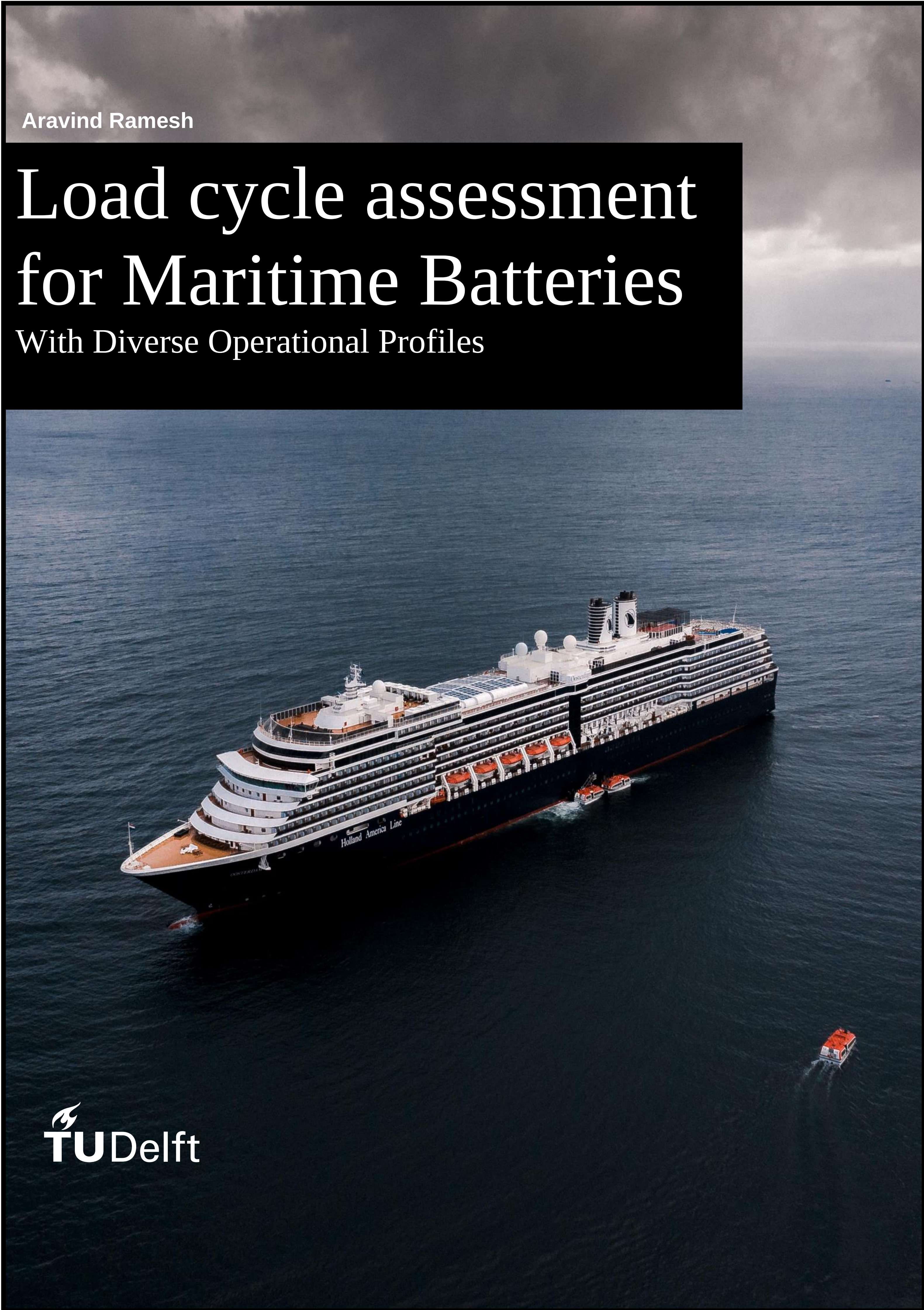
Aravind Ramesh

Load cycle assessment for Maritime Batteries

With Diverse Operational Profiles



TU Delft

Load cycle assessment for Maritime Batteries
with Diverse Operational Profiles

By

A. Ramesh

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Abstract

Increasing emissions have led to the search for alternate power systems to provide energy for maritime applications. The recent drop in battery prices (over 200 % in the last ten years) has made battery energy storage one of the practical alternatives for fossil fuels to curb emissions and reduce the carbon footprint of the maritime sector. The main criterion for choosing a ship's battery system is its operational profile. Therefore, this study estimated and studied the operational profiles of three use cases - Superyacht, Bulk Carrier and Ferry. The information about the power requirements for ship activities was obtained from the operational profile. Based on that information, different strategies were presented to implement battery energy storage for each use case. A rule-based controller was developed to simulate the power split between the IC engines and battery packs for hybrid systems. Battery packs were sized according to the batteries' energy consumption, which was found using the design criteria for each use case. A State of Charge (SOC) estimation model based on Coulomb Counting was developed to study the load cycles of the batteries. The SOC profiles were estimated for the proposed battery-powered systems and then characterised for each use case. Finally, a comparison between the conventional power system and the proposed battery power systems was made based on fuel consumption and greenhouse gas (GHG) emissions.

Preface

This report has been written to fulfil the Masters thesis in Mechanical Engineering (Multi-Machine Engineering track) from March 2022 to October 2022. This research focuses on the application of batteries in the Maritime sector to reduce emissions. The report defines the problem statement and then presents the findings based on the methodology.

I want to thank my daily supervisor, Ir. Alejandro Latorre Correa for regularly guiding and motivating me during the entire period of my Master thesis. I'm highly grateful for all the constructive criticism he gave me, which helped me understand the shortcomings in my work and guided me in the right direction.

I would like to thank my main supervisor, Dr Ir. Henk Polinder, for helping me to set up my research project. He helped me find connections in the Maritime sector whenever possible and ensured I always worked with the correct information.

I want to express my gratitude to Dr Ir. Udai Shipurkar from MARIN for providing me with the operational profile data of a Superyacht case. I would also like to thank Mr S. Raghunathan from Sri Chakra Marine College, Puducherry, India, for providing me with helpful information about the bulk carrier.

Finally, I would like to thank my Dad, who has always been my inspiration. I also thank my brother and friends for constantly supporting me throughout my journey at TU Delft.

Aravind Ramesh,
Delft, October 2022

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List of Acronyms

IMO	*International Maritime Organisation*
EEDI	*Energy Efficiency Design Index*
Ro-Ro	*Roll-on, Roll-off*
SOC	*State of Charge*
OSV	*Offshore Support Vessels*
DP	*Dynamic Positioning*
SFOC	*Specific Fuel Oil Consumption*
IC engine	*Internal Combustion Engine*
EMSA	*European Maritime Safety Agency*
AIS	*Automatic Identification System*
MPC	*Model Predictive Control*
DG	*Diesel Generator*
OCV	*Open Circuit Voltage*
EIS	*Electrochemical Impedance Spectroscopy*
MARIN	*Maritime Research Institute Netherlands*
MCR	*Maximum Continuous Rating*
GHG	*Greenhouse Gas*

Chapter 1

Introduction

1-1 Background

In the era of globalisation and free market, the maritime industry plays a crucial role as more than 90% of world trade happens due to marine transport [1]. But on the other side, the maritime sector is responsible for about 3% of the total global emissions [2] and also accounts for about 3-4 % of total CO_2 emissions in the European Union region [2]. The International Maritime Organisation (IMO) has imposed several restrictions to reduce these emissions. The IMO plans to reduce the total annual Greenhouse Gas (GHG) emissions from international shipping by 50 % by 2050 [3]. In addition, the IMO made the Energy Efficiency Design Index (EEDI) mandatory for all the new ships produced [4]. The EEDI promotes using more energy-efficient and less polluting equipment and engines for ships [4]. Due to these restrictions by the IMO, the maritime industry started to search for alternate fuels and prime movers for shipping.

Fortunately, in the last decade, many maritime industry researchers have started exploring ways to develop sustainable energy systems for shipping. To power the propulsive and other auxiliary energy demands of ships, alternate power sources such as fuel cells, batteries and supercapacitors are being explored. In addition, the advantages of using alternate energy systems such as fuel cells and batteries to improve the overall energy efficiency of the ship are also being analysed by researchers in the maritime sector.

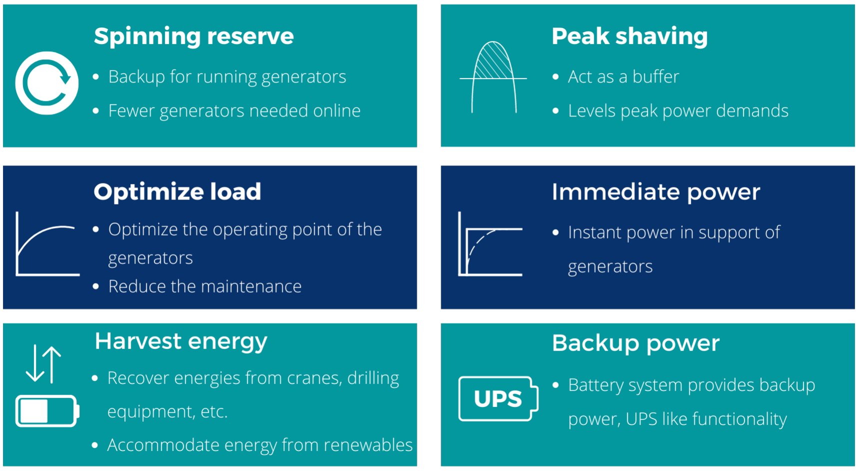
This research focuses on the different applications of batteries in maritime transport. Batteries can be used in different ways in maritime transport,

- They can be used as the primary source of energy supply for the ship's propulsion. This kind of system would cause zero emissions during the voyage if the batteries are charged with zero-carbon renewable sources such as hydro-power, wind or photovoltaics [5]. Small passenger or pleasure crafts, ferries and short-distance ro-ro(roll-on, roll-off) ships that operate in a limited range and speed use these systems [6].

- They can be used in ships that use hybrid-electric propulsion technology. The batteries are continuously used to enable fuel cells/combustion engines to work at their optimal operating points. This system can be used in medium-duty ships like inland container transport vessels and superyachts. [7] [8].
- They can be used in ships that use internal combustion engines or fuel cells to deliver power for propulsion, while batteries are used as spinning reserve. Battery power is not used continuously throughout the voyage but only when there is an excess power demand. This kind of system can be used in large ships like bulk carriers or container ships that cross the ocean over several days [9].

1-2 Objective

Different ships, such as ferries, bulk carriers, yachts, and container ships, have different power requirements from their propulsion and other auxiliary power systems during the voyage. If batteries are installed on these ships, the energy requirement will vary according to the ship type and the application. Some of the standard applications of batteries used in Maritime transport can be seen in the figure 1-1.



Spinning reserve
- Backup for running generators
- Fewer generators needed online

Peak shaving
- Act as a buffer
- Levels peak power demands

Optimize load
- Optimize the operating point of the generators
- Reduce the maintenance

Immediate power
- Instant power in support of generators

Harvest energy
- Recover energies from cranes, drilling equipment, etc.
- Accommodate energy from renewables

Backup power
- Battery system provides backup power, UPS like functionality

Figure 1-1: Development applications of maritime batteries (Adapted from DNV-GL) [10].

Due to varied applications of batteries in the maritime sector, the requirements of a battery will also vary accordingly. There should be some criteria to choose a battery for a specific application. Load cycles are one criterion that gives information about how the batteries are being discharged when they are in use and how they are charged when connected to a power source. State of Charge (SOC) estimation methods are mathematical models that can give approximate estimations of the load cycles of the batteries. Estimating the load cycles provides information about the energy requirement from the battery for a single cycle. The battery pack can be sized correctly if this energy requirement is known. The main goal of this thesis is to assess the load cycles of batteries used in maritime transport for different applications.

1-2-1 Research Question

How can the load cycles of maritime batteries that are used in different ships with diverse operational profiles be defined and characterised ?

This question arises from the research gap in studying the load profiles of maritime batteries. Ships have diverse operational profiles based on their applications. These ships can have batteries on board for different requirements. It is crucial to investigate those batteries' load profiles to understand how they are discharged and charged for the specific application. Eventually, the battery's energy requirement for the particular application can be estimated to size the batteries appropriately.

Sub-questions

Answering each sub-question below solves the main research question and provides structure to the thesis

1. *How can the operational profiles for different ships that utilise maritime batteries be estimated?*

   This subquestion focuses on estimating the operational profiles of different ships that can use maritime batteries in different ways. The operational profile of a ship can be determined based on historic voyage information or real-time ship speed and time data.

2. *How to estimate the load cycles of maritime batteries from the diverse operational profiles?*

   This subquestion focuses on estimating the load cycles of the maritime batteries which would be used to perform different ship activities in different types of ships.

3. *How to estimate the size of the battery pack for different ships based on the load cycles estimated ?*

   This subquestion focuses on finding the size of the battery pack for different ships from the estimated load cycles. It is important to find the right capacity and voltage of the battery bank to size the battery bank inside the ship.

4. *How can the load profiles of electric or hybrid electric ships of specific applications be compared with the load profiles of diesel engine ships with the same application ?*

   This subquestion focuses on comparing the load profiles of electric/hybrid electric ships to that of diesel-powered ships for specific applications. The comparison will be drawn based on the fuel consumption of both systems.

1-3 Methodology

An overview of the methodology followed in this thesis can be seen in the figure 1-2. A literature review is done to study and get helpful information about the latest developments related to maritime batteries and identify possible research gaps. After that, some ship types are selected as use cases for this research. Their operational profile is estimated using various surveys and by making realistic assumptions. Then, a battery implementation strategy is proposed for each use case. In the case of a hybrid electric system, a rule-based controller will be developed to estimate the load sharing between the battery pack and the IC engine. The energy consumption of the battery pack will then be calculated and the battery pack will be sized in a way that it meets the energy demand for each application. Then, the State of Charge(SOC) profiles will be estimated using a SOC estimation method for all the use cases. Finally, the fuel consumption and total emissions of the newly proposed battery-implemented ships will be compared with ships with conventional IC engines.

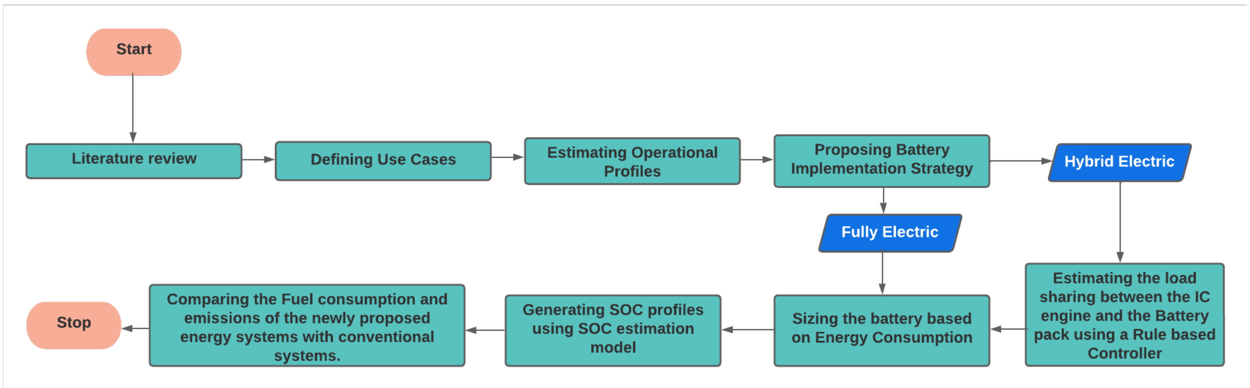


Figure 1-2: Overview of the Methodology used

1-4 Structure

The report aims to answer the sub-questions to get the solution for the main research question. The report has been structured as chapters. Chapter 2 gives details of the literature study on an overview of batteries used in maritime transport, operational profiles of different ships, different power split strategies used for hybrid ships, and different models to estimate the SOC of batteries. Chapter 3 will give an overview of the Operational profiles of some specific ship types and then they will be defined as different use cases for the rest of the study. Chapter 4 will delineate the hybrid power strategy used for every Use Case and then describe how the simulation model and the battery SOC model were designed for each use. Chapter 5 will include the results of the load profile estimations for each use case along with the battery sizing estimations. The comparison between a conventional diesel engine-powered system and a fully electric/hybrid electric system will be included in Chapter 6. Finally, the conclusions and recommendations for future work will be presented in the final chapter.

Chapter 2

Literature Review

The following chapter gives a literature background about batteries used in maritime transport, operational profiles of different ships, power split strategies used in hybrid electric ships and models to simulate power split and estimate state of charge profiles.

2-1 Overview of battery applications in Maritime transport

Maritime batteries have played a significant role in the search for sustainable drive and energy systems in marine transport due to their high energy density and easier availability than other power sources, such as fuel cells. In the last few years, there has been a significant drop in the price of lithium-ion batteries (from 1,160 to 176 US dollars per kilowatt-hour (kWh)) due to the developments in the automotive industry, which increased the scale of production of batteries [11]. Using batteries on board has many direct advantages, like reducing noise and vibrations and providing a quieter environment for the crew members. Using battery energy storage for peak shaving and load levelling will reduce fuel consumption of the engines and reduce maintenance costs as manual labour is not needed to keep batteries running [11]. Battery technology is commonly adopted in smaller ships like ferries, passenger cruise vessels, and fishing vessels. But nowadays, batteries are also installed in ocean-going vessels for both propulsion [12] [13] [14] and auxiliary power use [9], to save fuel and reduce emissions.

The Maritime Battery Forum is an organisation that maintains an online ship database. Since 2016, the Maritime Battery Forum has maintained a register to cover the number of ships that have batteries installed on board. The figure 2-1 adapted from the Maritime Battery Forum register shows that at the end of 2021, globally, more than 400 ships had batteries installed on board. According to the data, this trend is expected to follow in the coming years as more ship owners are looking to install batteries on their ships for some specific applications.

As discussed in section 1-2, batteries can be used for different purposes in a maritime vessel. Batteries can be used as the primary energy source to completely supply the ship's energy demand [16], or they can be used in hybrid power systems where batteries act as an energy

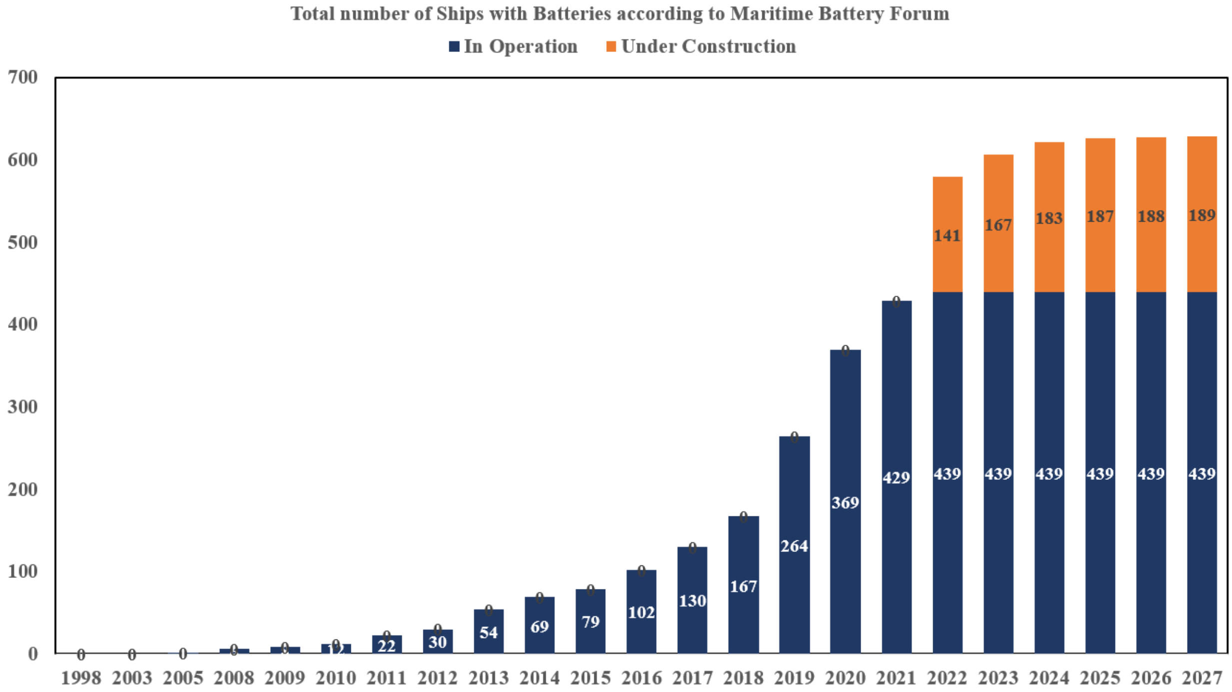


Figure 2-1: Total number of ships with battery installed onboard (globally) (adapted from Maritime Battery Forum) [15].

storage system that supports the IC-engine's operation [17]. There are two types of hybrid electric systems: hybrid and plug-in hybrid.

- A plug-in hybrid ship can use shore power to charge its batteries. A plug-in hybrid ship can operate on batteries alone on specific parts, for example, during manoeuvring or during stand-by operations [18] [19].
- A hybrid ship uses batteries to increase the IC-engine performance. In these ships, the battery systems are predominantly used to reduce peak loads in the IC engines and maintain the engine at its optimal load levels [18].

Two essential functions of batteries in hybrid ships are peak shaving and spinning reserve. Peak shaving essentially means to level out the peaks in energy demand of the vessel using a battery pack. In addition, batteries can also be used as a spinning reserve. Large vessels run multiple generators onboard to ensure redundancy. Using batteries as a spinning reserve for these ships ensures that fewer generators must be connected to the bus. The battery energy storage system picks up extra loads if required and is a backup if a generator goes down. Running fewer generators reduces fuel consumption and reduces the carbon footprint of the ship [20].

As discussed, different ships have different energy requirements from their power plant. Therefore, the applicability of batteries varies for different ship types. An overview of battery applications in some common ship types from the literature is discussed in the upcoming sections.

2-1-1 Electric Ferry

Ferries are ships used to transport passengers or goods over a short distance and as a regular service. As a ferry only travels a short distance, the energy demand is relatively lesser when compared to a cargo vessel or a yacht. Therefore, ferries can be entirely powered using battery energy storage. In 2015, the world's first all-electric ferry MF Ampere started operating in Western Norway [21]. Since batteries completely power it, it generates zero emissions and produces minimum sound during the voyage. The ferry operates on a 5.7 km crossing and approximately makes 34 trips a day, each trip taking around 20 minutes, excluding the 10 minutes for loading and unloading the passengers [22]. The gross tonnage of the ferry is 1598, and it has a passenger capacity of 350 people [22].

Figure 2-2: All electric ferry - MF Ampere [22].

Ferries represent the segment that has already seen significant acceptance in adapting to fully electric or hybrid electric solutions. Since the first electric ferry operation, there has been a tremendous effort to electrify ferries using batteries. A comprehensive study on the electrification of vessels, in particular ferries, was performed in the article in [23]. In that study, the performance attributes, such as the battery capacity and passenger and cargo capacities of different battery-electric ships, were compared. According to the study, the battery capacity used in fully electric vessels was 50-500 kWh with a median value of about 140 kWh.

2-1-2 Offshore support vessels

Offshore Support Vessels (OSVs) are specialised ships built for ocean operations with several applications. They are capable of supporting platform support, anchor handling, construction, maintenance, and other tasks. OSVs have already seen a large uptake of battery-powered systems [24] [10]. Many modern OSVs are typically diesel-electric, making them suitable for retrofitting battery packs [10]. OSVs usually have high redundancy requirements, especially when they operate in dynamic positioning (DP) mode [24]. Multiple generators need to be online during the DP mode to handle peak loads caused by extreme variations in winds and waves [24].

Figure 2-3: Platform Support Vessel - Viking Energy [25].

In the Master thesis of Leiv Børge Ferking Mjølhus [26], the effect and viability of implementing a hybrid electric system for a Platform Support Vessel (PSV) were investigated. This thesis discussed the hybrid electric system installed in the OSV Viking Energy 2-3. The battery energy storage was used as a redundant power source during critical operations like dynamic positioning in this OSV [26].

The OSV with battery energy storage installation was tested for a period of 6 months. It was then compared with a conventional diesel engine setup. The weighted product of Specific Fuel Oil Consumption (SFOC) decreased from 255.9 g/kWh to 219.9 g/kWh concerning the annual time distribution of the vessel [26]. Furthermore, there was a significant improvement in the overall efficiency of the power system as the battery pack acted as a passive redundancy contributor, i.e. spinning reserve [26].

2-1-3 Pleasure cruise vessels and Yachts

A cruise vessel or a Yacht is solely built for pleasure and hospitality purposes. When it comes to a sea holiday, people have to go on a cruise vessel or a yacht. The main difference between a cruise vessel and a yacht is that a cruise vessel has more passengers while a yacht is more of a personalised experience. These ships have a highly varying power demand from their propulsion and auxiliary power systems as they sail at different speeds, stay at ports overnight and have very high hotel loads [10].

Omer et al. [17] published an article that reviewed the current and future challenges of using battery-powered hybrid electric systems. According to the article, complete electrification of cruise ships or yachts is challenging due to high energy demand from hotel loads and propulsion when the ship is cruising fast. However, these ships can benefit from using a battery energy storage system that can be used when the ship stays at ports or sails at low economic speeds [17]. The article also mentions that using battery power for energy storage is more suitable than supercapacitors for fuel cells as the need for high power density is low in this application [17].

Figure 2-4: Cruise ship - MS Roald Amundsen [27].

In 2019, the commercial cruise company Hurtigruten launched a hybrid electric cruise vessel called MS Roald Amundsen [27], shown in figure 2-4 . The cruise uses battery power to support the conventional IC engine to provide increased power during specific times such as manoeuvring [27]. The cruise ship has a length of 140 meters and passenger capacity of 530 people [27] [10]. The battery's capacity installed in the ship was 3 MWh [27].

2-1-4 Fishing Vessel

Figure 2-5: Hybrid fishing vessel - Karoline [28].

A fishing vessel is a ship used to catch fish in the sea, a lake, or a river. Fishing boats can be suitable for battery hybrid power system installation since the batteries can be used when less energy is required, such as during hauling, when the boat is stationary at the field, or being discharged at the port [29]. The most practical applications of a battery for a fishing vessel would be to use it for load levelling and peak shaving, power regeneration or as a spinning reserve [29].

The hybrid electric fishing vessel Karoline, shown in figure 2-5, is powered by a battery energy storage system produced by the manufacturer Corvus Energy [28]. It was the first hybrid fishing vessel with two battery packs of 195 kWh and a 50 kW small auxiliary diesel engine. The diesel engine power is used to run the ship to and from the fishing grounds, while the battery power is used for fishing operations like fishing, loading and unloading. Karoline is a small fishing vessel, but larger industrial fishing vessels have also started using hybrid electric technology using high-capacity battery packs to reduce emissions and make the fishing industry sustainable [30][31].

2-1-5 Bulk carriers with cranes

Large container vessels and bulk carriers are the most vital part of maritime transport as they are crucial for the world trade and supply chain. But on the downside, they also have a large carbon footprint and are responsible for a large part of emissions from the shipping sector [32]. The energy demand from the propulsion systems of a large bulk carrier that crosses the ocean is significantly high [33]. Therefore, complete electrification of the ship only using batteries would be expensive. But there is the scope of using battery energy storage for supplying the auxiliary loads of the ship at the ports [9].

For example, for a bulk carrier, a battery pack can be used as an energy storage system that could support port operations such as anchoring and mooring [9]. In addition, the battery pack can also be used to support the crane operations while unloading the bulk material from the vessel as power regenerated from the crane operations can be used to charge the batteries [34].

Kyunghwa Kim et al., [9] performed an analysis of a Supercapacitor/Battery Hybrid Power System for a Bulk Carrier with four deck cranes. A power split strategy was proposed to support the gensets in the bulk carrier. Battery packs and Supercapacitors were used to support the port and crane operations. The battery pack and the supercapacitor were then sized according to the energy demand of those operations. The results of using the hybrid energy storage system for the auxiliary operations showed a significant decrease in the fuel consumption (from 34,271.3 kg to 17,618 kg) of the gensets and emissions (from 108,237.66 kg of CO_2 to 54,880.12 CO_2) [9].

DNV-GL and the European Maritime Safety Agency (EMSA) released a technical document in 2021 that discussed several Electrical Energy Storage Systems for Ships, predominantly maritime batteries [10]. Their technical document mentioned that batteries have a clear function for cargo handling and crane operations. They have also specified that batteries can be mainly used to support diesel genset operations like peak shaving and for using the cranes installed in the bulk carrier vessels [10]. Additionally, they have also mentioned that batteries can be used to prevent blackouts in bulk carriers.

Figure 2-6: Handymax bulk carrier with 4 deck cranes [35].

2-1-6 Conclusion

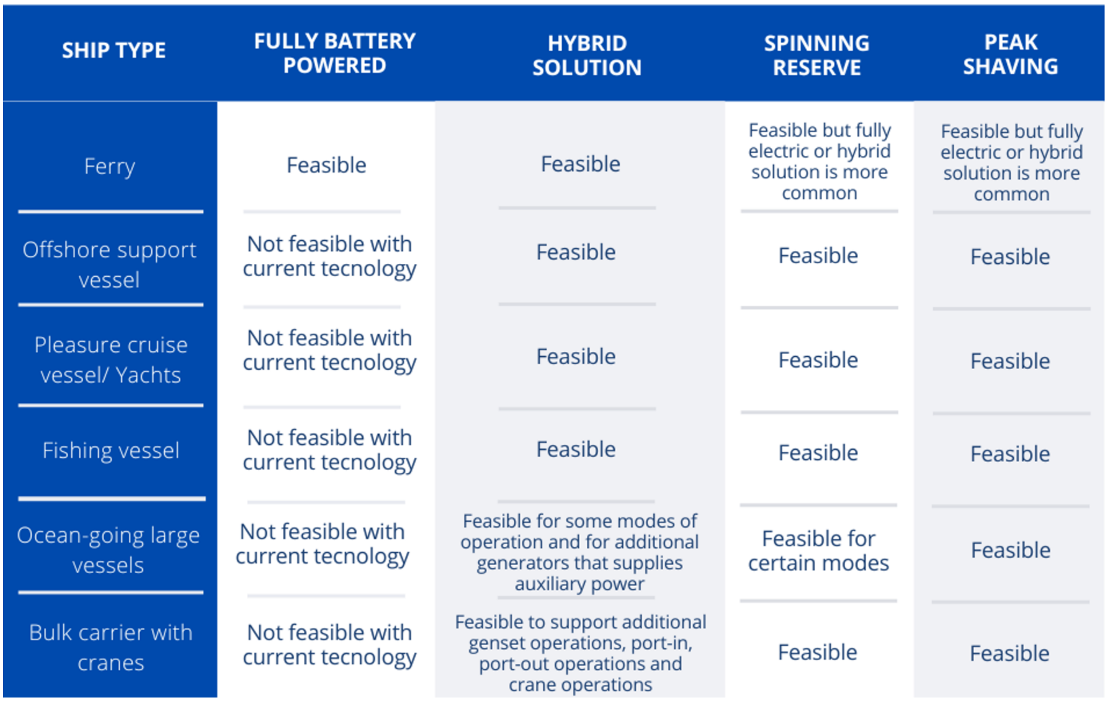
In this section, the diverse applications of batteries in different kinds of ships were reviewed. The extent of applicability of the batteries depends on the energy requirements of the ship in various scenarios during its journey. The ship's operational profile should be known to get information about the ship's energy requirements while performing different activities such as slow sailing, fast sailing, mooring etc., during different scenarios. Batteries can be strategically retrofitted in different ships if their operational power requirements are known. An overview of the applicability of the battery power systems for different ships based on the technical document of EMSA and DNV-GL is presented in the table 2-1

2-2 Operational Profiles of Ships

A ship's operational profile gives information about its activities and performance in terms and power. It provides information about the different power demands of the vessel while performing various activities such as anchoring, sailing, high-speed cruising etc. This data is essential to understand the energy demand of the ship from its propulsion and other auxiliary systems. In this section, the literature related to the operational profiles of the vessel is presented.

Using AIS big data, Jafarzadeh et al., [36] investigated the operational profiles of eight ship types in the Norwegian waters in 2016. The goal of that work was to identify ship types that would benefit from adapting to an electric (fully powered by batteries or fuel cells) or hybrid electric (batteries or fuel cells supporting the IC engine) power plant. According to the study, reefers (ships that carry refrigerated containers) spend most of their time at higher load levels that are favourable to the design engine design conditions. Therefore, they do not benefit significantly by adapting to an electric or hybrid electric power system to improve energy efficiency.

However, it was pointed out that inland container ships and Ro-ro (Roll-on Roll-off) ships operate at low load ranges. They can benefit substantially from adapting to an electric or



SHIP TYPE	FULLY BATTERY POWERED	HYBRID SOLUTION	SPINNING RESERVE	PEAK SHAVING
Ferry	Feasible	Feasible	Feasible but fully electric or hybrid solution is more common	Feasible but fully electric or hybrid solution is more common
Offshore support vessel	Not feasible with current tecnology	Feasible	Feasible	Feasible
Pleasure cruise vessel/ Yachts	Not feasible with current tecnology	Feasible	Feasible	Feasible
Fishing vessel	Not feasible with current tecnology	Feasible	Feasible	Feasible
Ocean-going large vessels	Not feasible with current tecnology	Feasible for some modes of operation and for additional generators that supplies auxiliary power	Feasible for certain modes	Feasible
Bulk carrier with cranes	Not feasible with current tecnology	Feasible to support additional genset operations, port-in, port-out operations and crane operations	Feasible	Feasible

Table 2-1: Overview of applicability of battery powered systems for different ship types based on EMSA and DNV-GL

hybrid electric power plant. Among the ship types considered in the study, it was observed that offshore and cruise passenger ships had the most dynamic operational profiles and they spend most of their operational time with lower loads; hence their energy efficiency is significantly reduced, making these ships most suitable for adapting to an electric or hybrid electric power plant [36].

Jafarzadeh et al., [36] gave a comprehensive overview of the operational profiles of different ship types. However, the scope of the work was restricted to identifying the ship types that would be suitable for implementing electric or hybrid electric power plants. How electric or hybrid electric power plants can be implemented and their energy demands for different ship types were out of the scope of the article.

The Master thesis of Boertz C [37], investigated the operational profiles of several cruise ships to calculate the energy demand for the propulsion and auxiliary systems. The main aim of that work was to estimate the energy demand for fuel cell-driven cruise ships under different loading and environmental conditions. The operational profiles of several cruise ships were extracted from AIS data and presented in the work. The operational profile data of the cruise ships was used to estimate the power required by different systems of the ship, such as the propulsion systems, the auxiliary systems and the hotel loads. This was done by converting the operational profile data into five typical days of operation [37].

For estimating the propulsive power, the empirical method of Holtrop and Mennen was used [38]. Mathematical prediction models were made to estimate the power demand of auxiliary and hotel systems, and the results were validated using historical data. But the goal of this work was to evaluate these power demands to implement a fuel cell system and size the fuel cell system sufficiently. Similar studies can also be done on implementing maritime batteries in different ships. The power demands for implementing battery systems for diverse applications of different ships can be estimated to understand the use of battery technology in maritime applications.

There are some publications that provide information for electric or hybrid electric ferries. Ye-Rin Kim et al., [39], provided an overall design for a battery-powered electric ferry, including the capacity of the battery storage system, the configuration of the power conversion systems for propulsion, and battery charging/discharging procedures. Monaaf D.A.Al-Falahi et al., [40] modelled an electric ferry with a hybrid power system and simulated the power management using classic and meta-heuristic optimisation in the Matlab/Simulink software. The results were validated according to the ferry's operational load profile, also presented in the paper. The paper showed that battery integration in electric ferries could reduce fuel, emissions and noises [40].

Fahd Diab et al., [41] presented a novel comparison study for the differences between Hybrid renewable energy sources on land and ships using the hybrid optimisation of multiple electric renewable (HOMER) software which has a maximum combination of renewable systems and performs optimisation to estimate feasible system configurations [41]. That study used real load profile data for an oil tanker ship that sailed from Dalian in China to Aden in Yemen.

Although some of the articles mentioned above have published the operational profiles of some ships [41], [40], [39], [37], most of these profiles are for smaller ships which travel for a short duration in the sea. To estimate the operational profiles for different ship types needed for this study, certain realistic assumptions have to be made about the power demands of the ship at specific times for specific operations. These estimated operational profiles will be presented in the next chapter.

2-2-1 Conclusion

In this section, the operational profiles of different ships published in the literature were reviewed. Using these operational profiles, the energy demand of the ship in different situations during the voyage can be estimated and used for this research.

2-3 Power split strategies for Hybrid Electric Ships

In Hybrid Electric ships, batteries are used as an energy storage system in combination with IC engines to satisfy the energy demands of the ship. There are multiple ways in which the energy from battery systems can be used in a hybrid electric ship, depending on the application and strategies for which it was designed. This section will review different power split strategies for hybrid electric ships and how they can be modelled.

Daeseong Park et al., [42] developed a Model Predictive Control (MPC) to replace the conventional direct power control (DPC) and integrated the DC-DC converters in the same control platform [42]. In this model, the MPC minimises the DC bus voltage fluctuations during fast load changes and then regulates the load sharing between different energy units. This model was also tested in a simulation with a real ship load profile in 3 different operating modes.

The results show that the proposed method provided fast and stable control performance. It also showed an effective load levelling function by using the battery power.

Muzaidi B Othman et al., [43], developed a control strategy to optimise the Diesel Generator (DG) operating point in a ship based on droop control. The droop coefficient was used as the variable to control the DG to have equal or unequal load sharing. The main idea of this load-sharing concept was to adjust the droop coefficient to have better fuel efficiency based on the DG's specific fuel consumption map. Therefore, an unequal load sharing between the DGs and the battery is achieved to maintain the DGs at optimal load factors. The advantage of using this strategy is that it is easy to tune the droop coefficient to achieve optimum performance from the energy system.

Gao Diju et al., [44], developed an energy management strategy for hybrid electric ships based on rule-based Fuzzy Logic control. This rule-based power control strategy was based on the Diesel generators' operating range, divided into different segments based on the efficiency and fuel consumption rate at each range. The output power of the diesel generator was modelled as a function of the operation mode of the diesel generator, the state of charge of the battery and the power demand of the supply. Based on the power demand and the battery SOC, the operation mode of the system is selected, and a corresponding rule-based strategy is chosen. This strategy was further improved using fuzzy sets to minimise fuel consumption and emissions from the energy system. This hybrid rule-based energy management system combined with fuzzy logic algorithm was simulated and validated in a hybrid ship simulation platform. The results showed that the model successfully implemented the power split and the energy system's efficiency improved. From this article, it was observed that a rule-based control strategy could be used to simulate power for different ship types based on the optimal operating range of the IC engine. This control strategy will be used for this work as it can be easily implemented to simulate the power split for different ship types by only changing the rules according to the strategy. Although rule-based control has limited accuracy and scalability in predicting the power split between different systems, the accuracy can be improved to an extent if the rules are properly defined.

Cheng Siong Chin et al., [14] studied a hybrid battery-powered power system on a Merchant Ship during a voyage to save fuel and reduce emissions. The journey of a model vessel with 82,000 deadweight tonnage capacity was simulated using weather routing software. The average speed and the power needed for the ship for this voyage were calculated. The feasibility of using battery energy storage to support the conventional diesel engine power was studied by simulations using different strategies to split the power between the two sources. The primary system included the battery power to support the diesel engine for load levelling and peak shaving. This strategy was based on the rule that the batteries pack gets charged when the measured power consumption of the ship is lesser than the target setpoint of the diesel engine of the engine and the battery gets discharged when the measured power consumption of the vessel is higher than the target set point of the diesel engine. This strategy enables the ship to travel at its average load. Furthermore, a detailed analysis of the reduction in Specific Fuel Oil Consumption (SFOC) and emission reduction due to the incorporation of battery systems was presented in the study. The study also explained how to simulate the power split between the battery and the diesel engine for load levelling.

2-3-1 Conclusion

Different power management strategies for predicting power split in hybrid electric ships were investigated in this section. A rule-based approach is chosen for this research work due to the flexibility it provides in changing rules based on different strategies for different ships and the reduced computational effort compared to other methods. Although the accuracy of the results from a rule-based approach is limited, it can be improved to an extent if the rules for power management are properly defined.

2-4 State of Charge (SOC) Estimation Models for Batteries

State of Charge (SOC) is a crucial parameter since it represents the amount of energy that is still available in a battery, giving information regarding charging and discharging methods and protecting the battery from overcharging and over-discharging.

M.A. Hannan et al., [45] made a comprehensive overview of the different state of charge estimation methods along with their benefits, drawbacks and estimation errors for electric vehicle applications. Some common methods of estimating the SOC of batteries are

- Open Circuit Voltage Method: This method uses the Open Circuit Voltage of a battery to estimate its SOC. The Open Circuit Voltage can be used to estimate SOC after the battery gets adequate resting to reach the balance [21]. There is an approximately linear relationship between OCV and SOC, but this relationship is not the same for all batteries. The relationship depends on the capacity and chemistry of the battery. This method is simple and accurate, but it takes a long rest time for the battery to reach the equilibrium condition. The accuracy of this method is reduced if the batteries are not rested for adequate time. Another main drawback is that it is not practical to implement this method for online battery models.

- Coulomb counting method: It is a SOC estimation method based on the integration of battery current concerning the time when the battery is charging or discharging. It is the simplest method to estimate the battery SOC and requires less computational power. But there can be inaccuracies in the estimation due to disturbances and variables like noise and temperature. In addition, if the state of health of the battery reduces, the accuracy of estimation from this model reduces.

- Internal resistance method: In this method, battery voltage and current are used to measure the battery's internal resistance. For a small duration of current change, the voltage is measured. The variation of the voltage and current results in DC resistance and that represents the capacity of the battery in DC. The main drawback of this method is that as it is an open loop estimation system, minor errors accumulate with time to the integration term leading to the source of significant inaccuracy. In addition, as the state of health of the battery reduces, the accuracy of estimation from this model reduces [46].

- Electrochemical Impedance Spectroscopy (EIS): It is a method that is extensively used to understand the electrochemical reactions occurring inside the batteries and to determine the SOC. EIS estimates the impedance of the batteries using inductances and capacitances over a wide range of frequencies [47]. Coleman et al., [48], estimate the battery EMF voltage using the impedance, terminal voltage and discharge current under load. This method cannot be used for online SOC prediction and therefore, it cannot be used for this research.

2-4-1 Conclusion

This section reviewed various State of Charge (SOC) estimation methods for predicting battery load cycles. An online battery model is required for this research to estimate the battery's State of Charge from the energy it consumes during operation. Coulomb Counting appears to be the best fit for this research because it requires low computational effort and can predict the State of Charge of the battery both during discharging and charging.

Chapter 3

Operational Profile and Use Cases

The first step in selecting the proper battery system is to define the operational profile for the power system. Different ships will have diverse operational profiles depending on the activities that the ship performs under different conditions. The battery design can be more precise and optimal if the ship's operational profile is well-defined. The chapter presents the operational profiles of different ship types as use cases for further research.

3-1 Operational Profile of a Superyacht

The operational profile presented in this section is of a superyacht. A superyacht is a large and luxurious pleasure vessel. They are mainly used for providing a comfortable stay for seafarers who spend their holiday in the sea. Maritime Research Institute Netherlands (MARIN) provided the data for this superyacht case.

3-1-1 Reference Ship Specification

The reference ship for estimating this Operational profile is a typical Sanlorenzo Motor Yacht. The design specifications of the chosen yacht are given in table 3-1 [49].

The operational profile for this use case is estimated for a 12-day busy leisure voyage. During this leisure voyage, the ship performs various activities like slow sailing, fast cruising, and anchoring. The distribution of events, i.e. the time ships spend performing each activity, can be seen in the figure 3-2.

From the figure 3-2, it can be inferred that the ship spends most of the time at port in anchoring or berthed mode, which is typical for a pleasure yacht, especially during night time. During this time, the propulsion power required would be zero and the only energy needed would be to supply the auxiliary loads required by the ship. But, it can also be seen that the ship is also in fast cruising mode for a significant amount of time during the voyage. During this time, propulsion power demand would be the maximum as the ship travels at the

Figure 3-1: Reference Superyacht - Sanloreno 57 Steel [49].

Model	57 Steel
Length overall	56.50 m
Maximum Beam	10.95 m
Maximum speed	16.5 knots
Draught at full load	3.0 m
Engines used	2 * CAT 3512 C [50]
Engine MCR	1500 kW [50]
Guest accomodation	12 people
Crew accomodation	12 people

Table 3-1: Technical Design Specifications of the reference Superyacht [49].

maximum design speed. During fast cruising, the power demand of the vessel would be high as there is a peak in propulsion power demand in combination with the constant auxiliary power demand.

The power needed for propulsion was estimated by MARIN using the speed of the vessel obtained from AIS data [51] and calculating the resistance of the reference ship. The propulsive power required and the auxiliary power demand were estimated for every event the ships performed during the voyage. Finally, the operational power profile of the reference ship for the busy leisure voyage case was calculated. Figure 3-3 shows the operational power profile.

The operational profile of the superyacht 3-3 shows the propulsion, auxiliary and total power demand. The propulsion power demand is zero when the ship is idle at anchor or berthed at a port. Only the power for the auxiliary system is needed when the ship is idle. The propulsive power demand is maximum when the superyacht cruises at high speed. The total power demand is the sum of the auxiliary and propulsive power demand.

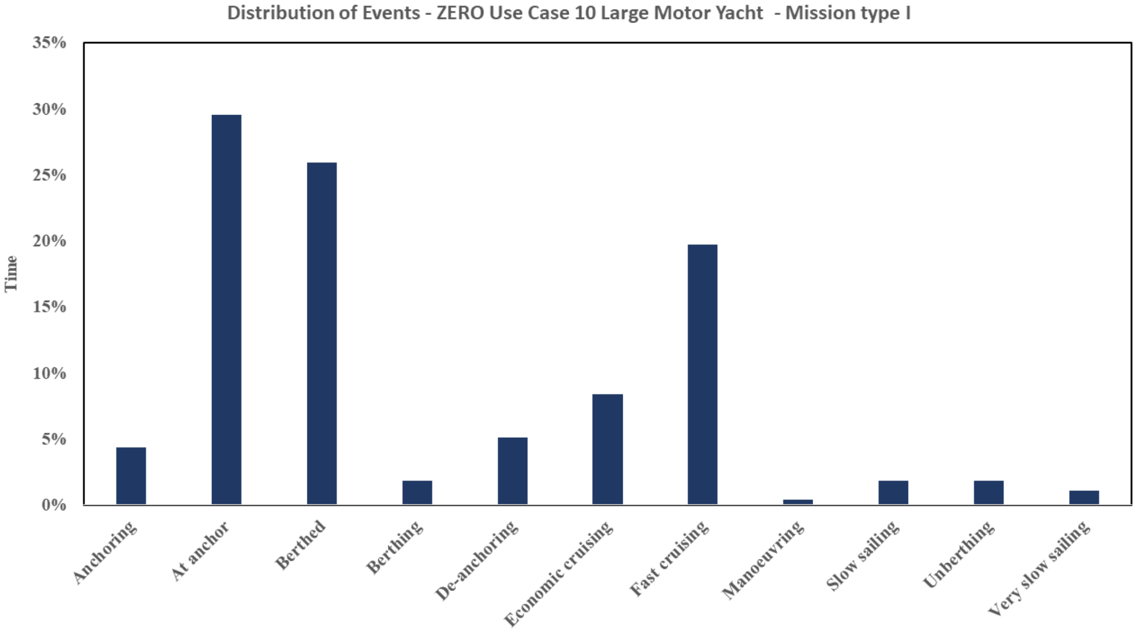


Figure 3-2: Time spent in each operation mode for the Superyacht during the Busy leisure voyage (Data adapted from MARIN)

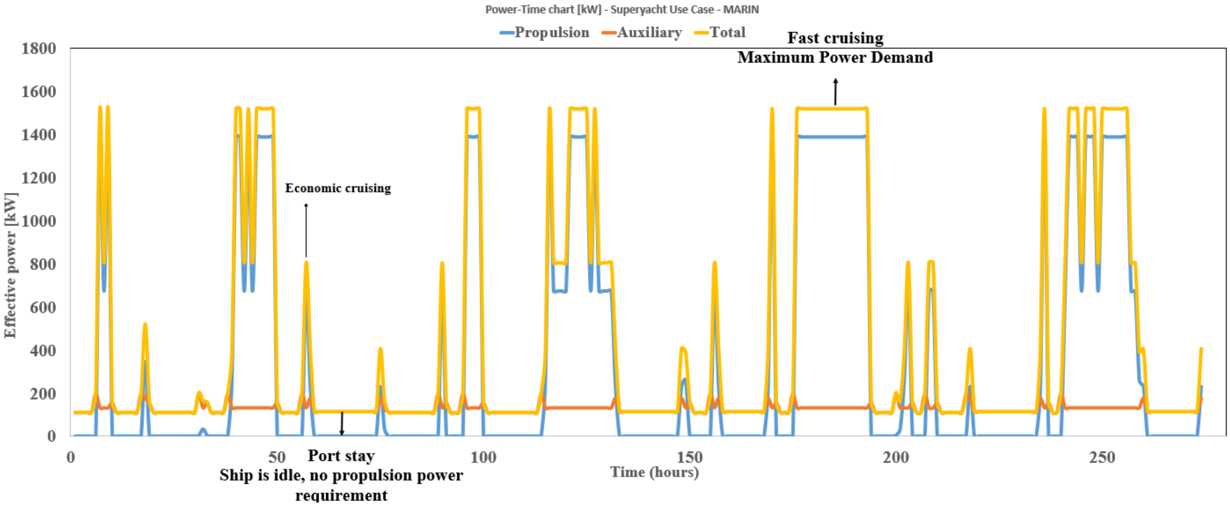


Figure 3-3: Operational Profile of the reference Superyacht (from MARIN).

3-2 Operational Profile of a Bulk Carrier

The operational profile presented in this section is of a Bulk Carrier. A bulk carrier is a large ship that carries non-liquid bulk cargo such as iron ore or coal. The size of the bulk carrier for this use case is a Handymax Bulk Carrier that has a deadweight capacity of about 50,000 tonnes. Some information about the typical operation of a Bulk Carrier was obtained from a survey with an Engineer from Sri Chakra Maritime College, Puducherry, India [52].

Figure 3-4: Handymax Bulk Carrier [35].

3-2-1 Reference Ship Specification

The reference ship for estimating this Operational profile is a typical Handymax Bulk Carrier. The design specifications of the bulk carrier are given in table 3-2 [53].

Type of Bulk Carrier	Handymax
Length overall	190 m
Average speed	14.5 knots or 7.45 m/s
Draft	11.1 m
Cargo capacity	57700 m^3
Main Propulsion Engine	3 MAJ SULZER [54]
Main Engine MCR	10000 kW
Auxiliary Gensets [55]	3 * MAN L23/30H Mk3 GenSet
Auxiliary Gensets MCR	3 * 700 kW
Number of Cranes	4

Table 3-2: Technical Design Specifications of a Typical Handymax Bulk Carrier [53].

The main engine of the Bulk Carrier is used for propulsion and has a power rating of about 6-10 MW. It is assumed that the ship uses conventional mechanical propulsion for this Bulk Carrier; hence, it is not considered for this study.

This study focuses on the auxiliary generator sets that consist of a prime mover and an AC generator. While the main engine is used to propel the ship, the auxiliary generators are used to supply all other electrical loads. The generator's prime mover is an IC engine coupled with an AC generator to produce electricity. The prime mover of the Auxiliary generators used in the Bulk carriers is mainly powered by diesel. The auxiliary generators supply all the ship's electric loads like the hotel loads needed to provide a living environment for the crew, HVAC loads, RADAR, operating pumps and other machines.

Apart from it, the diesel generator is also used for starting several types of machinery inside the bulk carrier. One example of this is starting the boilers in the steam plant of the ship. Apart from this, diesel generator sets are also used for crane operations. The bulk material is unloaded using the cranes in the bulk carrier and the power to operate these cranes is provided by the diesel generator sets. Apart from this, diesel generator sets are used for backup power and to bring the ship to life from a blackout. A diesel generator is kept as a reserve in case the other generator sets fail. In a typical Handymax Bulk Carrier, there are three diesel generators on board; in which one generator is used as the main generator and the second is used as a spinning reserve. The third generator is used for an emergency in case one of the generators fail.

3-2-2 Estimating the Operational Profile

Based on the information from the personal interview with Sri Chakra Maritime College [52] and from the study by Kyunghwa Kim et al., [9], the operational profile of the generator sets of a bulk carrier was estimated by making relevant assumptions.

To estimate the operational profile of the bulk carrier, it is essential to decide the sequence of operations of the bulk carrier. The sequence assumed for this case is port-in, sea voyage - port-out, i.e. the bulk carrier comes into the import terminal to load the bulk material, then travels in the sea till it reaches the destination terminal, where it unloads the bulk terminal using the cranes in the ship.

The typical port-in operations are lowering the anchor, hauling mooring ropes to the port side, bulk loading using shore conveyors, hoisting the anchor and winding the mooring ropes [9]. The same operations are carried out even while reaching the destination terminal, but instead of using shore cranes/conveyors, the bulk material is unloaded using the ship cranes. Therefore, the sequence of operations for the entire journey can be seen in the figure 3-5

3-2-3 Estimating the time spent for each ship activity

The time spent was every ship activity needs to be calculated to estimate the operational profile of the ship. This time spent by the Bulk carrier for port operations like anchoring and mooring was estimated by Kyunghwa Kim et al.,[9], and it is used in this work. In addition, time spent by the Bulk carrier for material loading/unloading and sailing was estimated by making suitable assumptions.

Figure 3-5: Sequence of operation of the Bulk Carrier

3-2-4 Time spent for Bulk loading

- Bulk loading rate using standard shore equipment like conveyors or shore cranes - 3500 tonnes per hour [56].
- Total load capacity of the ship 50,000 tonnes
- Total loading time = Total capacity/Bulk loading rate = 14.3 hours or 860 minutes.

3-2-5 Time spent for Bulk unloading

In this case, the bulk material is unloaded using the cranes on the ship.

Grab volume of a typical ship crane = 27 m^3 [57]
Single unloading cycle time = 240 seconds [9]
Bulk density (Coal) = 1.1 $tonnes/m^3$

$$Dischargerate(Q) = \frac{3600 * GrabVolume * BulkDensity}{CycleTime} \tag{3-1}$$

The discharge rate for a single crane was 445.5 tonnes per hour (tph). It is assumed that all four cranes are in operation simultaneously. Therefore the total discharge rate is 1782 tph. Unloading 50,000 tonnes at this discharge rate will take about 28 hours or 1683.50 minutes.

3-2-6 Time spent during sea voyage

- Makin an assumption that the Bulk carrier travels Rotterdam to Agadir in Morocco.
- Total sailing distance - 1600 nautical miles or 2963.2 km.
- Average ship sailing speed 14.5 knots or 7.45 m/s [35]
- Ship travelling 1600 nautical miles with 14.5 knots average speed reaches the destination in 5 days or 7200 minutes.

The estimated time spent for all the ship activities based on the calculations and the information from Kyunghwa Kim et al., [9] can be found in table 3-3.

Sequence of Operation	Time spent (mins)
Lowering the anchor (Port in)	10
Hauling in mooring ropes to the port side (Port in)	40
Bulk loading using shore cranes/conveyors	860
Hoisting the anchor	20
Winding the mooring ropes	40
Start voyage	10
Sailing in the sea	7200
Reaching destination	10
Lowering the anchor (Port out)	10
Hauling in mooring ropes to the port side (Port out)	40
Unloading using 4 ship cranes	1683.50

Table 3-3: Time spent for every ship activity of a Bulk Carrier [9]

3-2-7 Estimating the Power demand for each activity

The next important step in estimating the operational profile is to evaluate the auxiliary power demands of the Handymax Bulk Carrier. The power demand for port operations was defined by Kyunghwa Kim et al., [9] and used in this work. The power demand for port operations can be seen in the table 3-4

Operation	Power Demand (kW)
Lowering the anchor	-50 (Lowering)
Hauling in mooring ropes to port side	200
Hoisting the anchor	100
Winding the mooring ropes	150

Table 3-4: Power demand for Port operations of the Bulk Carrier

Apart from this, the nominal load on the generators to supply the necessary electrical power for the crew during sailing and bulk loading was obtained from the survey with Sri Chakra Maritime College. According to the survey,

- Average load of the generators during normal sailing and bulk loading is around 380-450 kW
- Load fluctuations due to switching on of machinery like boilers or compressors - 30-50 kW increase.

Based on the time spent and power demand for every Bulk carrier operation, the bulk carrier's operational profile was estimated 3-6 (excluding the bulk unloading using ship cranes).

From the operational profile 3-6, it can be seen that there is a surge in power demand during port operations as there is a need to use the windlass mooring winches for mooring. During the sea voyage, the power demand is almost constant except during the peaks due to the switching on of machines inside the ship.

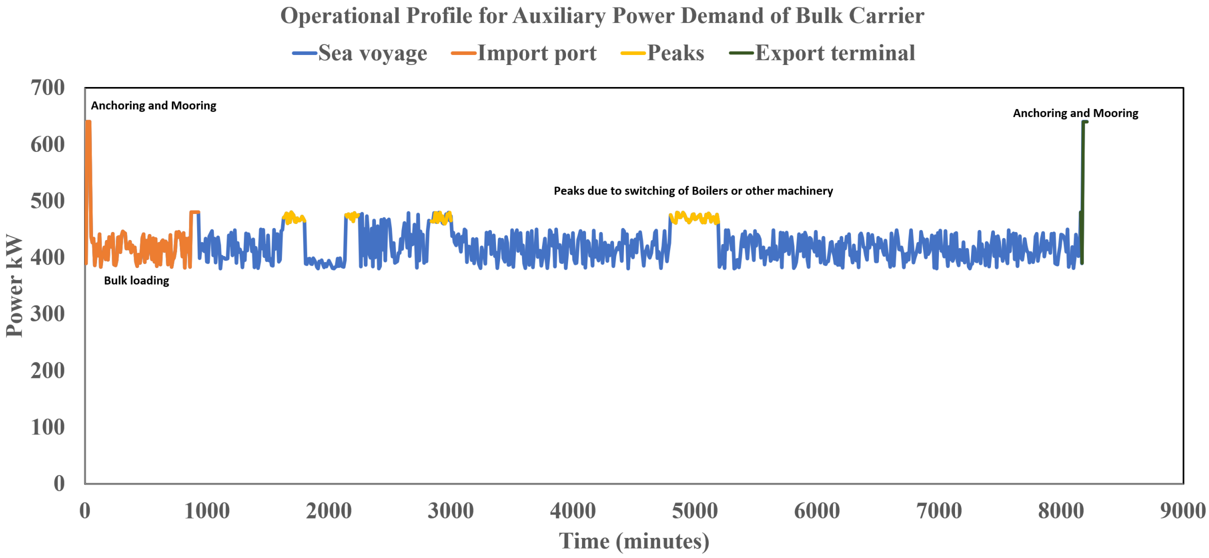


Figure 3-6: Operational Profile for the Auxiliary Power of a Bulk Carrier [9].

3-2-8 Crane Operations

The cranes in the ship are used to unload the bulk material in the destination port. Two auxiliary generator sets supply the power for operating the four cranes in the Handymax. Below is the list of operations performed by a ship to complete one cycle. The power demand for each operation, along with the time elapsed, was estimated by Kyunghwa Kim et al., [9] and it is used for this work 3-5. The total time elapsed for one unloading cycle of a crane was around 2 minutes (120 seconds).

In this study, it is assumed that all four cranes operate simultaneously, i.e. they perform all the operations at the same time. Therefore, the power demand for the deck crane operation would be four times the demand for one crane.

Sequence of Operation	Time (secs)	Power demand (kW)
Lowering with no load	20	-19.2
Grab (close)	10	20.0
Hoisting with full load	25	134.6
Luffing in (up)	5	86.5
Slewing to port side	15	34.6
Lowering with full load	15	-67.3
Grab (open)	5	20.0
Hoisting with no load	10	38.4
Slewing to ship side	10	23.1
Luffing out (down)	5	-43.3

Table 3-5: Power demands for Ship crane operations [9]

3-3 Operational Profile of a Ferry

The operational profile presented in this section is of a Ferry. Ferries are boats or small ships used to convey passengers or goods over a short distance and as a regular service. The operational profile presented in this section is based on a study to optimise the power management of hybrid power systems for ferries by Monaaf D.A. Al-Falahi et al., [40].

The study was conducted in the waters of the South-Eastern coast of Tasmania, Australia. It is a popular tourist attraction, encompassing around 363 square kilometres [40]. Two ferries operate in this region, and the ferry for this study is the Bowen Ferry which runs between Kettering and Bruny Island, according to [40]. The ferry operates six days a week and makes around seven rounds each day [40]. The design specifications of the ferry can be seen in table 3-6.

Service speed	7 knots
Ferry capacity	30 vehicles
Travel distance	6.2 km (round trip)
Travel duration	60 minutes
Engine MCR	2*320 kW
Length	35 m
Breadth	15 m

Table 3-6: Bowen Ferry Specifications [40].

The operational load profile of the Bowen ferry that takes 60 minutes to complete one round trip was measured and presented in the paper by Monaaf D.A. Al-Falahi et al., [40] and it can be seen in the figure below 3-7. From the operational profile, it can be seen that when the ferry is at the stations or stops, the power demand is low and when it starts cruising, the power demand increases.

The ferry loads passengers in the source station for the first 10 minutes. Then, the ferry starts cruising the Bowen island. The power demand reaches around 400-450 kW when the ferry cruises. The ferry cruises for 20 minutes to reach the destination station, where the

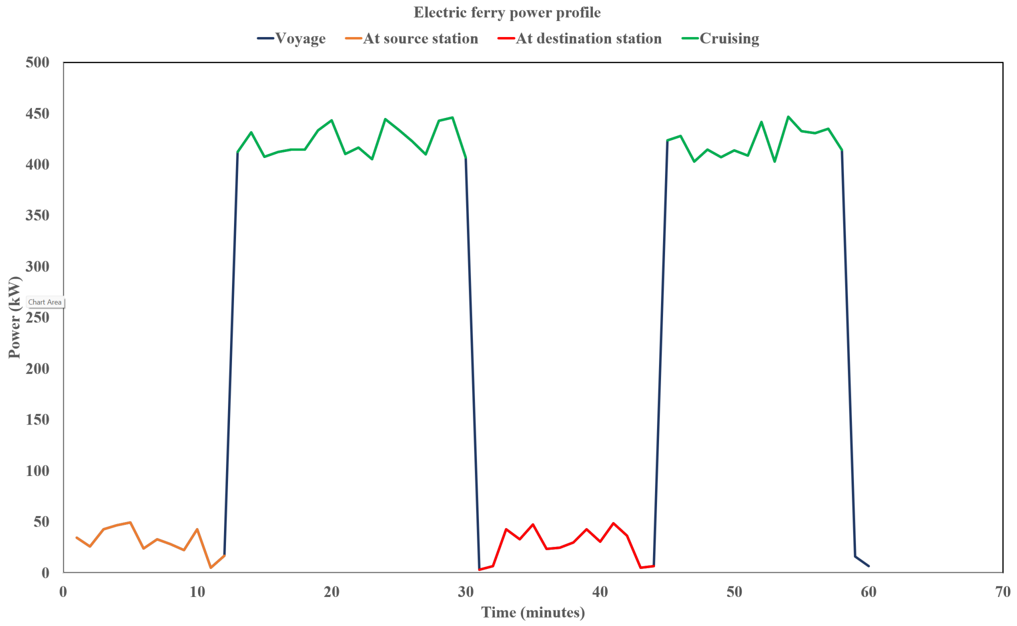


Figure 3-7: Operational Profile of Bowen Ferry [40].

passengers get down and new passengers get in. It takes around 10 minutes for the passenger loading. Then, the ferry starts returning to the source station. It cruises again for 20 minutes and goes back to the source station.

Chapter 4

Battery Implementation Strategies

This chapter will discuss different strategies to implement maritime batteries on the ships for which the operational profile was defined in the previous chapter. As discussed earlier, batteries can be implemented in different ways for different ships. For example, using a hybrid battery power system to support the main diesel engine can be one way, while using the battery to satisfy all the energy demands of the ship completely can be another.

4-1 Use Case 1 - Superyacht

From the operational profile of Superyacht 3-3, it can be seen that the Superyacht spends most of its time at a low load range (around 100-150 kW) during port stays and when it is anchored. These port stays happen predominantly in the night time. During these times, the propulsion power demand is zero and only auxiliary power to supply the hotel and other electrical loads are needed. Using a diesel engine continuously at such a low load level is inefficient in terms of fuel consumption. Apart from this, the superyacht also spends much time in fast cruising, where the propulsion demand is at its peak. Operating at peak power demand for a long duration would increase fuel consumption and noise in the overall operation.

The strategy that would be best for the superyacht case is to use batteries during port stays and maintain the diesel engine to operate at an optimal load range in terms of fuel consumption.

- The optimal load range for a diesel engine in which the fuel consumption will be minimum is between 60-90 % of the engine's Maximum Continuous Rating (MCR). The Load% vs SFOC graph 6-1 for a 4-stroke marine diesel engine is presented in chapter 6.
- The engine's power output is kept in the optimal range by using the battery energy storage system.

- When the required power demand is less than 60 % of MCR, the battery pack is charged (load filing).
- When the power demand is less than 60 % of MCR and the battery pack is already fully charged, then the engines are switched off and the entire power demand is supplied by the battery pack.
- When the required power demand is greater than 90 % of MCR, the battery pack is discharged to supply the excess energy demand.
- When the ship is idle during port stays during nights, the main engine is switched off and the battery power is used to supply the power demand as much as possible. This is desirable for a superyacht application as there will be a significant reduction in noise at night times.

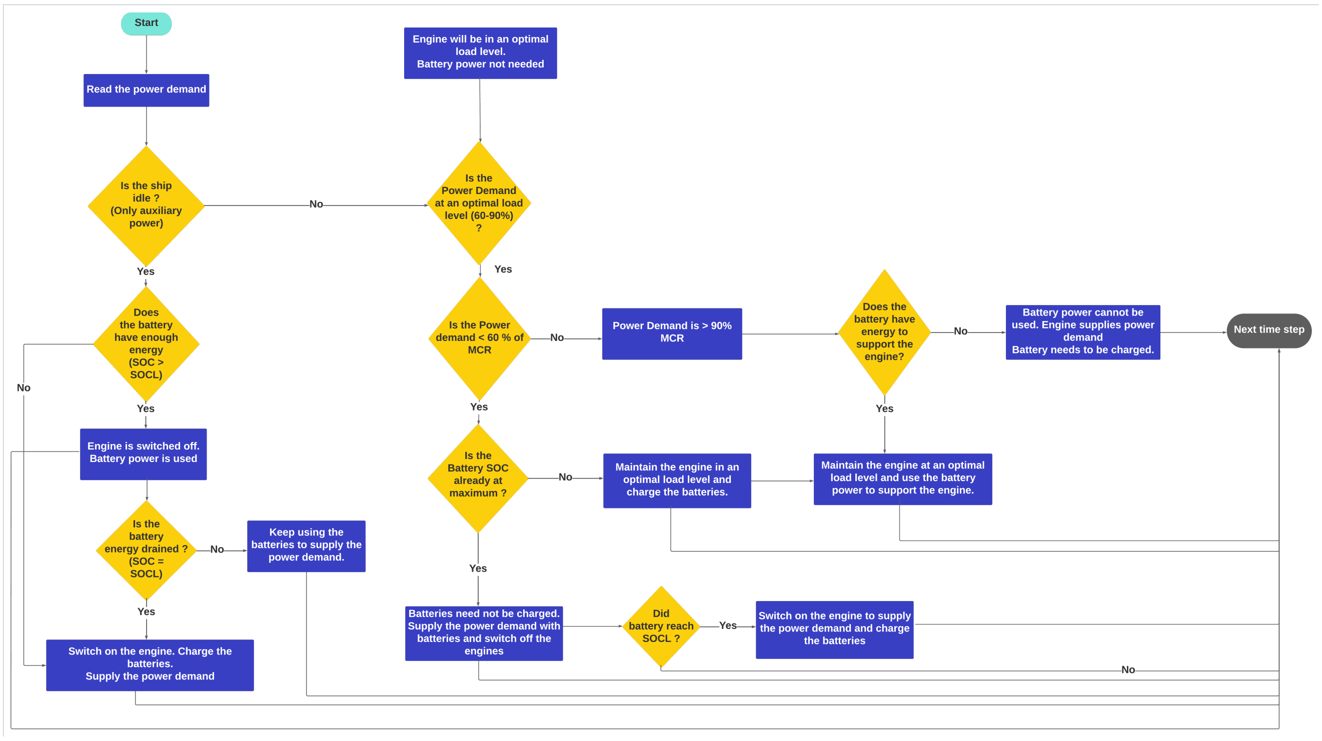


Figure 4-1: Flowchart of the Battery implementation strategy for the Superyacht.

As mentioned in table 3-1, the reference Superyacht uses two CAT-312 Diesel Engines, which have a maximum continuous rating of 1500 kW each. The second engine is a spinning reserve and it is used as a backup in case of failure of the first diesel engine. If battery energy storage is added to this system, then it can be used to operate the diesel engine at optimal load levels and switch off the engine during port stays. In case of failure of the first diesel engine, the battery can act as a backup to supply the entire power demand of the ship till the second diesel engine is switched on. The overview of the proposed hybrid strategy can be seen in the table 4-1.

	Fast Cruising	**Sailing**		**Port stays**
Power demand	Around 1500 kW	Above 90% of MCR	Below 60% of MCR	Around 110 kW
Conventional system	E1 + E2(spinning reserve)	E1 + E2(spinning reserve)	E1 + E2(spinning reserve)	E1 + E2(spinning reserve)
Hybrid system	E1 + BAT(Peak Shaving) E2 (Backup)	E1 + BAT(Peak shaving) E2 (Backup)	E1 + BAT (Load filing) E2 (Backup)	BAT (Discharge) + E1(Off) E2 (Backup)

Table 4-1: Proposed Battery Hybrid Strategy for the Superyacht.

The proposed hybrid strategy was simulated using a rule-based control based on the rules depicted in the flowchart 4-1. The simulations were performed in MATLAB/SIMULINK software. The MATLAB/SIMULINK files used for the simulation can be found in the repository [58].

4-2 Use Case 2 - Bulk Carrier

From the operational profile of the Bulk carrier, as can be seen in the figure, (3-6), the Auxiliary generators of the ship mainly operate at a constant load level when it is sailing. Still, there are occasional peaks due to the operation of other machinery, like pumps inside the ship. Additionally, running all four cranes during unloading increases power demand. Two generators satisfy that power demand during crane operation, leading to higher fuel consumption. Further, due to the dynamic power demands during crane operations, the diesel engine constantly fluctuates between different load levels, which is inefficient.

The flowchart of the strategy used for the Bulk Carrier can be seen in figure 4-2.

- Batteries are used along with diesel generators during port operations like mooring and anchoring. During these operations, there is a surge in power demand as there is a need to operate the windlass winches. Battery power is used to supply the excess energy during those operations. If the primary generator fails, the batteries act as a spinning reserve till the backup generator is switched on.

- During the sea operations, the generator powers all the electrical loads of the Bulk Carrier. If the primary generator fails, the battery power provides backup power till the backup generator is switched on.

- During the crane operations, batteries support the diesel generator. Batteries are charged during some crane operations due to the energy received by the regenerative control scheme [34]. If the primary generator fails, the batteries act as a spinning reserve and provide backup power until the backup generator is switched on.

	Port operations	**Sailing**	**Crane operations**
Power demand	Around 700 kW	Around 380-500 kW	Around 980 kW
Conventional system	G1 + G2(supply) G3(Spinning reserve)	G1 (supply) G2 (Spinning reserve), G3 (Backup)	G1 + G2 (supply) G3 (Spinning reserve)
Hybrid system	G1 + BAT(Support + Spinning reserve) G2 (Backup)	G1 + BAT (spinning reserve) G2 (Backup)	G1 + BAT (Support + Spinning reserve) G2 (Backup)

Table 4-2: Proposed Battery Hybrid Strategy for Bulk Carrier.

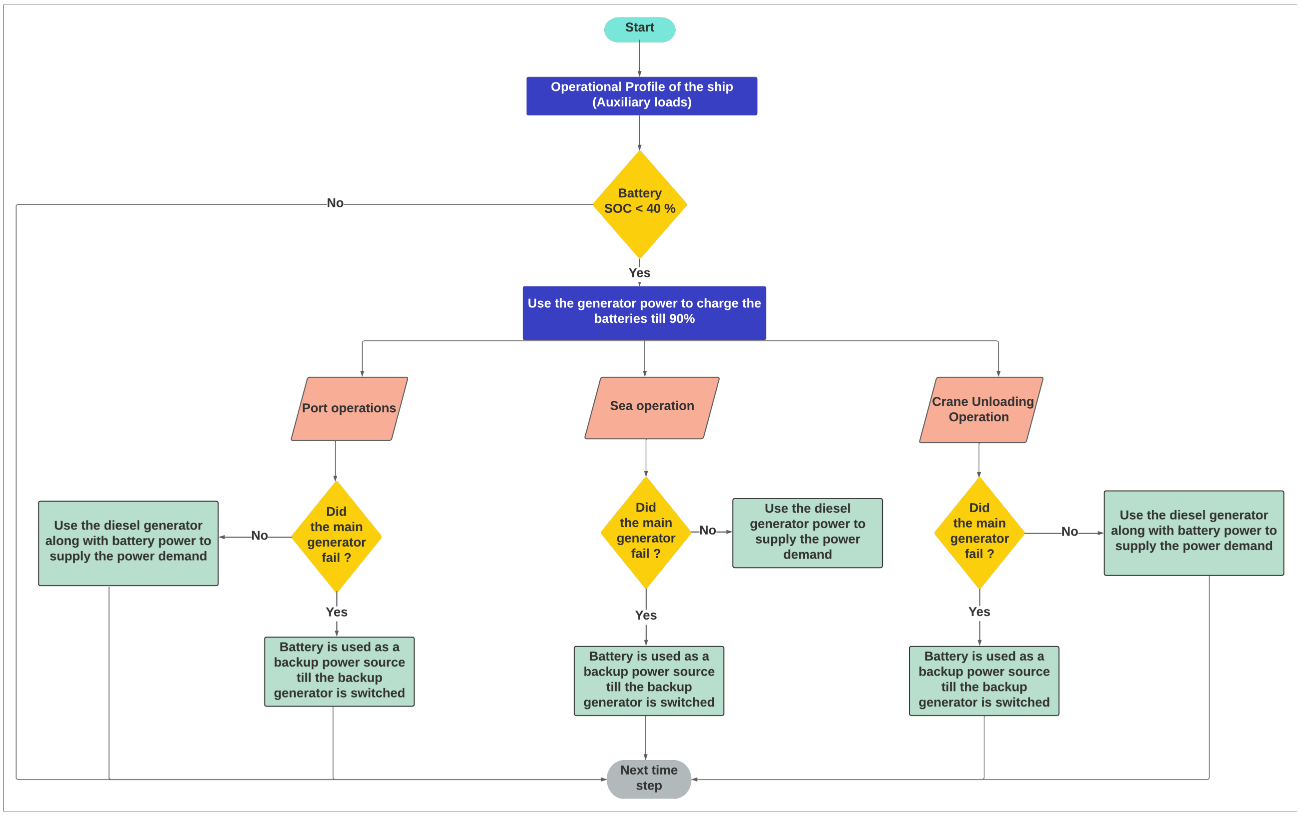


Figure 4-2: Flowchart of the Battery implementation strategy for the Bulk Carrier.

As mentioned in specifications table 3-2, a typical Handymax Bulk Carrier uses 3 Auxiliary Diesel Generators with a 700 kW rating. The third generator is used as a backup power source in case of unlikely events. The second auxiliary generator set was used as a spinning reserve to support crane and port operations. This generator set is replaced with a battery pack. This battery acts as a spinning reserve and provides backup power in case of emergencies. This battery pack also supports the primary generator during port and crane unloading operations. The overview of the proposed hybrid strategy can be seen in Table 4-2.

The proposed hybrid strategy is simulated in MATLAB/SIMULINK using the rule-based controller based on the flowchart depicted in figure 4-2. The MATLAB/Simulink files can be found in the repository [58].

4-3 Use Case 3 - Ferry

From the operational profile of the Bowen Ferry, 3-7 [40], it can be seen that the ferry needs around 400-500 kW power when it is cruising. For one round trip, it cruises for about 40 minutes in total. Using batteries to supply this power demand entirely is possible using current-day technology, and many shipping companies also do it.

- Battery packs will replace the IC engines. The batteries will supply the complete power to drive and propel the ship.

- Battery packs are sized according to the energy demand for a round trip.
- Battery packs will be charged once the ferry reaches the shore again.
- For zero-emission ferry operations, the batteries need to be charged with power generated from renewable sources like wind power, solar power etc. These zero-emission ferry charging stations are already implemented in many parts of Europe [59].
- Fast charging technology (3C) is used to quickly charge the batteries for the next trip when the passengers are being loaded. This is also a technology that has already been developed [60].

4-4 State of Charge Model

The critical goal of this thesis is to assess the load cycles of various applications of maritime batteries. For that, estimating the state of charge of the battery for a specific application is essential. State of Charge is a measure of the amount of energy available in the battery at a particular point in time expressed as a percentage. By knowing the state of charge of a battery, one can prevent battery over-discharging and overcharging. Therefore, for this study predicting the state of charge of batteries for all the proposed battery application strategies is crucial.

There are several methods available in the literature, as mentioned in section **??**, but for this study, the Coulomb Counting method is chosen.

- Coulomb counting method, also known as ampere-hour counting method, employs battery current readings mathematically integrated over the period of usage to calculate the State of Charge(SOC) of the batteries [61].
- This method calculates the battery's remaining capacity by accumulating the charge transferred in or out of the battery [61].
- Battery current reading and initial SOC of the battery are needed for estimating the SOC using this method.
- The capacity of the battery before usage should be known to calculate the SOC by integrating the charging and discharging currents over the period [61].
- For this study, a fresh battery is assumed to be installed for all cases. Therefore, the accuracy error due to reduced State of Health (SOH) of the batteries is minimised [61]. The mathematical model is described in the next section.

4-4-1 Modelling the State of Charge

- To implement the SOC model using Coulomb counting, the Battery current (I_b) should be known.
- Battery current can be calculated using the output power (P_b) that the battery delivers from the energy storage system in the ship.
- Battery current is calculated using the equation 4-1 [44].

$$P_b(t) = U_o I_b(t) - I_b^2(t) R. \tag{4-1}$$

where,

- U_o is the open circuit voltage.
- R is the internal resistance of the battery (a constant internal resistance of 50 $m\Omega$ is used for this model).
- P_b is the power output of the battery.
- I_b is the current output of the battery.

From the equation 4-1, the Battery current (I_b) is estimated. To calculate the SOC,

- The battery current (I_b) is integrated over the time period it is used.
- The initial battery capacity (Q_b) is known.
- The SOC is then calculated using the equation 4-2,

$$SOC(t) = \frac{Q_b - \int_0^t I_b d\tau}{Q_b}. \tag{4-2}$$

where,

- The time period of the battery usage is estimated from 0 to t in seconds.
- I_b is the battery current output.
- Q_b is the initial capacity of the battery.

4-5 Conclusion

In this chapter, the different strategies to implement battery energy storage systems for all the Use cases were introduced. In the subsequent chapter, the simulation results of the power split and the SOC profiles will be presented for each use case.

Chapter 5

Simulation Results and Battery Sizing

To assess the load cycles for the maritime batteries introduced for the Use cases mentioned in the previous chapter, simulations were performed in MATLAB/Simulink software. The results of the simulations will be presented in this chapter. Additionally, battery pack sizing calculations will be performed to ensure that the installed battery pack is appropriately sized and meets the energy demand for the specific application.

5-1 Use Case 1 : Superyacht

First, the simulation for the power split between the diesel engine and the battery energy storage, based on the proposed hybrid strategy, is performed. This simulation shows how the power is distributed between the battery pack and the diesel engine according to the rules listed in table 4-1. Through this simulation, it is possible to determine the total energy needed from the battery pack and show how batteries might be used for a Superyacht. The results of this simulation can be seen in the figure 5-1.

The graph shown in the upper half of the figure 5-1, shows the Power Demand (P_d) of Superyacht for a period of approximately 12 days (280 hours on the X-axis of the figure). The bottom half of the figure 5-1, shows how the Power Demand is split by the Diesel Engine (P_e) and the Battery Pack (P_b). It can be seen that the battery power is used to support the diesel engine operation when the ship is cruising fast. It can also be seen that only battery power is used during port stays. The battery pack is charged when the required power demand is less than the optimal operating range of the diesel engine.

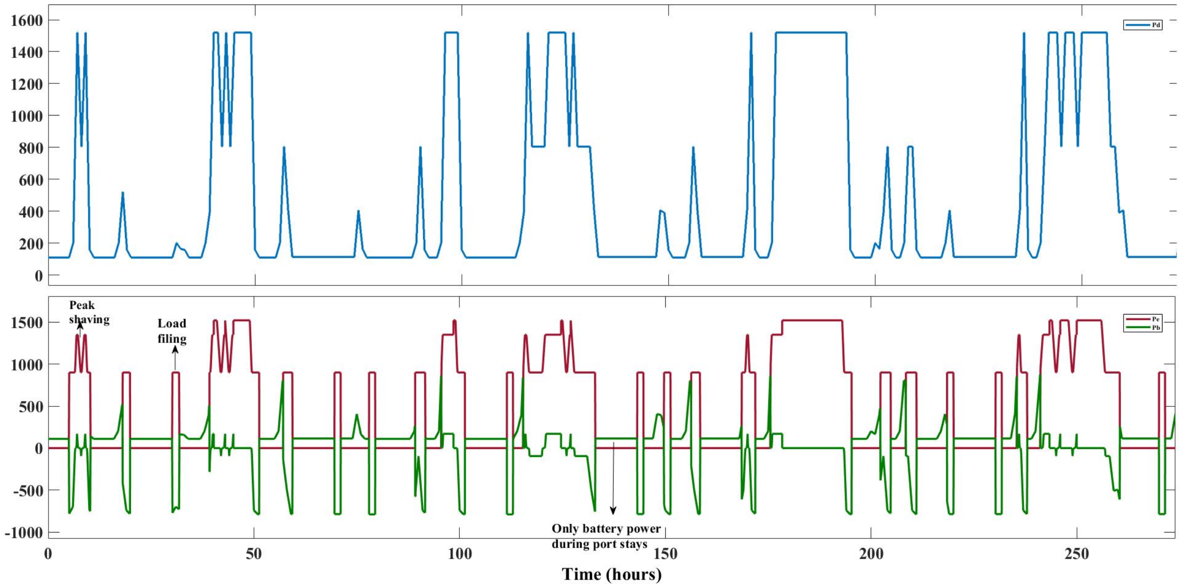


Figure 5-1: Power Split Simulation - Power Demand P_d vs Time (Top) , Engine Power P_e + Battery Power P_b vs Time (Bottom) .

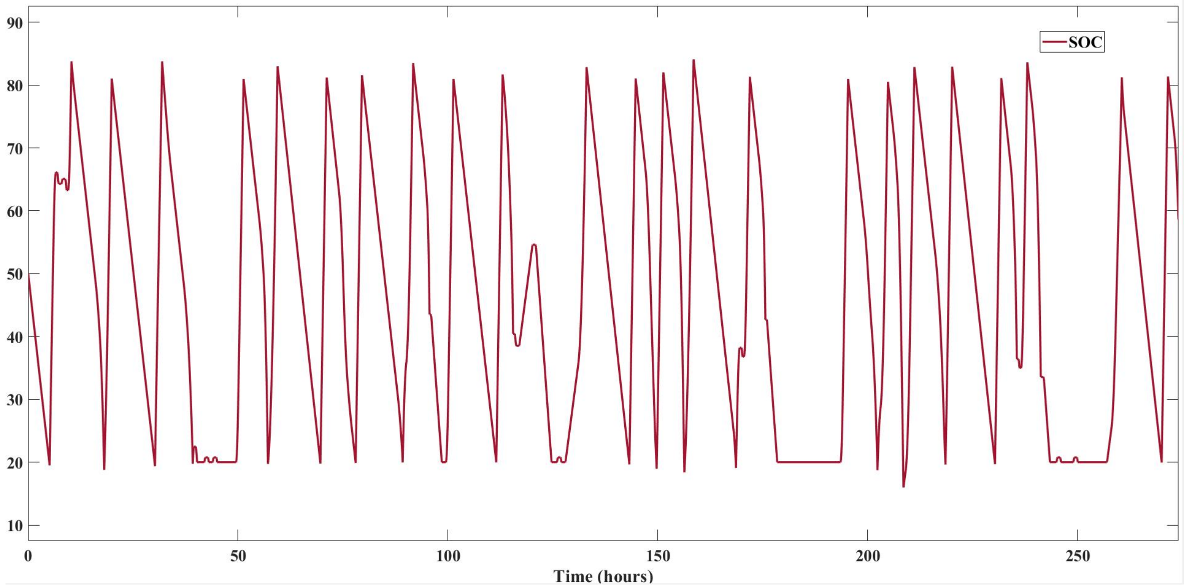


Figure 5-2: SOC Profile - Battery SOC vs Time (top) , Battery Power P_b vs Time (bottom)

5-1-1 Battery Sizing - Superyacht

- From the power split simulation, the total power that the battery pack needs to supply for this Use Case can be estimated.
- The battery supplies power around 110-120 kW during port stays at night times when only the battery power is used.
- The design criterion for sizing the battery for the superyacht is that the batteries should have sufficient energy to completely supply the auxiliary power demand of the ship during night time (10 hours continuously).
- Using only battery power during port stays at night times is desirable for a superyacht application as using only the battery power produces minimum noise.
- Therefore, the battery should have a net usable energy of 1100 kWh to supply the auxiliary loads for an entire night (10 hours).
- For this energy consumption, the battery's capacity can be estimated using the equation 5-1.

$$BatteryCapacity(Q) = \frac{Energy\ Consumption}{Depth\ of\ Discharge * Battery\ Voltage} \tag{5-1}$$

- If the Depth of Discharge of the battery is set to 0.6 (80 % - 20 %) to improve the lifetime of the battery, then according to the equation 5-1, for a rated voltage of 1000 V for the battery, the battery capacity needs to be 1850 Ah. Therefore, the total energy rating of the battery would be 1850 kWh.
- The SOC profile for the batteries with these specifications can be seen in the figure 5-2. The simulation was started with an initial SOC of 50 % to provide flexibility for the batteries to charge or discharge based on the operating mode.

5-1-2 Load cycle characteristics

- The load cycle estimation for the superyacht application can be seen in the figure 5-2.
- During the trip, the battery completes 23 full cycles and two half cycles.
- This can be considered as a deep load cycle as the depth of discharge chosen for this application is 60 %.
- The battery is charged during load filing and whenever the SOC reaches 20 %. During this scenario, the engine is turned on to supply the power demand as well as to charge the batteries. The load level of the engine is maintained at an optimal power level and the battery is charged at a rate of 0.45 C rate as charging at higher C-rates leads to higher capacity losses. Hence, the battery is charged to 80 % in about two hours.
- The discharge rate of the battery during port stays is as low as 0.1 C as the battery supplies low power for longer hours (10 hours for the whole night).

- The total energy supplied to the battery pack for charging was found by integrating the negative area of the Battery power (P_b) curve. The total energy supplied by the battery was found by integrating the positive area of the Battery power (P_b) curve. There was a five % loss in energy due to the battery's internal resistance. The battery's internal resistance value used for the simulation is 5 $m\Omega$.

5-2 Use Case 2 - Bulk Carrier

From the operational profile of the Bulk Carrier, as can be seen in the figure, 3-6, the Auxiliary loads of a Bulk carrier are almost constant when it is sailing apart from sudden peaks. Based on the rules listed in table 4-2, the power split simulation is carried out for the Bulk carrier.

- From the simulation results, which can be seen in the figure 5-3, it can be seen that the battery power is used whenever there is a surge in power demand during port operations.
- This surge in power demand occurs due to the operation of the windlass winches for mooring and for hoisting the anchor chain.
- Normally, during sea operation, the battery is not needed. The battery pack is used as a spinning reserve in case of a sudden rise in power demand or sudden failure of the diesel generator.
- One such scenario where the battery power supports the entire auxiliary loads during failure of a diesel generator can be seen in the figure 5-4
- The battery power acts as a backup for a period of 30 minutes to prevent a blackout. The second diesel generator is then switched on to take over the power demand from the battery pack. Usually, the standby generator is started within 15 minutes after the primary generator fails, but for this case, the design criterion is set for 30 minutes. The state of charge of the battery after being used as a backup for 30 minutes can be seen in the figure 5-5

5-2-1 Crane Operations

According to the proposed hybrid strategy, the battery pack supports the deck crane operations of the bulk carrier. The load fluctuates a lot during the crane operations of the bulk carrier and hence battery pack is used to handle the fluctuations. The battery pack is also charged in between the crane operations because of the regenerative control scheme. As a result, the battery power is used during peak power demands for operations like hoisting or lifting the grab and the battery pack is charged during operations like lowering the grab. The power split results for the four cranes during two cycles can be seen in figure 5-6. Figure 5-7 shows the SOC profile for the two cycles of crane operations.

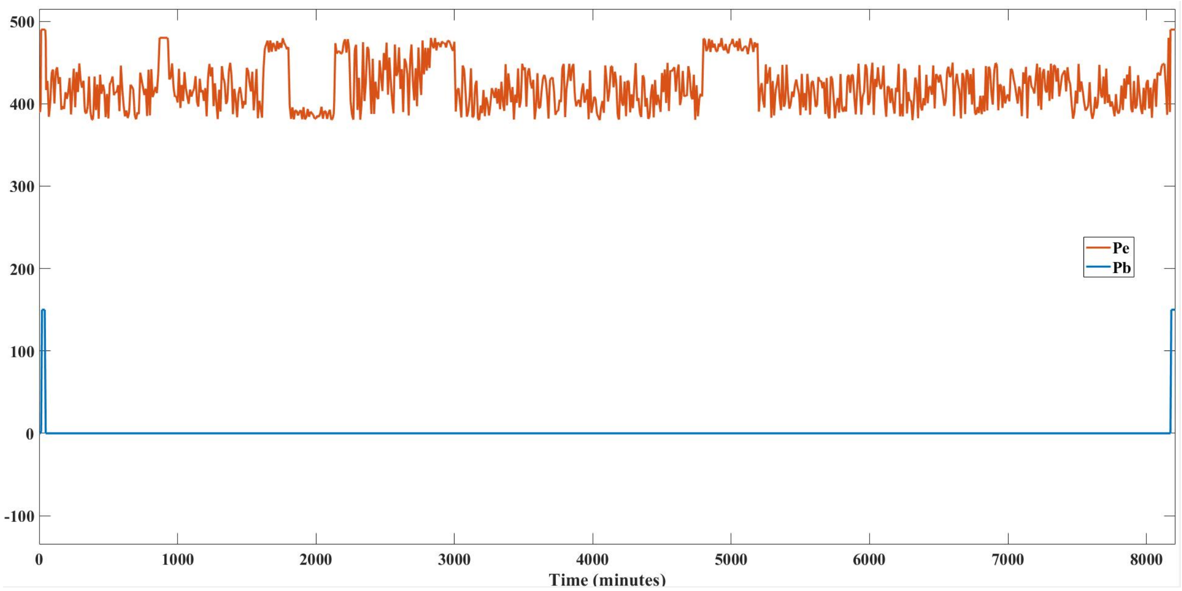


Figure 5-3: Power Split Simulation - Engine Power P_e + Battery Power P_b vs Time for the Bulk Carrier sea operations .

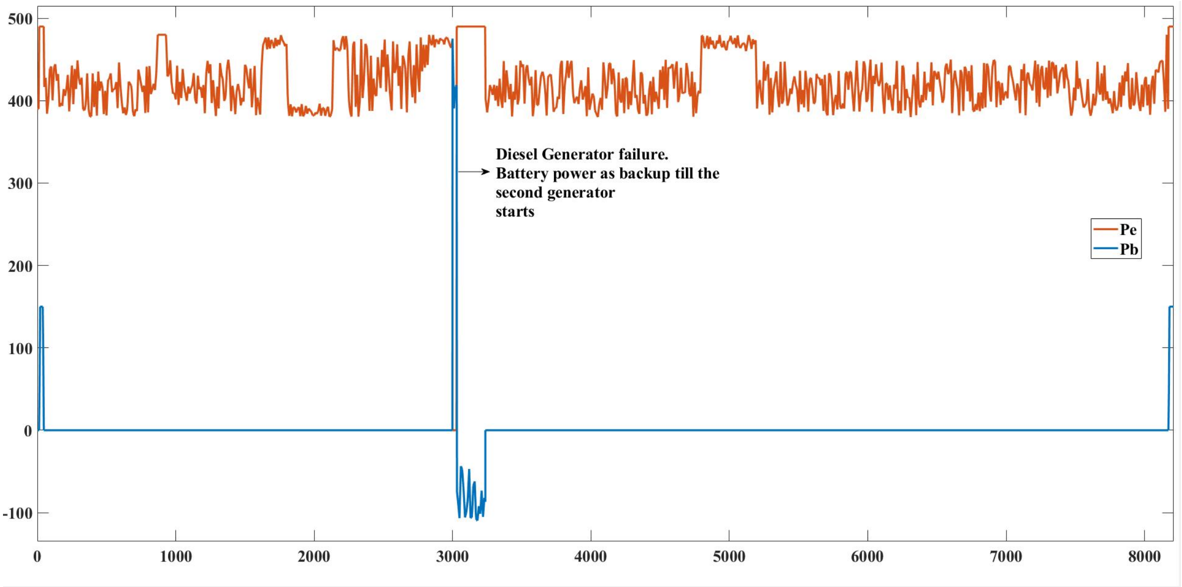


Figure 5-4: Power Split Simulation - Power Split Simulation - Engine Power P_e + Battery Power P_b vs Time for the Bulk Carrier generator failure scenario.

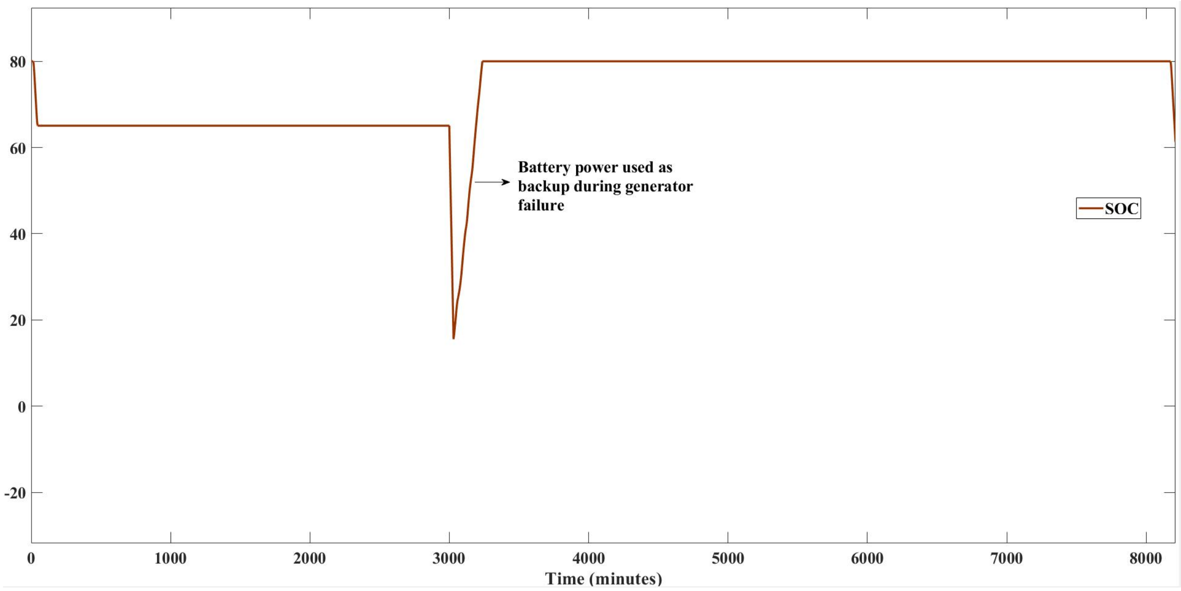


Figure 5-5: State of Charge Profile for Bulk Carrier generator failure scenario - Battery State of Charge vs Time

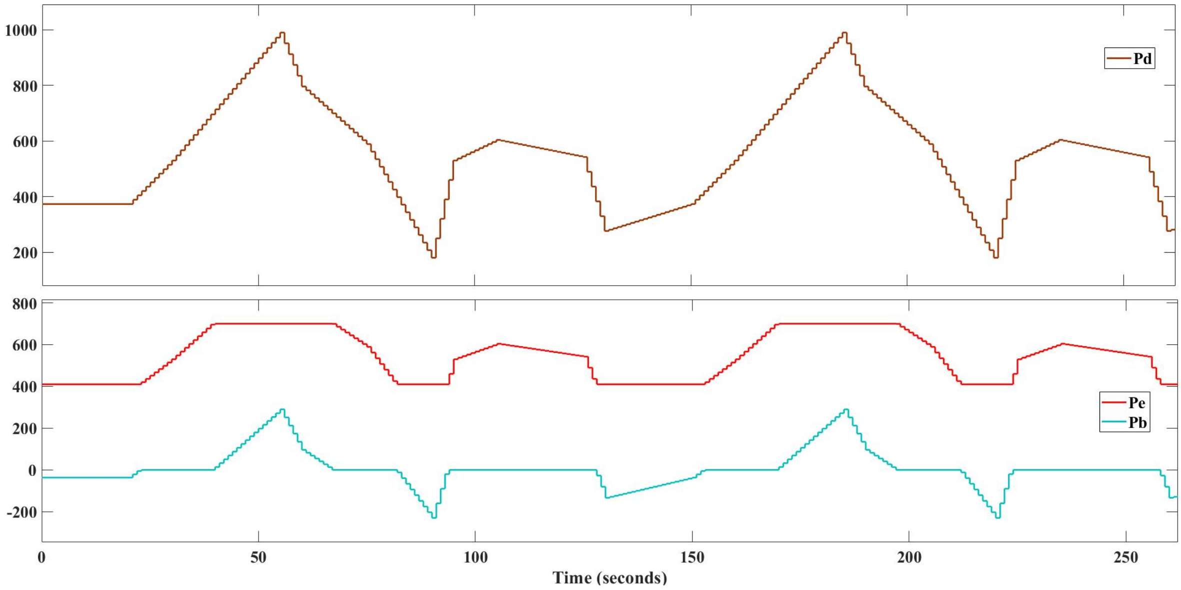


Figure 5-6: Power Split for Deck Crane Operations of a Bulk Carrier (3 cycles), P_d vs Time (top), $P_e + P_b$ vs Time (Bottom)

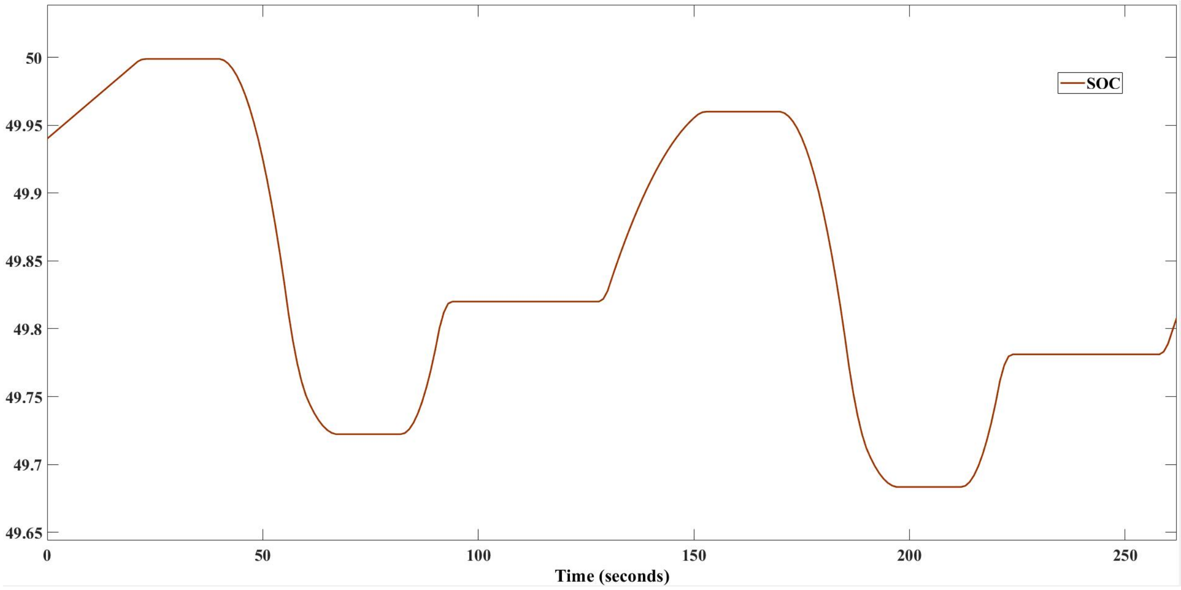


Figure 5-7: SOC Profile for Deck Crane Operations of a Bulk Carrier (3 cycles). SOC vs Time (top), P_b vs Time (Bottom)

5-2-2 Battery sizing for Bulk Carrier

- In the bulk carrier, the battery is primarily used as a spinning reserve.
- In addition to that, the battery is also used to support the port and crane operations. Therefore, the battery should have enough energy to handle peak loads during port and crane operations when the power demand is at its peak.
- The main design criterion to size the battery pack for the bulk carrier is that the battery pack should have enough energy to handle the entire auxiliary load of the ship for a period of 30 minutes (Before the backup generator starts) in case of failure of the first diesel generator.
- The battery pack should be able to handle 450-480 kW for a period of 30 minutes which gives an energy requirement of 225-250 kWh.
- Therefore, a 300 kWh battery can be installed in the bulk carrier to support the bulk carrier's auxiliary power demands.
- If a battery pack with a rated voltage of 500 V is chosen, then the battery capacity should be 600 Ah.

5-2-3 Load cycle characteristics

- The batteries are used primarily as a spinning reserve in the bulk carrier.
- When the primary diesel generator fails, the battery pack takes care of the entire auxiliary loads of the ship for 30 minutes. During this time, the battery pack must handle

around 450 kW for 30 minutes. The discharge rate of the battery in this scenario is 1.3 C.

- Whenever the bulk carrier reaches a state of charge less than 40 %, it is charged at 0.8 C to reaches to reach 80 % again. This is done to ensure that the battery has enough energy to function as a backup in case of an unlikely event in the future.
- During the crane operation, the battery completes multiple small cycles due to the constant energy supply and consumption.
- During the crane operation, the power supplied by the battery pack for one cycle is around 200 kW for about 30 seconds. Therefore it is discharged at around 0.66 C per cycle. The power consumed by the battery pack per cycle during crane operation while charging is around 150 kW. Therefore it is charged at around 0.5C per cycle.

5-3 Use Case 3 - Electric Ferry

The operational profile of the ferry 3-7, shows how the ferry completes one round trip in 60 minutes. The power demand of the ferry when it starts from the terminal is 50 kW and when it is cruising, it is around 450 kW. As mentioned in the chapter 4, this ferry application will be completely electrified using maritime batteries. Whenever the ferry completes one round trip, it waits for passengers or goods to load and the battery packs are charged in that time using shore charging [62].

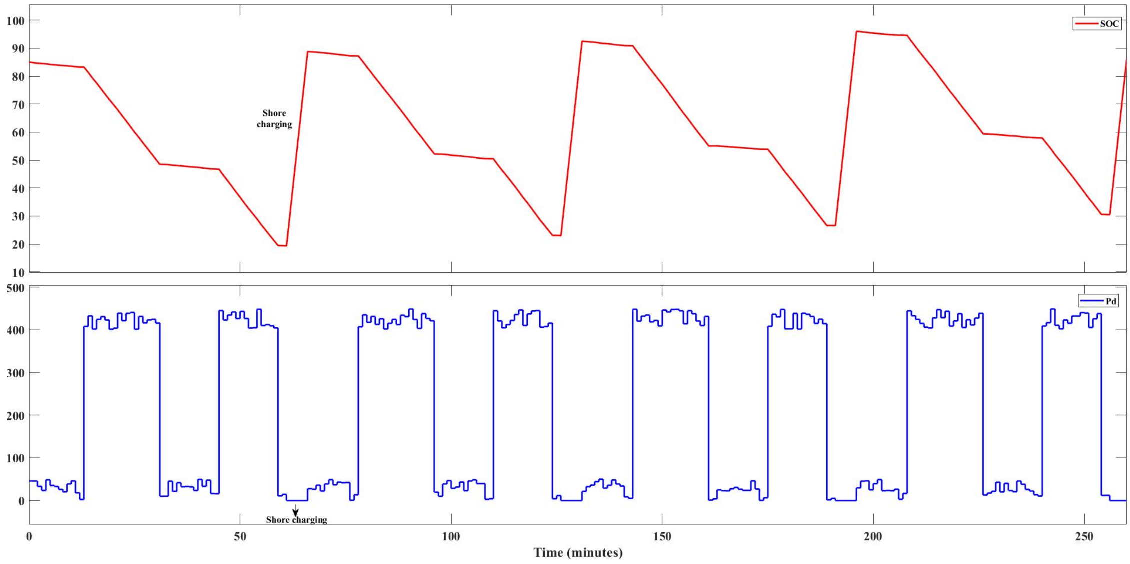


Figure 5-8: SOC Profile for Electric Ferry - Battery SOC vs Time (top) , Battery Power P_b vs Time (bottom)

5-3-1 Battery Sizing - Electric Ferry

- As the batteries are charged on the shore; it is enough to size the battery that is sufficient for a roundtrip.
- The energy demand of the ferry for one roundtrip is 330 kWh.
- The rated voltage of the battery pack was assumed to be 500 V, based on the battery packs used in the Electric ferries by DAMEN [63], which has a similar operation to the use case presented in this study.
- If a depth of discharge of 0.6 (80 % to 20 %) is used in the equation 5-1 along with 500 V rated voltage; then the resultant battery capacity would be 1100 Ah. Therefore, the net energy rating of the battery is 550 kWh.
- With these specifications, the SOC profile of the battery is generated from the simulation and can be seen in figure 5-8.

5-3-2 Load cycle characteristics

- The batteries are the primary energy storage of the electric ferry.
- During each trip, the power demand of the ferry during fast cruising is around 450 kW. The battery is discharged at 0.8C to supply this power demand during cruising.
- The ferry completes one cycle per trip and it is charged at the port again at 3C fast charging
- The depth of discharge of the battery pack used in the ferry is 60 %.

5-4 Summary of the Battery Systems

The battery systems proposed for all the Use Cases along with the sizing information is summarised in the table 5-1.

Use Case	Hybrid System	Battery application	Battery Pack Capacity (Ah)	Battery Pack Voltage (V)	C-Rate
Superyacht	Diesel Engine (1500 MCR) + Battery Pack	Load filing, Peak Shaving, Noiseless port stay	1850	1000	0.45C (Charge), 0.12 (Discharge)
Bulk Carrier	Main Propulsion Engine (10 MW MCR) + Auxiliary Genset (1*700 kW MCR) + Battery Pack + Reserve Genset (1*700 kW)	Spinning reserve, Supporting crane operations	600	500	1.3C (Discharge), 0.8 (Discharge)
Electric Ferry	1 Main Battery Pack	Completely powered by Batteries	1100	500	0.8 C (Discharge) 3C (Shore charging)

Table 5-1: Summary of the Battery Systems proposed

Chapter 6

Comparison with Conventional Systems

This chapter will present a detailed comparison between the conventional power systems and the proposed battery-implemented power systems. The comparisons will be made based on fuel consumption and greenhouse gas emissions. Reducing fuel consumption will save costs for the ship operator while also reducing greenhouse gas (GHG) emissions. Therefore, it is considered as the benchmark for this study.

6-1 Use Case 1 - Superyacht

For the superyacht, a hybrid battery power system was proposed in which batteries were used to power the ship during port stays completely and to maintain the diesel engine at load level during normal operations like sailing. In the conventional system, the superyacht's diesel engine operated at a high load level when it was cruising fast and a low level when it was idle on the shore. Working in those load levels is inefficient as the Specific Fuel Oil Consumption (SFOC) for those operating points is relatively high. The superyacht that was chosen as a reference uses two 3512C CAT 4-stroke diesel engines. The SFOC vs Load% for a 4-stroke marine diesel engine based on the article by Pramod Ghimire et al., [64] can be seen in the figure 6-1

For the hybrid electric superyacht, the load level is maintained at 60-90 % of MCR. The SFOC values in these operating points are minimal. It is possible to calculate the total fuel consumption along with the GHG emissions like CO_2, SO_x and NO_x using the SFOC values and estimated operational profiles. A comparison of the conventional and hybrid superyacht's fuel consumption and GHG gas emissions can be seen in the table 6-1. Formulas for the calculations can be found in the appendix A-1.

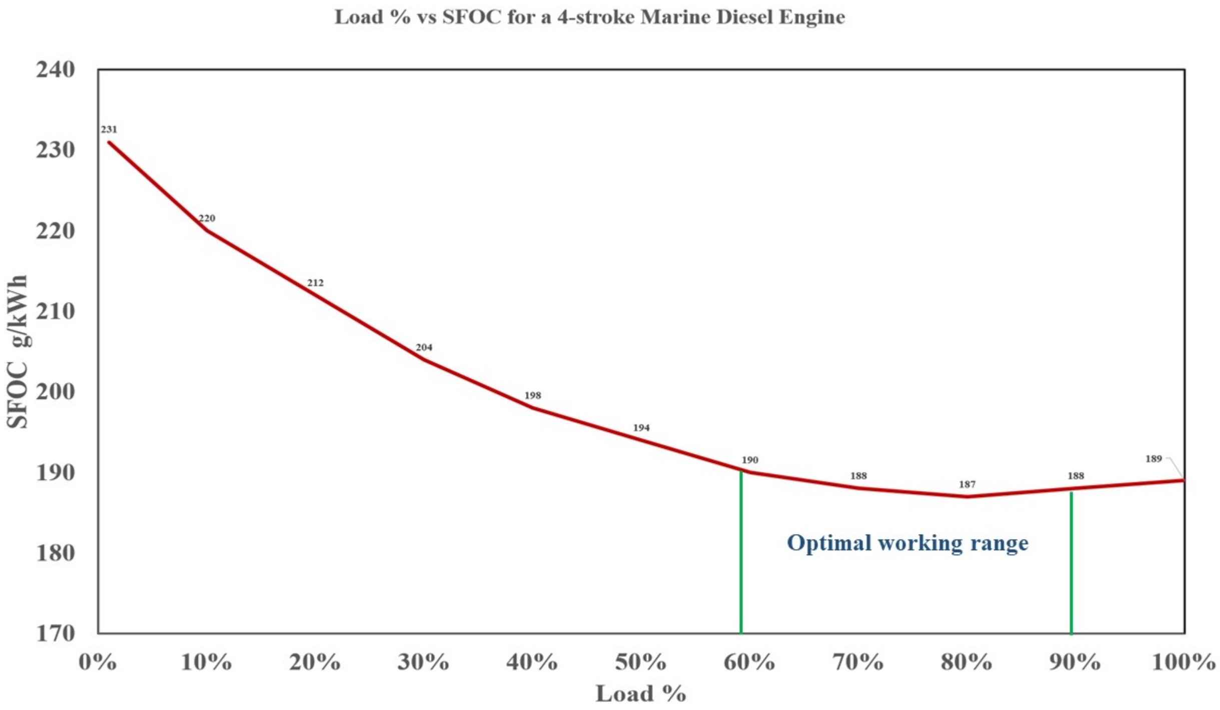


Figure 6-1: Load % vs SFOC for a 4-stroke Marine Diesel Engine based on [64], [65]

	Fuel Consumption (Liters)	CO_2 **(kg)**	SO_x **(kg)**	NO_x **(kg)**
Conventional Power System	39629.18	128002.12	2139.95	3249.59
Hybrid Power System	37108.60	119860.77	2003.86	3042.90

Table 6-1: Comparison of Fuel consumption and GHG emissions of the Conventional and Hybrid Power System for the Superyacht

- The fuel consumption of the conventional power system was estimated to be 39629.18 litres, whereas, for the hybrid power system, it was estimated to be around 37108.60 litres.

- Similarly, the CO_2, SO_x and NO_x were also estimated using standard emission factors. The emissions also decreased by using the hybrid power system.

- There is a 6.36 % decrease in fuel consumption and emissions for the proposed hybrid power system of the superyacht travelling in a busy leisure voyage.

- For the Superyacht, an 1850 kWh battery pack was proposed. A standard lithium ion lithium-ion costs around 132 € per kWh [66]. Therefore, the investment cost of the battery pack would be 244,200 €.

- Considering the cost of yacht diesel to be 1.2 € per litre, the fuel savings by adapting to the hybrid energy system would be 3024 € per trip.

- If the yacht makes 20 trips a year (240 days of operation), the total fuel savings per year would be 60,920 €
- The investment cost can be returned in terms of fuel savings within four years of operating with the hybrid energy storage system.
- With respect to the battery's cycle life, the maritime battery manufacturer EST Floattech, which produces Lithium Polymer NMC cell battery packs for maritime systems, promises around 7000 cycles for a battery with a depth of discharge of 0.6 [67].
- According to the load cycle estimated the superyacht makes a total of 20 cycles per trip. Considering 20 trips a year, the superyacht battery makes a total of 400 cycles per year.
- The battery starts degrading at least after ten years. Therefore, the investment cost can be returned as fuel savings during the battery's lifetime.

6-2 Use Case 2 - Bulk Carrier

For the Bulk Carrier, a hybrid battery power system was proposed in which batteries were used to support the auxiliary loads of the Bulk carrier along with the conventional diesel generators. The battery pack is essentially used to support the unloading operations using the ship cranes and during port operations. The typical SFOC vs Load % graph for typical auxiliary generator sets used in ocean-going ships were presented in the article by Eleftherios K.Dedes et al., [12] and it is adapted for this study.

	Fuel Consumption (Liters)	CO_2 **(kg)**	SO_x **(kg)**	NO_x **(kg)**
Conventional Power System (Sea + Crane Operations)	12560.16	40569.291	678.6938	1029.9054
Hybrid Power System	12134.94118	39195.3	655.59	995.761

Table 6-2: Comparison of Fuel consumption and GHG emissions of the Conventional and Hybrid Power System for the Bulk Carrier

- The fuel consumption of the conventional power system was estimated to be 12560.16 litres, whereas, for the hybrid power system, it was estimated to be around 12134.94 litres.
- Similarly, the CO_2, SO_x and NO_x also decreased for the hybrid power system
- There is a three % decrease in fuel consumption and emissions for the proposed hybrid power system for the Bulk Carrier auxiliary loads. This is mainly because the battery pack supports the primary auxiliary engine during crane operations, eliminating the second engine's fuel consumption during peak loads.
- If the cost of diesel used for the diesel generators is assumed to be 1.2 € per litre, around 510.26 euros can be saved for a trip.

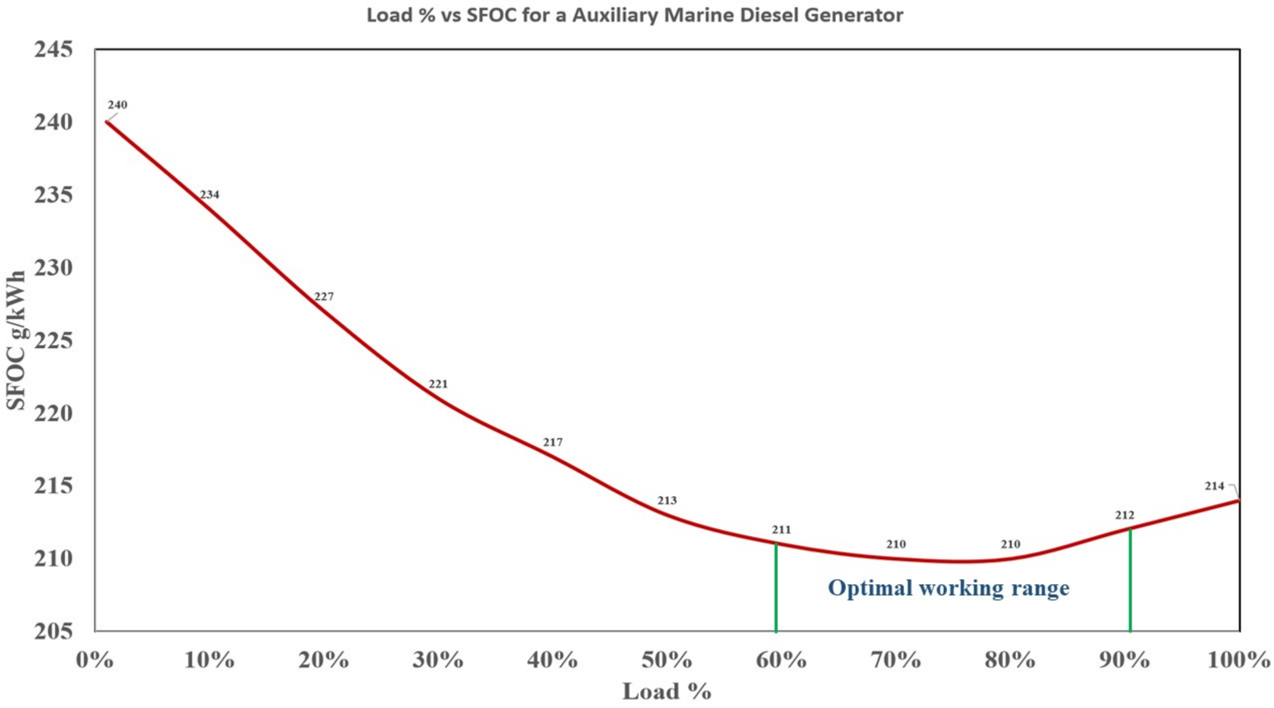


Figure 6-2: Load % vs SFOC for a Auxiliary Marine Diesel Generator based on [12]

6-3 Use Case 3 - Electric Ferry

For the ferry, a fully electric battery-powered system was proposed. In that case, usage of the fuel oil is eliminated.

- Using a completely electric ferry will eliminate the usage of fossil fuels. Therefore, the emissions from fossil fuels such as diesel are completely eliminated.
- Usage of renewable green energy to charge the batteries of the electric ferry will lead to zero emissions [68].
- In case the ferry is charged using normal electricity grid power, then CO_2 emissions in charging the batteries of the ferry need to be accounted for.
- The fuel consumption and the CO_2 emissions from using fossil fuel in conventional diesel power can be seen in the table 6-3. The SFOC curve of the ferry used was adapted from the article by Monaaf D.A. Al-Falahi et al. [40] and can be seen in the figure 6-3.
- The CO_2 emissions from charging the battery pack of the ferry using normal grid power can be seen in the table 6-3

- The CO_2 emissions from burning fossil fuel for one round of ferry operation were found to be 284 kg.

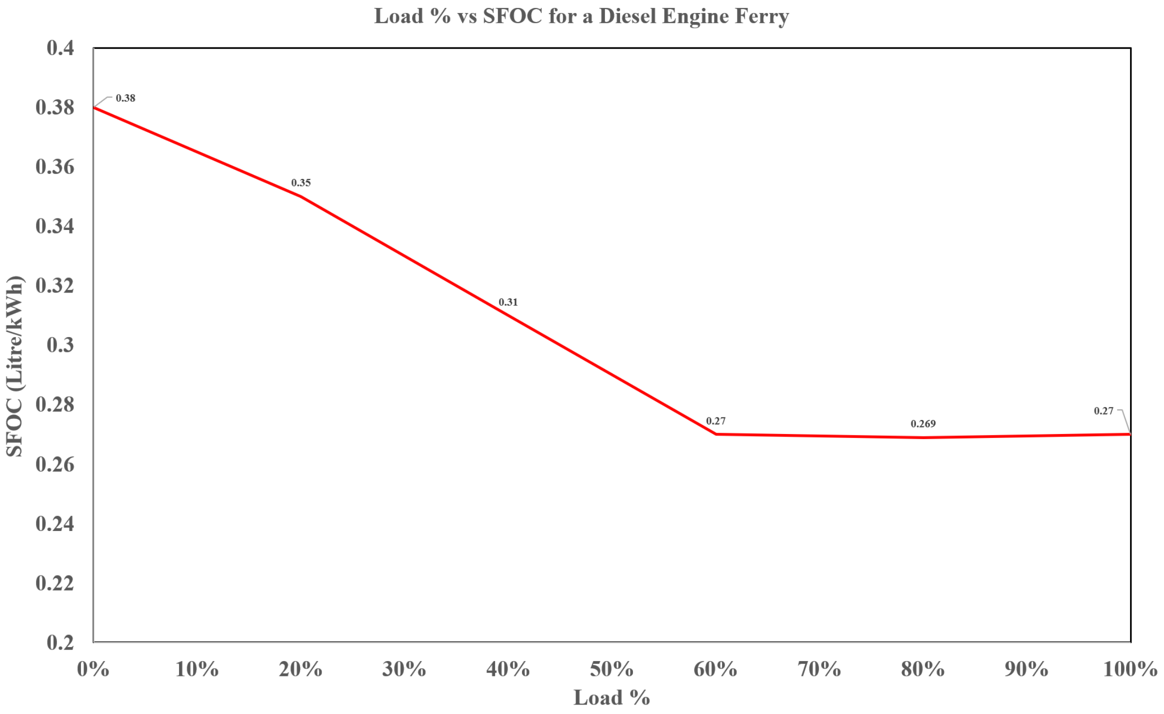


Figure 6-3: Load % vs SFOC for a Diesel Engine Ferry based on [40]

- The CO_2 emissions for charging the batteries on shore with renewable energy sources is zero. The CO_2 emission factor for electricity in the Netherlands is 0.32 kg/kWh [69]. Therefore, CO_2 emissions for charging the batteries on shore with grid power is 176 kg.
- There is a 38 % reduction in CO_2 emissions from the conventional system if the electric ferry is charged using grid power. If renewable sources are used, there will be a 100 % reduction in emissions which is the ideal scenario that the shipping industry is adapting to.

	Fuel Consumption (Liters)	**CO_2 (kg)**
Conventional Power System (for one round trip)	88	284
Fully electric (Charging with renewable power)	0	0
Fully electric (Charging with grid power)	0	176

Table 6-3: Fuel consumption and CO_2 emission comparison for the Ferry Use Case

Chapter 7

Conclusion

The aim of this thesis was to assess the load cycles of maritime batteries that are used in different ships with diverse operational profiles. The way batteries can be used for a specific ship highly depends on its operational profile. For this study, the operational profiles of three ship types, Superyacht, Bulk Carriers and Ferries were estimated and then studied.

The operational profile was estimated using various sources from literature and personal surveys with MARIN and Sri Chakra Maritime College, India. Certain realistic assumptions were made to estimate the power demand and time period of several operations of the ship. After estimating the operational profile, battery implementation strategies were proposed for three use cases.

For the superyacht, a hybrid battery power system was proposed. This application used the batteries to maintain the IC engine at optimal load range. Also, batteries were used to power the ship when it was idle at ports. A hybrid battery energy storage system was proposed for the Bulk Carrier to support the auxiliary operations. Batteries were used to support the port operations such as mooring, hoisting anchors and also for unloading operations using the ship cranes. Finally, a complete battery electric powered system was proposed for the ferry. In that case, the battery pack handled the entire energy demand of the ferry. The battery pack was charged on the shore after every round trip.

A rule-based controller was developed to simulate the power split for hybrid electric ships. The rule-based controller splits the power between the IC engine and the battery pack based on strategies proposed for each use case. The battery output power was estimated for each use case. The Coulomb counting method was used to simulate the battery's State of Charge (SOC) profile for each use case. The battery current was estimated from the battery power and it was used for calculating the SOC using the Coulomb Counting method.

The Power-split and SOC profile results were presented for each use case. The energy requirement of the battery pack was found out for each use to size the battery packs appropriately. Finally, a comparison was drawn between the conventional power system and the proposed battery electric or hybrid system. The comparison benchmark was the fuel consumption by both the conventional and newly proposed systems. It was seen that there was a 6.3 % decrease in fuel consumption for the superyacht use case, a three % decrease in fuel consumption for the Bulk carrier and a 38 % decrease in emissions of the electric ferry (also considering the emissions to charge the batteries using grid power).

In an age where reducing emissions in every sector is a priority, researchers in the maritime industry are responding by continuously contributing to sustainable energy systems for marine vessels. This work also adds to those contributions in the form of a detailed study about the use of batteries in the maritime sector. The results of this study can be used as one of the starting points in sailing towards the destination of complete electrification of the shipping sector.

7-1 Answering Research Questions

1. *How can the operational profiles for different ships that utilise maritime batteries be estimated?*
    - The data for the shipping activity, along with the power required and time elapsed for every activity, was collected from several scientific sources and personal surveys with MARIN and Sri Chakra Maritime College, India.
    - The data for time elapsed for loading and unloading the material to the bulk carrier was estimated using simple formulas and calculations.
    - After acquiring the information about the sequence of operation, time spent to perform each operation and power demand for each operation, the operational profile was plotted for three different ships.
2. *How to estimate the load cycles of maritime batteries from the diverse operational profiles?*
    - A rule-based controller was developed to simulate the power split between the IC engine and the batteries for hybrid electric ships. From that, the power profile of the battery pack during the entire journey was estimated.
    - For a fully electric ship, the entire power demand was supplied by the battery pack throughout the journey.
    - A battery model was created for each ship and the load cycles of the batteries was estimated by generating the State of Charge (SOC) profiles using the Coulomb Counting method.
    - The SOC profiles showed how the batteries were charged during charge cycles and how the batteries were discharged during the discharging cycles throughout the journey.
    - The load cycles were then studied and characterised for each application.
3. *How to estimate the size of the battery pack for different ships based on the load cycles estimated ?*

  - The size of the battery was estimated according to the design criteria for each use case
  - For the Superyacht, the design criterion was to ensure that the battery pack has enough energy to supply the entire power demand during port stays at night (continuously for 10 hours). The energy requirement was estimated for that and the battery pack was sized appropriately to satisfy that energy requirement.
  - For the Bulk Carrier, the design criterion was to ensure that the battery functions as a spinning reserve and as a backup when the primary generator fails. The maximum time to switch on the reserve generator was approximated to 30 minutes. Therefore, the battery pack was designed to supply the entire auxiliary power demand of the ship for 30 minutes.
  - For the Electric Ferry, the design criterion was to ensure that the battery pack has enough energy to supply the energy required for the ferry to complete one round trip. The ferry was charged after every round trip; therefore the battery pack was sized to provide energy for one round trip.

4. *How can the load profiles of electric or hybrid electric ships of specific applications be compared with the load profiles of diesel engine ships with the same application ?*

  - The main benchmark for comparison between the conventional systems and the hybrid electric systems was fuel consumption. The fuel consumed by both systems was estimated and compared. The amount of money saved by reducing fuel consumption by adapting to a hybrid electric system was also estimated.
  - The investment cost of implementing a battery energy storage system was estimated. The number of load cycles of the batteries per trip was calculated to estimate the lifetime of the battery. A cost-benefit analysis was made by comparing the money saved by reducing fuel consumption with the investment cost of the batteries.
  - The CO_2, SO_x, and NO_x emissions were estimated for both the conventional system and the electric/hybrid electric system and were compared. The results of the comparisons were presented.

7-2 Contributions

- The load cycles presented in this work can be used as a reference to see how batteries should be charged and discharged for the applications covered.
- The characteristics of the load cycles of the batteries were presented for each application.
- These load cycle estimations can be a starting point in designing battery energy storage systems for the ship applications dealt with in this study.
- A realistic estimation of the operational profile for the Auxiliary operations of a Bulk Carrier was introduced in this study.

- A rule-based controller was developed as a simulation tool to simulate the load sharing between the battery system and the IC engine. The simulation files are uploaded in a repository [58].
- An estimation of fuel consumption reduction by implementing electric or hybrid electric battery power systems was presented in this work to emphasise the advantages of using battery-powered solutions in the maritime sector.

7-3 Scope for Future Work

Some directions to further improvise this study include

- Operational Profiles of other different ship types can be estimated using real-time ship data
- Different SOC estimation models can be implemented to improve the accuracy of the estimation.
- The State of Health (SOH) of batteries for different applications can be studied to get information about battery degradation.
- Different battery chemistry can be studied and compared to see which is the most suitable for maritime applications.

Appendix A

Fuel Consumption and Emissions

This chapter describes the calculations of Fuel consumption and Emissions for all the use cases presented in chapter 6.

A-1 Superyacht

A-1-1 Conventional System

The time spent at each load level by the superyacht can be seen in the table A-1

Number of hours in each load level in % of MCR			
>90%	**60-90%**	**20-60%**	**0-20%**
54	23	16	181

Table A-1: Number of hours the superyacht with conventional energy system spends in each load level (in of %MCR)

From the figure 6-1, the Specific Fuel Oil Consumption (SFOC) for each load level was found out. The Fuel consumed per hour was then found out using the equation A-1.

$$Fuel\ consumed\ per\ hour\ (g/hr) = Power\ at\ specific\ load\ level\ (kW) * SFOC\ (g/kWh) \tag{A-1}$$

Then the total fuel consumption was found using the equation A-2 and it was found 39629.19 liters for the conventional superyacht.

$$Fuel\ consumed\ (g) = Fuel\ consumed\ per\ hour\ (g/hr) * Number\ of\ hours\ (hr) \tag{A-2}$$

The emission factors for the GHG gases can be seen in the table A-2. Product of fuel consumed and the emission factors will give the total GHG emissions estimation.

CO2	3.23	kg/liter
SOx	0.054	kg/liter
NOx	0.082	kg/liter

Table A-2: Emission factors for GHG gases

A-1-2 Hybrid System

Number of hours, the superyacht spends in each load level can be seen in the table A-3

Number of hours in each load level (% of MCR)				
>90%	**60-90%**	**20-60%**	**0-20%**	**Off**
0	122	0	0	165

Table A-3: Number of hours the superyacht with hybrid energy system spends in each load level (in of %MCR)

The fuel consumed per hour at each power level was estimated using the equation A-1. The total consumption was then found by the sum of fuel consumed at each power level estimated from the equation A-2

The greenhouse gas emissions is estimated using the emission factors listed in the table A-2

A-2 Bulk Carrier

A-2-1 Conventional system

The time spent at each load level by the auxiliary generators of the Bulk Carrier can be seen in the table A-4

Number of hours spent in each load level (in % of MCR)		
>95%	**50-60%**	**60-70%**
1.166667	126.1667	9.5

Table A-4: Number of hours the Bulk Carrier generator spends in each load level (in % of MCR)

From the figure 6-2, the Specific Fuel Oil Consumption (SFOC) for each load level was found out. The Fuel consumed per hour for the bulk carrier was then found out using the equation A-1. Then the total fuel consumed was found out using the equation A-2 and it was found to be 12560.16 litres.

The greenhouse gas emissions is estimated using the emission factors listed in the table A-2

A-2-2 Hybrid System

The batteries are used for supporting crane operations and port operations of the bulk carrier. Therefore, the need of the second generator which was used as a spinning reserve is eliminated. The second generator was used during peak power demands during crane operations and port operations such as mooring. Therefore, by eliminating the second generator as spinning reserve, the fuel consumption was estimated to be 12134 litres using equations A-1, A-2.

The greenhouse gas emissions is estimated from the emission factors listed in the table A-2

A-3 Ferry

The time spent at each load level by the ferry with conventional diesel engine power system can be seen in the table A-5

Number of hours the ferry spends at each load level (in % of MCR)	
60-80 %	**<30 %**
0.533333	0.466667

Table A-5: Number of hours the ferry spends in each load level (in % of MCR)

In the table A-6, the SFOC of the Diesel engine powered ferry at the listed load levels according to figure 6-3 is presented. Along with that, the average power output of the engine in that load level is also presented. The fuel consumed per hour in that load level is estimated by the equation A-1. The fuel consumption in grams is estimated from the equation A-2

Load level	**60-80%**	**<30%**
SFOC (l/kWh)	0.269	0.33
Power (kW)	450	130
Fuel consumption/hr	121.05	42.9
Fuel consumption (g)	64.56	20.02

Table A-6: Fuel consumption estimation

The greenhouse gas emissions is estimated from the emission factors listed in the table A-2.

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