately leading to suboptimal outcomes or even infeasibilities.

With respect to space constraints, the results indicate that fuel cell technology is penalized due to the low volumetric efficiency of fuel cells and their associated tanks, which results in a slight increase in the levelized costs of energy. However, considering weight limitations could change this scenario significantly. Additionally, higher CO2 prices or reduced costs for hydrogen technologies would favour the adoption of hydrogen solutions. The low power demand during operations near ports aligns well with the efficient operation of fuel cells. In further analysis additional boundary conditions for the power dispatch like the limitation of startups and shutdowns can be implemented as well.

5 REFERENCES

[1] Hilpert, S., Kaldemeyer, C., Krien, U., Gu nther, S., Wingenbach, C. and Plessmann, G. 2018. The Open Energy Modelling Framework (oemof)-A new approach to facilitate open science in energy system modelling, *Energy strategy reviews*, 22, pp.16-25.

[2] Polic, D., Melloh, T., Malhotra, A., Zadeh, M., & Dunger, T. 2024. Design of sustainable integrated energy systems for green ports - selection and sizing, *J. Phys.: Conf. Ser.* 2867.

[3] Geertsma, R. D., Negenborn, R., Visser, K., & Hopman, J. J. 2017. Design and control of hybrid power and propulsion systems for smart ships: A review of developments, *Applied Energy*, 194, 30-54.

[4] Inal, O. B., Charpentier, J. F., & Deniz, C. 2022. Hybrid power and propulsion systems for ships: Current status and future challenges, *Renewable and Sustainable Energy Reviews*, 156, 111965.

[5] Damian, S. A., Wong, L. A., Shareef, H., Ramachandaramurthy, V. K., Chan, C. K., Moh, T. S., Tiong, M.C. 2022. Review on the challenges of hybrid propulsion system in marine transport system, *Journal of Energy Storage*, 56, 105983.

6 ABBREVIATIONS

PV	photovoltaics
OEMOF	open energy modelling framework
BESS	battery energy storage system
MPC	model predictive control
ECMS	equivalent consumption minimization strategy
LP	linear programming
OPS	onshore power supply
CI	cold ironing
AC	alternating current
KPIs	key performance indicators
CAPEX	capital expenditures
OPEX	operational expenditures
LCOE	levelized cost of energy