An analysis of maritime battery requirements and a decision tree for optimal chemistry selection

Durgaprasad, Sankarshan; Coraddu, Andrea; Polinder, Henk

DOI
10.1016/j.egyr.2025.11.086

Publication date
2025

Document Version
Final published version

Published in
Energy Reports

Energy Reports 14 (2025) 4851–4871

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

An analysis of maritime battery requirements and a decision tree for optimal chemistry selection

Sankarshan Durgaprasad *, Andrea Coraddu, Henk Polinder

Faculty of Mechanical Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, South Holland, The Netherlands

ARTICLE INFO

Keywords:
Battery
Charge
Discharge
Energy
Lithium-ion
Maritime

ABSTRACT

Batteries have emerged as a promising solution across diverse vessel segments, offering benefits in operational efficiency, cost reduction, and emissions reduction. This study investigates the specific requirements of batteries onboard 7 vessel types, such as tugboats, ferries, cruise ships, yachts, fishing vessel, vessels with cranes, and dynamic positioning vessels, through an in-depth analysis of load profiles and operational needs. By identifying 24 potential operational requirements, ranging from battery electric operation to silent operations and load smoothing, a mixed-integer linear programming model is used to optimize the power and energy allocation for each requirement. This framework enables a generalization of battery requirements for various vessel segments and enables the assessment of three lithium-ion battery chemistries: Lithium Iron Phosphate, Nickel Manganese Cobalt Oxide, and Lithium Titanate Oxide. The results indicate that different vessel types prioritize either high energy density batteries or those capable of delivering high power relative to energy capacity. To guide battery selection, a decision tree is presented that matches battery types with specific vessel needs. Lithium Titanate Oxide batteries are well-suited for applications requiring frequent, high power cycles, especially where fast charging is needed. Lithium Iron Phosphate batteries are best for energy-intensive operations, while Nickel Manganese Cobalt Oxide batteries perform well in both high power and high energy applications. This study offers a practical approach, an inventory of battery requirements, and guidance on selecting the chemistries best suited to various vessel types and operational needs.

1. Introduction

The Fourth IMO Greenhouse Gas (GHG) study 2020 reports that total shipping emissions (including international, domestic, and fishing) increased by 9.6% from 2012 to 2018. The CO_2 emissions rose by 9.3% during this period, and the share of global shipping emissions slightly increased. Carbon intensity increased by 21–32% compared to 2008 levels but slowed down after 2015. Emission projections suggest a rise of 90–130% by 2050, though the long term impact of COVID-19 may slightly reduce this increase (International Maritime Organization, 2024b).

To combat this, regulations are being put in place. For example, the 2023 IMO strategy on reducing GHG emissions from ships outlines key actions, including reducing CO_2 emissions per transport work by at least 40% by 2030 compared to 2008 levels (International Maritime Organization, 2024a). It also aims to increase the use of zero or near zero GHG emission technologies to at least 5%, striving for 10% by 2030. The strategy targets net zero emissions by around 2050, emphasizing energy efficiency, innovative technologies, and economic measures such as GHG emissions pricing and marine fuel standards.

The European Union (EU) is also taking steps to reduce emissions in the shipping sector. This includes incorporating shipping into the EU Emissions Trading System from 2025 to 2027, requiring ships to monitor, report, and verify their emissions, and implementing the FuelEU maritime regulation to limit the GHG content of fuels used by ships (European Commission, 2024).

In response, the maritime industry is increasingly adopting batteries across various types of vessels. DNV's Alternative Fuel Insights reported that the maritime fleet with batteries grew from 486 vessels in 2020 to 944 vessels in 2024, with another 451 on order (DNV, 2024). In Fig. 1, the statistics for the maritime fleet size are depicted. Approximately 64% of the existing maritime battery fleet is hybrid, 17% are plug-in hybrids with cold ironing capabilities, and 19% are purely battery electric. Car and passenger ferries make up 31.8% of the entire fleet, with 73% of the battery electric fleet being comprised of ferries. This is largely due to ferries' predictable routes and fixed charging infrastructure, making battery adoption and operation more feasible.

Batteries are utilized on board vessels for multiple advantages, the most notable being fuel efficiency and emissions reduction (Inal

* Corresponding author.
E-mail address: s.durgaprasad@tudelft.nl (S. Durgaprasad).

https://doi.org/10.1016/j.egyr.2025.11.086
Received 12 May 2025; Received in revised form 2 October 2025; Accepted 20 November 2025
Available online 25 November 2025

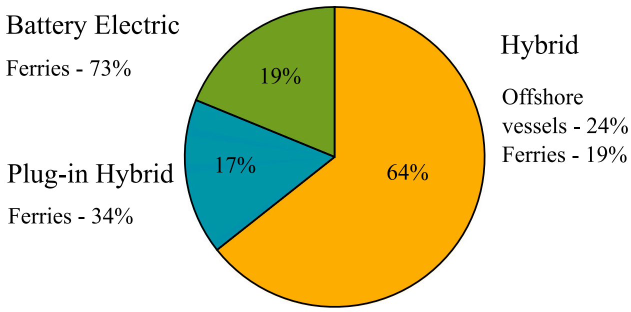


Fig. 1. Distribution of battery powered ships by type as of 2024, highlighting the share of hybrid, plug-in hybrid, and battery electric vessels (DNV, 2024).

Table 1
Example of available battery options.

Supplier	Module	Type	τ_{cont}	τ_{peak}
Corvus Energy NMC	Dolphin NxtGen	Energy	0.5	1 (10 s)
		Power	1.5	2.5 (10 s)
Praxis LFP	Green battery	Energy	1 (derating at 45 °C)	
		Power	3 (derating at 45 °C)	
Van Meer LTO	LTO214	Energy	2	3.5
		Power	3	12

et al., 2022). These benefits can be achieved through fully battery powered systems or hybrid power operations, with the latter being more common among ship segments that do not frequently access ports (Anon, 2021). The main advantages of using batteries on vessels are extensively covered in Inal et al. (2022) and Damian et al. (2022), highlighting critical benefits such as enhanced operational efficiency, reduction in noise and vibration, reduced running hours for diesel engine generators (DEG), and improved fuel cell longevity. These advantages are realized through various battery applications, often referred to as "functions" (Damian et al., 2022; Qazi et al., 2023), "functional roles" (Anon, 2021), or "services" (Lucà Trombetta et al., 2024). Examples include providing spinning reserves, optimizing the operation of other onboard sources, or capturing regenerative energy from cranes (Qazi et al., 2023).

The maritime industry typically adopts systems engineering principles while integrating batteries onboard vessels (Wilkins et al., 2024). The typical factors influencing the viability of batteries onboard vessels are highlighted in the work of Chalfant (2015), which emphasizes addressing ship functions, power system configuration, and operational profiles throughout the design phases. The concept design phase defines ship functions and the initial power system configuration. During engineering design, the power system is refined based on the vessel's operational profile. Finally, in production design, control systems are integrated to ensure proper management of power systems in operation. Therefore, the first step in integrating batteries into maritime systems is to define their intended purpose clearly. After identifying the benefits, the next step is determining the battery's specific function within the vessel. Finally, the batteries must be sized and controlled appropriately according to these functions to maximize the desired benefits.

Batteries' wide variety of benefits and functions is supported by a range of battery chemistries provided by maritime battery suppliers, each catering to different power and energy requirements. For example, Corvus Energy, a supplier of Nickel Manganese Cobalt Oxide (NMC) batteries, offers two variants of its Dolphin NxtGen battery modules: a high energy module with a capacity of 8.2 kWh and a high power module with a capacity of 6.56 kWh (Corvus Energy, 2024a). The high energy module delivers a maximum continuous C-rate (Γ_{cont}) of 0.5 C and a peak C-rate (Γ_{peak}) of 1 C for up to 10 s, while the high power module supports Γ_{cont} of 1.5 C and Γ_{peak} of 2.5 C for 10 s. Lithium Iron Phosphate (LFP) batteries from Praxis Automation (Praxis Automation, 2024) and Lithium Titanate Oxide (LTO) batteries Van Meer (Van Meer Industrial Services, 2024) are other examples of modules available with different characteristics as shown in Table 1.

The maritime industry requires a range of battery chemistries due to the wide variety of ship and vessel types and their diverse operational requirements. Unlike the automotive industry, which benefits from a standardized set of drive cycles for benchmarking drivetrain performance (Micari et al., 2022; Tekin and Karamangil, 2024; Safdari et al., 2022; Barcellona et al., 2015; KoteswaraRao et al., 2024; Naseri et al., 2022), the maritime industry lacks such standardized testing frameworks. For instance, the authors of Micari et al. (2022) and Barcellona et al. (2015) use the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) to conduct experimental tests that evaluate battery ageing under realistic driving conditions. In Tekin and Karamangil (2024), WLTC conditions are used to parameterize battery cells and assess the accuracy of different modelling approaches. Drive cycles are also critical in designing thermal management systems. In Safdari et al. (2022), the New European Driving Cycle (NEDC) is used in a study that combines numerical optimization and experimental validation to develop a phase change material-air battery thermal management system. A comparison of the performance of fuel cell-battery hybrid powertrains under both NEDC and WLTC drive cycles is presented in KoteswaraRao et al. (2024). Similarly, Naseri et al. (2022) utilizes both WLTC and NEDC to demonstrate the superior performance of hybrid energy storage systems designed for electric vehicles with fast-charging capabilities.

The variation in operations across and within vessel segments makes it challenging to generalize a specific battery type or to select appropriate options. There is a gap in the literature regarding the analysis of battery requirements based on the different operational needs of vessels and how various lithium-ion battery chemistries perform under these conditions. This issue is further highlighted and discussed in Section 2. With this in mind, the paper aims to address the following two research questions.

Question 1 Can maritime battery requirements be generalized in terms of expected power, energy, and cycle demands for different vessels and operational requirements?

Question 2 Which lithium-ion battery chemistry best suits each vessel type and its specific operational requirements?

In response to these research questions, the paper seeks to make two major contributions by considering a pool of 7 different vessel segments: tugboats, ferries, fishing vessels, cruise ships, yachts, dynamic positioning (DP) vessels, and vessels with cranes. In addition, 24 different requirements are analysed and the following contributions are made,

Contribution 1 Identification of the battery requirements for different vessel segments and operational requirements, including the necessary power and energy capacities.

Contribution 2 A decision tree for maritime batteries that categorizes the preferred lithium-ion chemistries based on vessel type and operational requirements.

This study makes two main contributions. First, to the best of the authors knowledge, no prior work has systematically decoupled energy storage requirements while providing an overview across a wide variety of maritime vessels with multiple operational profiles. In this study, the decoupling is performed along three dimensions: charging power, discharging power, and net energy requirements. Determining these three factors for each vessel segment and operational requirement creates a foundation for developing energy storage chemistries specifically tailored to the maritime industry. This approach extends beyond existing lithium-ion technologies instead of relying on adaptations from the automotive sector. The second contribution is practical. The study provides a decision tree for selecting lithium-ion battery types across different vessel segments. This contribution operates on two levels. For industry, it informs early-stage design by identifying suitable chemistries for distinct vessel classes. For researchers, it offers a structured framework of feasible options, enabling investigations into operational control, system integration, and lifecycle management without requiring chemistry feasibility and sizing studies.

The remainder of the paper is structured as follows. Section 2 provides a review of existing literature, covering the operations of various vessel segments, potential battery applications, and sizing techniques. Section 3 details the methodology and system modelling framework used in this study. Section 4 presents the findings, offering a comprehensive discussion of the results and their implications. Finally, Section 5 summarizes the key contributions of the study and highlights future research directions.

2. Literature review

This section discusses the literature relevant to addressing the research questions. Section 2.1 reviews existing studies on battery selection and sizing for maritime applications, while Section 2.2 explores different vessel types and their operational requirements.

2.1. Battery sizing, selection and utilization

The authors of Rasul and Kim (2024) compare several battery technologies for maritime applications, including lead–acid, nickel–cadmium, nickel–metal hydride, sodium sulphur, sodium nickel chloride, and lithium-ion batteries. They assess these technologies based on factors like energy density, power density, cycle life, and cost. Lithium-ion batteries stand out as the most promising due to their higher energy and power densities, longer cycle life, and cost effectiveness. The paper highlights the role of batteries in hybrid and fully electric ships. They are used for propulsion, peak shaving, spinning reserves, and energy recovery. The growing use of battery systems, whether through retrofitting or new builds, is predominantly driven by the need to meet regulations and boost efficiency.

A lithium-ion-centred review for maritime applications is presented in Lucà Trombetta et al. (2024). This paper reviews the integration of lithium-ion batteries in the maritime industry, focusing on their role in supporting the global energy transition and reducing emissions. The authors provide a list of vessel segments, detailing the potential range of installed capacities and favourable lithium-ion chemistries for each segment. However, the review does not explore how these potential chemistries compare for different functions within each vessel segment.

Several methods are used to configure the capacity of energy storage devices, such as the equivalent calculation method, which takes into account the maximum load variation in the system; the rule of thumb method, based on the practical experience of designers; and optimization based techniques (Guo et al., 2024). Optimization based methods can be further divided into classical methods (Xie et al., 2022) and meta-heuristic methods of optimization (Guo et al., 2024). Capacity estimation and energy management are guided by various objectives, as highlighted in Xie et al. (2022). These objectives include but are not limited to, minimizing fuel consumption, reducing overall investment costs, and optimizing parameters such as weight and volume, depending on the specific benefits desired from the battery system.

In Georgescu et al. (2018), a set of algebraic formulas is introduced to estimate the maximum fuel savings achievable by integrating electrical energy storage into onboard power systems. This method calculates the equivalent specific fuel consumption for various system configurations and degrees of hybridization, where the degree of hybridization refers to the ratio of energy storage power to the total installed power onboard. The approach also accounts for transmission losses and the specific operational conditions of the vessel. The results show that the efficiency improvements achieved through the integration of energy storage can range from a decrease of 48% to an increase of 57%.

The authors of Al-Falahi et al. (2019) use a set of rule-based equations and power management strategies to determine optimal energy storage and energy configurations for short-haul Ferries based on key voyage parameters. The study compares three configurations: a hybrid system with two diesel gensets and a battery, a hybrid system with one genset and a shore charged battery, and a fully electric system. Results show that the fully electric configuration offers the highest operational cost savings, with reductions of up to 51.23%. The battery is represented as a voltage source, and its lifetime is factored into the model by adjusting the required battery size based on a Depth of Discharge (DoD) versus the number of cycles function. This approach optimizes the battery size according to the desired lifespan and operational requirements. The investment costs are not included in the analysis, and the selection of different lithium-ion battery chemistries is not evaluated.

In Li et al. (2024), the authors apply NSGA II to solve a multi-objective non-linear optimization problem with linear constraints. The study focuses on optimizing the hybrid energy storage capacity for a system combining diesel engines, batteries, and supercapacitors. The objectives are to minimize investment and operational costs, DEG ramping, and battery throughput. It establishes a correlation between the battery's energy capacity and its maximum continuous power output. The Pareto front reveals conflicting objectives, requiring trade offs between them. However, the study does not analyse specific types of lithium-ion batteries.

A comprehensive lifetime design, cost and operation analysis is done in Mylonopoulos et al. (2024) for a retrofit cargo vessel. The authors develop a methodology to iteratively size batteries numerically while considering the effects of cycle ageing and calendar ageing for LFP batteries. However, the study does not analyse specific types of lithium-ion batteries.

The paper Bordin and Mo (2019) presents a mixed integer linear programming (MILP) based methodology for the optimal selection and sizing of energy storage systems in maritime vessels. It incorporates technical and safety constraints, operational modes, and storage lifetime requirements into optimization models. Battery degradation and lifetime are integrated into investment decisions. The study analyses the effects of load profiles, engine types, and operational constraints on battery investments. Lifetime degradation is addressed by assigning a specific energy throughput to each battery size. The model developed by the authors allows for a selection between two types of batteries: one capable of providing one unit of power for every unit of energy installed and another capable of providing two units of power for every unit of energy installed.

The study Kistner et al. (2024) assesses the economic viability and constraints of battery electric propulsion for container ships, comparing diesel engines with lithium-ion batteries (LFP, NMC, LTO). It addresses factors like safe state of charge (SOC) levels, charging/discharging limits, power output matching, and battery weight/volume constraints, aiming to keep annual costs feasible. The model uses the Extended Ant Colony Optimization algorithm from PyGMO and is implemented in Modelica with OpenModelica. The Rint model of lithium-ion cells is used, accounting for nonlinear charge–discharge voltage curves. Results show that while batteries are not competitive for long distances due to high costs and low energy density, they are viable for short routes under 2500 km with future cost reductions and carbon taxes. To the authors' knowledge, this is the only study that specifically compares LFP, NMC, and LTO chemistries for a single operational requirement: battery-electric functionality.

The authors (Pourrahmani et al., 2022) investigate a hybrid power system combining proton exchange membrane fuel cells with lithium-ion batteries to power an 800 kW ferry. It analyses 25 configurations using five battery types based on LTO, NMC, and LFP chemistries. The batteries are compared in terms of energy density, weight, cost, and response to dynamic loads. Using a custom performance metric, the study finds that LTO batteries paired with nine fuel cells offer the best overall system performance.

The studies reveal that most studies pre-select lithium-ion battery chemistry, leading to results and optimal power splits that are specific to that chemistry. Additionally, a fixed power-to-energy ratio is often assumed without detailing the necessary charging, discharging powers, and energy capacities.

Only a limited number of studies have undertaken a comparative analysis of different battery usage scenarios in vessels or examined how energy storage requirements and the selection of battery chemistry may differ across various applications. This highlights a significant gap in the literature, specifically in the assessment of battery requirements tailored to diverse operational needs of vessels and the comparative evaluation of the performance of various lithium-ion battery chemistries under these conditions.

Although real time control and optimization are not the primary focus of this study, they are relevant in the context of how such methods influence the utilization of onboard batteries. Such studies have been extensively reviewed in the literature (Xie et al., 2022; Frangopoulos, 2020; Roslan et al., 2022; Mylonopoulos et al., 2023; Khan et al., 2025) and Mao et al. (2025). Beyond optimization-based strategies, the authors of Xie et al. (2022), Frangopoulos (2020) and Mylonopoulos et al. (2023) discuss the objectives and constraints employed in real-time optimization models. These formulations directly influence energy management strategies and, in turn, determine how batteries are utilized within the system. In the context of this paper, the most relevant insight from such optimization studies is not the strategy itself, but the resulting operational role assigned to the battery under specific objectives and constraints. A complementary perspective is provided by reviewing propulsion and power-plant architectures in Roslan et al. (2022), where different structural configurations of hybrid systems and different energy management strategies are reviewed. These architectural choices have consequences for battery operation, shaping whether the battery primarily provides peak power support, long term energy supply, or other functions. While batteries remain the dominant form of onboard energy storage, hybrid energy systems are receiving increasing attention in literature as studied in Mao et al. (2025). In such systems, the role of batteries shift as complementary devices (e.g., supercapacitors) are introduced. Typically, supercapacitors handle rapid, high-frequency power fluctuations, while batteries assume the more energy dense, longer duration load, thereby changing the functional allocation of energy storage technologies. The relevant aspect of energy and power management optimization studies in the context of this paper is how batteries are used and what functions they serve when the power and energy system is optimally utilized, subject to a specific objective.

Examples of optimization-based real-time control include model predictive control (Pang et al., 2024) and equivalent consumption minimization strategies (Löffler et al., 2025; Kalikatzarakis et al., 2018). In Pang et al. (2024), model predictive control is applied to a liquefied natural gas-battery hybrid power plant with the objectives of minimizing fuel consumption, reducing emissions, and limiting battery degradation. In this configuration, the battery is used to smooth engine loading by discharging during high demand and charging during periods of low load.

In Löffler et al. (2025), an equivalent consumption minimization strategy is applied to a DEG-battery-fuel cell hybrid power plant with multiple objectives of minimizing both fuel consumption and emissions. The battery in this case supports optimal loading of the generator and the fuel cell, ensuring that both operate closer to their efficient regions. Similarly, Kalikatzarakis et al. (2018) applies an equivalent consumption minimization strategy to a DEG-battery hybrid power plant, where minimizing fuel consumption leads the battery to provide load levelling and to be recharged through onshore power when available.

A hybrid propulsion-based power plant is studied in Hong et al. (2024), where the energy management strategy is derived from a global optimization solution obtained through dynamic programming. The objective of operating the DEG and battery hybrid power plant efficiently is realized through several battery operation modes: a battery power mode, a boost mode in which the battery supplements the DEG during periods of high demand, and a valley filling mode where the battery is recharged during periods of low demand. In Mylonopoulos et al. (2024), a low-pass filter-based control strategy is employed for a fuel cell-battery hybrid power plant. In this case, the battery operates to smooth the load profile experienced by the fuel cell. The authors of Jin et al. (2018) apply an inverse droop control strategy to a DEG and fuel cell hybrid power plant. Here, the battery again functions to smooth the load experienced by both the generator and the fuel cell. In addition, the battery supports the ON and OFF operation of the generator, enabling it to optimally load itself and to recharge during periods of low demand.

These examples demonstrate that the battery can assume multiple functions in hybrid power plants, from direct propulsion support to load smoothing and coordinated DEG management. This implies that analysing maritime battery requirements for vessels requires accounting for the different potential roles and functions that the battery may assume. These roles are strongly dependent on the specific operational objectives of the power and propulsion system.

2.2. Vessel mission profile

This subsection explores the different modes of operation for various vessels, including the duration spent in each mode and the associated power requirements. It also seeks to determine whether any generalizations regarding their operational patterns can be derived. For the sake of generality all power requirements are normalized.

2.2.1. Tugboat

Tugboats are popularly discussed in literature with the application of batteries. In a previous study by Laryea and Schiffauerova (2024), a 250 kW Tugboat was tracked using AIS via MarineTraffic. The authors found it operates year round, completing 2–5 daily assignments along the U.S. West Coast. These daily assignments comprise different modes of operation such as loitering (sailing), assisting, waiting and at the port (Jung et al., 2024). Fig. 2 represents the percentage of time spent by the tugboat in each mode of operation based on load profiles considered in the literature (Kumar et al., 2019, 2020; Chua et al., 2018; Chen et al., 2023; Diniz et al., 2023). During sailing the vessel typically sails at constant speeds with relatively constant power demand requested to the power system (Hwang et al., 2024). What is unique to the tugboat is that its peak power does not come at full speed sailing but rather during assisting where the boat is either pushing or maneuvering another vessel. The percentage of power based on installed capacity or maximum utilized power is shown in Table 2.

Fully electric tugboats are not uncommon in the industry. For example, the harbour tugboat "Sparky" is fully battery electric with a peak power of 10 MW (Echandia, 2024). Batteries can be used in a hybrid system, as discussed in Jung et al. (2024). The authors describe three battery use cases: (a) for valley filling and peak shaving with constant output from other sources, (b) peak shaving with other sources following up to a threshold, and (c) providing power during high load fluctuations, offering immediate ramp support for other power sources.

2.2.2. Ferry

Batteries can be most commonly found on electric ferries as previously discussed. Fully battery powered or hybrid propulsion systems have been in use for some time owing to their predictable operations, short durations, and consistent, year round fixed routes. Fully battery powered ferries are possible when the battery system can store sufficient energy and provide sufficient peak power for the duration

Table 2
Tugboat boat power requirement as a percentage of maximum power. NA refers to not applicable.

Mode of operation	Percentage of power per reference			
	Kumar et al. (2019)	Kumar et al. (2020)	Chua et al. (2018) and Chen et al. (2023)	Diniz et al. (2023)
Loitering (%)	13	0–20	5–30	10
Waiting (%)	10	20–40	5–25	10
Assisting High (%)	90	80–100	85	90
Assisting Medium (%)	NA	NA	NA	50
Assisting Low (%)	45	50–70	30–45	20

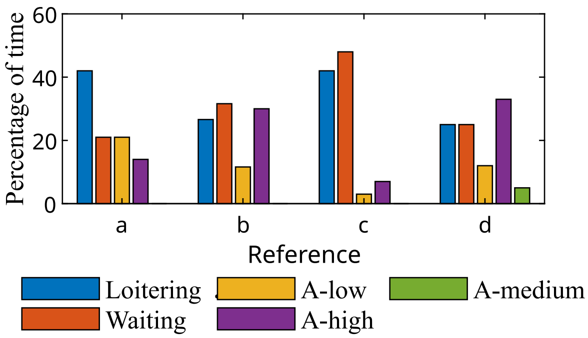


Fig. 2. Percentage of time spent per mode of operation, a - Kumar et al. (2019), b - Kumar et al. (2020), c - Chua et al. (2018), Chen et al. (2023), d - Diniz et al. (2023). "A-low" refers to assist-low.

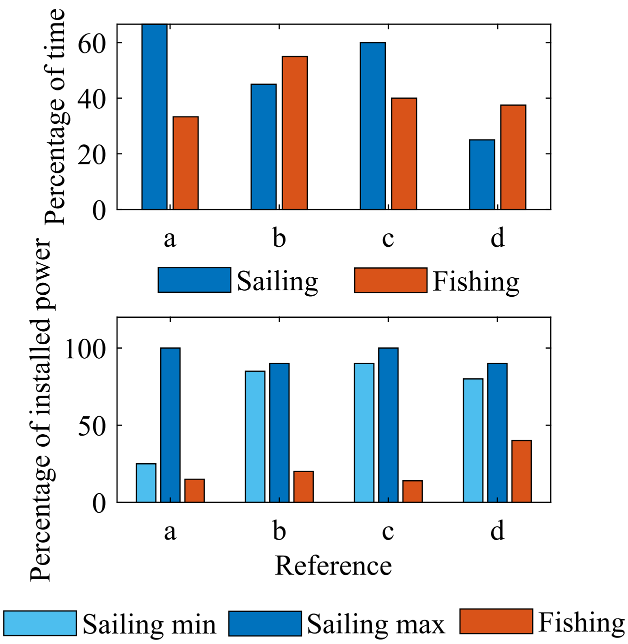


Fig. 3. Percentage of time and power spent outside stand-by, a - Ganjian et al. (2024), b - Hwang et al. (2022), c - Aarsaether (2017), d - Gabrielii and Jafarzadeh (2020).

of the trip. However, when this is not possible or shore charging is unavailable, hybrid power systems are chosen. Ferries tend to operate throughout the day. For example, a fleet of ferries working at the river Thames operates for 18 h a day (Wang et al., 2021). Similarly, a popularly discussed ferry in literature the MV Bowen (Al-Falahi et al., 2019) operates between 15–16 trips a day from 5:20 am–11:10 pm (17 h and 50 min) (Ferries, 2020). The ferry spends roughly ten minutes at the terminals before sailing for roughly 20 min. These trips are large compared to the ferry analysed in Bennabi et al. (2021) where the ferry makes 126 crossings daily, each taking about 3 min. The docking time for passengers and cars ranges from 3 to 10 min. The ferry also takes three 30-minute breaks daily, roughly one after every 40 crossings. Additionally, it remains docked for 8 h overnight.

These examples demonstrate that the operational requirements for ferries can vary significantly. Factors such as the availability of cold ironing infrastructure at terminals, the time spent at terminals, and the power available for cold ironing are crucial considerations when designing batteries, as noted in Rafiei et al. (2021). In a similar study Banaei et al. (2020), the authors analyse optimal operation scenarios for the same vessel, considering six different requirements for using fuel cells with the battery system. The study highlights that batteries help ramp up fuel cells and manage power peaks when fuel cells alone cannot meet the demand.

2.2.3. Fishing vessel

The fishing sector consumes 1.2% of global oil and emits approximately 134 million tonnes of CO_2. Fuel costs can account for up to 60% of operational expenses in this sector (Koričan et al., 2023). The fishing sector comprises two categories of vessels: fishing Vessels and fish farming vessels (Anon, 2021). Fishing Vessels are further divided into active and passive categories (Perčić et al., 2023). These vessels typically travel at economic speeds and use auxiliary equipment, such as cranes, during fishing operations. Energy storage systems provide power during manoeuvres and help lower noise and vibrations, benefiting the crew and the fish (Mijnders, 2023). Interestingly, studies such as Ganjian et al. (2024), Hwang et al. (2022) and Gabrielii and Jafarzadeh (2020) consider load profiles for 10–24 h, reflecting the entire workday of a fishing vessel. In Gabrielii and Jafarzadeh (2020) the load profile is equipped with a freezer that runs 24 h a day and contributes close to 15% of the total load. A longer seasonal analysis was done in Aarsaether (2017), noting that the vessel spends 90% of its time on standby. This implies that calendar ageing could play a significant role if batteries were present on the vessel. These studies suggest that, unlike power intensive operations that require analysis over shorter time periods, the energy intensive load profile of fishing vessels should be examined over longer durations to capture the full scope of their energy demand.

The typical modes of a fishing vessel are sailing, fishing and stand by. The percentage of time spent by fishing vessels outside stand by is shown in Fig. 3. The maximum power consumption typically occurs during sailing operations. The percentage of time spent fishing compared to sailing can vary depending on the distance of the fishing location from the shore.

2.2.4. Cruise vessel

Cruise ships are multi-MW vessels that are ocean-going, and the propulsion is designed to supply one or two (sometimes three) main propellers. The propulsion design criteria are designed for maximum propulsion speed but with the flexibility of operating it at different speeds as well (Hansen and Wendt, 2015). Considering this, the power plant is then designed for the propulsion power and the electrical consumers and heating/cooling power demands (hotel loads). According to Ghimire et al. (2024), the non-propulsion load can contribute to up to 40% of that total power demand. The distribution of the operational modes is shown in Fig. 4, obtained from Baldi et al. (2018)

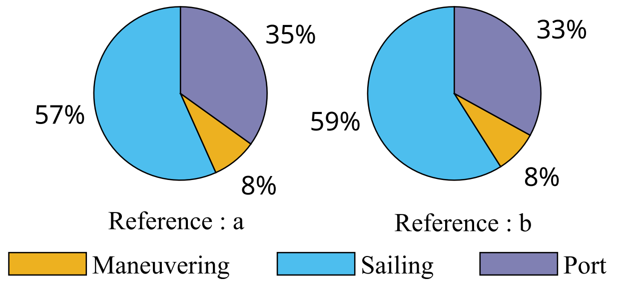


Fig. 4. Cruise ship modes of operation in Baldi et al. (2018) (a) and Ancona et al. (2018) (b) as a percentage of time.

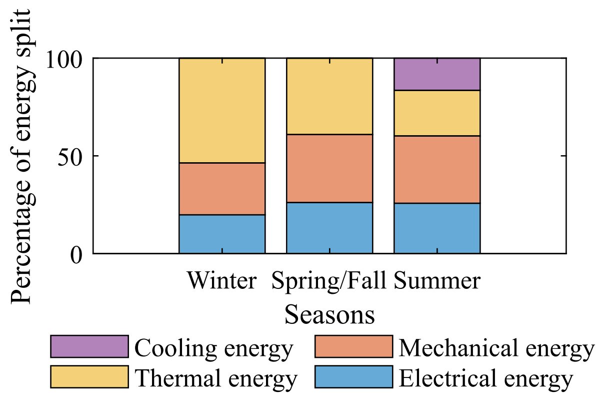


Fig. 5. Energy intensiveness for different seasons.

(a) and Ancona et al. (2018) (b). Such vessels spend nearly a third of the time at the port where the propulsion power is zero, but the hotel loads still exist.

The type of loads on a cruise vessel can be predominantly split into four parts: propulsion loads, electrical consumers, thermal loads and cooling loads (Ancona et al., 2018). Variations in propulsion loads depend on the weather conditions and the vessel's speed; however, seasonal changes in the thermal and cooling loads are significant, as shown in Fig. 5. According to Ancona et al. (2018), the vessel spends 182 days in winter, 121 days in Spring/Fall and 62 days in summer. Winter periods constitute high thermal power requirements, as shown in Fig. 5, whereas summer periods demand cooling power from the power system. While battery electric cruise ships face significant challenges due to high thermal, cooling, and mechanical energy demands, hybrid systems offer a feasible alternative and are already in operation.

2.2.5. Yacht

The operational analysis of 130 yachts for 1 year was performed in van Eesteren Barros and Pruyn (2022) and for 8 yachts for 9 months was performed in de Figueiredo and Hekkenberg (2018). The common modes of operation identified are harbour, at anchor (station keeping), loitering/maneuvering and cruising at different speeds. The summary of the operational hours can be seen in Fig. 6. It is evident from this that yachts spend most of their time in the port whereas very little time cruising. In addition to this, a significant portion of time is also spent anchoring. Typically, the sequence of operation for yachts involves harbouring followed by loitering/maneuvering cruising to destination and finally, stationing at anchor and returning back.

One of the highly desirable features of yachts is the ability to have noiseless cruising and anchoring, no smell or harmful fumes in the harbour and access to restricted emission areas (EST-Floattech, 2024). Currently hybrid yachts are popular, yachts are also sometimes equipped with solar panels (Yachts, 2024) or wind assisted propulsion (Corvus Energy, 2024b).

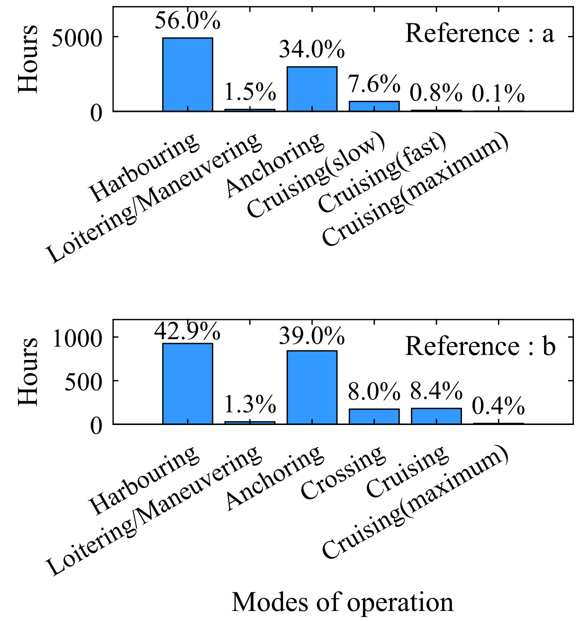


Fig. 6. Modes of operation Yachts (a) van Eesteren Barros and Pruyn (2022), (b) de Figueiredo and Hekkenberg (2018).

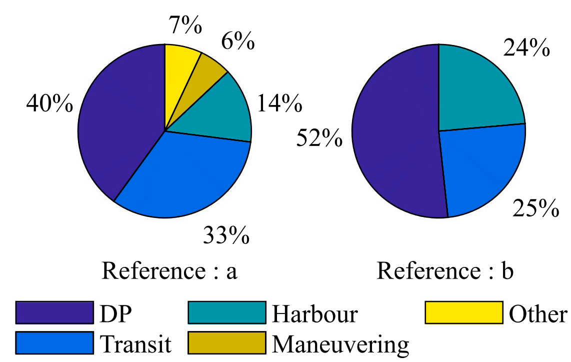


Fig. 7. Position keeping vessels modes of operation (left Swider and Pedersen 2019, right Balsamo et al. 2020).

2.2.6. Dynamic position vessels

Position keeping vessels have been extensively examined in the literature Rao et al. (2016), Zahedi et al. (2014), Vieira et al. (2022), Swider and Pedersen (2019), Balsamo et al. (2020), Montonen et al. (2022), Morales Vásquez (2016), Johansen et al. (2014), Dinh et al. (2018) and Ghimire et al. (2022). These vessels typically operate in several modes: DP operation, which is used most frequently and involves additional redundancy; transit mode, where the vessel runs at nearly full installed power; and harbour mode, characterized by low load operations (see Fig. 7).

During DP operations, the vessel typically operates at lower modes of installed power capacity, as indicated by various studies: [33–53%] in Rao et al. (2016), Zahedi et al. (2014), [15–49%] in Dinh et al. (2018), and [13–23%] in Balsamo et al. (2020), Morales Vásquez (2016). An example of the distribution of power during DP operation is shown in Fig. 8. However, extra redundancy is required due to class requirements, leading to the parallel operation of traditional DEG's at these low operational modes. Batteries have been utilized in different ways during DP operations. For instance, in Bordin and Mo (2019), batteries are used as a standby redundancy. In Montonen et al. (2022), batteries are used for redundancy and to allow the DEGs to operate at average load power over a window length of 120 s, with batteries

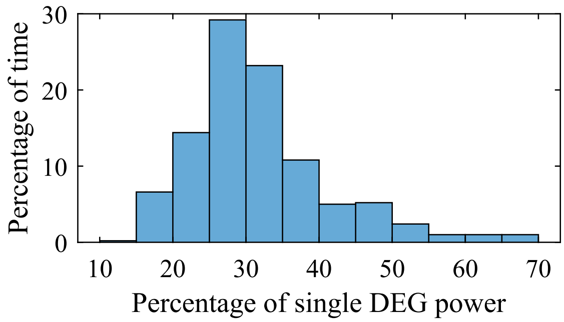


Fig. 8. Distribution of power during DP operation from Ghimire et al. (2022).

compensating for the remaining load. Additionally, batteries and DEGs can operate in isochronous control mode. It can be seen in Montonen et al. (2022) that the mean frequency is 0.9936 pu of the power system when the battery system contributes to the power demand during DP mode, whereas if only one DEG is ON, the mean frequency is 0.9083. A study He et al. (2024) conducted on 10 offshore support vessels and the effectiveness of battery systems installed for DP operations demonstrates a fuel efficiency increase ranging from 6.14% to 15.06% in some cases.

2.2.7. Vessels with crane

In the case of the electrical machine in the crane, it can function as a generator and produce regenerative power when lowering or braking the crane. Moreover, the regenerated power can be fed into the ship's main grid and integrated with the existing power source (Ovrum and Bergh, 2015). Depending on the ship's type, this application can be applied to versatile cranes as shown below Kim et al. (2016):

1. Deck (gantry) crane/Cargo carrier (dry, log, pipe, general)
2. Gantry crane/Barge carrier
3. Heavy-lift crane/Offshore support vessel
4. Hose-handling crane/Tanker vessel
5. Onboard crane/Container vessel.

The authors in Kim et al. (2016) state that 60%–70% of power can be regenerated, and the rest is lost due to friction losses. There are two instances where batteries can be used during crane operations. The first one is where a Bi-directional converter is available, and regenerative power is present (Kim et al., 2019), or if there is a unidirectional converter supplying power to the crane, the batteries can be used to average the power of the alternative source onboard (Ovrum and Bergh, 2015).

3. Methodology and modelling

This section discusses the methodology and model developed to address the research question. Section 3.1 outlines the adopted methodology, while Section 3.2 details the developed model.

3.1. Methodology

The battery requirements are determined using the methodology outlined in Fig. 9. The first step involves selecting the type of vessel. As previously mentioned, 7 different vessel types have been chosen. The load profiles of these vessels are depicted in Fig. 10. The time scales for the operation cycles of these vessels vary. For instance, the time scale for DP vessels and cranes was chosen in seconds, while for ferries and tugboats, the operation cycles ranged from minutes to hours. Fishing Vessels and yachts have an operational period of one day, and cruise ships have an operational period of more than one day.

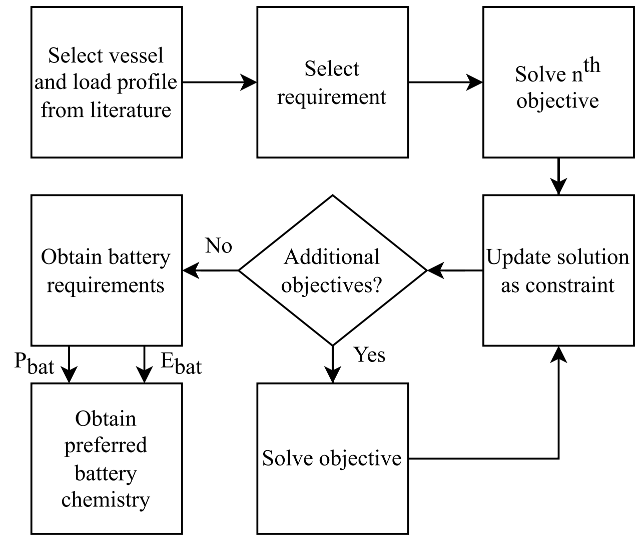


Fig. 9. Methodology.

In the second step, the operational requirements need to be selected. An inventory of various requirements has been compiled, and these vary for different vessels, as shown in Table 3. Requirements T1 for tugboats, F1, F2 for ferries, FV1 for fishing vessels, and CR1 for cranes represent examples of battery electric operation, where the battery system is the sole power source onboard. Requirement T1 for tugboats and FV1 for fishing vessels specifies battery-electric operation, with access to port charging available after completing one operational trip. For ferries, requirement F1 assumes port charging is available at the end of each trip, while requirement F2 limits charging access to a single location, i.e., one charging point is available for the entire round trip. The battery-electric requirement for cranes, CR1, assumes no access to port charging, instead, it relies on energy regeneration during the hoisting down operations.

Meanwhile, requirements T2 for tugboats, FV2–FV4 for fishing vessels, and Y1–Y4 for yachts highlight unique vessel specific requirements. For instance, yachts and fishing vessels require silent operation during specific modes of operation. For tugboats, requirement T2 specifies that the hybrid power plant must operate in silent mode during both sailing and waiting periods. Fishing vessel requirements FV2 through FV4 impose similar silent operation constraints during low power demand and fishing activities, but with key differences: FV2 does not allow access to port power, FV3 permits port power for battery charging, and FV4 adds the additional requirement of optimal DEG loading while retaining access to port power. For yachts, requirements Y1–3 require silent operation while anchored, with Y2 further extending silent (battery-electric) operation to low-power operational situations and Y3 introducing the need for optimal DEG operation during cruising. Finally, requirement Y4 specifies reduced DEG power relative to the maximum power required.

Requirements T3 for tugboats, F3 for ferries, FV4 for fishing vessels, C1 for cruise ships, and Y3 for yachts focus on optimizing the loading of the DEG onboard with the battery system, where the DEG is sized to provide a maximum power of 1 pu. For these operational requirements, DEG units are supported by batteries to maintain their optimal operating range.

The requirements T4 for tugboats, F4 for ferries, FV5 for fishing vessels, C2 for cruise ships, and Y4 for yachts analyse the battery requirements when the capacity of the DEG onboard is reduced. The onboard DEG power is reduced relative to the maximum power necessary onboard. The reduction in size is different amongst these requirements for different vessel segment as shown in Table 3.

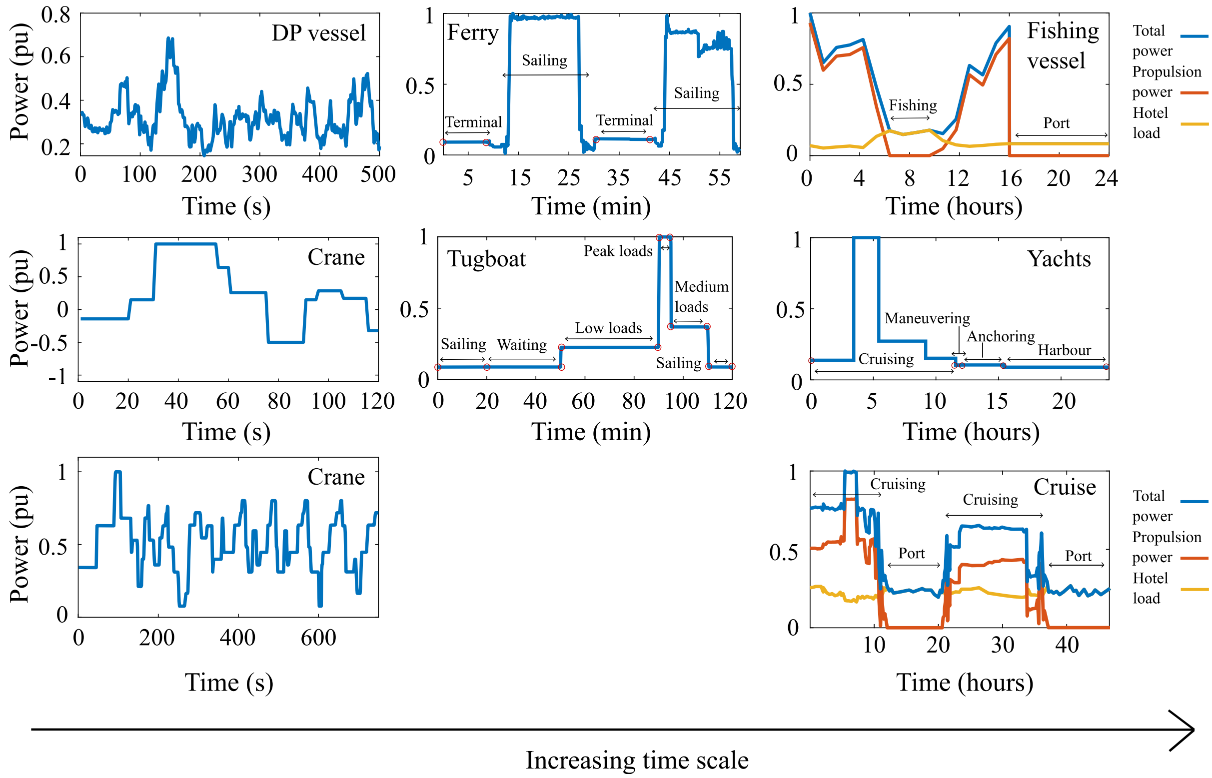


Fig. 10. Load profiles of various vessels and systems, reconstructed from multiple sources: Tugboat profile from Diniz et al. (2023), Ferry and Fishing vessel profiles from Al-Falahi et al. (2019) and Ganjian et al. (2024), Cruise ship and DP load profiles from Ghimire et al. (2022), Yacht profile from Bucci et al. (2020), and Crane load profiles with regenerative power from Kim et al. (2019) (top) and without regenerative power from Ovrum and Bergh (2015) (bottom), as referenced in Ghimire et al. (2022).

For DP vessels, requirement D1 the battery functions as a spinning reserve, i.e. the battery is only there to support in case there is a fault in one of the DEG. The second requirement analysed in this study for DP vessels is requirement D2 where the battery helps in smoothening the load experienced by the DEG during DP operations. Finally, requirements CR2 and CR3 for cranes onboard analyses battery requirements when they perform load smoothing and assist the DEG. Requirements CR2 and CR3 differ based on the two possible power flow configurations of the crane.

A MILP-based optimization framework is employed to analyse battery requirements across segments, as detailed in Section 3.2. The optimization problem is solved sequentially by minimizing the objectives outlined in Table A.8, ensuring a realistic operational power split and battery sizing. The solution to the solved objective becomes an equality constraint for the next objectives solved. Once all objectives are solved, the battery requirements, including charging and discharging powers, net energy storage capacity, and possibly power from the port, are determined. Additionally, energy throughput values are calculated to determine the number of equivalent cycles required from the battery system.

The final step involves comparing LTO, NMC, and LFP batteries across different vessel segments and operational requirements, analysing their performance in terms of required onboard capacity, cost, weight, and volume.

3.2. Modelling

As previously mentioned, a MILP-based formulation is developed to represent the onboard power and energy system. The objectives necessary for the comprehensive analysis of system requirements are defined in Eqs. (1a)–(1e). Objective $\mathcal{O}_1$ determines the minimal required battery size, while Objective $\mathcal{O}_2$ minimizes port power consumption. Objective $\mathcal{O}_3$ reduces DEG ramping, whereas Objective $\mathcal{O}_4$ minimizes switching between ON–OFF states. Finally, Objective $\mathcal{O}_5$ seeks to minimize battery throughput. The model constraints are shown in Eq. (2). Eq. (2a) depicts the load balance equations where $P_{DEG}(t)$ is the DEG power, $P_{bat}(t)$ is the battery power and P_{demand} is the power demand. For battery electric requirements or during silent operations, $P_{DEG} = 0$. At the harbour/port, the power balance equation is provided by Eq. (2b), where $P_{port}(t)$ refers to the port power. The energy in the battery is denoted by E_{bat} and Eqs. (2c) and (2d) represent the energy present in the battery at time t. In Eq. (2d), E_{bat}^{init} refers to the initial energy content in the battery. The output power and state of the DEG is limited by Eqs. (2e) and (2f) where $P_{DEG_{min}}$, $P_{DEG_{max}}$ refer to the maximum and minimum power the DEG can provide and $U_{DEG}(t)$ is the binary decision variable the decides the state of the DEG. For optimal loading requirements, $P_{DEG_{min}}$ (up) and $P_{DEG_{max}}$ (up) are 70% and 90% of DEG capacity (1), respectively. For other hybrid system requirements, $P_{DEG_{min}}$ and $P_{DEG_{max}}$ are 20% and 100% of DEG capacity. The ramp rate of the DEG is modelled in Eq. (2g). Here, R_{max} refers to the maximum allowable ramping rate for the DEG, which is 0.05 pu/second. The change in power between two consecutive time steps is represented by the decision variable $\Delta P_{DEG}(t)$. This is used in Objective $\mathcal{O}_3$ to minimize the ramping of the DEG. In Eq. (2h), $\Delta U_{DEG}(t)$ captures any change in the state of the DEG, representing transitions between ON and OFF states. The absolute difference $\left|U_{\mathrm{DEG}}(t) - U_{\mathrm{DEG}}(t-1)\right|$ records these state changes over time. This term is used in $\mathcal{O}_5$ to minimize the frequency of switching the DEG ON and OFF. Both Eqs. (2g) and (2h) are modelled using the Big-M integer method. The decision variables $P_{\mathrm{port}}(t)$, $P_{\mathrm{DEG}}(t)$, and $E_{\mathrm{bat}}(t)$ hold values greater than or equal to zero, as represented in the inequality constraint in Eq. (2i). Finally, Eq. (2j) ensures that the energy in the battery is always lesser than the net battery capacity.

The generalized battery requirements obtained from the MILP model are used to derive chemistry specific requirements as detailed in Eq. (3).

Table 3
Vessel specific requirement.

Vessel	Requirement	Port
Tugboat	T1. Battery electric	Yes
	T2. Silent sailing and waiting	Yes
	T3. Optimal DEG loading	No
	T4. DEG power (0.5 pu)	Yes
Ferry	F1. Battery electric	2x
	F2. Battery electric	1x
	F3. Optimal DEG loading	2x
	F4. DEG power (0.5 pu)	2x
Fishing Vessel	FV1. Battery electric	Yes
	FV2. Silent low power and Fishing	No
	FV3. Silent low power and Fishing	Yes
	FV4. Silent low power and Fishingand optimal DEG loading	Yes
	FV5. Silent low power and Fishingand DEG power (0.5 pu)	Yes
Cruise	C1. Optimal loading during cruisingand max 0.5 pu in port	No
	C2. Max DEG power = 0.75 puand max 0.375 pu in port	No
Yacht	Y1. Silent anchoring	Yes
	Y2. Silent low power cruisingdemand ≤ 0.5 pu and anchoring	Yes
	Y3. Optimal DEG operation in cruisingand silent anchoring operation	Yes
	Y4. DEG power (0.75 pu)	Yes
DP	D1. Battery as spinning reserve	No
	D2. Battery for load smoothing	No
Crane	CR1. Battery electric	No
	CR2,3. Battery for load smoothing	No

The battery's charge and discharge power are calculated using Eqs. (3a) and (3b). The required number of cells is determined according to Eq. (3c), where the maximum number of cells necessary to meet the charging power, discharging power, and net energy requirements is considered. Fractional values for the number of required cells are rounded up.

$$\mathcal{O}_1 = \min E_{bat}^{net} \tag{1a}$$

$$\mathcal{O}_2 = \min P_{port} \tag{1b}$$

$$\mathcal{O}_3 = \min \sum_{t=1}^{T} \Delta P_{DEG} \tag{1c}$$

$$\mathcal{O}_4 = \min \sum_{t=1}^{T} \Delta U_{DEG} \tag{1d}$$

$$\mathcal{O}_5 = \min \sum_{t=1}^{T} |P_{bat}| \tag{1e}$$

A refined approach is employed, wherein each cell's charge and discharge power is determined by the minimum power it can consistently deliver across its state-of-charge range. The minimum state of charge at which the battery can potentially operate is set at 10%. Accordingly, the minimum power that the cell can provide at this state of charge is determined using Eqs. (3d) and (3e). The minimum continuous cell power and energy values are presented in Table 4. The open circuit voltage values V_{oc}, C-rates Γ, cell charge capacity Q_{cell}, and internal resistance r are taken from the study (Kistner et al., 2024). The number of cells N_{cell} calculated is used to determine the battery's energy, required weight, required volume, and the cost of the installed battery. Eqs. (3f)–(3i) show the chemistry-specific battery requirements. Here, E_{req} is the required capacity, Wt_{req} is the system weight, Vol_{req} is the volume, and $Cost_{req}$ is the battery cost.

$$P_{DEG}(t) + P_{bat}(t) = P_{demand}(t) \tag{2a}$$

$$P_{bat}(t) = P_{demand}(t) - P_{port}(t) \tag{2b}$$

$$E_{bat}(t) = E_{bat}(t-1) - P_{bat}(t)\Delta t \tag{2c}$$

$$E_{bat}(1) = E_{bat}^{init} - P_{bat}(1)\Delta t \tag{2d}$$

$$P_{DEG}(t) \geq P_{DEG_{min}} \cdot U_{DEG}(t) \tag{2e}$$

Table 4
Parameters calculated from (Kistner et al., 2024).

Cell and system (sys) Parameters	LFP	NMC	LTO
Energy (kWh) (E_{cell})	0.733	0.252	0.053
Discharge power (kW) ($P_{cell}^{discharge}$)	0.504	0.592	0.199
Charge power (kW) (P_{cell}^{charge})	0.536	0.234	0.223
Weight (kg/kWh) (Wt_{sys})	6.485	9.009	19.802
Volume (l/kWh) (Vol_{sys})	6.579	8.333	12.920
Cost (€/kWh) ($Cost_{sys}$)	460	500	700

$$P_{DEG}(t) \leq P_{DEG_{max}} \cdot U_{DEG}(t) \tag{2f}$$

$$|P_{DEG}(t) - P_{DEG}(t-1)| \leq R_{max} = \Delta P_{DEG}(t) \tag{2g}$$

$$\Delta U_{DEG}(t) = |U_{DEG}(t) - U_{DEG}(t-1)| \tag{2h}$$

$$P_{port}(t), P_{DEG}(t), E_{bat}(t) \geq 0 \tag{2i}$$

$$E_{bat}(t), E_{bat}^{init} \leq E_{bat}^{net} \tag{2j}$$

$$P_{bat}^{discharge} = \max P_{bat}(t) \quad \forall t \tag{3a}$$

$$P_{bat}^{charge} = |\min P_{bat}(t)| \quad \forall t \tag{3b}$$

$$N_{cell} = \max\left(\frac{P_{bat}^{charge}}{P_{cell}^{charge}}, \frac{P_{bat}^{discharge}}{P_{cell}^{discharge}}, \frac{E_{bat}^{net}}{E_{cell}}\right) \tag{3c}$$

$$P_{bat}^{cell} = V_t^{SoC=0.1} \cdot \Gamma \cdot Q_{cell} \tag{3d}$$

$$V_t = V_{oc} - \Gamma \cdot Q_{cell} \cdot r \tag{3e}$$

$$E_{req} = N_{cell} \cdot E_{cell} \tag{3f}$$

$$Wt_{req} = E_{req} \cdot Wt_{sys} \tag{3g}$$

$$Vol_{req} = E_{req} \cdot Vol_{sys} \tag{3h}$$

$$Cost_{req} = E_{req} \cdot Cost_{sys} \tag{3i}$$

4. Results and discussion

This section presents the results for each vessel type, followed by a discussion, as outlined in Sections 4.1 to 4.7. Additionally, Sections 4.8 and 4.9 focus on the generalizations derived from the results, including

Table 5
Results: General battery requirements relative to maximum power demand.

Vessel	Req.	$P_{bat}^{discharge}$ (pu)	P_{bat}^{charge} (pu)	E_{bat}^{net} (pu h)	P_{port} (pu)
Tugboat	T1	1	0.81	0.4	0.81
	T2	0.1	0.07	0.08	0.07
	T3	0.289	0.51	0.19	0
	T4	0.5	0.02	0.04	0.02
Ferry	F1	1	1.26	0.24	1.31
	F2	1	2.97	0.45	3.06
	F3	0.29	0.69	0.05	0
	F4	0.51	0.49	0.11	0.51
Fishing	FV1	1	0.99	7.99	1.08
	FV2	0.26	0.57	0.83	–
	FV3	0.32	0.44	0.83	0.19
	FV4	1	0.63	0.83	0.1
	FV5	0.5	0.34	1.66	0.28
Cruise	C1	0.37	0.33	1.08	–
	C2	0.25	0.26	0.54	–
Yacht	Y1	0.1	0.04	0.4	0.14
	Y2	0.27	0.26	2.62	0.35
	Y3	0.3	0.74	0.4	0.13
	Y4	0.25	0.47	0.5	0.1
DP	D1	1	–	0.5	–
	D2	0.24	0.16	10^{-4}	–
Crane	CR1	1	0.5	0.009	–
	CR2	0.7	0.7	0.005	–
	CR3	0.24	0.25	$6 \cdot 10^{-4}$	–

the power, energy, cycle, and chemistry preferences across various vessel types.

4.1. Tugboat

The results obtained for requirements T1–T4 for the tugboat are visually shown in Fig. A.14 (Appendix), and the battery requirements are detailed in Table 5. Only requirement T1 includes a complete charge and discharge cycle, as expected, since the system is battery electric. The maximum discharge power $P_{bat}^{discharge}$ is sustained only for 5 min during peak assisting mode of operation. In requirement T2, where the battery is used for silent sailing and waiting, the pu charge and discharge capacity is substantially lower than that of requirement T1 since the battery can be charged onboard during low loads and medium loads during assisting periods. This lower charging requirement is also reflected in the port power necessary. Forcing the DEG to load as in the case of requirement T3 optimally, the battery requires a higher charging capacity compared to T2 since it has to take the difference between the 0.7 pu of power that the DEG provides and the power demand. For such a requirement port charging would not be necessary. Reducing the capacity of DEG to 0.5 pu of the maximum power demand allows for reduced charge rates since the DEG is operational throughout the operating profile and charges the battery slowly during low demands. However, higher discharge power is necessary to provide for high peak loads of the assist phase. Among all requirements for tugboats, the power-to-energy ratio is greater than 1 h^{-1}, implying that high power batteries are necessary. However, the need for high power is only significant during the assisting mode, which constitutes a small portion of the operational profile. It is worth noting that covering 50% of the power demand with a DEG can reduce E_{bat}^{net} by a factor of 10 compared to running the tugboat on battery electric operation. Since these vessels complete around five trips per day, the battery is expected to undergo a high number of cycles.

4.2. Ferry

Full electric requirements of ferries F1 and F2 both require higher charging than discharging power as shown in Table 5 and visually depicted in Fig. A.15 (Appendix). The number of equivalent cycles experienced by the battery system doubles when the number of charging terminals increase (2 for requirement F1 and 1 for requirement F2). However, this comes with the benefit of reduced net energy capacity. Additionally, the port power needed in requirement F2 increases more than a factor of 2 as compared to requirement F1. Therefore, increasing the number of charging terminals on a ferry can reduce the required battery capacity on board and the port power demands, resulting in a higher number of equivalent cycles. In the case of requirement F3, the DEG should be optimally loaded while not at the terminal/port, resulting in the smallest battery size. The batteries are only used to cover the power demand above the optimal range of operation of the DEG. Requirement F3 has the highest energy throughput among all requirements because the battery is constantly in use. The usage is either discharging at the terminals or charging during low loads while sailing or discharging during high loads of sailing. Much like requirement F3, F4 charges its batteries during low propulsion periods. However, it also uses the port power available to compensate for the extra energy needed during higher power demand, as shown in Fig. A.15. For ferries, a higher charging power is required compared to the discharging power. This means that fast charging batteries are essential. The size of the ferry's battery is typically limited by the amount of power it can handle during charging compared to discharging. Ferries make significantly more trips per day compared to tugboats. It is crucial to avoid charging the batteries to full capacity and leaving them overnight, as this can accelerate calendar ageing. Proper charging strategies are essential to balance capacity needs and battery longevity.

4.3. Fishing vessel

The general requirements for fishing vessels, listed in Table 5 and visually represented in Fig. A.16 (Appendix), highlight the need for batteries with higher energy density, as indicated by the power-to-energy ratio being below 0.5 h^{-1} in all cases except requirement FV4. Battery electric fishing vessels require around units of energy for every unit of discharge power, reflecting low C-rate needs. Although requirements FV2–FV4 require the same battery size, they differ in energy throughput and power-to-energy ratios due to the long low power fishing operations. The power produced by the DEG showcases powerdrops in Fig. A.16(d) for requirement FV4. These power drops are a representation of a feasible power split between the DEG and the battery for the optimization problem. Smoother power splits can be obtained if additional constraints are imposed. Charging methods also impact battery cycles onboard charging (FV2) leads to full cycles, while port charging (FV3) results in irregular cycles with varying depths of discharge. Across all cases, fishing vessels require less port power than ferries, as they spend more time in the harbour, often experiencing half cycles, as seen in requirements FV3 and FV5. Every requirement except FV1 necessitates more than 1.5 net cycles per day. Since the operation of such vessels can be seasonal, it is essential to pick batteries where calendar ageing is not as prominent.

4.4. Cruise ship

The cruise ship requirement C1 is determined by minimizing the throughput of the battery, corresponding to objective $\mathcal{O}_5$. The optimal power split between the battery and the DEGs is illustrated in Fig. A.17 (Appendix). For this requirement, the battery system operates the DEGs between 0.7 and 0.9 pu during cruising, while the battery covers peaks when power demand exceeds 0.9 pu. The Table 5 details the net energy and power capacities required for this operation. The power-to-energy ratio for requirement C1 is less than 1 h^{-1}, indicating the need for batteries with high energy density. Furthermore, Fig. A.18 (Appendix) depicts the cycle profile of the battery for requirement C1. The majority of the battery's throughput comes from large cycles, i.e., DoD ≥ 0.2. However, a significant number of cycles occur with DoD ≤ 0.2, showing a mix of both large and small cycles in the operation. Much like requirement C1, C2 has a power-to-energy ratio of less than 1 h^{-1} and a large number of small cycles as shown in Fig. A.18. However, the major energy throughput comes from the large charge–discharge cycle. Interestingly, a 25% reduction in DEG capacity does not lead to an increase in battery power and energy requirements. This highlights the importance of optimal sizing for the battery and other power sources.

4.5. Yacht

The yacht requirements Y1 for silent anchoring does not demand significant discharging power from the battery system, as outlined in Table 5 and visualized in Fig. A.19 (Appendix). The lowest power-to-energy ratio requirement occurs in requirement Y3. Requirement Y3 requires silent operation and low speed cruising on battery power, necessitating a larger onboard battery capacity. In this scenario, the DEG is primarily used during high power cruising. The requirement Y3 also demands the highest charging power since the battery must compensate for the power gap between the demand and the minimum optimal DEG loading (0.7 pu). As shown in Fig. A.19, this results in multiple charge–discharge cycles to keep the battery optimally loaded, because the DEG's optimal operation range exceeds the power demand. Consequently, the battery charges and the DEG must turn off once the battery is fully charged. In requirement Y4, reducing the DEG capacity by 0.25 pu results in only a 0.1 pu h increase in battery size, but there is a significant rise in energy throughput during the operational cycle. Among the yacht requirements, Y3 experiences the highest energy throughput and charging power demands. The discharge power-to-energy ratio is consistently less than 1 h^{-1}, implying that, in hybrid yachts, batteries with higher energy density are preferred over those with higher power density. Since yachts spend most of their time inactive, their annual cycle demands are lower compared to ferries and tugboats but their batteries must be resilient to calendar ageing due to long periods of inactivity.

4.6. Dynamic position vessels

The power and energy requirements for DP vessels, D1 and D2, are outlined in Table 5. For D1, where the battery serves as a spinning reserve without actively contributing to the load, the required power is 1 pu, and the energy requirement is 0.5 pu h. As per DNV GL class regulations (2015), energy storage systems can be used as spinning reserves, and they must provide the necessary power to the power plant for at least 30 min in the event of a single fault (Sorensen et al., 2017). In the case of D2, where the battery also helps maintain average power demand over a given period, the requirements of D1 still apply, along with additional criteria detailed in Table 5. The power-to-energy ratio for D2 is significantly higher than in previous examples. Moreover, the battery experiences multiple microcycles, as shown in Figs. A.20 and A.21 (Appendix), underscoring the importance of testing batteries for such cycling demands in DP vessel applications. Over a year, the energy throughput results in only 59 cycles, even if the battery is used 52% of the time for load smoothing during DP operations. A split bus system would require two such batteries. When used only as a reserve, the battery remains fully charged and idle, which can accelerate calendar ageing. Additionally, DP vessels have other modes of operation where batteries can be utilized differently.

4.7. Vessels with crane

For crane operations, the requirements CR1 and CR2 are applied to load profiles with and without regenerative power, as shown in Fig. 10. Requirement CR1 is applied to the profile with regenerative power, while CR2 is applied to both profiles. The details of charge and discharge cycles for the regenerative load profile are in Table 5, where the power-to-energy ratio exceeds 100 h^{-1} in both cases. In CR1, the required charge power is lower than discharge power, and the number of cycles increases with crane usage, although the DoD remains small relative to battery size. For CR2, the DEG involved in the regenerative load profile (see Fig. A.22-CR2, Appendix), both battery size and charging power requirements decrease. In the non-regenerative profile, the DEG power is smoothened. In this requirement, the power-to-energy ratio reaches 400 h^{-1}, with a higher number of charge–discharge cycles (see Fig. A.22-CR3, Appendix). This indicates that batteries for such operations must provide high power relative to energy capacity to meet the demands of crane functions.

4.8. Power, energy and cycles generalization

Fig. 11 shows the generalized requirements from Table 5 with the corresponding power-to-net energy ratios. In Fig. 11(a), only 5 of the 24 operational scenarios across 7 vessel types have charge ratios greater than 10. Four of these relate to load smoothing, three in crane operations and one in DP vessels. A similar distribution appears in Fig. 11(b), where discharge ratios follow the same trend.

The shaded regions highlight different battery requirements. The blue region marks ratios below 1, where high energy density is needed, while the red region marks ratios between 1 and 10, dominated by ferry and tugboat operations. Out of 24 requirements, 12 fall into the blue region for charging, including all fishing vessels, most yachts, both cruise ship cases, and some tugboats. For discharging, 10 cases fall into the blue region. The red region captures 7 ferry and tugboat cases across both charging and discharging.

Overall, 19 of the 24 requirements lie below a ratio of 10. Of these, 13 charging and 10 discharging requirements are below 1. This indicates that most vessel operations can be met with existing lithium-ion chemistries. Since the study is based on net energy, oversizing batteries to meet lifetime requirements would further reduce these ratios. Large batteries sized for other functions can also support load smoothing, which on its own would require a high power-to-energy ratio.

Fig. 12 illustrates the potential installed capacities across various vessel segments and their specific requirements. The range of potential installed capacities is based on data from Lucà Trombetta et al. (2024). As expected, cruise vessels and yachts require the largest battery capacities compared to other vessel types. Similar discharge power levels, comparable to those of cruise vessels, yachts, and ferries, are found in multi-megawatt DP vessels, which require batteries as a backup in case of emergencies. In contrast, the energy required for crane operations is several orders of magnitude lower than the energy storage required for other vessel types. The discharge and charging power requirements are similar to those of fishing vessels for tugboats, although fishing vessels require significantly larger battery capacities than tugboats.

These generalizations have been further simplified and are presented in Table 6. Tugboats, ferries, DP vessels, and cranes require batteries with higher power densities and lower cost per kW, in contrast to fishing vessels, cruise ships, and yachts, which prioritize higher energy densities. The number of cycles per day, in terms of energy throughput, is highest for tugboats and ferries, while DP vessels and cranes may undergo many cycles with smaller depths of discharge throughout the day. Tugboats, DP vessels, and ferries can expect consistent cycling throughout the year, whereas fishing vessels and yachts experience cycles that depend on seasonal usage. For cruise ships, the number of yearly cycles is determined by the time spent sailing versus time at port, with more time spent sailing resulting in more cycles.

4.9. Chemistry specific generalizations

Based on the general requirements outlined in Tables 5, 6 and 12, a chemistry specific analysis is summarized in Table 7. Additionally, Figs. A.23–A.26 (Appendix) provide graphical representations of installed capacity, cost, weight, and volume for each battery chemistry. A maritime

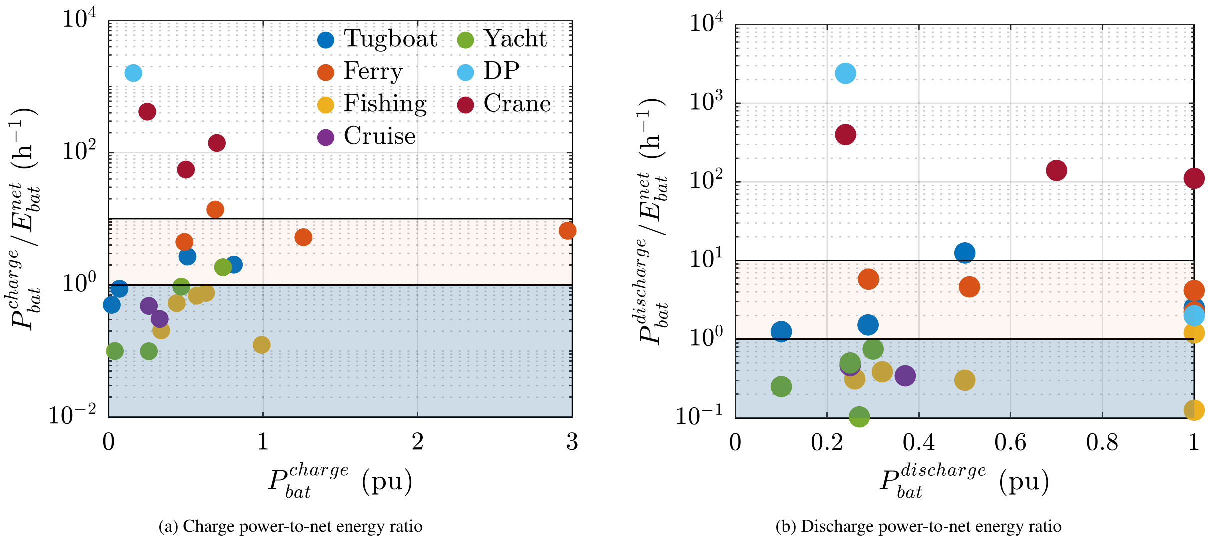


Fig. 11. Categorization of power-to-energy ratios.

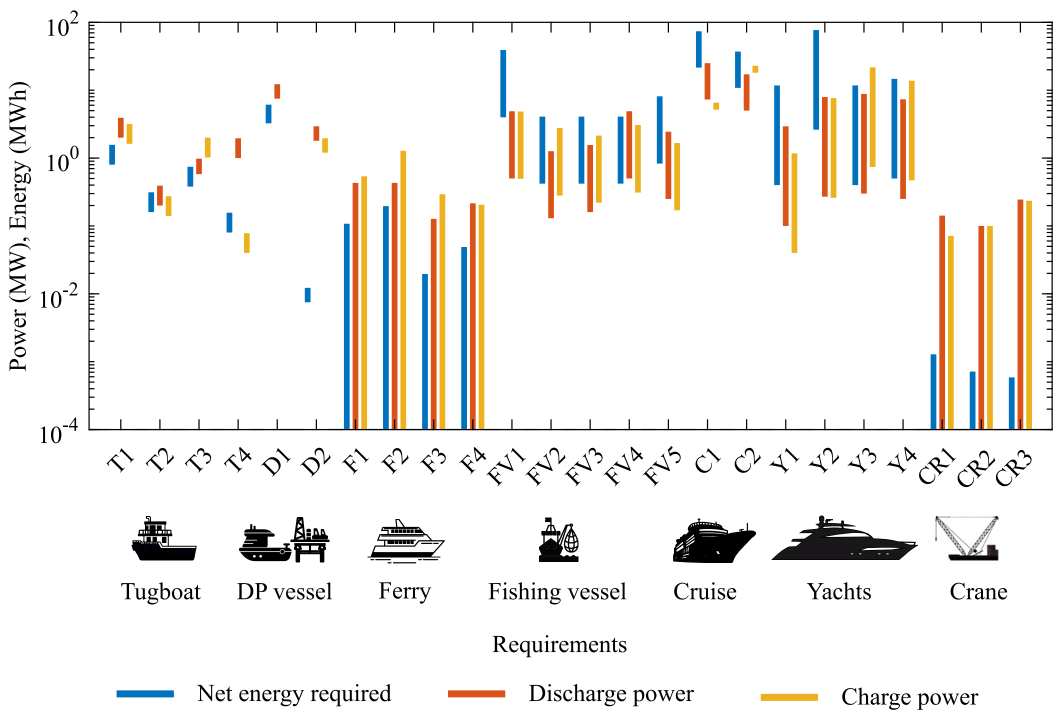


Fig. 12. Generalized battery requirements and potential installed capacities for various vessel types, including Tugboats, DP vessels, Fishing Vessels, Cruises, and yachts (data from Lucà Trombetta et al. 2024), Ferries (data from Al-Falahi et al. 2019), and vessels with cranes (data from Ovrum and Bergh 2015 and Kim et al. 2019)

battery decision tree, synthesized from the previously discussed results, is presented in Fig. 13.

The high charge power requirements for tugboats make LTO and NMC batteries more favourable than LFP. While LTO batteries are typically considered heavier and bulkier, they perform better than LFP in situations where power demand limits installed capacity. This is because a smaller LTO battery can deliver more power. However, NMC batteries remain competitive with LTO for this vessel segment.

In the case of DP vessels, under requirement D1, both NMC and LTO batteries have the same installed capacity (kWh). However, NMC batteries are a better choice due to their lower cost, weight, and volume per kWh compared to LTO. For load smoothing, in requirements D2, CR2, and CR3, where significantly higher power is required compared to energy, LTO batteries are preferable over NMC and LFP batteries. In Table 7, requirement D2 is highlighted in green, though LTO requires a smaller battery size. This is because during DP operation, spinning re-

Table 6
Generalized requirements.

Vessel	$\frac{P_{bat}}{E^{net}_{bat}}$ (h^{-1})	$\frac{P^{charging}_{bat}}{P^{discharging}_{bat}}$	Daily cycles	Yearly cycles
Tugboat	>1	–	4–10	Consistent
Ferry	>3	>1	$Trips \cdot Ports$	Consistent
Fishing	<1	–	<2	Seasonal
Cruise	<1	≈	–	Port stay
Yachts	–	–	≥ 1	Seasonal
DP	>2	–	Micro cyclesor standby	Consistent
Cranes	>100	≤ 0.5	High	–

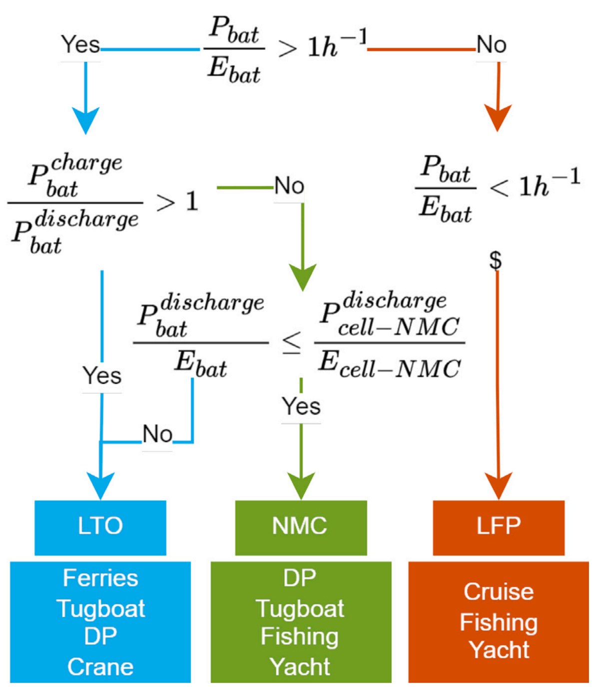


Fig. 13. Maritime battery decision tree.

serve requirements (D1) must be met alongside D2. For the requirement D1, NMC performs better.

For ferries which demand high charging power, LTO batteries are more favourable than NMC and LFP in terms of installed energy, cost, weight, and volume. Ferries also have high energy throughput and equivalent daily cycles, meaning the number of cycles per day is large. Due to their lower cycle life compared to LTO, both NMC and LFP batteries would need to be oversized to match the depth of discharge requirements. This further strengthens the case for LTO batteries in this vessel segment.

Energy intensive applications, such as fishing vessels, cruise ships, and yachts, are constrained by the energy required onboard (with the exception of requirement FV4). This means that regardless of the battery chemistry, the same amount of energy is needed. However, the lower volume per kWh (l/kWh) and kilogrammes per kWh (kg/kWh) of LFP batteries make them more favourable for applications where energy requirements are the primary constraint. For vessels like yachts and fishing vessels, where energy throughput and equivalent cycles are not as demanding as in tugboats and ferries, LFP and NMC batteries are more suitable. Even from a lifetime perspective, these chemistries are more advantageous in such cases.

There are clearly preferred battery types for different classes of vessels, based on their operational requirements. This is depicted in the maritime battery decision tree shown in Fig. 13. For vessels that demand higher charge power compared to discharge power and where the power-to-energy ratio > 1 h^{-1}, LTO batteries are the most favourable due to their high C-rate capability, with NMC being the second choice and LFP being the least favourable. On the other hand, for vessel segments that require higher discharge power than charge power and a power-to-energy ratio > 1 h^{-1}, NMC batteries are preferred over LTO because of their lower cost, weight, and volume. This is evident, for example, when analysing the spinning reserve requirement in case D1. Lastly, for vessels where the power-to-energy ratio is ≤ 1 h^{-1}, LFP batteries are highly favourable. Despite NMC and LTO batteries requiring similar installed capacities, the lower volume, weight, and cost of LFP make it the ideal candidate, as seen in the requirements for fishing vessels, cruise ships, and yachts.

5. Conclusion

The research focused on addressing two main questions. First, can generalizations be made regarding the battery requirements for different vessel segments in the maritime industry? Second, among the existing lithium-ion battery chemistries used in maritime applications, which is best suited for specific requirements?

The results obtained from the MILP-based optimization framework provide answers to the first research question by identifying optimal battery sizing and operational power distribution across vessel segments. Tugboats, ferries, DP vessels in load-smoothing mode, and hybrid cranes all exhibit power-to-energy ratios > 1 h^{-1}, indicating a need for batteries with higher power delivery per unit energy. Ferries typically require more charging than discharging power, and battery electric operation for tugboats and ferries is more energy-intensive than hybrid modes, but power capacity remains the limiting factor. Yachts, cruise ships, and fishing vessels generally have power-to-energy ratios < 1 h^{-1}, favouring higher energy densities over power. However, optimizing DEG loads (F3, FV4, Y3) demands power-to-energy ratios ≥ 1 h^{-1}. Cranes require power-to-energy ratios ≥ 100 h^{-1} for all operations, with discharge power exceeding charging during regeneration. Smoothing the load experienced by DEGs (as seen in requirements D2, CR2, CR3) also consistently requires power-to-energy ratios ≥ 100 h^{-1}.

The second research question is addressed by evaluating battery C-rates alongside volume, weight, and cost. Preferred battery types vary by vessel class based on operational requirements, as shown in the maritime battery decision tree (Fig. 13). For vessels with power-to-energy ratios > 1 h^{-1} and higher charge than discharge power, LTO batteries are most favourable due to their high C-rate, followed by NMC and LFP. Conversely, for vessels with higher discharge than charge power and power-to-energy ratios > 1 h^{-1}, NMC batteries are preferred over LTO for their lower cost, weight, and volume, as seen in spinning reserve requirement D1. For vessels with power-to-energy ratios ≤ 1 h^{-1}, LFP batteries are ideal due to their lower volume, weight, and cost, despite similar installed capacities to NMC and LTO, as evident in fishing vessels, cruise ships, and yachts.

While the research questions have been successfully addressed, certain limitations in the research could potentially influence the results. For instance, energy throughput and equivalent cycles were only briefly discussed in the analysis. In the case of Tugboats, specifically for requirement T2, NMC batteries were identified as the preferred choice. However, tugboats typically require a large number of daily equivalent cycles, which LTO batteries can provide more reliably than NMC batteries at a specific depth of discharge. This implies that NMC batteries might need to be sized larger than the indicative values discussed. This limitation becomes more pronounced when the daily equivalent cycles are greater than or equal to one and NMC or LFP batteries are selected. Secondly, the batteries' minimum continuous charge and discharge power was calculated assuming a 10% state of charge. While this assumption does not significantly impact the required capacities

Table 7
Chemistry specific requirements.

Vessel	Req	Size (kW)	LFP	NMC	LTO	LFP	NMC	LTO	LFP	NMC	LTO	LFP	NMC	LTO
			Energy (kWh)			Cost (Million €)			Weight (Tons)			Volume (cubic meter)		
Tug boat	T1	2000	2909	1748	800	1.34	0.87	0.56	18.87	15.75	15.84	19.14	14.57	10.34
	T2		291	160	160	0.13	0.08	0.11	1.89	1.44	3.17	1.91	1.33	2.07
	T3		1396	1100	380	0.64	0.55	0.27	9.06	9.91	7.52	9.19	9.17	4.91
	T4		1455	425	265	0.67	0.21	0.19	9.44	3.83	5.25	9.57	3.54	3.43
Ferry	F1	450	776	612	134	0.36	0.31	0.09	5.03	5.51	2.65	5.11	5.10	1.73
	F2		1830	1442	316	0.84	0.72	0.22	11.86	12.99	6.25	12.04	12.02	4.08
	F3		425	335	73	0.20	0.17	0.05	2.76	3.02	1.45	2.80	2.79	0.95
	F4		334	238	61	0.15	0.12	0.04	2.17	2.14	1.21	2.20	1.98	0.79
Fishing vessel	FV1	500	3996	3995	3995	1.84	2.00	2.80	25.91	35.99	79.11	26.29	33.29	51.62
	FV2		416	415	415	0.19	0.21	0.29	2.70	3.74	8.22	2.73	3.46	5.36
	FV3		416	415	415	0.19	0.21	0.29	2.70	3.74	8.22	2.73	3.46	5.36
	FV4		728	415	415	0.33	0.21	0.29	4.72	3.74	8.22	4.79	3.46	5.36
	FV5		830	830	830	0.38	0.42	0.58	5.39	7.48	16.44	5.46	6.92	10.72
Cruise	C1	20000	21600	21600	21600	9.94	10.80	15.12	140.08	194.60	427.72	142.11	180.00	279.07
	C2		10800	10800	10800	4.97	5.40	7.56	70.04	97.30	213.86	71.05	90.00	139.54
Yachts	Y1	1000	400	400	400	0.18	0.20	0.28	2.60	3.61	7.92	2.63	3.33	5.17
	Y2		2620	2620	2620	1.21	1.31	1.83	16.99	23.60	51.88	17.24	21.83	33.85
	Y3		1013	798	400	0.47	0.40	0.28	6.57	7.19	7.92	6.66	6.65	5.17
	Y4		644	507	500	0.30	0.25	0.35	4.17	4.57	9.90	4.23	4.23	6.46
DP	D1	7500	10910	3750	3750	5.02	1.88	2.63	70.75	33.78	74.26	71.78	31.25	48.45
	D2		2618	1295	478	1.20	0.65	0.33	16.98	11.66	9.46	17.23	10.79	6.17
Crane	CR1	134.6	196	73	36	0.09	0.04	0.03	1.27	0.66	0.71	1.29	0.61	0.46
	CR2		137	102	25	0.06	0.05	0.02	0.89	0.92	0.50	0.90	0.85	0.32
	CR3	1250	437	337	80	0.20	0.17	0.06	2.83	3.04	1.58	2.87	2.81	1.03

for LFP batteries, due to their relatively flat voltage curve across the SoC range, NMC and LTO batteries exhibit a higher $\frac{\Delta P}{\Delta SoC}$, meaning a smaller battery capacity could be sufficient if the minimum charge and discharge power is considered at a higher SoC. In such cases, the required installed energy capacity for NMC and LTO batteries might be lower, particularly when power is the limiting constraint.

With this analysis, the battery requirements for different vessel segments and functions, including the power and energy capacities needed for various applications, have been successfully identified. This contributes significantly to the process of selecting, testing and developing appropriate batteries for maritime use cases. Additionally, the most suitable existing battery chemistries for different functional requirements have been determined, providing a clear framework for optimizing battery selection based on vessel-specific needs.

CRediT authorship contribution statement

Sankarshan Durgaprasad: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Andrea Coraddu:** Writing – review & editing, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization. **Henk Polinder:** Writing – review & editing, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

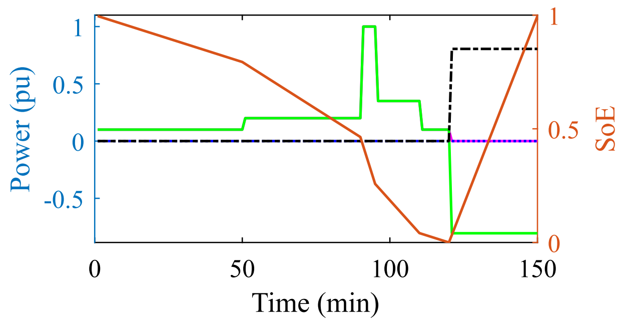
This research was funded by NWO through the KIC program on "Emission-free and Circular Shipping," specifically the Maritime Batteries (reference number KICH1.KICH1.21.002) research project.

Appendix

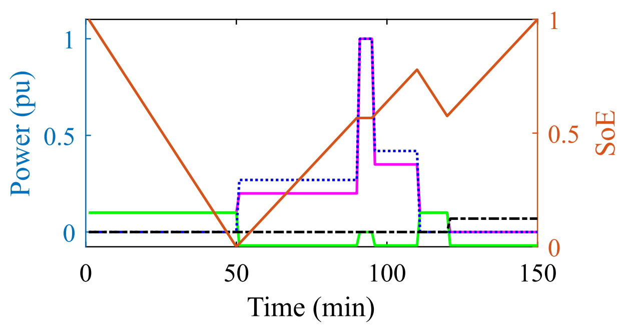
See Figs. A.14–A.26 and Table A.8.

Data availability

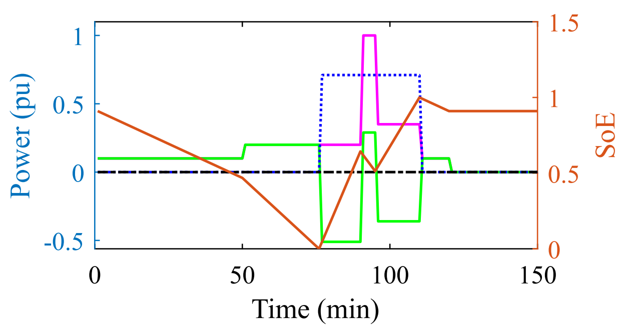
Data will be made available on request.



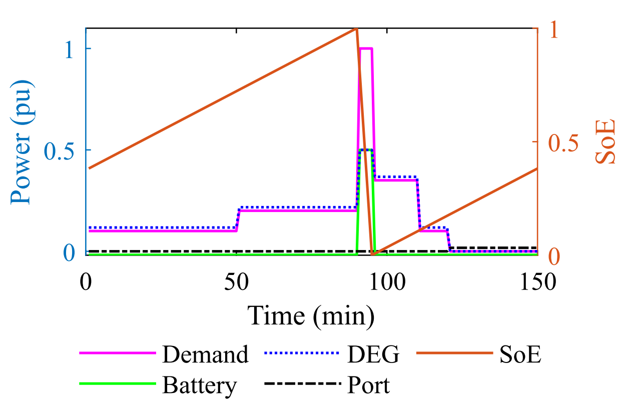
(a) Requirement T1 for Tugboat



(b) Requirement T2 for Tugboat

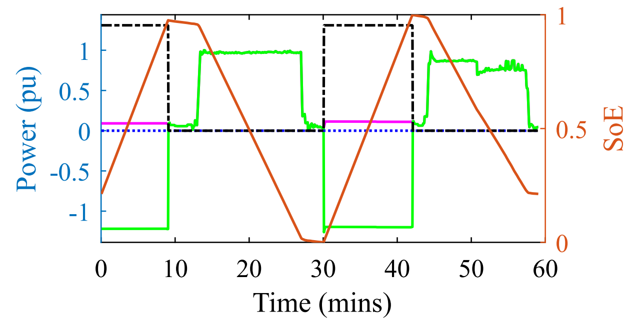


(c) Requirement T3 for Tugboat

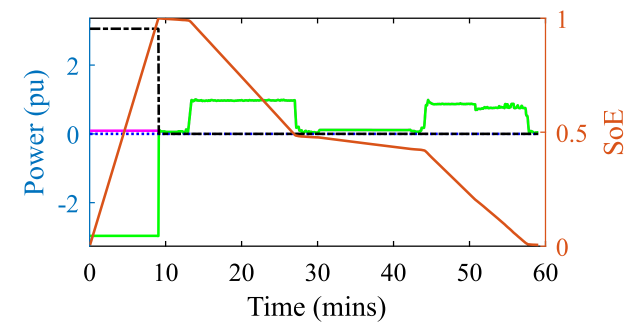


(d) Requirement T4 for Tugboat

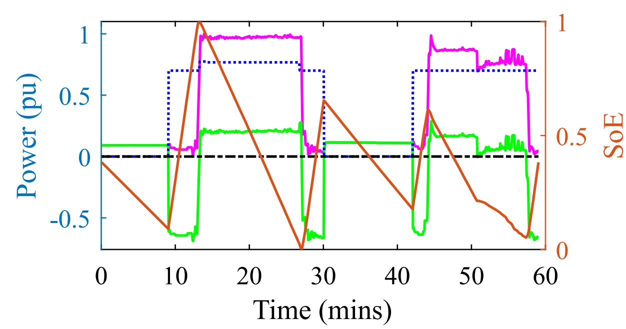
Fig. A.14. Power split for requirements T1–T4.



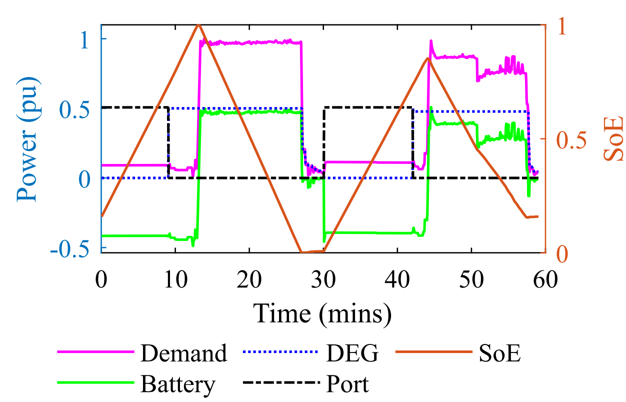
(a) Requirement F1 for Ferry



(b) Requirement F2 for Ferry

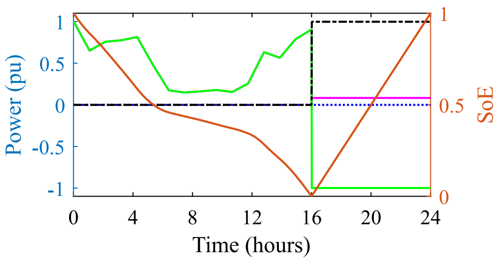


(c) Requirement F3 for Ferry

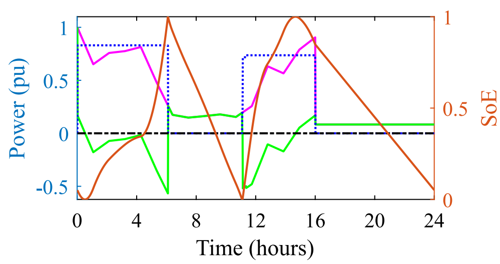


(d) Requirement F4 for Ferry

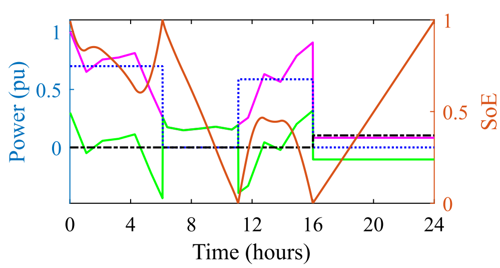
Fig. A.15. Power split for requirements F1–F4.



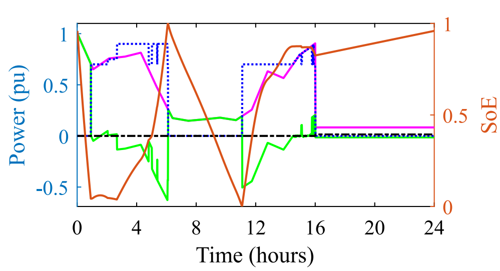
(a) Requirement FV1 for Fishing vessel



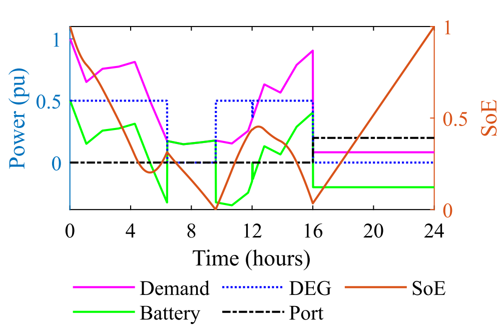
(b) Requirement FV2 for Fishing vessel



(c) Requirement FV3 for Fishing vessel

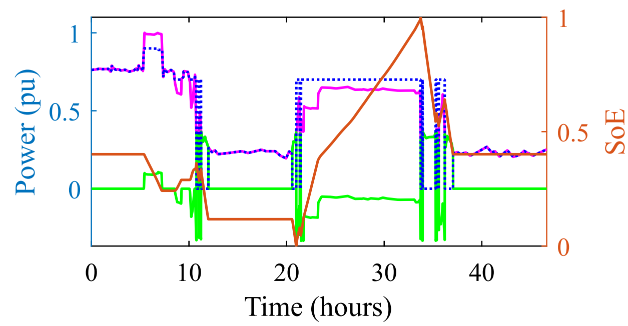


(d) Requirement FV4 for Fishing vessel

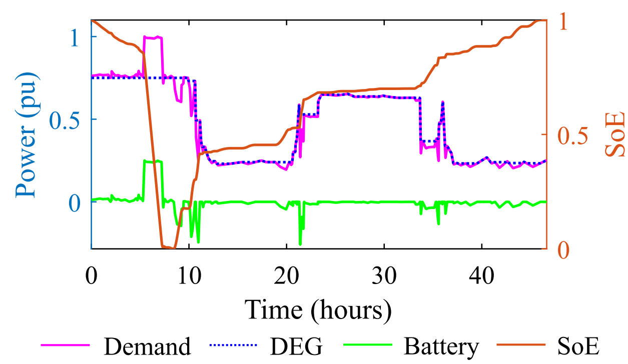


(e) Requirement FV5 for Fishing vessel

Fig. A.16. Power split for requirements FV1–FV5.

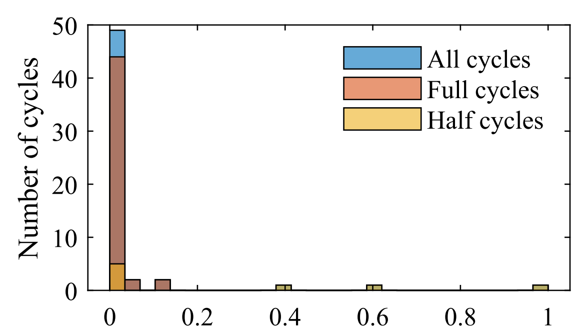


(a) Requirement C1 for Cruise ship

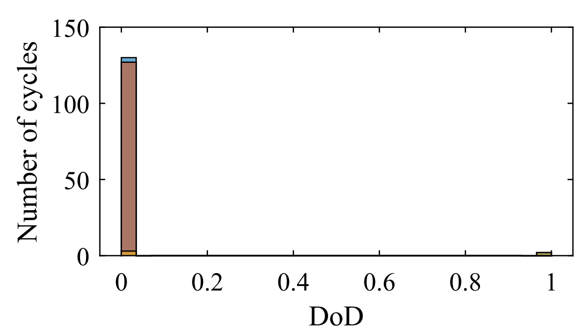


(b) Requirement C2 for Cruise ship

Fig. A.17. Power split for requirements C1 and C2.

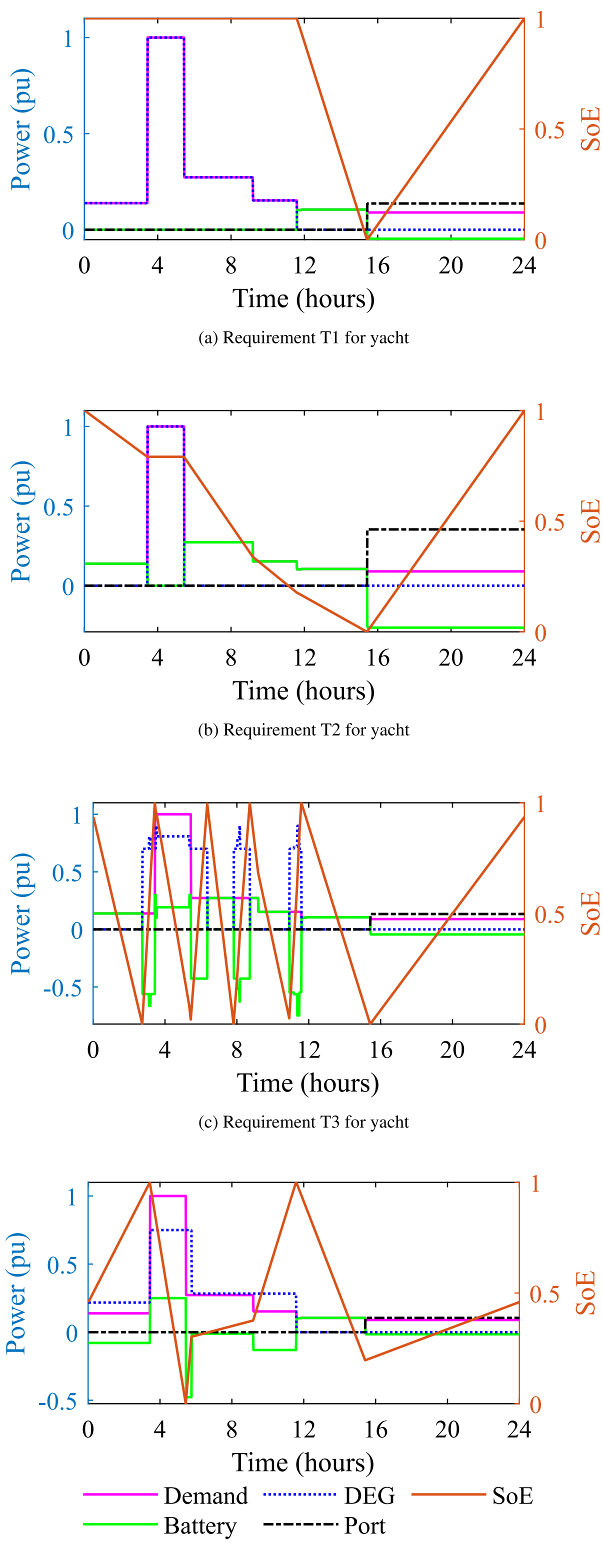


(a) Cycle types for requirement C1 for Cruise ship



(b) Cycle types for requirement C2 for Cruise ship

Fig. A.18. Cycle requirements for Cruise ship.



(a) Requirement T1 for yacht

(b) Requirement T2 for yacht

(c) Requirement T3 for yacht

(d) Requirement T4 for yacht

Fig. A.19. Power split for requirements Y1–Y4.

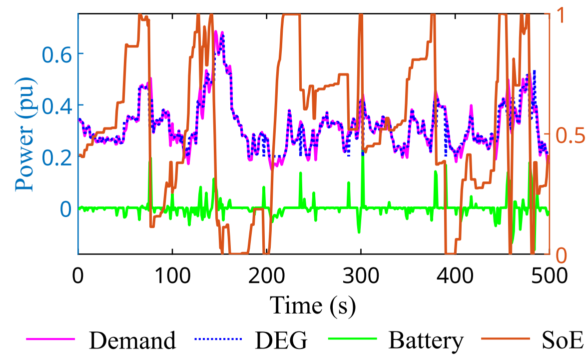


Fig. A.20. Requirement D2 for DP vessels.

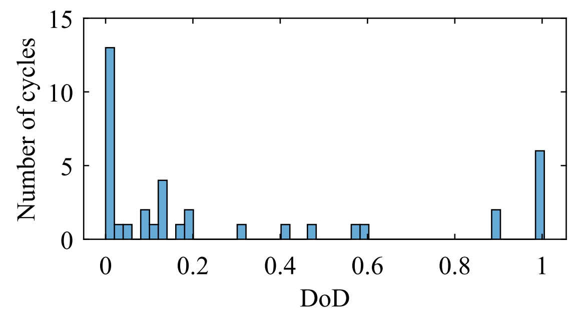
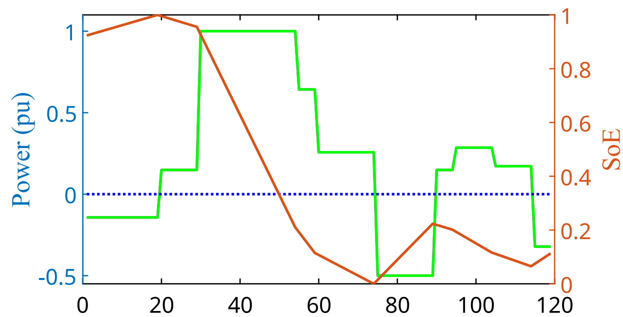


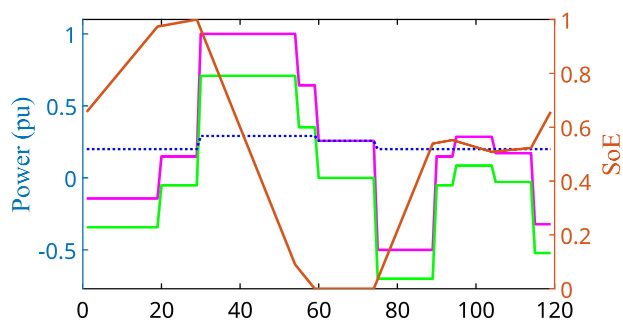
Fig. A.21. Cycle requirement D2 for DP vessels.

Table A.8
Sequence of solving objectives.

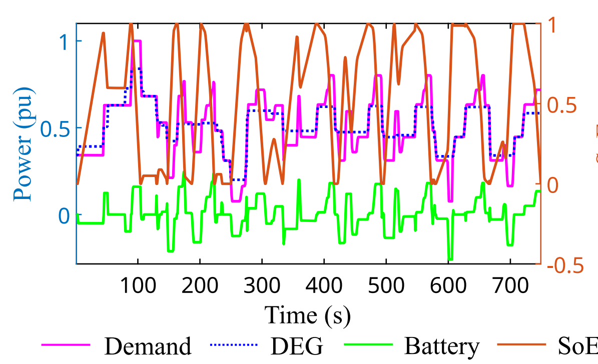
Vessel	Req	Objectives
Tugboat	T1	$\mathcal{O}_1, \mathcal{O}_2$
	T2	$\mathcal{O}_1, \mathcal{O}_2$
	T3	$\mathcal{O}_3, \mathcal{O}_1$
	T4	$\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3$
Ferry	F1	$\mathcal{O}_1$
	F2	$\mathcal{O}_1$
	F3	$\mathcal{O}_1$
	F4	$\mathcal{O}_1$
Fishing	FV1	$\mathcal{O}_1, \mathcal{O}_2$
	FV2	$\mathcal{O}_1, \mathcal{O}_3$
	FV3	$\mathcal{O}_1, \mathcal{O}_3$
	FV4	$\mathcal{O}_1, \mathcal{O}_2$
	FV5	$\mathcal{O}_1$
Cruise	C1	$\mathcal{O}_5$
	C2	$\mathcal{O}_5, \mathcal{O}_1, \mathcal{O}_3$
Yacht	Y1	$\mathcal{O}_1$
	Y2	$\mathcal{O}_1$
	Y3	$\mathcal{O}_1, \mathcal{O}_4$
	Y4	$\mathcal{O}_1, \mathcal{O}_3$
DP	D1	$\mathcal{O}_1$
	D2	$\mathcal{O}_1$
Crane	CR1	$\mathcal{O}_1$
	CR2	$\mathcal{O}_1$
	CR3	$\mathcal{O}_1$



(a) Requirement CR1 for crane



(b) Requirement CR2 for crane



(c) Requirement CR3 for crane

Fig. A.22. Power split for requirements CR1–CR3.

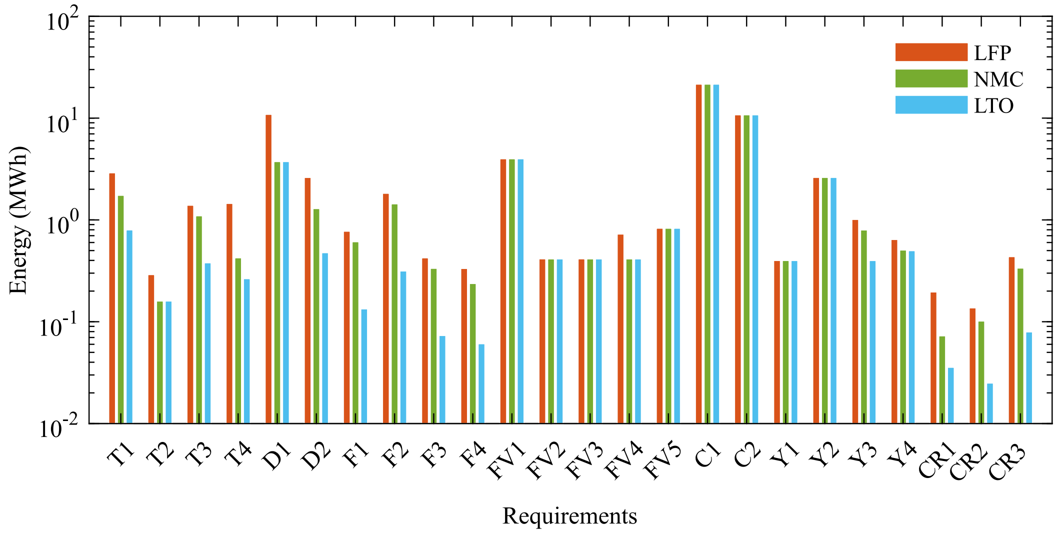


Fig. A.23. Required capacity based on chemistry.

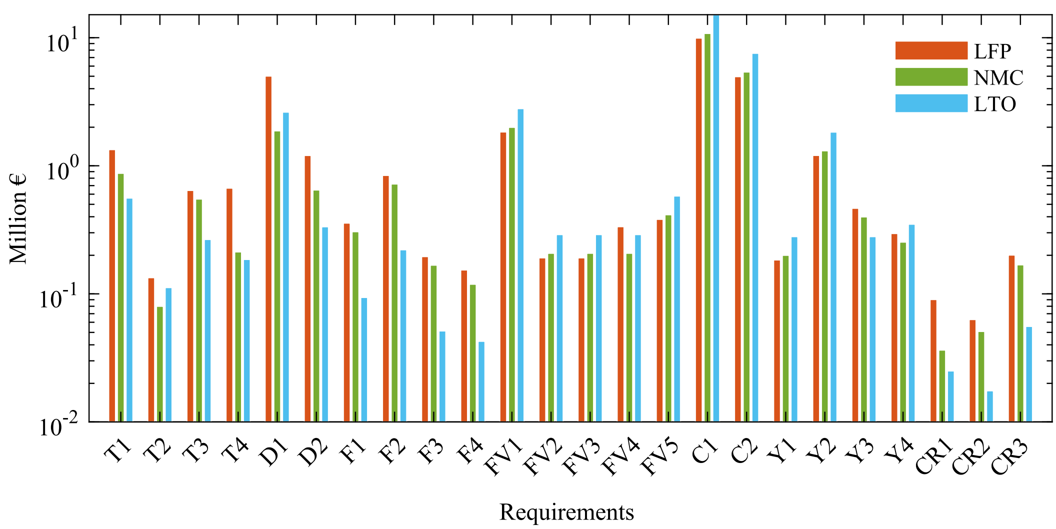


Fig. A.24. Required cost based on chemistry.

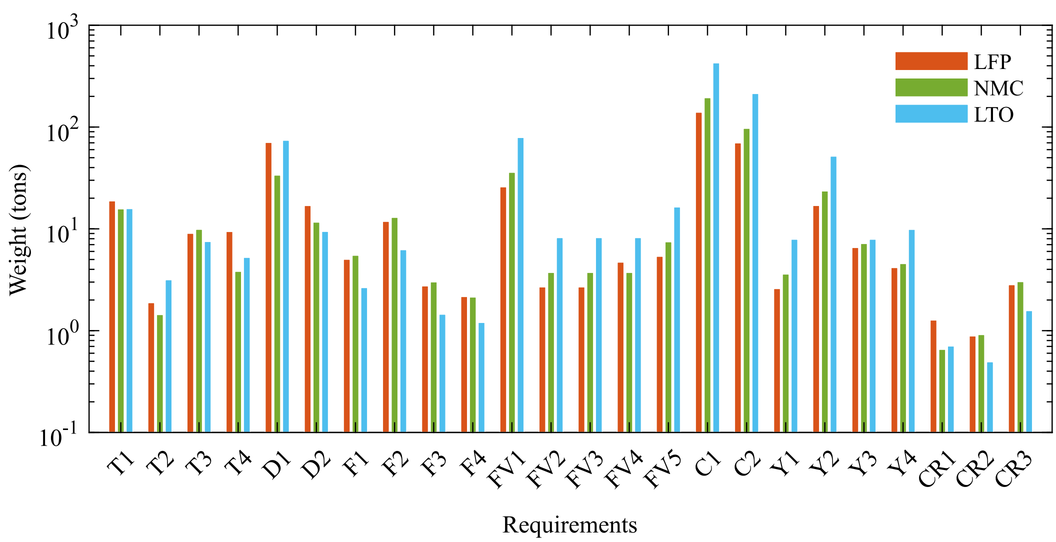


Fig. A.25. Required weight based on chemistry.

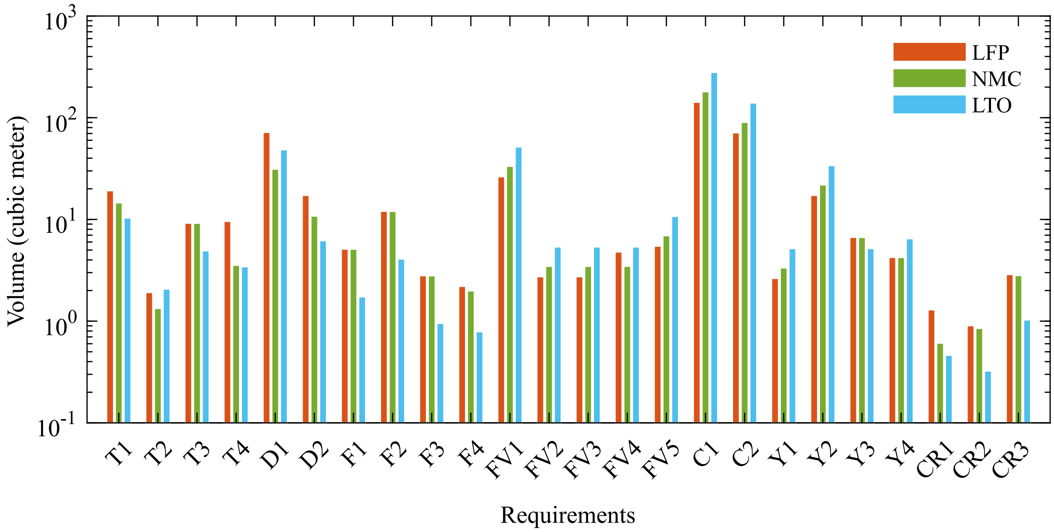


Fig. A.26. Required volume based on chemistry.

References

Aarsaether, K.G., 2017. Energy savings in coastal Fisheries: Use of a serial battery hybrid power system. IEEE Electrif. Mag. 5 (3), 74–79. http://dx.doi.org/10.1109/MELE.2017.2718863.

Al-Falahi, M.D., Jayasinghe, S.D., Enshaei, H., Baguley, C., Madawala, U., 2019. Diesel, hybrid or fully electric ferry: A method for operating cost analysis and battery size optimisation. In: 2019 9th International Conference on Power and Energy Systems. ICPES, pp. 1–9. http://dx.doi.org/10.1109/ICPES47639.2019.9105602.

Ancona, M.A., Baldi, F., Bianchi, M., Branchini, L., Melino, F., Peretto, A., Rosati, J., 2018. Efficiency improvement on a cruise ship: Load allocation optimization. Energy Convers. Manage. 164, 42–58.

Anon, 2021. Study on electrical energy storage for ships. URL https://www.emsa.europa.eu/publications/item/3895-study-on-electrical-energy-storage-for-ships.html.

Baldi, F., Ahlgren, F., Nguyen, T.-V., Thern, M., Andersson, K., 2018. Energy and exergy analysis of a cruise ship. Energies 11 (10), 2508.

Balsamo, F., De Falco, P., Mottola, F., Pagano, M., 2020. Power flow approach for modeling shipboard power system in presence of energy storage and energy management systems. IEEE Trans. Energy Convers. 35 (4), 1944–1953. http://dx.doi.org/10.1109/TEC.2020.2997307.

Banaei, M., Rafiei, M., Boudjadar, J., Khooban, M.-H., 2020. A comparative analysis of optimal operation scenarios in hybrid emission-free ferry ships. IEEE Trans. Transp. Electrif. 6 (1), 318–333. http://dx.doi.org/10.1109/TTE.2020.2970674.

Barcellona, S., Brenna, M., Foiadelli, F., Longo, M., Piegari, L., 2015. Battery lifetime for different driving cycles of EVs. In: 2015 IEEE 1st International Forum on Research and Technologies for Society and Industry Leveraging a Better Tomorrow. RTSI, pp. 446–450. http://dx.doi.org/10.1109/RTSI.2015.7325138.

Bennabi, N., Menana, H., Charpentier, J.-F., Billard, J.-Y., Nottelet, B., 2021. Design and comparative study of hybrid propulsions for a river ferry operating on short cycles with high power demands. J. Mar. Sci. Eng. 9 (6), 631.

Bordin, C., Mo, O., 2019. Including power management strategies and load profiles in the mathematical optimization of energy storage sizing for fuel consumption reduction in maritime vessels. J. Energy Storage 23, 425–441.

Bucci, V., Mauro, F., Vicenzutti, A., Bosich, D., Sulligoi, G., 2020. Hybrid-electric solutions for the propulsion of a luxury sailing yacht. In: 2020 2nd IEEE International Conference on Industrial Electronics for Sustainable Energy Systems. IESES, Vol. 1, pp. 280–286. http://dx.doi.org/10.1109/IESES45645.2020.9210696.

Chalfant, J., 2015. Early-stage design for electric ship. Proc. IEEE 103 (12), 2252–2266. http://dx.doi.org/10.1109/JPROC.2015.2459672.

Chen, W., Tai, K., Lau, M.W.S., Abdelhakim, A., Chan, R.R., Kåre Ådnanes, A., Tjahjowidodo, T., 2023. Optimal power and energy management control for hybrid fuel cell-fed shipboard DC microgrid. IEEE Trans. Intell. Transp. Syst. 24 (12), 14133–14150. http://dx.doi.org/10.1109/TITS.2023.3303886.

Chua, L.W., Tjahjowidodo, T., Seet, G.G., Chan, R., 2018. Implementation of optimization-based power management for all-electric hybrid vessels. IEEE Access 6, 74339–74354. http://dx.doi.org/10.1109/ACCESS.2018.2883324.

Corvus Energy, 2024a. Corvus energy - marine batteries and energy storage systems. URL https://corvusenergy.com/, (Accessed: 2024-09-09).

Corvus Energy, 2024b. MY sea eagle II project. URL https://corvusenergy.com/projects/my-sea-eagle-ii/, (Accessed: 2024-10-11).

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

de Figueiredo, L.M., Hekkenberg, R., 2018. The yacht of 2030. (Master's thesis). Technical University of Delft, Delft, pp. 1–140, Available from the Delft Repository.

Dinh, T.Q., Bui, T.M., Marco, J., Watts, C., Yoon, J.I., 2018. Optimal energy management for hybrid electric dynamic positioning vessels. IFAC-PapersOnLine 51 (29), 98–103.

Diniz, G.H., Miranda, V.d., Carmo, B.S., 2023. Dynamic modelling, simulation, and control of hybrid power systems for escort tugs and shuttle tankers. J. Energy Storage 72, 108091. http://dx.doi.org/10.1016/j.est.2023.108091.

DNV, 2024. Alternative fuels insight. Accessed: May 2024.

Echandia, 2024. Tugboat sparky - world's first all-electric tugboat. URL https://echandia.se/projects/tugboat-sparky/, (Accessed: 2024-10-10).

EST-Floattech, 2024. Yachting market - EST-floattech. URL https://www.est-floattech.com/markets/yachting/, (Accessed: 2024-10-11).

European Commission, 2024. Reducing emissions in the shipping sector. URL https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en, (Accessed: 2024-09-09).

Ferries, B., 2020. MV Bowen Schedule, URL https://www.bcferries.com/web_image/hc2/heb/9008323461150.pdf, Vancouver (Horseshoe Bay) to Bowen Island (Snug Cove).

Frangopoulos, C.A., 2020. Developments, trends, and challenges in optimization of ship energy systems. Appl. Sci. 10 (13), 4639.

Gabrielii, C.H., Jafarzadeh, S., 2020. Alternative fuels and propulsion systems for fishing vessels. SINTEF Rapport, SINTEF Energi AS.

Ganjian, M., Bagherian Farahabadi, H., Alirezapouri, M.A., Rezaei Firuzjaei, M., 2024. Optimal design strategy for fuel cell-based hybrid power system of all-electric ships. Int. J. Hydrog. Energy 50, 1558–1571. http://dx.doi.org/10.1016/j.ijhydene.2023.07.258.

Georgescu, I., Godjevac, M., Visser, K., 2018. Efficiency constraints of energy storage for on-board power systems. Ocean Eng. 162, 239–247.

Ghimire, P., Zadeh, M., Thapa, S., Thorstensen, J., Pedersen, E., 2024. Operational efficiency and emissions assessment of ship hybrid power systems with battery; effect of control strategies. IEEE Trans. Transp. Electrif. 1. http://dx.doi.org/10.1109/TTE.2024.3365351.

Ghimire, P., Zadeh, M., Thorstensen, J., Pedersen, E., 2022. Data-driven efficiency modeling and analysis of all-electric ship powertrain: A comparison of power system architectures. IEEE Trans. Transp. Electrif. 8 (2), 1930–1943. http://dx.doi.org/10.1109/TTE.2021.3123886.

Guo, X., Lang, X., Yuan, Y., Tong, L., Shen, B., Long, T., Mao, W., 2024. Energy management system for hybrid ship: Status and perspectives. Ocean Eng. 310, 118638.

Hansen, J.F., Wendt, F., 2015. History and state of the art in commercial electric ship propulsion, integrated power systems, and future trends. Proc. IEEE 103 (12), 2229–2242. http://dx.doi.org/10.1109/JPROC.2015.2458990.

He, W., Valøen, L.O., Olsen, K.V., Kjeka, K.M., Fredriksen, B.M., Petiteau, M., Touat, A., Såtendal, H., Howie, A., Howey, D., et al., 2024. Lessons learned from the commercial exploitation of marine battery energy storage systems. J. Energy Storage 87, 111440.

Hong, S.H., Kim, D.M., Kim, S.J., 2024. Power control strategy optimization to improve energy efficiency of the hybrid electric propulsion ship. IEEE Access 12, 22534–22545. http://dx.doi.org/10.1109/ACCESS.2024.3364374.

Hwang, J., Kim, J., Jeon, H., Kim, S., 2022. A study on the application of hybrid propulsion system of small size fishing vessels in South Korea. J. Int. Marit. Saf. Environ. Aff. Shipp. 6 (4), 206–215. http://dx.doi.org/10.1080/25725084.2022.2149176.

Hwang, S., Lee, C., Ryu, J., Lim, J., Chung, S., Park, S., 2024. Optimal EMS design for a 4-MW-class hydrogen tugboat: A comparative analysis using DP-based performance evaluation. Energies 17 (13), 3146.

Inal, O.B., Charpentier, J.-F., Deniz, C., 2022. Hybrid power and propulsion systems for ships: Current status and future challenges. Renew. Sustain. Energy Rev. 156, 111965.

International Maritime Organization, 2024a. 2023 IMO strategy on reduction of GHG emissions from ships. URL https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx, (Accessed: 2024-09-09).

International Maritime Organization, 2024b. Fourth IMO greenhouse gas study 2020. URL https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx, (Accessed: 2024-09-09).

Jin, Z., Meng, L., Guerrero, J.M., Han, R., 2018. Hierarchical control design for a shipboard power system with DC distribution and energy storage aboard future more-electric ships. IEEE Trans. Ind. Inform. 14 (2), 703–714. http://dx.doi.org/10.1109/TII.2017.2772343.

Johansen, T.A., Bø, T.I., Mathiesen, E., Veksler, A., Sørensen, A.J., 2014. Dynamic positioning system as dynamic energy storage on diesel-electric ships. IEEE Trans. Power Syst. 29 (6), 3086–3091. http://dx.doi.org/10.1109/TPWRS.2014.2317704.

Jung, W., Choi, M., Jeong, J., Lee, J., Chang, D., 2024. Design and analysis of liquid hydrogen-fueled hybrid ship propulsion system with dynamic simulation. Int. J. Hydrog. Energy 50, 951–967.

Kalikatzarakis, M., Geertsma, R., Boonen, E., Visser, K., Negenborn, R., 2018. Ship energy management for hybrid propulsion and power supply with shore charging. Control Eng. Pract. 76, 133–154.

Khan, A.A., Timilsina, L., Muriithi, G., Arsalan, A., Moghassemi, A., Papari, B., Ozkan, G., Edrington, C.S., Boghrabadi, N.S., Wang, Z., 2025. Energy management systems for maritime microgrids: A comprehensive review of intelligent optimization strategies. IEEE Access 1. http://dx.doi.org/10.1109/ACCESS.2025.3613231.

Kim, K., An, J., Park, K., Roh, G., Chun, K., 2019. Analysis of a supercapacitor/battery hybrid power system for a bulk carrier. Appl. Sci. 9 (8), 1547.

Kim, K., Park, K., Ahn, J., Roh, G., Chun, K., 2016. A study on applicability of Battery Energy Storage System (BESS) for electric propulsion ships. In: 2016 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific). IEEE, pp. 203–207.

Kistner, L., Bensmann, A., Hanke-Rauschenbach, R., 2024. Potentials and limitations of battery-electric container ship propulsion systems. Energy Convers. Manag.: X 21, 100507.

Koričan, M., Frković, L., Vladimir, N., 2023. Electrification of fishing vessels and their integration into isolated energy systems with a high share of renewables. J. Clean. Prod. 425, 138997. http://dx.doi.org/10.1016/j.jclepro.2023.138997.

KoteswaraRao, K.V., Srinivasulu, G.N., Rahul, J.R., Velisala, V., 2024. Optimal component sizing and performance of Fuel Cell–Battery powered vehicle over world harmonized and new european driving cycles. Energy Convers. Manage. 300, 117992.

Kumar, B.A., Selvaraj, R., Chelliah, T.R., Ramesh, U., 2019. Improved fuel-use efficiency in diesel–electric tugboats with an asynchronous power generating unit. IEEE Trans. Transp. Electrif. 5 (2), 565–578. http://dx.doi.org/10.1109/TTE.2019.2906587.

Kumar, B.A., Selvaraj, R., Desingu, K., Chelliah, T.R., Upadhyayula, R.S., 2020. A coordinated control strategy for a diesel-electric tugboat system for improved fuel economy. IEEE Trans. Ind. Appl. 56 (5), 5439–5451. http://dx.doi.org/10.1109/TIA.2020.3010779.

Laryea, H., Schiffauerova, A., 2024. A novel standalone hybrid renewable energy systems onboard conventional and autonomous tugboats. Energy 131948.

Li, Y., Liu, X., Zhao, Y., He, T., Zeng, H., 2024. Optimization design of hybrid energy storage capacity configuration for electric ship. Energy Rep. 11, 887–894.

Löffler, C., Geertsma, R., Polinder, H., Coraddu, A., 2025. Energy management for hybrid and fully electric vessels via a multi-objective equivalent consumption minimization strategy. Energy Convers. Manage. 343, 120150.

Lucà Trombetta, G., Leonardi, S.G., Aloisio, D., Andaloro, L., Sergi, F., 2024. Lithium-ion batteries on board: A review on their integration for enabling the energy transition in shipping industry. Energies 17 (5), 1019.

Mao, R., Qian, Y., Liu, K., Li, Y., Li, G., Zhang, H., 2025. A comprehensive survey of battery energy in maritime transportation: Trends, challenges, and future perspectives. Ocean Eng. 337, 121881.

Micari, S., Foti, S., Testa, A., De Caro, S., Sergi, F., Andaloro, L., Aloisio, D., Leonardi, S.G., Napoli, G., 2022. Effect of WLTP CLASS 3B driving cycle on lithium-ion battery for electric vehicles. Energies 15 (18), 6703.

Mijnders, P., 2023. Fishery and aquaculture - EST-floattech. URL https://www.est-floattech.com/markets/fishery-aquaculture/.

Montonen, J.-H., Lindh, T., Lana, A., Peltoniemi, P., Pinomaa, A., Tikkanen, K., Pyrhönen, O., 2022. Comparison of different power balance control methods for battery energy storage systems on hybrid marine vessels. IEEE Access 10, 58578–58588. http://dx.doi.org/10.1109/ACCESS.2022.3179716.

Morales Vásquez, C.A., 2016. Evaluation of medium speed diesel generator sets and energy storage technologies as alternatives for reducing fuel consumption and exhaust emissions in electric propulsion systems for PSVS. Cienc. y Tecnología de Buques 9 (18), 49. http://dx.doi.org/10.25043/19098642.128.

Mylonopoulos, F., Durgaprasad, S., Coraddu, A., Polinder, H., 2024. Lifetime design, operation, and cost analysis for the energy system of a retrofitted cargo vessel with fuel cells and batteries. Int. J. Hydrog. Energy (ISSN: 0360-3199) 91, 1262–1273. http://dx.doi.org/10.1016/j.ijhydene.2024.10.235, URL https://www.sciencedirect.com/science/article/pii/S0360319924044410.

Mylonopoulos, F., Polinder, H., Coraddu, A., 2023. A comprehensive review of modeling and optimization methods for ship energy systems. IEEE Access 11, 32697–32707. http://dx.doi.org/10.1109/ACCESS.2023.3263719.

Naseri, F., Barbu, C., Sarikurt, T., 2022. Optimal sizing of hybrid high-energy/high-power battery energy storage systems to improve battery cycle life and charging power in electric vehicle applications. J. Energy Storage 55, 105768.

Ovrum, E., Bergh, T., 2015. Modelling lithium-ion battery hybrid ship crane operation. Appl. Energy 152, 162–172.

Pang, B., Liu, S., Zhu, H., Feng, Y., Dong, Z., 2024. Real-time optimal control of an LNG-fueled hybrid electric ship considering battery degradations. Energy 296, 131170.

Perčić, M., Koričan, M., Jovanović, I., Vladimir, N., 2023. Environmental and economic assessment of batteries for marine applications: Case study of all-electric fishing vessels. Batteries 10 (1), 7.

Pourrahmani, H., Gay, M., Yavarinasab, A., et al., 2022. Optimization and dynamic responses of an integrated fuel cell and battery system for an 800 kW ferry: A case study. Energy Rep. 8, 9757–9776.

Praxis Automation, 2024. Praxis automation - electric energy storage products. URL https://www.praxis-automation.eu/index.php/products/electric-energy-storage, (Accessed: 2024-09-09).

Qazi, S., Venugopal, P., Rietveld, G., Soeiro, T.B., Shipurkar, U., Grasman, A., Watson, A.J., Wheeler, P., 2023. Powering maritime: Challenges and prospects in ship electrification. IEEE Electrif. Mag. 11 (2), 74–87. http://dx.doi.org/10.1109/MELE.2023.3264926.

Rafiei, M., Boudjadar, J., Khooban, M.-H., 2021. Energy management of a zero-emission ferry boat with a fuel-cell-based hybrid energy system: Feasibility assessment. IEEE Trans. Ind. Electron. 68 (2), 1739–1748. http://dx.doi.org/10.1109/TIE.2020.2992005.

Rao, S.K., Chauhan, P., Panda, S.K., Wilson, G., Liu, X., Gupta, A.K., 2016. An exercise to qualify LVAC and LVDC power system architectures for a platform supply vessel. In: 2016 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific). pp. 332–337. http://dx.doi.org/10.1109/ITEC-AP.2016.7512973.

Rasul, M.J., Kim, J., 2024. Comprehensive review and comparison on battery technologies as electric-powered source in marine applications. J. Energy Storage 88, 111509.

Roslan, S.B., Konovessis, D., Tay, Z.Y., 2022. Sustainable hybrid marine power systems for power management optimisation: a review. Energies 15 (24), 9622.

Safdari, M., Ahmadi, R., Sadeghzadeh, S., 2022. Numerical and experimental investigation on electric vehicles battery thermal management under new European driving cycle. Appl. Energy 315, 119026.

Sorensen, A.J., Skjetne, R., Bo, T., Miyazaki, M.R., Johansen, T.A., Utne, I.B., Pedersen, E., 2017. Toward safer, smarter, and greener ships: Using hybrid marine power plants. IEEE Electrif. Mag. 5 (3), 68–73. http://dx.doi.org/10.1109/MELE.2017.2718861.

Swider, A., Pedersen, E., 2019. Data-driven methodology for the analysis of operational profile and the quantification of electrical power variability on marine vessels. IEEE Trans. Power Syst. 34 (2), 1598–1609. http://dx.doi.org/10.1109/TPWRS.2018.2876252.

Tekin, M., Karamangil, M.İ., 2024. Comparative analysis of equivalent circuit battery models for electric vehicle battery management systems. J. Energy Storage 86, 111327.

van Eesteren Barros, J., Pruyn, J., 2022. Modeling the electric power consumption of a yacht. (Master's thesis). Technical University of Delft, Delft, pp. 1–74, Available from the Delft Repository.

Van Meer Industrial Services, 2024. Van meer - electrical energy storage solutions. URL https://www.vanmeer.nl/en/electrical-energy-storage, (Accessed: 2024-09-09).

Vieira, G.T., Pereira, D.F., Taheri, S.I., Khan, K.S., Salles, M.B., Guerrero, J.M., Carmo, B.S., 2022. Optimized configuration of diesel engine-fuel cell-battery hybrid power systems in a platform supply vessel to reduce CO2 emissions. Energies 15 (6), 2184. http://dx.doi.org/10.3390/en15062184.

Wang, H., Boulougouris, E., Theotokatos, G., Zhou, P., Priftis, A., Shi, G., 2021. Life cycle analysis and cost assessment of a battery powered ferry. Ocean Eng. 241, 110029.

Wilkins, S., Shipurkar, U., Dadikozyan, A., Veldhuis, C., 2024. Co-design and energy management for future vessels. In: Modelling and Optimisation of Ship Energy Systems 2023. http://dx.doi.org/10.59490/moses.2023.666, URL https://proceedings.open.tudelft.nl/moses2023/article/view/666.

Xie, P., Guerrero, J.M., Tan, S., Bazmohammadi, N., Vasquez, J.C., Mehrzadi, M., Al-Turki, Y., 2022. Optimization-based power and energy management system in shipboard microgrid: A review. IEEE Syst. J. 16 (1), 578–590. http://dx.doi.org/10.1109/JSYST.2020.3047673.

Yachts, S., 2024. Silent yachts - the solar powered catamaran. URL https://silent-yachts.com/, (Accessed: 2024-10-11).

Zahedi, B., Norum, L.E., Ludvigsen, K.B., 2014. Optimized efficiency of all-electric ships by DC hybrid power systems. J. Power Sources 255, 341–354. http://dx.doi.org/10.1016/j.jpowsour.2014.01.031.