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**Accurate Sizing and Utilization of BESS on Ships
with Power-Generating Units Having Weak Load
Ramping Capabilities to Improve Fuel Efficiency**

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UNIVERSITY OF VAASA**School of Technology and Innovations****Author:** Enobong Ette**Title of the thesis:** Accurate Sizing and Utilization of BESS on Ships with Power-Generating Units Having Weak Load Ramping Capabilities to Improve Fuel Efficiency**Degree:** Master of Science in Technology**Discipline:** Smart Energy**Supervisor:** Mustafa Alrayah Hassan Ibraheem**Year:** 2024 **Pages:** 89

ABSTRACT:

The maritime industry is undergoing a significant transformation driven by the urgent need to embrace new and environmentally sustainable technologies for merchant vessels. Energy saving with batteries, cost and emission reduction are the main aspects toward the optimum utilisation of the ship's electric power generation. This transition is a vital goal for meeting international regulations and maritime policies aimed at curbing emissions and enhancing energy efficiency. Battery energy storage system (BESS) plays a significant role in reaching this goal, which helps to improve the overall power generation efficiency. BESS can be used to support the shaft generator (SG) and auxiliary generator (AG) to balance the load, peak shaving and load levelling with optimum operation.

This thesis aims to improve the generation efficiency and operational flexibility of the merchant vessels by applying an optimisation algorithm that allows optimal operation of the battery with SG and AG. The main benefits of utilising batteries in this study were peak shaving during manoeuvring to meet short-time load transients, spinning reserve and load optimisation during normal seagoing conditions instead of starting additional generators to meet the power demand by either charging or discharging, thereby reducing the number of AG starts and stops. Overall, the batteries were used to balance the supply and demand, thus bringing flexibility to the shipboard microgrid (SMG) and improving the loading conditions and fuel efficiency of the generators. This thesis also aims to provide an accurate sizing of the batteries, which reduces the cost and enhances economic and technical benefits. The generator loading conditions and fuel efficiency were improved, leading to reduced fuel consumption.

The outcome of the optimisation was the optimal energy management system (EMS) strategy and optimal battery size. The EMS strategy controlled the economic dispatch of the AGs, SG, and battery utilisation based on the power demand and the cost-effectiveness of the power sources per time. BESS optimisation is valuable as it gives a clue on the minimum battery size to be used. In marine applications, battery utilisation is more effective for dynamic load profiles with transient peaks, as in this case study. Fuel savings achieved were between 1.4% - and 15%, depending on the battery usage and during peak loads, the battery contributed about 27% to the total power required during manoeuvring. Shore power is an expensive option for shipowners due to electricity prices; hence, generating electricity on the ship during harbouring is still preferred except when faced with regulatory demands.

KEYWORDS: Merchant vessels, energy storage, optimisation, fuel efficiency

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Abbreviations

| | |
|------|---------------------------------------|
| AFE | Active Front End |
| AG | Auxiliary Generator |
| BESS | Battery Energy Storage System |
| BMS | Battery Management System |
| CII | Carbon Index Indicator |
| CPP | Controllable Pitch Propeller |
| DOD | Depth of Discharge |
| ECA | Emission Control Area |
| EEXI | Energy Efficiency eXisting ship Index |
| EMS | Energy Management System |
| GAMS | General Algebraic Modelling System |
| HESS | Hybrid Energy Storage System |
| HFO | Heavy Fuel Oil |
| IMO | International Maritime Organization |
| MDO | Marine Diesel Oil |
| ME | Main Engine |
| MGO | Marine Gas Oil |
| MIQP | Mixed Integer Quadratic Programming |
| PTO | Power Take Out |
| SFOC | Specific Fuel Oil Consumption |
| SG | Shaft Generator |
| SMG | Ship Microgrid |
| SOC | State of Charge |
| VFD | Variable Frequency Drive |

1 Introduction

Climate change, cost and fuel efficiency are critical issues that maritime transport is continuously addressing. Over 95% of ships are diesel engine-powered (Iqbal et al., 2024), and maritime transport contributes about 2.5% of global GHG emissions by generating 1000 million tons of CO₂ annually (Vieira & Peralta, 2017). Using fossil fuels is the primary cause of CO₂ emission in marine environments. In 2007, 277 million tonnes of fuel was used in international shipping, majorly by liquid bulk carriers, container vessels and dry bulk carriers, with annual consumption of about 65 million, 55 million and 53 million tonnes of fuel, respectively (Dedes et al., 2012). In 2050, CO₂ emissions from ships are predicted to increase between 50-250% (Mutarraf et al., 2018). Some organisations have proposed policies to limit emissions and promote energy efficiency, such as the 2023 International Maritime Organization (IMO) Strategy on Reduction of GHG Emissions from Ships to reduce CO₂ emissions by at least 40% by 2030 and the European Commission's climate agreement to reduce global emissions by 60% for newly built ships and Energy Efficiency Existing Ship Index (EEXI) requirements for existing vessels were enforced to measure energy efficiency and collect data on the ship's annual operational carbon intensity factor (CII) and equivalent CII rating. About 84% of existing merchant vessels are yet to attain this standard (https://www.classnk.or.jp/hp/pdf/activities/statutory/eexi/eexi_rev3e.pdf).

The focus of this thesis is to determine how energy storage systems (ESS) can improve electricity generation on a short-distance merchant vessel during short transient load ramps to avoid the frequent starts and stops of the AGs and improve fuel efficiency. The main objectives of this thesis are to review different ESS technologies and their suitability for marine applications, determine the accurate size of ESS that increases fuel efficiency and improves energy efficiency for ship owners and operators in line with the International Maritime Organization (IMO) 2023 IMO Strategy on Reduction of GHG Emissions from Ships.

This thesis does not consider cruise ships and ferries but is limited to merchant vessels that have a shaft generator and a four-stroke auxiliary engine as the main power

sources. It aims to establish ESS's advantages in reducing fuel consumption and promoting energy efficiency.

1.1 Problem Statement

Energy storage systems used in land-based applications, residential and industrial, have been streamlined and defined as a mature technology. For example, in the power system, ESS is used to reduce the curtailment of renewable energy generation, peak shaving, ancillary services, etc., and it can be used as backup power in home applications, electric vehicles, and trains. ESS use in ships is relatively new and gaining attraction in passenger vessels such as ferries and utility vessels like platform supply vessels and tugboats. However, the adoption of ESS among merchant ship owners is slower due to safety, battery health, power, and energy density limitations. These concerns can be addressed by accurate sizing and effective utilisation of the ESS, which depends on using an optimal energy management system control strategy to control and dispatch all the power units. This accuracy in design and implementation can be achieved using optimisation. Without this, the battery size selection would be under or oversized and not effectively utilised to provide the required outcome. This thesis addresses accurate ESS sizing and economic dispatch strategy to maximise the benefits of ESS, such as fuel savings and improved fuel efficiency on short-distance merchant vessels.

1.2 Research Motivation

This thesis is based on the current trend in energy transition in the shipping industry. Although everyone agrees that ESS is the way to reduce fuel consumption and improve energy efficiency, there still exists a knowledge gap on the ESS potentials and their accurate sizing, which makes it difficult for ship designers and owners to decide whether to integrate batteries into the SMG. The results of this thesis will help the decision-making process by providing convincing reasons for why and how ESS can be maximally

utilised. It will also help shipyards, vessel owners, sales, and design engineers choose an optimal ESS solution tailored to merchant vessels.

1.3 Research Methodology

This study uses mixed-methods research combining one qualitative and one quantitative research component (Schoonenboom & Johnson, 2017). The decision to use this method was made for flexibility and results validation. The qualitative research involved interviewing sales managers, sales engineers, and a consultant to gain insights into the merchant shipping business and shipowner reasoning behind ESS integration. The interview questions helped streamline the optimisation objective and constraints of the model.

The optimisation problem was solved using mixed integer quadratic programming (MIQP) in GAMS. It was divided into two parts: EMS strategy using the actual BESS size and finding the optimal BESS size. The inputs for the EMS strategy are generator data, such as minimum and maximum power limits, power demand, battery data, fuel cost, etc., and the outputs are the generator loading and power output per time, the battery cycle and utilisation. The inputs for the ESS optimal sizing include all the inputs of the EMS strategy, the battery and inverter costs. Different decision variables and constraints were applied to the problems.

Due to the nonlinearity associated with this SMG ESS sizing problem, optimisation programming such as linear programming (LP), mixed integer linear programming (MILP), and mixed integer nonlinear programming (MINLP) sometimes ignore or linearise nonlinear problems making them unsuitable (De Mel et al., 2022). Because the SMG ESS sizing problem cannot be accurately solved without considering an energy management strategy, it consists of many inputs, variables, parameters, and constraints, which increases its complexity. As seen in Equations (1), (2) and (19), the objective function of this problem contains quadratic terms, integers and continuous variables, hence, the use of the MIQP mathematical model to solve the problem is the most

suitable model type for this two-fold optimisation work. The SBB solver is used to solve the MIQP optimisation in GAMS. Figure 1 below shows the optimisation process.

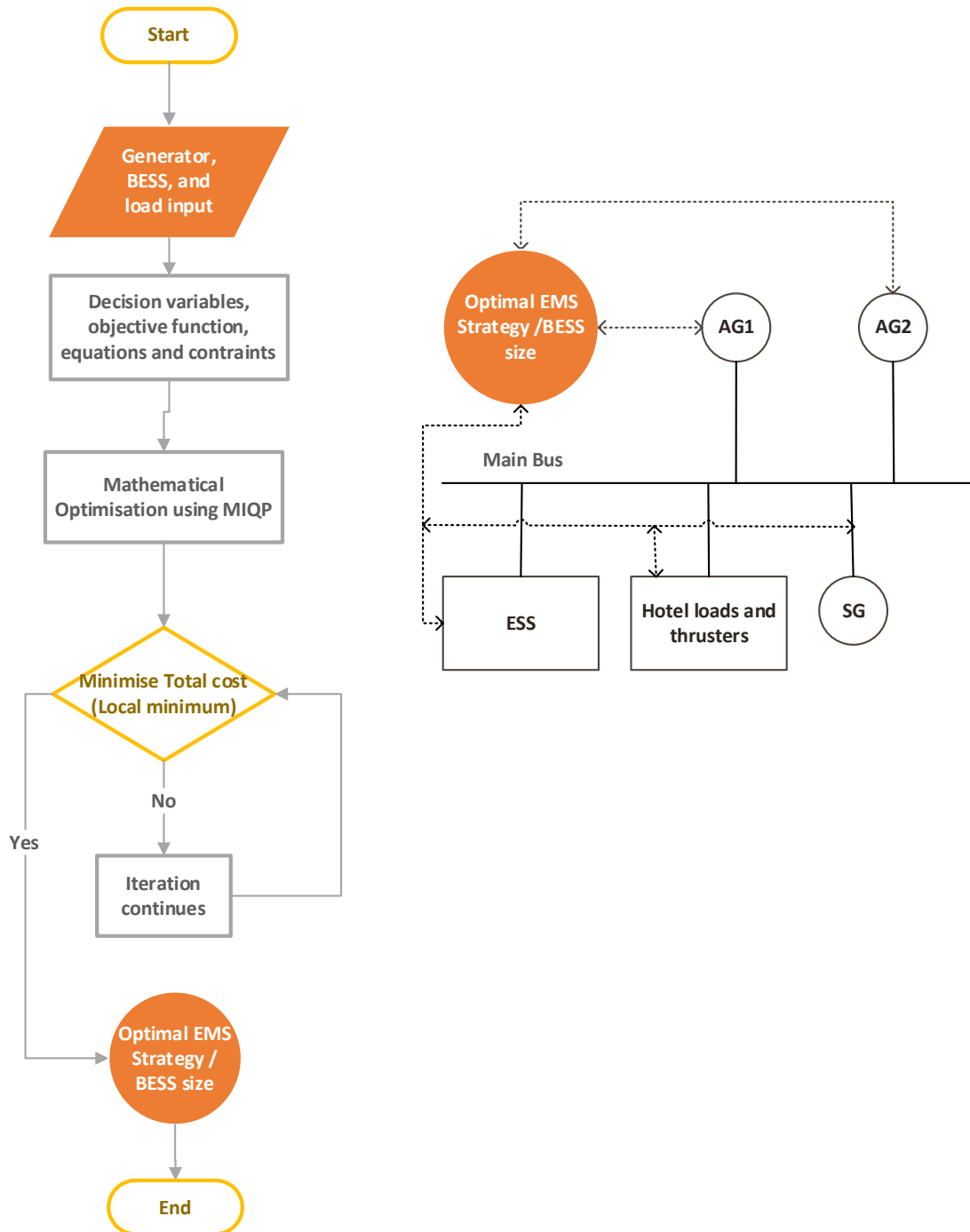


Figure 1: Optimisation process

1.4 Literature Review

The shipbuilding industry is a conservative sector that takes some time to adopt new technologies; hence, the push from international legislation and maritime policy is essential to compel shipowners to invest in new innovative and environmentally friendly technologies (Dedes et al., 2012). To comply, shipyards, ship designers, owners, and relevant stakeholders seek environmentally friendly and energy-efficient solutions to reduce fuel consumption without jeopardising energy availability. It is unrealistic for the ship to depend on a single energy source due to structural and operation limitations, hence the need to reduce emissions by improving fuel efficiency (Iqbal et al., 2024). Some environmentally friendly and energy-efficient solutions proposed by researchers include alternative fuels, e.g. biofuel and electrofuels (Kanchiralla et al., 2023), exhaust gas cleaning, e.g. using SO_x and NO_x scrubbers (C.-H. Wu et al., 2024), hybrid propulsion (Mutarraf et al., 2018), carbon capture and storage, nuclear, hydrogen, hull, and propeller redesign etc. (Issa et al., 2022), waste-energy recovery, DC power, energy storage systems, and shaft generators. Overall, the power system choice highly depends on technology availability, availability of components, cost, space, weight, redundancy, and classification requirements (Skjong et al., 2016).

The power system on a ship has some similarities with land-based power systems. It can be described as a microgrid operated in island and grid-connected modes and has localised generation, distribution, and consumption. The ship is in islanded mode when sailing and in grid-connected mode when connected to the shore's electrical network (Mutarraf, Terriche, Khan Niazi, et al., 2019). Like a microgrid in islanded mode, a ship requires strict energy independence and quality of service for extended periods. Although a system failure is more critical for a ship than for land-based systems, some similarities between a ship microgrid and a land microgrid are voltage and frequency control scheme, power quality improvement strategies, load balancing and power system management strategies (Skjong et al., 2016). To mitigate system failure, SMG requires high redundancy that supports high variable load.

The conventional electrical network of a ship consists of auxiliary diesel engines, the main engine, and the loads. Diesel engines have a high running cost, including fuel, spare parts, lubricant, and repairs (Vieira & Peralta, 2017). Fuel cost accounts for 60% of a vessel's operational cost, and bulk tankers are one of the heaviest energy consumers in deep-sea shipping. Marine diesel engines use Heavy Fuel Oil (HFO), Marine Diesel Oil (MGO), Liquefied Natural Gas (LNG), and Biodiesel for operation. Each fuel produces a percentage of emissions due to higher combustion temperatures. Cheaper fuels like HFO produce more emissions than the more expensive ones, such as biodiesel and LPG. Previously, the choice of fuel was based on the economic operation of the vessel, but lately, with the IMO directive, new limitations have been placed on marine vessel emissions (Tummakuri et al., 2020). Therefore, continuous improvements to increase the efficiency of marine diesel engines and reduce the SFOC and pollution (Dedes et al., 2012).

The generation capacity of the vessel must be sufficient to accommodate peak demand and service load growth margins (Hebner et al., 2016). Hence, planning the energy management systems of ships is essential for economically efficient power generation and optimal prime mover loading conditions. The prime movers' speed depends on the engine's frequency control, and fuel efficiency depends on the prime mover's loading and determines the engine's specific fuel oil consumption (SFOC). Due to speed variations caused by dynamically changing loads, the frequency of an AC SMG does not remain constant. Speed variations also increase the shaft's wear and tear, increasing maintenance costs. Because power availability depends on the starting and stopping of the prime movers, prime movers operate under low load conditions to ensure energy security on the vessel. However, this is not optimal (Skjong et al., 2016). A vessel's fuel capacity and power requirements are determined by functionalities such as "voyage, operation style, design of the ship, fuel consumption, space, weight", etc. (Kanchiralla et al., 2023).

Energy storage systems for land and short-distance vessels, e.g., ferries and tugboats, are being adopted quickly as mature technology. However, for long-distance vessels such as merchant vessels, e.g. LNG carriers, bulk tankers, etc., the adoption is still in the infancy stage due to challenges such as enormous energy and power requirements, space and weight constraints, cost, and other technical constraints (EMSA European Maritime Safety Agency., 2020). The benefits of energy storage systems such as batteries, supercapacitors, flywheels, etc., to the SMG are improving stability by supporting the engine's slow response to load fluctuations, reducing operational and maintenance costs, power storage, providing redundancy and flexibility, ancillary services such as load levelling, improving power quality, frequency, and voltage control (Nivolianiti et al., 2024). Batteries can also reduce the number of times the generators start and stop, the number of online prime movers, and reduce fuel consumption (Acanfora et al., 2022). The primary function of ESS on board a vessel can be summarised as load levelling and peak shaving, which directly impacts fuel consumption and emissions (Nagalingam et al., 2022). However, the point of common coupling (PCC) of the ESS can affect the system's cost, reliability, and efficiency (Mutarraf et al., 2019). Using a DC power system reduces the weight of heavy AC machines and transformers used for power generation, promotes advanced and bi-directional power flow, allows easy integration of ESS, and eliminates parameter synchronisation and harmonics (Jayasinghe et al., 2017). Also, a DC power system eliminates reactive power and instability caused by linear loads and increases efficiency, reliability, and stability (Mutarraf et al., 2019).

WE Tech is an energy solution provider headquartered in Vaasa aimed at providing energy-efficient power solutions to vessels globally to reduce the customer's operation costs and emissions and achieve future energy sustainability requirements. This thesis aims to review different ESS technologies, their suitability and application in marine, and the optimal size that improves fuel efficiency. This will help shipyards, vessel owners, sales, and design engineers choose an optimal ESS solution tailored to the merchant vessels. The electrical network considered in this thesis follows WE Tech's solution one,

which integrates a variable frequency drive, PTI or PTO shaft generator, and optional ESS or shore connection.

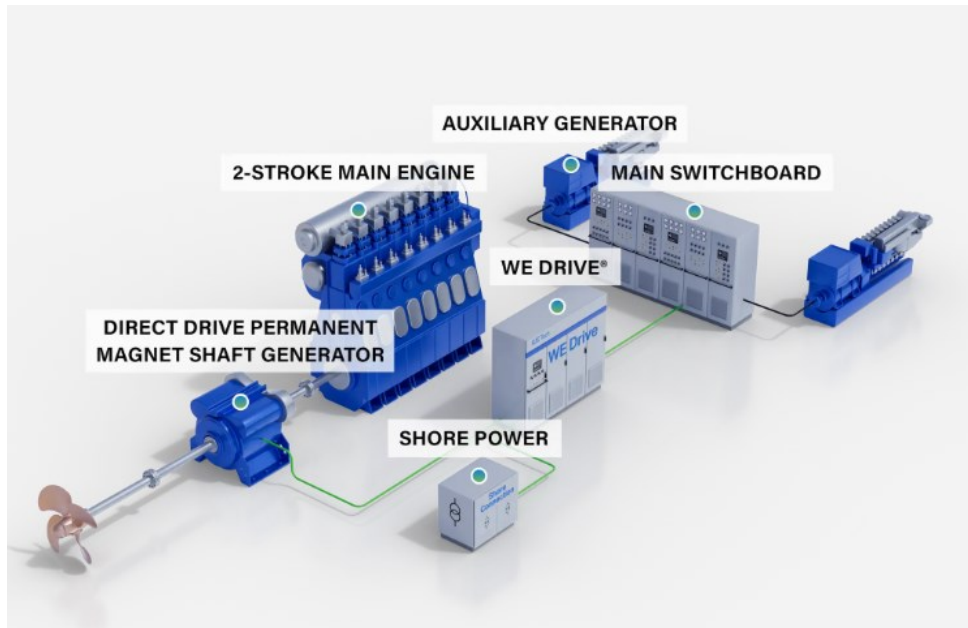


Figure 2: WE Tech's Standard PTO Solution

1.5 Scope and Limitations

This thesis examines ESS use on a short-distance vessel using WE Tech's standard PTO solution. The focus is on determining how ESS can support voyage operation during quick power demand ramps to avoid the start of the auxiliary generators. Cruise ships, ferries, primary engine fuel consumption, and DC SMG are not considered.

1.6 Research Question

Studying the ESS on a short-distance merchant vessel will help address the following questions while filling the existing knowledge gap on this topic.

- i. What ESS technology best supports marine applications, such as high-power or high-energy-density batteries?
- ii. Can ESS provide the required spinning reserve to replace or support auxiliary diesel gensets when accurately sized?

- iii. How is ESS utilisation for land applications different from marine applications, and do they have the same functionalities, for example, peak shaving and load levelling?
- iv. What is the best way to maintain the battery State of Health on a ship considering the long time at sea and short stay at shore?
- v. How can ESS be utilised during shore power connection?

1.7 Research Objective

The objectives of this thesis are:

- i. To review different ESS technologies such as mechanical, electrochemical, chemical, electrostatic and magnetic ESS and their suitability and application in marine.
- ii. Determine the accurate ESS size and its utilisation in short-distance merchant vessels to promote fuel efficiency.
- iii. Provide insight into how ESS utilisation affects cost and fuel efficiency to help ship owners and operators make good energy transition decisions in accordance with the International Maritime Organization (IMO) 2023 Strategy on Reduction of GHG Emissions from Ships.
- iv. Highlight the need to have an accurate EMS strategy in the ship's microgrid.

The thesis is organised as follows: Chapter two presents the different types of ESS technologies used in the shipping industry and their applications, how they are interconnected with other parts of the ship's electrical network, factors to consider when selecting batteries, how ESS are used for different types of vessels and optimisation techniques. Chapter three gives an overview of merchant vessels, their operating profiles, and the utilisation of shaft generators for electricity generation. Chapter Four discusses the case study used in this thesis, the unique design

considerations, the problem definition, and the tool used to solve it. Chapter Five presents the results of the optimisation and sensitivity analysis of the factors that affect the results. Finally, chapter six discusses the conclusion and future works of this thesis

2 ESS in Shipping and Optimisation

This chapter discusses different battery technologies considered suitable for marine operation, current battery applications on ships and connection topologies, the effects of ESS application on fuel consumption and efficiency, and ESS optimisation techniques.

2.1 ESS Technologies

An energy storage system includes an energy storage device, power converter and control method. The use of ESS in terrestrial applications is more advanced than that of marine applications. ESS reduces capital and operating costs when integrated with the grid while providing grid-supporting services like power quality improvement and load levelling. Previously, the use of ESS in marine has been limited to emergency backup power. However, they have the potential for power generation to support functions such as dynamic positioning of offshore vessels during grid failure (Mutarraf et al., 2018) and load levelling during propulsion fluctuations to offset the effects of ramps on the generator (Acanfora et al., 2022). ESS utilisation is rapidly growing in short-distance vessels due to the short voyage time and quick recharge time, e.g. 5-9mins without an affection sailing schedule. This provides significant fuel savings, less noise and emissions, and improves the customer experience (Kolodziejcki & Michalska-Pozoga, 2023). ESS have distinct characteristics such as “life cycle, discharge time, discharge loss, energy density and wattage rating,” and can be classified into six groups: “mechanical, thermal, chemical, electrochemical, electrical and hybrid systems” (Nadeem et al., 2019). Despite the wide adoption of ESS in marine and terrestrial applications, challenges such as weight, size, cost, environmental impact, safety, durability, and performance still limit their utilisation (Nivolianiti et al., 2024).

2.1.1 Mechanical ESS (MESS)

Mechanical ESS stores electrical energy in the form of mechanical energy. Examples of MESS are “pumped hydro storage (PHS), flywheel energy storage (FES), compressed air energy storage (CAES) and gravity energy storage systems (GES)” (Nadeem et al., 2019). Flywheel energy storage (FES) stores energy in the form of kinetic energy and can be used as a motor and generator. Some advantages of FES are high peak power for a short duration, high cycle, high efficiency of up to 85% and a lifespan of about 20 years (Kermani et al., 2022). The equal charge and discharge of FES make them suitable for improving “power quality, peak shaving, and load levelling”, although, due to space limitations, they can only be used on large ships (Nivolianiti et al., 2024). On vessels, FES has been studied to have “dark start capability” sufficient to support the starting of a gas turbine after a power failure (Mutarraf et al., 2018). FES have infinite charge and discharge cycles, making them suitable for transportation applications (Vazquez et al., 2010).

2.1.2 Electrostatic and Magnetic Energy Storage Systems (EMESS)

Electrostatic and magnetic energy storage systems store energy through electrical charges. Examples of EMESS are supercapacitor energy storage (SCES) and superconducting magnetic energy storage (SMES) (Nadeem et al., 2019). A supercapacitor is also known as an ultracapacitor (UC) that stores electrical energy on electrodes as an applied electric field between two conducting plates. This gives it a higher power density when compared to batteries and makes it capable of withstanding peak loads (Kermani et al., 2022) without creating thermal and power disturbances to the SMG (Nadeem et al., 2019). UCs are suitable for transportation due to their quick charge and discharge rates, long life cycle and high-power density, but they are highly susceptible to over-voltage and over-charging. SMES is a relatively new technology in marine applications compared to batteries, UC, and FES. It uses a magnetic field to store energy generated by a superconducting coil. SMES, compared to other ESS, has higher

efficiency, >95%, because it does not require any energy conversion for storage and electricity generation. Other advantages are high power density, an extended lifespan of 30 years, and fast charging and discharging rates (Nivolianiti et al., 2024).

2.1.3 Chemical Energy Storage (CES)

Chemical energy storage stores energy through chemical bonds of molecular compounds through fuel cells. Fuel cells (FC) are environmentally friendly, as heat and water are the only by-products of chemical reactions (Nadeem et al., 2019). FCS Alsterwaser passenger ship is powered by fuel cells, proving its use case in marine. Storage and hydrogen fuel distribution are the main challenges of using FC for larger ships, as FC has a lesser energy density/m² than LNG or MDO. Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) contain hydrocarbon fuels suitable for propulsion. For example, the 330kW MCFC powers Viking Lady, an offshore supply vessel (OSV) (Mutarraf et al., 2018).

2.1.4 Electrochemical Energy Storage System (EcSS)

An electrochemical energy storage system is the most mature energy storage technology where DC power is stored in an electrolyte using a reversible chemical reaction. Electrochemical cells are connected in series and parallel to form a battery storage. Batteries have different operational characteristics and can be classified into “storage integrated BES systems and external storage BES systems. (Nadeem et al., 2019).” The commonly used batteries used in marine applications are;

- i. **Lithium-Ion (Li-ion) Batteries:** Li-ion batteries are the most technologically advanced rechargeable batteries. They have grown in adoption following the increased utilisation of consumer electronics and electric vehicles (Deng, 2015). Various studies have been carried out to prove the suitability of lithium batteries for marine applications. Lithium iron phosphate (LFP) batteries are lightweight and have high energy density and electrochemical properties. However, they are

- expensive and have a low tolerance to heat, making them unstable and unsafe (Mutarraf et al., 2019; Mutarraf et al., 2018). Lithium titanium oxide (LTO) is also used in marine applications; it has better thermal stability for fast charging and discharging than LFP (P. Wu & Bucknall, 2016). Boveri et al. (2019) use Li-ion to reduce fuel consumption and operational costs of a platform supply vessel and ferry.
- ii. Nickel manganese cobalt (NMC): NMC is quickly replacing lithium manganese oxide and lithium cobalt oxide in consumer electronics. NMC power and energy densities vary depending on the nickel, manganese, and cobalt composition (EMSA European Maritime Safety Agency.,2020). It has gained high adoption in marine and automotive applications, although there are reasonable safety and ethical concerns regarding its usage. NMCs have high-energy density but are highly susceptible to thermal runaway, which increases the cell temperature and leads to fire outbreaks that are difficult to extinguish. This is a significant drawback ship owners consider when choosing between LFP and NMC, even though LFP is more expensive and has about 35% less energy than NMC. Lithium NMC technology is used in battery-electric boats that travel up to 50km (Verma & Kumar, 2021).

Overall, the choice of battery depends on the operating conditions and requirements (Acanfora et al., 2022). Ampere ferry, the world's first battery-powered car ferry, is a solid example of batteries that can be used in marine areas for short-distance routes. Although the overall SMG efficiency is improved when using battery propulsion, batteries alone cannot be used for long-distance routes (Mutarraf et al., 2018). Adopting batteries in marine is limited by their energy density, power density, life span, etc., which influences the operational performance, i.e. speed and range of the vessel. It might require the ports to have additional infrastructure for charging. Also, comparing the power density of MDO to that of batteries, we see that batteries do not provide an economic justification (P. Wu & Bucknall, 2016). However, because the choice of marine

electrification is no longer centred on cost but includes environmental impact, an alternative way to integrate ESS is proposed.

The battery management system (BMS) is a critical component of an ESS that provides electronic control and protection to the device. The BMS ensures the battery's safe operation and performance by monitoring its temperature, voltage, state of charge, and state of health. BMS varies for different battery technologies and is calibrated accordingly to maintain the balance between the voltage and battery cells. The BMS is integrated with the ship's power management system (PMS) and energy management system (EMS) for effective battery functionality (Kolodziejski & Michalska-Pozoga, 2023).

2.2 ESS Application in Marine

The cost of batteries has decreased in recent years and is predicted to decrease by 40% in 2030. The cost reduction will drive BESS adoption and development for marine applications (Kolodziejski & Michalska-Pozoga, 2023). Batteries used in marine applications are expected to have high energy density and long discharge time with minimal voltage drop over time (Dedes et al., 2012). However, using a single ESS is not feasible due to the different technical characteristics of ESSs, such as energy density, power rating, discharge rate, lifecycle, and cost. A hybrid energy storage system (HESS) with different complementary characteristics is a superior alternative to using a single ESS. HESS creates a robust system by combining high-power ESS for short-term high-power demand with high-energy ESS for long-term power demand to improve the efficiency and response time of the system. HESS optimises storage costs by reducing storage size and improving storage capacity. It also enhances power quality and control by balancing power supply and demand (Nivolianiti et al., 2024). ESS integration depends on cost, space, efficiency, reliability, etc. (S.-Y. Kim et al., 2015).

2.2.1 Spinning Reserve

Spinning reserve is the “unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power” (Rebours, 2005). ESS can provide spinning reserve by reducing the number of gensets running per time and serving as backups for generators mainly used in diesel-electric dynamic positioning vessels (Kolodziejski & Michalska-Pozoga, 2023).

Bhujade et al. (2018) studied a drill ship. They noted that unlike cruise ships, which have a flat load profile mainly fluctuating due to the ship velocity, wind and wave, merchant vessels experience higher power fluctuations due to the operation of heavy loads such as “drilling drives, heavy compensators, cranes, pumps, winches and hotel loads” in addition to the “wave-induced ship motion”. Running diesel generators (DG) during the up and down ramp conditions increases wear and tear, maintenance costs, and fuel inefficiency of the genset. Also, due to the short duration of the ramps, using the genset to support this operation is uneconomical, as operating the genset below minimum loading increases the operational cost. A HESS comprising lithium-ion and supercapacitor is proposed as an economically viable solution to support ramp fluctuations and mitigate operating the genset below the manufacturer’s minimum loading specification. The investment impact of several types and sizes of ESS on the AC bus with three 15.2 MW DGs and two primary loading operations, drilling and dormant loads are considered.

Without storage, the three gensets were in continuous operation, sharing equal power to meet the fluctuation demand. More than not, the gensets were operated below minimum loading, which increased the wear and tear of the gensets, fuel inefficiency and the Levelized Cost of Energy (LCOE) over five years of operation was \$413.75/MWhr. With storage, one or two generators remained off during the ship’s operation while the other operated above 30% of their capacity. The supercapacitor mitigates the effects of quick ramps during drilling, and both ESS were charged during low-load operations. The

LCOE was reduced to \$383/MWhr, reducing fuel consumption by 9.18%, although the physical size of the ESS was a limitation.

2.2.2 Peak Shaving

Integrating an energy storage system into the SMG can help shave off-peak loads and balance the load distribution in the network. On land, peak shaving is achieved by charging ESS when demand is low (off-peak period) and discharging when demand is high (Uddin et al., 2018). In marine, due to the low ramp rate of the generator to supply and maintain the power demand of pulse loads, ESS is applied to increase the power supply within a short period, thereby providing instant support for the generators. Li-ion batteries and SMES can be hybridised to help the SMG quickly respond to the propulsion variations and quick ramps between 9MW-14MW, which can cause voltage sag on the DC bus (Alafnan et al., 2018).

Acanfora et al. (2022) explore a Ro-Pax ferry with lithium batteries and supercapacitors HESS connected to the DC link through a double-stage power converter to interface with the propulsion engine, the generator, and the loads. The decision to use lithium-ion and ultracapacitors is made because Lithium-ion is light and has high power and energy densities, which is suitable for high-energy applications. Ultracapacitors have very high power and are suitable for instantaneous power supply. The results show that ultracapacitors can smoothen the propulsion variation and increase the efficiency of the prime mover. Battery and UC can be hybridised internally on the electrode level and externally using a hardwire connection (Mutarraf et al., 2018).

Also, Hou et al., 2018 utilise UCs and batteries to reduce the effect of propulsion variation of the DC bus. Tang & Khaligh, 2010 proposed a zonal distribution system with high and medium bus voltage for navy ships. The HESS consists of li-ion batteries and UC connected to the network via a dual active full bridge converter. The high voltage serves the propulsion and other loads, while the ESS is connected to the medium voltage. The

HESS explored in Kermani et al., 2022 for port crane operations are ultracapacitors and FES, battery and FES, ultracapacitors and batteries.

Mutarraf et al. (2019a) discuss BESS solutions for long-distance ferries. The BESS is dedicated to the propulsion load. It is coupled in parallel to the DC link capacitor without a buck-boost converter to minimise cost and increase efficiency and reliability. An active front-end (AFE) converter is integrated between the diesel generator and the DC link to minimise THD levels. At the same time, the inverter stabilises the power flowing between the propulsion motor and the DC link. The results show that the BESS can absorb and increase the recovery time of voltage and frequency sag caused by propulsion ramps.

Mutarraf, Terriche, Nasir, et al. (2019) studied a HESS comprising a Li-ion battery, and UC connected parallel to the DC link via a buck-boost converter to eliminate high-frequency fluctuations and smoothen and stabilise the DC link voltage. The results showed that ESS can be used to smoothen power oscillations when connected to the propeller motors. Also, because the demand fluctuations can increase the battery's temperature, Bø & Johansen (2017) recommend using a bandpass filter to protect the battery. Li et al. (2023) use a battery and flywheel HESS to improve the power quality by smoothening out power fluctuations and maintaining the DC voltage within the acceptable range. Elsayed & Mohammed (2015) utilise flywheel, ultracapacitor and lead acid to minimise voltage and frequency fluctuations on the AC and DC busbar. Minimum deviations were achieved, although it was noted that using only the battery and flywheel gives equivalent results. The latter is preferred due to its lower weight and size.

2.2.3 Load Optimization

ESS can achieve even loading of the genset and reduce maintenance costs. The ESS can be charged when the total power demand is lower than the total DG power to buffer the genset loading. Farrier et al. (2017) studied the characteristics of ESS to minimise

the fuel consumption and genset run hours of a PSV. The vessel had 4 DG generating at a total of 6.3MW and simulated with a 175kWhr battery at 80% DOD. The results showed that the ESS achieved load levelling, reduced DG run hours by 29%, and reduced fuel consumption by 0.95% per voyage under optimal loading strategies. Also, it was noted that the fuel consumption reduction rate is directly proportional to the battery capacity. A battery size of less than 25kWh increased the generator run hours due to frequent start and stop to charge the battery. Above 125kWh, the DG run hour was reduced by 12.5%. ESS can also handle fast load variations while the gensets produce slow, varying power (Kolodziejcki & Michalska-Pozoga, 2023).

The auxiliary genset takes a while to go from idle and is switched off to full loading conditions with increased pressure and temperature. Here, the ESS can be used for load optimisation pending when the genset is fully operational (Dedes et al., 2012).

2.2.4 Backup Power

Just as in terrestrial applications, batteries are used in case of genset failure to allow a smooth transition from grid-connected to islanded mode and ensure continuous operation of critical loads. In ships, batteries can be used for load shedding to power essential loads during emergencies. This can happen when a backup generator fails to start, overloading the online generator(s). On ships, load shedding is handled by the PMS and requires less negotiation because all loads are centralised (Hebner et al., 2016). Ports in Emission Control Areas (ECAs) with cold ironing infrastructure allow batteries to be fully charged at the end of the voyage. Fully charged batteries can be used for voyages at average or lower speeds while approaching the ports, for cargo handling, and for departure without operating the engines. Accurately sized batteries can be used during departure from the ports. (Dedes et al., 2012).

2.3 ESS Connection Topologies

Various authors have proposed ESS connection topologies for different purposes, such as cost and efficiency. Mutarraf, Terriche, Khan Niazi, et al. (2019) used a variable frequency drive (VFD) to integrate ESS into the SMG in a three-step process – rectification, smoothing and inverting. The rectification stage converts the AC to DC, a DC link capacitor then smoothens and stores the DC power, and the inverter converts the DC back to AC. The conversion process can sometimes cause harmonic distortions to the network; hence, an insulated gate bipolar resistor (IGBT) is used to reduce the total harmonic distortion to 3%. Kim et al. (2015) directly connect a 1000kW BESS to the DC link of the propulsion system using an active front-end (AFE) converter to improve the voltage and frequency quality and to reduce the grid current harmonics, cost, weight, and loss of DC/DC converter. Hardan & Tricoli (2023) connect a UC, li-ion and SMES ESS to individual converters and then to a DC-bus of the SMG. The study showed that UC and SMES have quick response rates proportional to the propulsion variation and maintained the bus bar voltage at 750V while the battery response was slower. Farrier et al. (2017) connected the ESS directly to the main switchboard to reduce the need for multiple cabinets because distributing the ESS to sub-switchboards is only necessary for naval applications. In Elsayed & Mohammed (2015), the battery is connected to the DC link via a buck-boost converter, the flywheel via the permanent magnet synchronous machine, and the ultracapacitor is connected directly to the DC bus. Li et al. (2023) use a battery and flywheel connected to the DC bus bar using DC/DC and DC/AC converters.

From the studies, the three primary ways of integrating HESS are (Vazquez et al., 2010):

- i. Direct parallel connection ensuring both ESS have a matching output voltage, i.e. $V_1=V_2$. The output to the load is based on source impedance mismatching, which causes the “low impedance ultracapacitor to supply power during high power pulses, while the high-energy battery supplies the long-term lower power demand.” This connection type is suitable for automotive applications.
- ii. A power converter is connected between two ESS to control their output. The power converter controls the output current of ESS1, permitting voltage

variation, while ESS2 supplies the remaining power required. Examples of HESS for this topology are FC and battery, SMES and battery.

- iii. Connecting each ESS to a dedicated power converter with a common output. This topology is more flexible as more control strategies can be implemented, and each ESS can be optimally utilised.

The electrical configuration of ESS within the SMG is determined by 1) the point of common coupling, 2) the ESS hardware structure, and 3) the control method.

Different connection topologies and HESS functionality have been reviewed to determine the efficiency and optimal PCC and supporting functions they provide to the SMG to improve the performance and energy efficiency of the vessel. Some essential functions are discussed below:

2.4 Factors to consider when choosing ESS

- i. **C-rate:** The C-rate of a battery refers to the rate at which a battery is discharged relative to its maximum capacity. 1 C-rate means that the entire battery will be discharged in 1 hour, 2C in 30mins, 3C in 20mins, etc. (MIT Electric Vehicle Team, 2008). The power and energy capacity of an ESS depends on the technology.
- ii. **DOD and SOC:** State of Charge (SOC) is a percentage of power in the battery relative to the total capacity. "It is calculated using current integration to determine the change in battery capacity over time available". Depth of Discharge (DOD) complements the SOC as it is the energy taken out of the battery. For example, a "battery is full at 0% DOD and empty at 100% DOD" (MIT Electric Vehicle Team, 2008; DNV GL, 2019). For ships, the SOC determines the distance the ship can sail with the remaining battery charge and ensures economical fuel consumption on hybrid-electric propulsion systems (Kolodziejski & Michalska-Pozoga, 2023)

- iii. **Battery lifespan and Degradation:** A battery's rate of use, charge and discharge cycles are directly proportional to its degradation. BES degradation is caused by calendric ageing due to BES not being used and cyclic ageing from charging and discharging. These factors should be considered when designing the ESS to avoid early replacement. ESS technologies have different DOC versus degradation relationships (Alsaidan et al., 2018).

2.5 The Effects of ESS on Fuel Consumption and Ramp Rates

I. Platform Supply Vessel

Satpathi et al. (2017) reviewed a platform supply vessel mainly used for logistics and dynamic positioning cruising operations to support offshore supply vessels. Solar PV and ESS were coupled to the DC bus with DC/DC converters and used as alternative energy for the proposed DC PSV. The primary function of the ESS here is for storage and to cater to the power ramps without variations in cost caused by load levelling and peak shaving, as in land applications. The BESS was sized at 10% of the total power demand, and the results showed no significant reduction in fuel consumption when using ESS compared to when the gensets were running on full loads for optimised variable speed and constant speed operation.

Nagalingam et al., (2022) studied the effects of ESS on an offshore supply vessel equipped with gensets, main engine, winches, tunnel thruster, azimuth thruster and auxiliary loads. Operating between 85% - 100% without ESS, the SFOC was 190.05 – 193.2g/kWh. The proposed long-term and short-term peak shaving schedule was to start the standby genset at 70% loading of the running genset or 60% ESS SOC for charging instead of the conventional 50% loading of the running genset. The results showed that using ESS for long-term and short-term peak shaving reduced the need to run the second genset and reduced fuel consumption by 8.44%.

After converting to a battery hybrid-electric system with a 442kWh Li-ion battery, Viking Lady reduced fuel consumption by 10-15% and GHG emissions by 30%. Following this success, batteries were installed on three more similar PSVs, achieving 10-17% fuel reduction and a 36% reduction in engine run time (Kolodziejski & Michalska-Pozoga, 2023). Other results of ESS utilisation were “reduced emissions, improved machinery utilisation and flexibility and reduced maintenance cost involving fewer engine running hours, less running on low loads, longer intervals between planned maintenance and less planned maintenance” ((EMSA European Maritime Safety Agency., 2020).

II. Merchant Vessels

Roh et al., (2019) studied the impact of hybrid power comprising 100kW fuel cells, 30kW battery and 50kW diesel generator on fuel consumption and CO₂ emissions on a 5500 TEU Reefer Container, a 13000 TEU Container, a 40 k DWT Bulk Carrier, 130 k DWT LNG Carrier, and 300 k DWT very large crude oil carrier (VLCC). Different operating profiles for individual vessels were considered, although the operating profiles were scaled down using the linear interpolation method. The 5500 TEU Reefer Container reached a maximum fuel consumption of 40kgoe/h during normal seagoing (with reefer) mode and a minimum of 17kgoe/h during the normal seagoing (without reefer) mode. The effect of the hybrid power on the maximum and minimum consumption was a reduction to 18kgoe/h and 8kgoe/h, respectively. The 13000 TEU Container reached a maximum fuel consumption of 43kgoe/h during the port in/out (with thruster) mode and a minimum consumption of 14kgoe/h during the load/unload mode. The effect of the hybrid power on the maximum and minimum consumption was a reduction to 35kgoe/h and 23kgoe/h, respectively. The fuel consumption of the 40k DWT Bulk Carrier was a maximum of 43kgoe/h during the loading (deck crane) mode and a minimum of 13kgoe/h during the harbouring mode. The effect of the hybrid power on the maximum and minimum consumption was a reduction to 35kgoe/h and 23kgoe/h, respectively. The fuel consumption of the 130k DWT LNG Carrier was a maximum of 43kgoe/h during the port discharging mode and reached a minimum of 23kgoe/h during the port idle gas-free mode. The effect of the hybrid power on the maximum and minimum consumption

was a reduction to 35kgoe/h and 21kgoe/h, respectively. The fuel consumption for the 300k DWT Very Large Crude Oil Carrier (VLCC) was at a maximum of 43kgoe/hr during the port in/out mode and, at minimum, 25kgoe/h during the normal seagoing mode. The effect of the hybrid power on the maximum and minimum consumption was a reduction to 35kgoe/h and 23kgoe/h, respectively. In summary, hybrid power reduced fuel consumption from 43.3kgoe/h to 35.6kgoe/h, equivalent to an 18% reduction. According to Dedes et al., (2012), the fuel savings in merchant vessels when using AG and SG is between 0.5% - 28%.

III. Passenger Vessels

Yu et al. (2018) reviewed a short-routed sightseeing passenger vessel to determine the effect of ESS on fuel consumption and operation cost. The ship has an AC SMG consisting of a 75kW diesel generator, 12kW solar PV and a 3*54kWh lithium battery. The ship operates 9.3 hours daily for 200 days yearly and has a life span of 30 years. The results show that the batteries can produce 96.7kWh without PV, reducing fuel consumption from 51kg/day to 18kg/day. The batteries' SOH is maintained by fully charging the batteries to 100% SOC overnight at a nearby port.

Ritari et al. (2020) studied the effect of BES on diesel mechanical propulsion for a RoPax passenger ferry operating in the Baltic Sea. The ship operates for 48 hours, cruising at 18 knots. One of the benefits of integrating ESS on the ship is that it reduces the power requirement from the engines to meet demand. The efficiency of diesel engines reduces below 50% and quickly deteriorates if the engine is constantly maintained. The electrical network of the RoPax ship consists of four 8145kW DE, two ME, shore connection and a Li-ion battery. The thruster and hotel loads are the primary consumers; peak loads occur during manoeuvring and require additional auxiliary gensets to support the demand. Depending on the battery capacity and operating mode, the simulation results show that the battery provided peak shaving and power generation redundancy. However, during cruising, the battery mainly functioned as reserve power, underutilising the large battery capacity. Overall, reduced fuel consumption and CO₂ emissions were achieved.

2.6 ESS Optimization Techniques

Optimisation is applied in every field of study as the need to improve accuracy increases. The decision-making process of finding the best solution using mathematical formulations is known as an optimisation problem. Solving optimisation problems requires that some functions of the problem are either maximised or minimised depending on the given alternatives. Optimisation problems exist within boundaries known as constraints, which are a range of values within which lies the optimal solution. Optimisation problems that contain integer decision variables are called integer programming problems; when the decision variables have both integer and continuous values, they are called mixed-integer programming (MIP) problems. Generally, optimisation problems consist of variables, objective functions (maximising or minimising) and constraints. Solving optimisation problems is tasking and requires iterative algorithms to solve the problem in real-time, hence the need for high computing tools. Embedded optimisation, however, has made it possible to apply optimisation to automotive, power electronics, robotics, and aerospace problems (Naik, 2018).

Power systems optimisation problems broadly consist of operation and planning decisions. The operational problem considers how to effectively utilise the existing power plants, e.g. optimal power flow, unit commitment, demand side management etc. The planning decisions include expansion and investment decisions, ESS allocation, PMU allocation, etc (Soroudi, 2017). ESS plays a significant role in future power systems, and ESS optimisation is required to realise its full benefits. Optimal sizing of ESS considers factors such as ageing, cost efficiency, optimal charging and discharging, power oscillation, load ramps, etc (Hannan et al., 2021). Misallocating ESS within the power network can reduce the power quality and reliability of the system. Installing ESS in the correct location within the network improves the system's effectiveness and power quality, reduces the network cost, etc (Das et al., 2018).

Optimisation can be defined as the accurate sizing and placement of ESS that is economical and energy-efficient for consumers (Hannan et al., 2021). It also determines the battery's location, capacity, and power rating (Sedghi et al., 2016). An oversized BES is economically unattractive, while an undersized BES is not technically beneficial, hence the need for optimisation (Alsaidan et al., 2018). Some optimisation techniques relevant to ESS sizing and allocation are reviewed below.

- i. **Dynamic Programming (DP):** This is also called dynamic optimisation, which is an optimisation technique that breaks down complex problems into simpler ones. DP can be described as multistage and requires the user to make multiple decisions over a period, and the performance of the results is a function of the decisions made (Fu et al., 2014). DP is used in Oudalov et al. (2007) to determine the optimal operating strategy and battery size of lead acid and vanadium redox (VRF) batteries in an industrial application. The purpose of the battery is for peak shaving application, and the critical determining factor is economic by measuring the reduction of electricity bills. Assumptions made by the authors are that the BESS fixed and O&M costs are known for the different battery technologies. For lead acid, the optimisation results showed that it was not profitable for peak shaving applications of more than 1 hour, and the payback time was six years. The recommended battery capacity was 250 kWh, and the battery power was 280 kW, suitable for replacement for over 20 years. Also, the electricity bill was reduced by 4%. The VRF optimisation had results equivalent to the former, except the recommended capacity was 750kWh.

Mashayekh et al. (2012) used DP to determine the optimal size of the ESS and generator control strategy (first stage) for an electric ferry ship to achieve optimal fuel savings (second stage). The results showed that the size of the battery is directly proportional to the fuel savings and the reduced ramp on the generators. However, it reaches a point of saturation where an increase in battery size does not increase fuel savings.

- ii. Quadratic Programming: A quadratic program (QP) problem has a quadratic objective function and linear constraints. QP is a general representation of linear programming (LP) and is a special type of nonlinear programming (NLP). QP can be applied to engineering ed signal and image processing, computer vison etc, portfolio optimisation, model predictive control, etc. The complexity of QP problems depends on whether the quadratic form is positive semidefinite (PSD). If the quadratic form is PSD, the problem then becomes a convex quadratic program (Moura, 2014).
- iii. Mixed integer linear programming (MILP): MILP solves optimisation problems with linear objective functions and constraints. The objective function depends on two sets of variables, x and y , where x contains continuous variables, and y contains integer variables (Edgar et al., 2001). Ritari et al. (2020) used MILP to create an optimal power management strategy and ESS size for a RoPax ship with the aim of reducing the battery installation cost. The auxiliary genset, battery and shore connection models were created and optimised using GUROBI, which can solve complex problems with high decision variables. A mixed integer quadratic problem (MIQP) is a subset of MINLP for which the decision variable contains both integer and continuous values, and the objective function is quadratic with linear constraints. In MIQP, the quadratic functions are optimised over points in a polyhedral set that have both integer and continuous components (Pia et al., 2014). (Bao et al., 2021) use MIQP to model the optimal ESS sizing problem considering the ESS energy management strategy in a ferry ship. The results showed that ESS utilisation influences the DG optimal loading and reduces CO₂ emissions.

In this thesis, the ESS sizing problem is formulated as an NLP, while the EMS strategy, which includes the generators' unit economic dispatch problems and ESS optimal schedule, is expressed as an MIQP.

2.7 Conclusion

This chapter discussed the use case of ESS in marine in different aspects. Due to ships' unique load profile and criticality, the discussions focused on ESS utilisation on ships. The types of ESS used in marine, their connection topologies, and hybridization were presented. The application of ESS in marine and its effect on fuel efficiency was also discussed, reviewing PSV, passenger vessels, and merchant vessels. An overview of optimisation and different ways optimization problems are defined and solved were presented.

3 Merchant Vessels

Merchant vessels are long-distance ships primarily used to transport consumer and commercial goods such as cars, food, oil, etc. The ship's weight and operating characteristics must be considered to select an optimal energy storage system (Dedes et al., 2012). About 80% of global trade in goods is transported by sea, and trade growth is projected to increase by 3.2% in 2024. Global GHG emissions from international shipping are approximately 3%. An increase in trade volumes will translate to an increase in carbon dioxide (CO₂) emissions from the sector, which is projected to increase from about 90% - 130% of 2008 emissions for energy transition (UNCTAD, 2023). In the Baltic region, the cumulative carbon emission from tankers, dry bulk and general cargo, containers, and roll-on/roll-off vehicle carriers in 2022 was approximately 9MT compared to 0.63MT from passenger and cruise ships (Jalkanen et al., 2023). This highlights the need for decarbonization in this sector to be focused on merchant shipping, especially container shipping, which is made of relatively large vessels sailing at high speeds, leading to high fuel consumption (Dedes et al., 2012). To ensure that shipping remains profitable while decarbonising, policy bodies such as IMO and MARPOL must agree on portfolio measures with shipowners to better align with the GHG emission reduction targets (UNCTAD, 2023).

This chapter introduces the basic architecture of ships' microgrids and merchant vessel operating profiles. The structure of merchant vessel components such as shaft generators, auxiliary gensets and thrusters are also discussed.

3.1 A Ship's Microgrid Electrical Architecture

Power on a ship is required for propulsion and the service loads (P. Wu & Bucknall, 2016). Marine power systems have a long history and have undergone several evolutions, from steam engines to diesel-electric and fully electric vessels. The electrification of marine power systems started from Jacobi's experiment of small

electric-propelled boats to MF Ampere's fully electric-powered passenger and car ferry, showing that continuous research and innovation are required to achieve sustainability and a modern marine power system. As a result, there has been a significant increase in energy efficiency from 91.3% to 92.3%, reliability, space management and the introduction of All Electric Ships (AES) or Integrated Power Systems (IPS), which allows all loads on the vessels to be supplied from a common busbar and generator compared to the conventional power system that had separate power sources for both propulsion and auxiliary loads. IPS allows quick response, power sharing, flexibility and availability, and using fewer prime movers and generators, improving fuel efficiency and lowering exhaust emissions (Mutarraf et al., 2019; Skjong et al., 2016).

The shipboard microgrid (SMG) can range from 1MW - to 100MW soon, raising the need for energy efficiency (Hebner et al., 2016). It comprises electrical and communication networks integrated to enable easy coordination. The Power management system (PMS) coordinates the scheduling and power distribution within the SMG (Nivolianiti et al., 2024). It was common to have the electrical power system as a radial network consisting of diesel generators (DE), thrusters, propulsion systems and hotel loads tied to a 3-phase 400kVA- 4MVA main busbar (Mutarraf et al. et al., 2019). The radial power system is flawed because of the lack of reliability, survivability, efficiency, and inability to handle complex systems. This has led to the emergence of the zonal electrical distribution (ZED) to mitigate these limitations. ZED separates power generation and distribution into zones for easy fault detection and isolation to prevent total blackouts (Jayasinghe et al., 2017).

Planning power dispatch in land-based applications is predictable and manageable by studying the load profiles that seldom vary over time. The load continuously varies on marine vessels due to the change in propulsion load, hence the need to optimise power generation based on the different operation demands (Satpathi et al., 2017). Due to these unpredicted variations, the load calculation for newly built ships is usually based on values from a similar operating ship. The calculations are updated during shipbuilding,

and the final load consumption value is derived after commission and sea trials (Valkeejärvi, 2013). The electrical loads on a vessel are the propulsion system, which has the highest consumption (about 90%); hotel loads for lighting, ventilation, and water purification (Skjong et al., 2016); and pulse loads, e.g. radar and sonar. These loads are highly dynamic, periodic, uncertain, and dependent on environmental factors (Nivolianiti et al., 2024), influencing the ship's operation, load profile, and energy demand. For example, load fluctuation is increased on ships using a heave compensator and dynamic positioning to mitigate the effects of the wave, while cruise vessels have very minimal load fluctuations (Bhujade et al., 2018). In bulk tankers, cargo pumps and compressors are the majority consumers (Valkeejärvi, 2013). It is important to note that the relationship between speed and power is not directly proportional (Tang & Khaligh, 2010) but depends on the ship type, power coefficient, water density and hull characteristics (P. Wu & Bucknall, 2016).

3.2 Merchant Vessel Operating Profiles

Wen et al. (2016) reviewed an oil tanker with dimensions 332.95m, 60m, 30.5m(LWH) and dwt 100,000 tons. The ship sailed four times yearly and took 20 days to navigate from China to Yemen. The hourly load profile of the ship was classified under five conditions: regular cruising, full-speed sailing, docking, loading, and unloading, and anchoring with respective minimum and maximum loads in kW as follows: (1485-1815) (1611-1969), (1480-1810), (1161-1419), (450-550). An equivalent oil tanker reviewed by (Huang et al., 2021) had the following parameters: dimensions 330m, 62m(LW), dwt 100,000 tons, and 25 sailing days from China to Egypt. The vessel operated in cruise, dock, loading and unloading, full speed and anchor with maximum loads of 1580kW, 1650kW, 1290kW, 1790kW, and 500kW. In a Post-Panamax fleet, auxiliary gensets are operated in parallel to support peak loads above 600kW, increasing fuel consumption and reducing overall efficiency (Dedes et al., 2012).

Although some characteristics are the same, generalising a merchant ship's operating profile is quite challenging due to the variation in operation.

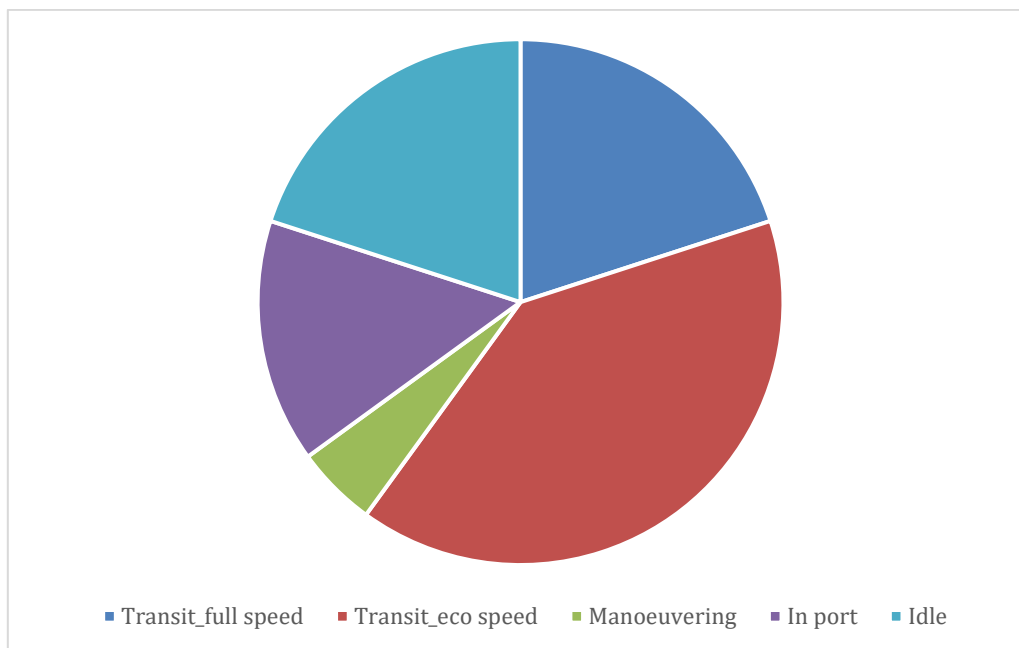


Figure 3- A sample of operating mode time distribution (EMSA European Maritime Safety Agency.,2020)

Merchant ships are expected to provide economical transportation, and solely depending on batteries to reduce emissions defeats that purpose. Due to the long voyage, depending solely on batteries can affect the ship's speed and distance (P. Wu & Bucknall, 2016); instead, it requires a hybridisation of alternative fuels. Using a controllable pitch propeller (CPP), shaft generator, BESS, and shore connection is fast becoming the standard. This combination is called a mechanical hybrid setup, which allows the propulsion and electricity demand to be provided by two or more sources (Kolodziejcki & Michalska-Pozoga, 2023).

Shore power connection, also known as cold ironing, allows electricity to be delivered to the ship from shore. With shore power, the auxiliary gensets are switched off, which creates fuel savings and reduces emissions (Caprara et al., 2021). Depending on the ship size and type, ships spend about 25% of the sailing time at port, so shore connection could also be used to fully charge the batteries during these times, as shown in the table below (K. Kim et al., 2016). The number of port visits and time at port could be used to determine the possibility of charging the ESS using shore power.

| Ship type | Average nominal power (kW) | Number of visits at the same port (p.a) | Time at port per visit (h) |
|-------------------------------------|----------------------------|---|----------------------------|
| Container (2500+TEU feeder service) | 1,200 | 52 | 9 |
| Container (5000+TEU global service) | 2,500 | 8 | 24 |
| Tanker | 1,200 | 20 | 24 |
| Bulk | 800 | 5 | 168 |

Table 1- Power Requirements and Time at Port

3.3 Shaft Generator Technology

As mentioned, technology adoption does not happen quickly in the merchant vessel shipbuilding business. This is mainly due to the sensitivity of sailing operations; hence, only highly matured technologies are adopted, and the industry focuses on technologies with short-term returns on investment. The advantages of electric propulsion and DC SMG are appealing; however, combining full electrification with conventional main engine propulsion using shaft generators is fast becoming a mature technology.

Shaft generators (SG) have historically been used in commercial and naval ship applications. SGs have about 95% efficiency and can deliver full active power from the ME propulsion to meet power demand. They can also be infinite buses (Prousalidis et al., 2005). A shaft generator is a direct drive integrated into the propulsion line of the main engine. The SG converts the excess mechanical power from the ME to electricity for the hotel loads. This is more economical and efficient as it prevents running auxiliary generators, reducing emissions, fuel, and maintenance costs (Michalopoulos et al., 2016). Shaft generators can be operated in generator mode (PTO mode) for medium speed, booster mode (PTI mode) for high speed, and E-motor mode (PTH) for low speed to support electricity production based on demand (K. Kim et al., 2016). The rotation of the main engine depends on the speed and voyage condition; hence, it varies, causing

the SG to produce a varying output frequency. The variable frequency drive then smoothens and stabilises the frequency through the DC link. Shaft generators are sized to power about 80% of the total electrical loads, and they do not require any fuel for electricity production; hence, they create fuel savings. They are space-efficient, have low maintenance costs, are highly reliable, have a lifespan, and generate low noise compared to conventional generators (Prousalidis et al., 2005).

3.4 Auxiliary Generator

The SMG electrical network typically operates on 60Hz and consists of 2 – 10 gas or diesel generators as the primary power source, including an emergency backup generator (Hebner et al., 2016). The low-speed two-stroke is the most used auxiliary engine in marine applications (Dedes et al., 2012). These engines are categorised based on the working principle, design, rpm, power output, fuel used, etc, and are summarised as high-speed four-stroke engines with shaft speeds up to 100kW, high-speed four-stroke engines with shaft power 100 – 10, 000kW, medium-speed four-stroke engines with a shaft power between 5000 - 30, 000 kW and low-speed two-stroke crosshead engines with a shaft power of 1500 – 100,000 kW with 50 - 250 rpm. Fuels such as Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO) are used in these engines, with the main operational costs arising from fuel costs and spare parts (Vieira & Peralta, 2017).

The operation of marine AG contributes to GHG emissions such as nitrogen oxides (NO_x), particulate matter or soot (PM), sulphur Oxides (SO_x), and unburned Hydrocarbons (HC), which form acid rain (Dedes et al., 2012). AG generators like MAN have improved diesel engine technology to operate close to the IMO NO_x limits to ensure compliance with IMO Tier III regulations (Project Guide, 2024).

3.5 Thrusters

Vessels are primarily propelled by thrusters located at the stern. However, manoeuvring a vessel in close quarters, such as at a quay with other vessels nearby, may require additional manoeuvrability. To address this, extra thrusters are designed and installed

to create a transverse water jet. These additional thrusters, when positioned at the bow of a vessel, are known as bow thrusters, and when fitted at the stern of the vessel, they are known as stern thrusters. Nowadays, most inland and ocean-going vessels are equipped with a bow thruster for improved manoeuvrability (Chuku & Theophilus-Johnson, 2017).

Thrusters are smaller propellers installed at either the bow or stern of the vessel. They help improve the ship's manoeuvrability at lower speeds near coastal waters and channels and during port entry and exit. Compared to trading propeller-rudder systems, bow thrusters have better manoeuvrability during ship positioning (Yukun et al., 2020). The use of stern and bow thrusters during manoeuvring eliminates the need to assist tugboats, thereby saving time and cost. Bow and stern thrusters can be powered by either electric, hydraulic, or diesel. They are usually controllable pitch propellers (CPP), which allow the direction of the thrust to be changed (Umana et al., 2022).

3.6 Conclusion

In this chapter, some insight into merchant vessels, their electrical architecture, and major operational profiles was reviewed. Although there are various solutions to reduce carbon emissions, the adoption of these technologies in the merchant shipping industry is slow due to the profit driven business. Shaft generator technology in marine is now a matured technology that has seen widespread adoption. The use of shore power connection during harbouring is gaining adoption due to need to reduce emissions at the ports. Also, the utilisation of shore power depends on the ship's duration at the harbour, power infrastructure compatibility and the cost of shore electricity compared to onboard electricity.

4 Vessel Structure and Optimization Algorithm Design

This chapter discusses the case study features, configuration, simulation and its limitations, data collection and analysis, and methods used in this thesis. This thesis aims to determine the optimal use of ESS to support auxiliary generators and improve energy efficiency in a merchant vessel. The main research question of this study is: How can the ESS onboard a merchant vessel be used to create fuel savings?

The interviews indicated that although most of the academic literature papers reviewed foresee merchant vessels being 100% powered by batteries, this is far from reality as batteries cannot be solely used to power long-distance ships. However, they can serve as catalysts for SMG technology, improvements in fuels, ME, AUX gensets, navigation equipment, etc., as the marine transportation sector is quite delicate, and the ship owners are not yet confident in the solution. It is important to note that although existing vessels with batteries have recorded some cost savings, the monetary values of benefits such as reduced emissions and improved brand image and value arising from supporting the green movement can be difficult to evaluate but should be considered by the shipyard and owners during investment decision making. This simulation is aimed at analysing the possibilities of fuel-saving potentials if the accurate size of batteries is utilised.

Energy system optimisation is divided into design and operations solutions. The system design considers the capacity and placements of the power-generating devices, while the system's operation determines the dispatch strategy of the energy resources per time. The problem defined in this thesis is solved in two levels using GAMS.

4.1 Case Study

The analysed ship is a short-distance merchant vessel under construction and expected to be delivered in 2025. The auxiliary gensets and battery storage system sizes were

determined in the design phase to meet the expected load demand. The load profile and number of sailing days were approximated using available data. It is assumed that a single sail takes about 30 days, during which time the ship will make 3 -5 port calls. This estimation is derived from a similar vessel's automatic identification system (AIS) data.

The ship's SLD and main electrical components are shown in Figure 4 and Table 2

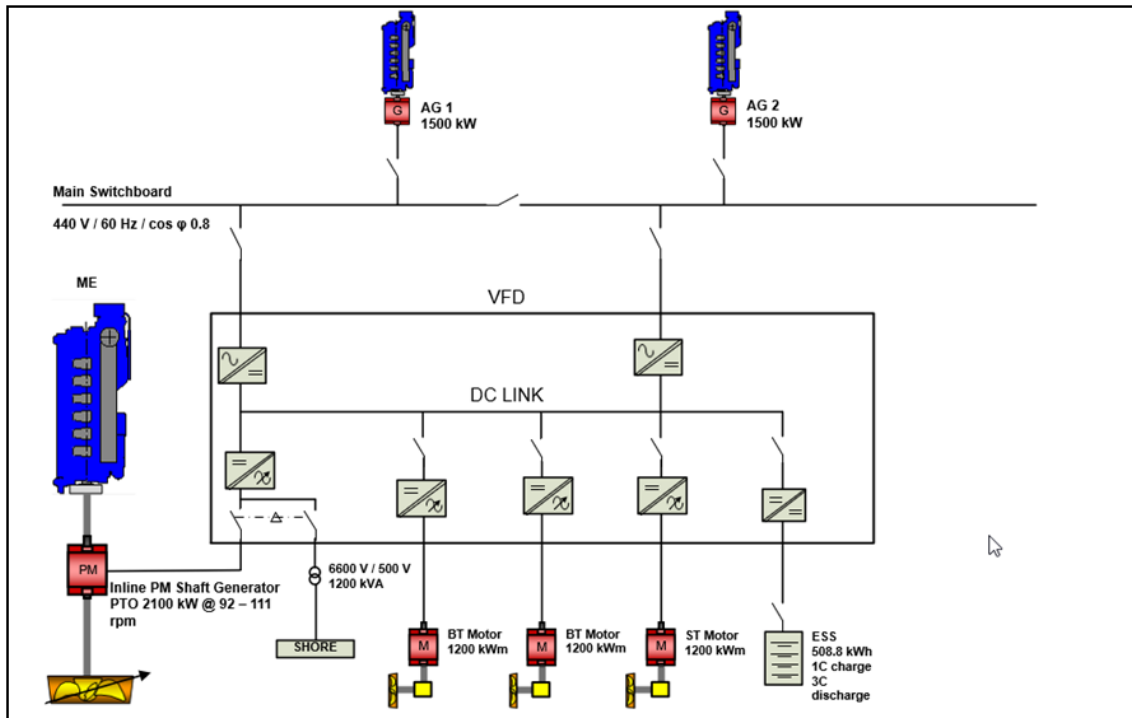


Figure 4: Short-distance merchant vessel SLD

| Components | Nominal size | Number of units |
|-------------------|---|-----------------|
| Auxilliary genset | 1500kW | 2 |
| NMC Battery | 508.8kWh Charge Limit: 1C Discharge Limit: 3C | 1 |
| Bow Thruster | 1200kWm | 2 |
| Stern Thruster | 1200kWm | 1 |
| Shaft Generator | 2100kW | 1 |

Table 2- Vessel's System Parameters

The propulsion system consists of a main engine that drives a single propeller directly connected to the shaft generator. The SG is connected to the electrical network via a VFD and operates in PTO mode as the main power source supplying all loads. Auxiliary

power is produced by two auxiliary generators rated at 1500kW each. Aside from the propulsion systems, the main electricity consumers are the hotel loads, thrusters, and garage ventilation systems. Although ships manoeuvre when crossing canals and high-traffic zones, the case study only considers an estimated 24-hour load profile shown in Figure 5 starting from when the ship approaches the port to berth to show the battery usage and savings. For simulation purposes, the load profile is used to determine the fuel consumption and ESS usage for 30 days per voyage, 11 times a year for 25 years, considering the vessel's lifespan. The average hotel load ranges from 1000kW to 1700kW and is stable but increases to about 4777kW during manoeuvring, with the thrusters functioning at full power for 10-15mins. The thrusters are controlled by converters, which vary their speed depending on the thrust required. Hence, they are connected to the DC link through converters, which ensures the ESS optimally supports the thruster ramps, as seen in the load profile, proving the use case for the batteries. It should be noted that the load profile presented in Figure 5 is assumed to be cyclic between voyages and can be extended for a longer timeline to improve the accuracy of the results.

The ship's load profile has six main operating modes and their specified power consumption: normal seagoing excluding cargo ventilation (1027kW), normal seagoing including ventilation (1669kW), manoeuvring with reduced thruster power (4027kW), manoeuvring with full thruster power (4777kW), loading/unloading including cargo ventilation (2253kW), and harbouring (722kW). To capture the ESS utilisation in transient and steady loads, it is assumed that the ship will manoeuvre three times hence the peak, twice with reduced thruster power and once with full power at t6, t10 and t15, then loading and unloading occur once from t18 – t22. Normal seagoing excluding ventilation occurs at t1-t2, t5, t8-t9, t12-t13, and t16, normal seagoing including ventilation occurs at t3-t4, t7, t11, t14, and t17 while harbouring happens during times t23 – t24. The change from one mode to another affects the power demand, hence the need for an optimal EMS strategy to allocate the power sources effectively.

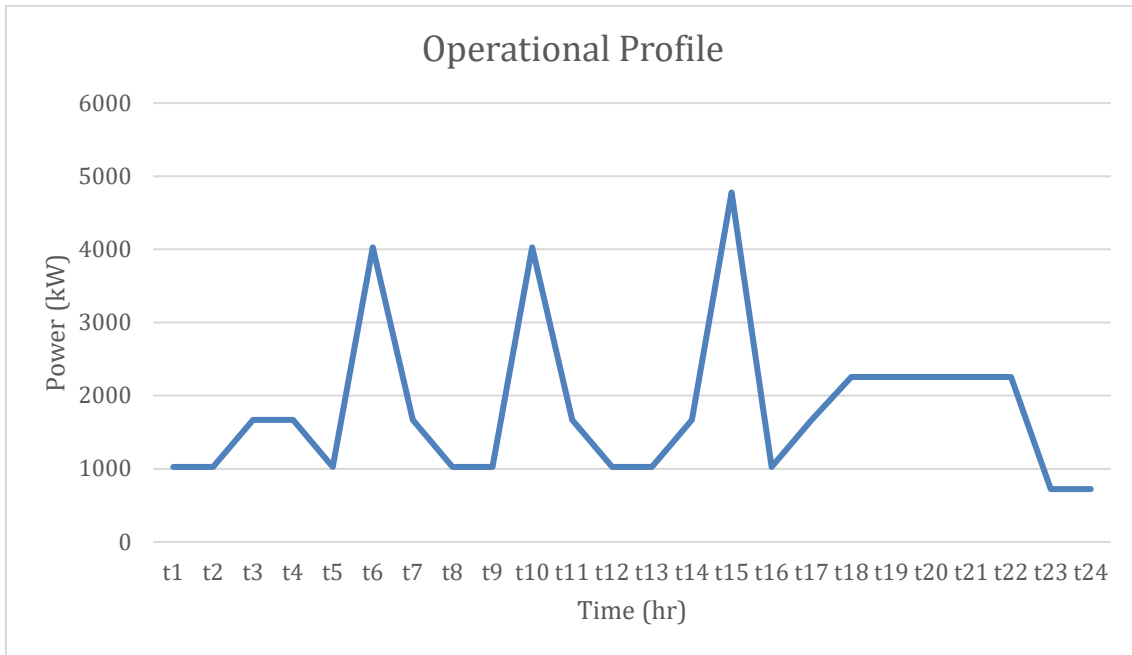


Figure 5: Load profile for 24-hour reference operation.

4.2 Design Considerations

When the ship is approaching the harbour, two auxiliary gensets must be started to meet the transient load demand of the thrusters, the garage ventilation systems, and base hotel loads. The two AGs are synchronised in parallel with the SG to supply the power demand. The total load is equally shared among the gensets to ensure that the engine speed remains balanced during load fluctuations. During normal operation, the second AG provides redundancy, although it causes the AGs to run below minimum loading conditions, reducing their efficiency and increasing fuel consumption. A battery system, when sized accurately, can be used to support the shaft generator and auxiliary genset during demand ramps to reduce the start and stop times of the gensets and provide the required redundancy. For long-term use, batteries are expected to be the same size as an auxiliary genset and be capable of delivering power in all scenarios (Ritari et al., 2020). Currently, long-term battery use and sizing are not feasible in the merchant ship business due to the cost, capacity and efficiency of battery systems.

In this thesis, the battery is mainly sized for 15 minutes of peak shaving during manoeuvring, which is the highest power consumption on the electrical network. Other battery functionalities include blackout prevention and a spinning reserve. During manoeuvring, the hotel loads will be reduced to 1177kW while the SG will be loaded at 52% due to speed limitation on the ME (1092kW), 92% (2700kW) for the two AGs, and 100% (3600kW) for the thrusters. The estimated total power demand during this scenario is 4777kW; hence, there is a need to utilise all four energy sources during manoeuvring. The SoC varies depending on the operating mode, but for ease of simulation, the maximum and minimum values are set at 83% and 13%, respectively, and the max DoD is 80%. Although the vessel is expected to make 3 – 5 port calls during a single voyage, charging the battery during harbouring depends on the electricity price at shore vs the AG's fuel cost (Mashayekh et al., 2012), availability of shore power infrastructure at the port, especially at ports outside the Emission Control Areas (ECAs), and the time spent at the port. Hence, the battery is not always fully charged at the end of the voyage. Due to these limitations, the guaranteed way to charge the batteries is onboard using the SG during low load conditions.

The main engine is MAN 8S50ME-C9.7-GI-HPSCR, the auxiliary engine is WÄRTSILÄ Wärtsilä 8L20DF rated at 1200rpm, 1,500kWe power at 95% nominal generator efficiency, and the shaft generator is The Switch PMM1500-08-AA. For this thesis, MGO has been chosen as the fuel for the ME and AG because the AGs need to run on MGO when in ECA and during harbouring in port. The AGs and SG are used during manoeuvring, while either is used during normal seagoing conditions. The AG optimal fuel efficiency is attained when the engine operates at 75% - 85% loading. Because the SG is directly coupled to the ME and cannot operate without it, the ME's SFOC is used to calculate the SG's generator cost function. Both engine's SFOC was derived from (*Wärtsilä 20DF - Product Guide*, 2018; "Project Guide," 2024), the fuel price is the EMEA average MGO price from December 2023 to June 2024 ([EMEA Average Bunker Prices - Ship & Bunker \(shipandbunker.com\)](https://www.shipandbunker.com) accessed 05.06.2024).

| Load (%) | SFOC (g/kWh) |
|--------------------------------|--------------|
| Wärtsilä 8L20DF | |
| 100 | 197,2 |
| 85 | 196 |
| 75 | 197,2 |
| 50 | 208 |
| MAN S50ME-C9.7-GI-HPSCR | |
| 100 | 168 |
| 75 | 161 |
| 50 | 159 |

Table 3: Generator SFOC values

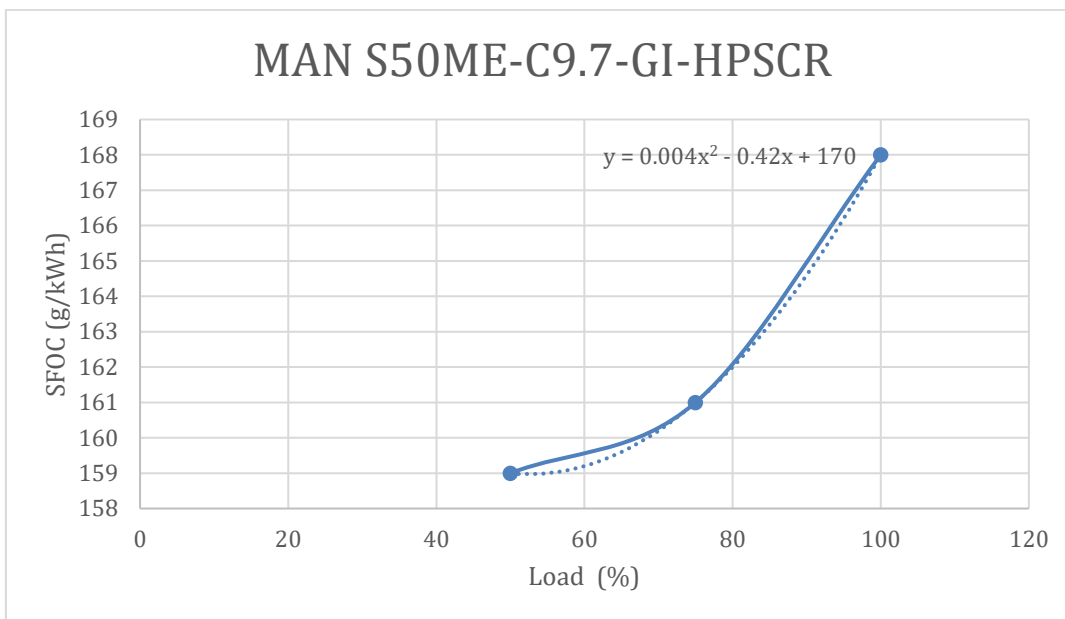


Figure 6: MAN S50ME-C9.7-GI-HPSCR SFOC curve

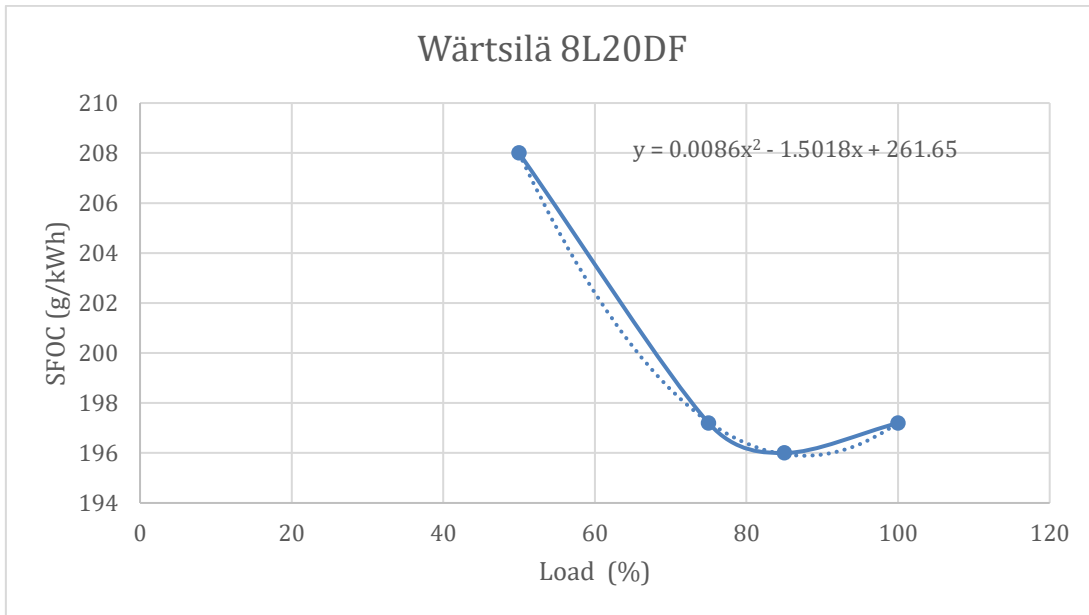


Figure 7: Wärtsilä 8L20DF SFOC curve

The SFOC is an engine efficiency metric that provides information on the amount of fuel oil consumed by the generators per unit of energy output. The curves indicate that the SFOC and power output are lower when the generators are initially started. The SFC continuously increases along with the power output and is not directly proportional to the engine's fuel efficiency performance.

Regarding shore connection, the probability of usage during harbour is not guaranteed; hence, the choice to use this depends on the optimisation tool. The electricity price used is the EU average price for the second half of 2023, €0.2847 per kWh ([Electricity price statistics - Statistics Explained \(europa.eu\)](#)). The voyage fuel and electricity consumption are simulated to compare fuel savings achieved using batteries.

4.3 Modelling and Simulation with GAMS

General Algebraic Modelling System (GAMS) is a modelling language that uses relational algebra to provide "partial derivatives on multidimensional, very large, and sparse structures". Solving mathematical programming and optimisation problems with GAMS

is simpler than using other optimisation tools, which require a high level of proficiency. This is because GAMS provides a convenient way to express optimisation problems, objective functions, constraints, and other parameters using algebraic equations, which the user can enter in a concise and elemental form. However, some knowledge is required to take full advantage of the tool's features. GAMS uses solvers such as CPLEX, Gurobi, SBB, MOSEK, etc, depending on the model type LP, NLP, MIP, etc. GAMS can be used in different fields, such as science, engineering, agriculture, water, finance, etc. The choice to use GAMS in this thesis is because it is user-friendly, the model can be easily represented in human and machine-readable forms, and it supports a wide range of solvers (GAMS, 2024).

4.3.1 Problem Definition

The simulation aims to assess the fuel-saving potentials and the optimised battery size for the short-distance merchant vessel. Finding the optimal ESS size is dependent on obtaining an optimal EMS strategy. The EMS strategy determines the start and stop of the AGs, SG, and battery utilisation based on demand and the cost-effectiveness of the power sources per time. For example, during normal seagoing, the energy demand is low, and it can be covered by the shaft generator while the battery charges or absorbs the load fluctuation instead of running an AG while the ESS can cover the entire load during harbouring. Formulated as a two-fold problem (Bao et al., 2021; Boveri et al., 2019), the EMS strategy provides results such as the charge and discharge power and cycle, the SOC, the energy supplied by each generating unit and battery, the specific fuel consumption, and the total operational cost. These results are useful in determining the accurate ESS size. This optimisation problem is defined in two-fold. First, the optimal EMS strategy is determined, and lastly, the accurate ESS size is determined. The first part is defined as a multi-objective cost-fuel minimisation economic dispatch problem that involves scheduling all power sources, generators, and ESS to meet the demand over the study time. This scheduling is known as the EMS strategy. As shown in Figure 3, the generators, loads, and batteries are modelled using GAMS. GAMS is used to

minimise total costs and fuel consumption and derive the optimal EMS strategy. The second part determines the optimal ESS size by including all known costs, such as the cost of battery and inverter unit and operation cost, including fuel cost and the number of battery replacements, in the calculation to determine the optimal battery size. In GAMS, the problem is formulated as a mixed integer quadratic programming (MIQP) problem solved using the SBB solver to minimise the sailing cost and fuel consumption.

4.4 Problem Formulation

The optimisation problem aims to find the optimal battery size that provides the best cost savings by reducing fuel consumption and providing an optimal EMS strategy. It is divided into two parts: finding the accurate EMS strategy and optimal ESS sizing.

4.4.1 Generation Cost Function and EMS Algorithm

The auxiliary generators have operational parameters such as the maximum power output (P_{imax}), minimum power output (P_{imin}), specific fuel oil consumption (SFOC), and minimum and maximum up and downtimes (UT and DT). For optimal operation, both SG and ME should not be operated below minimum loading points for prolonged periods; otherwise, they are switched off (Bhujade et al., 2018). The minimum uptime (UT) and maximum downtime (DT) of the generators are penalised to minimise the start/stop frequency and operation costs, while the minimum and maximum power limit the generator's outputs.

As shown in Table 3, the specific fuel consumption of the generators is fitted into a polynomial curve to derive the quadratic function in Figure 6 and Figure 7. a_i , b_i , and c_i are generator cost coefficients that can reflect the relationship between power output, fuel usage, and cost. The yearly voyage specific fuel consumption throughout the ship's lifespan is expressed in the Equation (1).

$$SFC_i^{fuel} = \sum_{i,t}^G (a_i P_i^2 + b_i P_i + c_i * 11 * 25 * 30) \quad (1)$$

Where;

- i – generator index
- t – time interval during optimisation
- G – number of generators
- P_i – power generated by the generator (kW)
- a_i (g/kW²h), b_i (g/kW), c_i (g/h)

The total generator operating cost is expressed in Equation (2):

$$C_i^{fuel} = \sum_{i,t}^G (a_i P_i^2 + b_i P_i + c_i u_{i,t} * FC * 10^{-6} * 11 * 25 * 30) \quad (2)$$

- $u_{i,t}$ – binary function indicating the start-up/shut-down status of the generator i at time t
- FC – per unit cost of fuel (€/MT)
- 10^{-6} is used to convert the grams and metric tonnes to kilograms, thereby aligning the units.

The generator units are modelled using an economic dispatch approach with the binary function, $u_{i,t}$. This indicates that the generator does not consume any fuel when shut down. Hence, the power generated per time step is within the maximum and minimum boundaries (Bhujade et al., 2018) as below:

$$u_{i,t} \cdot P_{imin} \leq P_{i,t} \leq u_{i,t} \cdot P_{imax} \quad (3)$$

Additional start-up ($v_{i,t}$) shutdown ($w_{i,t}$) variables are given by Equation (4)-(6), showing the difference between the generator's states at the time $u_{i,t-1}$ and $u_{i,t}$. The value of these variables can only be 0 or 1.

$$v_{i,t} - w_{i,t} = u_{i,t} - u_{i,t-1} \quad (4)$$

$$u_{i,t} \geq \sum_{t=1}^T UT \cdot v_{i,t} \quad (5)$$

$$1 - u_{i,t} \geq \sum_{t=1}^T DT \cdot w_{i,t} \quad (6)$$

Where T represents the total time step of the study.

The EMS algorithm is derived by integrating the ESS with the generator. The battery state of charge (SoC) is related to the capacity available during charge and discharge at the t-th time step. At time step 1, the initial SoC (kW), SoC_0 , has the same value as SoC_t as:

$$SoC_t = SoC_0 \text{ when } t = 1 \quad (7)$$

Otherwise as in (Soroudi, 2017),

$$SoC_t = SoC_{t-1} + (P_{ess(t)}^c \cdot \eta_c - \frac{P_{ess(t)}^d}{\eta_d}) \Delta t \quad (8)$$

Where,

- η_d, η_c – discharge and charge efficiency (%)
- Δt – change in time (h)
- SoC_{t-1} – SoC at the previous interval

Both the battery system's charge and discharge power are constrained limits, as expressed in Equations (9)-(12). Equation (12) ensures that the battery is charged to at least the initial SoC value at the start of the voyage.

$$0 \leq P_{ess(t)}^d \leq C_d \cdot E_{ess_{nom}} \quad (9)$$

$$0 \leq P_{ess(t)}^c \leq C_c \cdot E_{ess_{nom}} \quad (10)$$

$$SoC_{min} \leq SoC_t \leq SoC_{max} \quad (11)$$

$$SoC_t = SoC_0 \text{ for } t=24 \quad (12)$$

Where,

- C_c and C_d - battery charge and discharge rate
- $E_{ess_{nom}}$ - the nominal ESS energy
- SoC_{min}, SoC_{max} are the minimum and maximum state of charge
- SoC_0 is the initial SOC at time t=1

The following constraints are applied to the EMS algorithm, as expressed in Equation (13), to ensure energy supply and demand balance.

$$\sum_{t=1}^G P_{i,t} + P_{ess(t)}^d + G_t \geq L_t + P_{ess(t)}^c \quad (13)$$

Where,

- L_t = load demand for the study period

4.4.2 ESS Optimal Size Selection

GAMS is used to minimise the total installation and operational costs throughout the ship's lifetime. The ESS sizing is integrated with the EMS problem by introducing five additional constraints and variables. This addition does not increase the computational burden of the tool. A detailed description of the equation is given below.

i. Problem input

The parameters of the battery, such as charge current C_c , discharge current C_d , rated power in charge P_{ESSc} and discharge mode P_{ESSd} , maximum E_{ESSmax} and minimum energy E_{ESSmin} capacity, initial State of Charge SoC_0 , nominal cost of the BESS per kWh $C_{instESS}$, cost of the inverter $C_{instINV}$, number of battery replacement N_{rep} throughout the ship's lifespan and the charge and discharge efficiency, η_c, η_d , of the ESS.

ii. Problem Variable

The battery size, E_{ESS} is the only decision variable considered, and due to the ship's space constraints, the optimal size is constrained to Equation (14).

$$E_{essmin} \leq E_{ESS} \leq E_{ESSmax} \quad (14)$$

iii. Objective function

The objective function is to minimise the total cost of the generator and batteries over the ship's entire life span. The total cost TC is calculated as the sum of the installation cost of the ESS and DC/DC converter, IC , and the operation cost OC of the ship as expressed in Equation (15).

$$TC = IC + OC \quad (15)$$

The installation cost IC is the sum of the installation costs C_I of both the ESS and the DC/DC converters and their replacement costs C_R as expressed in Equation (16)

$$IC = C_I + C_R \quad (16)$$

The initial cost comprises the ESS C_{ESS} and the DC/DC converter C_{INV} costs. The ESS cost is calculated as the product of the per kWh of the ESS $C_{instESS}$ and its size E_{ess} . These costs are expressed in the Equation (17) – (18).

$$C_I = C_{ESS} + C_{INV} \quad (17)$$

$$C_{ESS} = C_{instESS} * E_{ess} \quad (18)$$

Considering the ship's operational life span of 25 years, the systems replacement cost C_R depends on battery features such as the DoD and $N_{C_{Tot}}$ and the EMS strategy adopted. If the DC/DC converter has the same lifespan as the vessel and would not require replacement, the calculated replacement only included the battery, which, according to the manufacturer's datasheet, has a lifespan of 10 years. The replacement cost C_R is expressed in Equation (19).

$$C_R = C_{instESS} * E_{ess} * N_{replacement} \quad (19)$$

Where C_{ESS} , and $N_{replacement}$ are the cost and number of replacements for the ESS. The number of replacements for the ESS depends on the battery discharge parameters, such as the total number of daily charge /discharge cycles and the total cycle throughout the battery lifespan. To represent the business scenario where the battery replacement is not certain and depends on operational cost, the number of replacements is fixed as 1.

Now, Equation 15 can be rewritten, as shown in Equation (20).

$$TC = C_{instESS} * E_{ess} * (N_{rep} + 1) + C_{INV} + OC \quad (20)$$

It is important to note that the total cost, TC, does not account for the battery and generator maintenance cost and the generator capex but only considers generator fuel consumption vis a vis ESS installation.

IV. Constraints

Additional constraints are added to the energy management problem to adequately size the battery, as expressed below.

$$0 \leq P_{ess(t)}^d \leq C_d * E_{ess} \quad (21)$$

$$0 \leq P_{ess(t)}^c \leq C_c * E_{ess} \quad (22)$$

$$0.13 * E_{ess} \leq SoC_t \leq 0.83 * E_{ess} \quad (23)$$

$$E_{ess_{min}} \leq E_{ess} \leq E_{ess_{max}} \quad (24)$$

Where $E_{ess_{max}}$ and $E_{ess_{min}}$ are the search range for the optimal ESS size.

Table 4 provides the parameters used for the simulation.

| Parameters | Values |
|-------------------------------------|--|
| Inputs: | |
| AG Pmin and Pmax | 450kW and 1350kW |
| SG Pmin and Pmax | 600kW and 1890kW |
| Fuel cost (FC) | 806.83€/Mt |
| C_c and C_d | 1C and 3C |
| Generator sizes (Pmax) @92% loading | 2*1350kW + 1890kW |
| N_{rep} | 1 |
| SoC_{min} and SoC_{max} | 66.144kWh and 422.304kWh |
| $E_{ess_{nom}}$ | 508.8kWh |
| η_d, η_c | 0.9 and 0.95 |
| G | 3 |
| T | 24 |
| SG cost coefficient | a= 0.004, b=-0.42, c= 170 |
| AG cost coefficient | a =0.0086, b=-1.5018, c=261.65 |
| $C_{inst_{ESS}}$ | € 676,547 |
| $C_{inst_{INV}}$ | € 23.000,00 |
| Variables: | |
| $P_{i,t}$ | Power generated by the generator at time t |
| $v_{i,t}$ | Start-up variable |
| $w_{i,t}$ | Shut-down variable |
| SoC_t | State of charge at time t |
| $P_{ess(t)}^d, P_{ess(t)}^c$ | Charge and discharge power at time t |
| E_{ess} | Energy capacity of the battery |

Table 4: Optimisation Parameters

4.5 GAMS Code Snippets

The GAMS code snippet below is a set that corresponds to the indices in the algebraic representation of the model. The set declared below is the time of and the generator index. The term 'Alias' means that the indices t is the same as h.

```

sets
t 'time' /t1*t24/
i 'generator index' /g1*g3/;
Alias (t,h);

```

In the GAMS code snippet below, g1, g2, and g3 represent the auxiliary genset 1 (AG1), auxiliary genset 2 (AG2) and the shaft generator. Other data in the table are the generator coefficients, Pmin and Pmax, and the uptime and downtime constraints as expressed in Equations (2), (3), (5), and (6).

Table gendata (i,*) generator cost characteristics and limits

| | a | b | c | Pmin | Pmax | UT | DT |
|-----------|----------|----------|----------|-------------|-------------|-----------|-----------|
| g1 | 0.0086 | -1.5018 | 261.65 | 450 | 1500 | 4 | 3 |
| g2 | 0.0086 | -1.5018 | 261.65 | 450 | 1500 | 4 | 3 |
| g3 | 0.004 | -0.42 | 170 | 600 | 2100 | 4 | 0; |

The load profile presented in Figure 5 is represented in GAMS snippet below. The keyword `Parameter` is a GAMS identifier that declares the parameter load and its assigned values.

```

Parameter load(t)/t1 1027,t2 1027,t3 1669,t4 1669,
t5 1027,t6 4027, t7 1669,t8 1027,t9 1027,t10
4027,t11 1669,t12 1027,t13 1027,t14 1669,t15
4777,t16 1027,t17 1669,t18 2253,t19 2253,t20
2253,t21 2253,t22 2253,t23 722,t24 722/;

```

The GAMS snippet below represents all the problem decision variables. The term `Variable` is a GAMS identifier indicating the variable statement. The keyword `binary variable` indicates a discrete variable that only takes values of 0 and 1. These values are unknown until the model is solved.

```

Variables TC Total Cost
p(i,t) Power generated by DG
SFC Fuel Consumption
SOC(t), Pc(t), Pd(t);
binary variable U(i,t), y(i,t), z(i,t);

```

The GAMS snippet below represents some of the problem's constraints, where p_{lo} and p_{up} represent the generators' lower and upper bounds i.e. their minimum and maximum values. As stated earlier in the design considerations, during manoeuvring, the rotational speed of the ME is restricted, hence affecting the power that can be generated from the SG at that time. Only 52% of the SG's

capacity can be used at this time the limit on g3, line 3. Lines 4-10 indicate that the SG is switched off at times t18-t24 during loading/unloading and harbouring. Lines 11-12 correspond to the operator's requirement that only one AG can be used during harbouring at times t23-t24.

```
p.lo(i,t) = 0*gendata(i,"Pmin");
p.up(i,t) = 0.9*gendata(i,"Pmax");
p.up('g3', 't15') = 0.52*gendata('g3',"Pmax");
p.up('g3', 't18') = 0*gendata('g3',"Pmax");
p.up('g3', 't19') = 0*gendata('g3',"Pmax");
p.up('g3', 't20') = 0*gendata('g3',"Pmax");
p.up('g3', 't21') = 0*gendata('g3',"Pmax");
p.up('g3', 't22') = 0*gendata('g3',"Pmax");
p.up('g3', 't23') = 0*gendata('g3',"Pmax");
p.up('g3', 't24') = 0*gendata('g3',"Pmax");
p.up('g2', 't23') = 0*gendata('g2',"Pmax");
p.up('g2', 't24') = 0*gendata('g2',"Pmax");
```

The GAMS snippet below represents the scalar data, which is a parameter with no domain and a single value. SOC0 is the initial SoC which varies from 30%-75%, Socmax, Soc.up and Soc.lo are all SoC constraints, as expressed in Equation (10). eta_c, eta_d are the charge and discharge efficiencies as in Equation (7). Eessnom is the nominal ESS capacity as expressed in Equation (8), Cinst_ess is the cost of installing one kWh of battery, Nrep is the number of replacements, Cinst_inv is the total cost of the battery converters, Dt is the change simulation step time, and FC is the fuel cost. Pc.up(t), Pc.lo(t), Pd.up(t), and Pd.lo(t) are the charge and discharge power constraints as expressed in Equations (20) and (21). SoC.fx('t24') = SOC0 allows the battery to be charged up to the initial SoC value at the end of the voyage, as expressed in Equation (10).

Scalar

```
SOC0/152.64/,SOCmax/422.304/,eta_c/0.95/,eta_d/0.9/,Eessnom/508.8/,Cinst_ess/676.547/,Nrep/1/,Cinst_inv/23000/,Dt/0.25/,FC/806.83/;
SOC.up(t)=Socmax; SOC.lo(t)=0.13*eessnom;
Pc.up(t)=1*Eessnom;Pc.lo(t)=0;Pd.up(t)=3*Eessnom;
Pd.lo(t)=0;
SoC.fx('t24') = SOC0;
```

The GAMS snippet below represents equations used in this problem. The keyword Equations shows the relationship between the data and the

variables. `Genconst3` and `Genconst4` are the generator constraints expressed in Equation. `TCcalc` is the mathematical expression in Equation (20), `SFCcalc` is the mathematical expression in Equation (1), `balance` is the mathematical expression in Equation (12), `ESSconst1` is the mathematical expression in Equation (7), and `uptime` and `Dntime` are the mathematical expressions in Equations (4) and (5).

In these **Equations**, `=e=`, `=g=`, and `=l=` are mathematical relations that state equality, greater than or equal to, and lower than or equal to, respectively.

```

Equations Genconst3, Genconst4, TCcalc, SFCcalc,
balance, ESSconst1, uptime, Dntime;
TCcalc..TC=e=sum((t,i),(gendata(i,'a')*sqr(p(i,t))
)+gendata(i,'b')*p(i,t)+gendata(i,'c')*u(i,t))*FC
*power(10,-6)*11*25*30)+
Cinst_ess*ees*(Nrep+1)+Cinst_inv;
SFCcalc..SFC=e=sum((t,i),(gendata(i,'a')*sqr(p(i,
t))+gendata(i,'b')*p(i,t)+gendata(i,'c'))*11*25*3
0);
Genconst3(i,t)..p(i,t)=l=U(i,t)*0.9*gendata(i,'Pm
ax');
Genconst4(i,t)..
p(i,t)=g=U(i,t)*gendata(i,'Pmin');
ESSconst1(t)..SOC(t)=e=soc0$(ord(t)=1)+SOC(t1)$(o
rd(t)>1)+dt*(Pc(t)*eta_c-Pd(t)/eta_d);
Uptime(i,t)..u(i,t)=g=sum(h,gendata(i,"UT")*
y(i,t));
Dntime(i,t)..1-
U(i,t)=g=sum(h,gendata(i,"DT")*z(i,t));
balance(t)..sum(i,p(i,t))+Pd(t)=g=load(t)+Pc(t);

```

In the GAMS snippet below, the keyword `Model` represents all the equations listed in the code to be handled and `solve` is used to solve the declared model. The `solve` statement calls the model name `OptimalESS`, the type of model `us miqcp`, the aim of the object function `min`, and the variable to be optimised `TC`. The keyword `option limrow` is used to maximise the number of rows listed in one equation block, and here, it is set to 3 to reduce the listings of all equations. It is important to note that this does not affect the correctness of the results. The parameter `report(t,*)` is used to make reporting easy, `display` shows the load, cumulative power generated by the units, the `SoC`, power discharge, and power charge per time throughout the study period.

```

Model OptimalESS /all/;
option limrow=3;
Solve OptimalESS us miqcp min TC;

```

```

Parameter report(t,*);
report(t, 'Load') = load(t);
report(t, 'Pit') = sum (i,p.l(i,t));
report(t, 'SoC') = SOC.l(t);
report(t, 'Pd') = Pd.l(t);
report(t, 'Pc') = Pc.l(t);
display report;

```

In the snippet below, the `execute_unload` command is used to create a GDX file called `OptimalESS.gdx`. The solution `P` and the marginals of `P` in the GDX file can be written to the Excel file `OptimalESS.xlsx` using the `GDXXRW` tool

```

execute_unload 'OptimalESS.gdx' P.l
execute 'gdxxrw.exe OptimalESS.gdx var=P rng=P
TC!a1'
execute_unload 'OptimalESS.gdx' rep
execute 'gdxxrw.exe OptimalESS.gdx par= report
rng=report! a1'

```

4.6 Conclusion

This chapter discusses the research methods used to break down the problem into solvable parts. It discusses the peculiarity of the case study and declares the assumptions made on it, which could affect the accuracy of the results. The problem is divided into two parts: the EMS strategy and the ESS sizing, which are solved using GAMS. An EMS strategy is required to adequately utilise and allocate the energy sources, generator and battery on the vessel. The problem is formulated as a mixed integer quadratic problem (MIQP) and solved as an economic dispatch problem using the SBB solver. The problem inputs, such as the battery and generator parameters, variables and constraints that ensure that the system operates within permissible limits, are defined. These values are useful information for selecting the optimal ESS size. The main input for the simulation is summarised in Table 4.

5 Results and Discussion

This chapter discusses the application of the proposed research method to the short-distance merchant vessel under study. The load profile in Fig 3. is static and only considers the vessel's main operational modes. The duration of each mode is based on manoeuvring, which is planned for 15 minutes. For easy simulation, it has been restricted to two hours from the vessel's approach to the harbour. The load demand increases as the modes change. During normal seagoing, excluding cargo ventilation, it is expected that either the SG or one AG supplies power; when cargo ventilation is included, it is expected that two AGs or the SG supplies the power. During manoeuvring with reduced thruster power, the two AGs and the SG should provide the power; peak load is reached during full thruster power; hence, two AGs and SG are the main power sources, while the battery storage assists with load management. During loading and unloading at the harbour, two AGs are expected to supply power, and during idle harbouring, only one AG is expected to supply power. It is important to note that the limitation on the genset operation limits the flexibility of the solver in assigning units.

Due to the limited availability of consumption data, a 24-hour consumption is modelled, and the total fuel consumption is calculated. Although the load profile remains the same throughout the simulation, the variation in SoC levels at the beginning and end of the voyage affects the cost of operation and fuel consumption. The simulation has been made to ensure that the battery is charged at the harbour at the end of the voyage to its initial capacity at the start of the voyage. Load optimisation using the battery at different SoC levels is shown in Figure 6. This ensures that the generator operates at optimal points during the low load conditions and that the battery can be used for peak shaving during manoeuvring out of the port.

5.1 Sensitivity Analysis

A sensitivity study on how varying the ESS SoC and size affects fuel savings has been performed. Also, the fuel consumption if the ESS is replaced with an auxiliary generator is studied.

5.1.1 EMS Strategy and Optimisation Using the Actual ESS Size

The results below analyse the resulting optimised EMS strategy using the exact ESS size of 508.8kWh to show the battery utilisation and effects on fuel consumption over the ship's 25-year life span.

5.1.1.1 75% SoC at The Start and The End of Voyage

The results below in Figures 7 -9 show the battery and generator's behaviours when the battery SoC is 75% at the beginning and end of the voyage. In Figure 9 and Figure 10, at time t1, AG1 and the ESS supply power to the loads; at time t2, the SG is the only power source while charging the ESS; at t3-t4, the SG and the ESS are the power sources; at t5, the SG is the only power source while charging the ESS. During the peak at t6, all three gensets and the ESS supply power to the loads. When the load reduces at t7-t9, the SG, AG1 and AG2 supply power while charging the ESS. Due to a further reduction in the load at t8-t9, AG2 is switched OFF while AG1 and SG are ON. The manoeuvring at t10 and t15 increases the power demand; hence, AG1, AG2, SG and ESS are utilised. The ESS is then charged when the load reduces at t11-t14, with the AG1, AG2 and SG running at t11, then only SG at t12-t13 until the demand gradually increases at t14, requiring the starting of AG1. The ESS is then charged when the load is reduced at t16-t17 while the AG1 and SG and AG1, AG2, and SG supply the required power. During loading and unloading at t18-t20, the ME is switched OFF; hence, the SG cannot be used. Therefore, AG1, AG2, and the ESS supply the power. It is expected that only one AG will operate during harbouring at t23-t24; hence, AG1 supplies the power while the ESS charges. Charging the ESS at the end of the voyage is important so that the ESS can be used for

manoeuvring when leaving the port. This optimal EMS strategy ensures that none of the generators operate below its minimum loading values, as shown in Figure 8, and prioritises the SG as the main power source to meet the power demand except at the harbour during load, unloading, and harbouring, as seen in Figure 9. Figure 8 shows the load optimisation ability of the battery, and Figure 9 shows the battery's peak shaving and spinning reserve function during peak loads at t6, t10, and t15. Instead of starting additional AGs at t1, t3, t4 and t18 - t22, the battery is discharged to provide power.

The calculated SFC using Equation (1) in this scenario is 2144.2MT. A high SoC at the start of the voyage is good and enables the battery to be utilised for manoeuvring when leaving the port; however, it increases the SFC due to the need to charge the battery to the same level at the end of the voyage hence the high fuel consumption compared to the other cases where the SoC is 50% and 30% at the beginning and end of the voyage. Also, comparing this scenario with the scenario without a battery has no fuel savings, -1%. This establishes that battery usage affects cost and fuel savings.

In summary, for this scenario, AG1 and SG are used more as the prioritised power sources, while AG2 and the ESS are used as supplementary power sources. The cumulative start and stop of the generators, as well as the battery charge and discharge cycle, are recorded in Table 5.

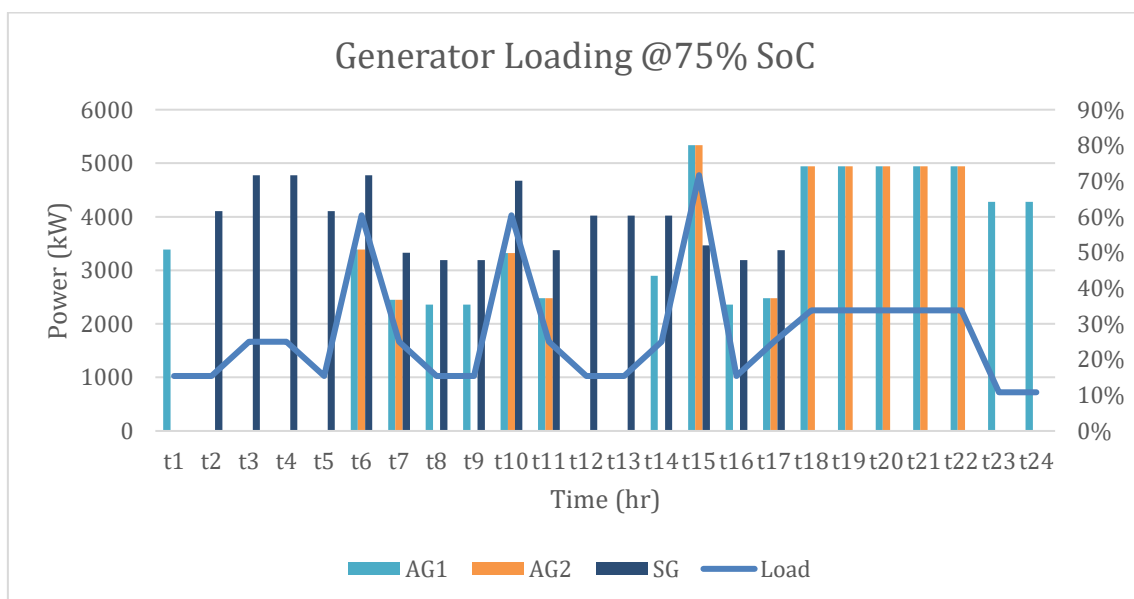


Figure 8: Load Optimization and EMS Strategy

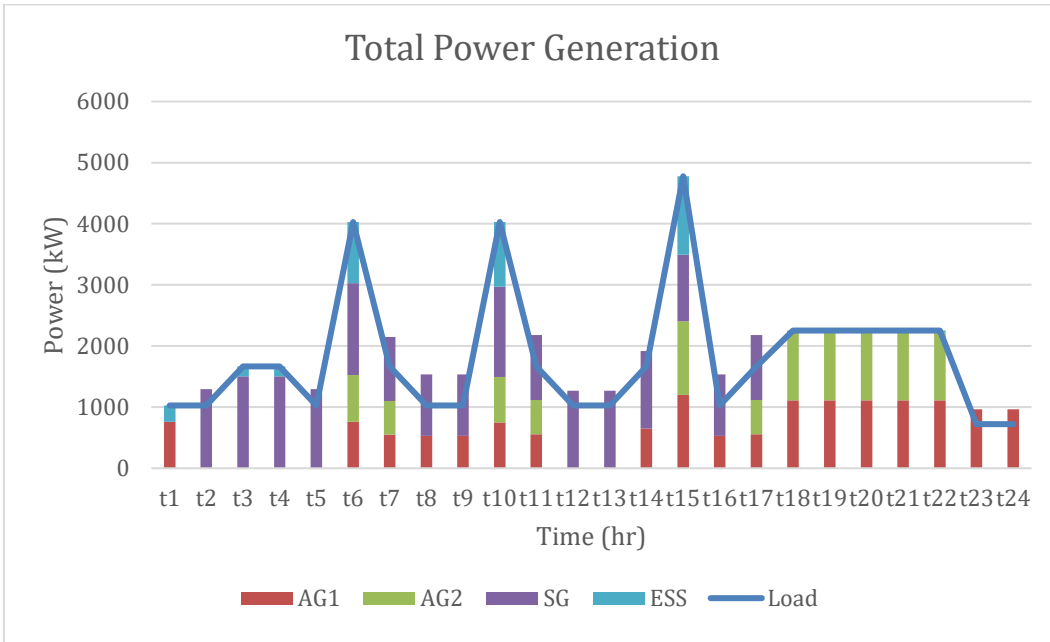


Figure 9: Total Power Generation from All Sources.

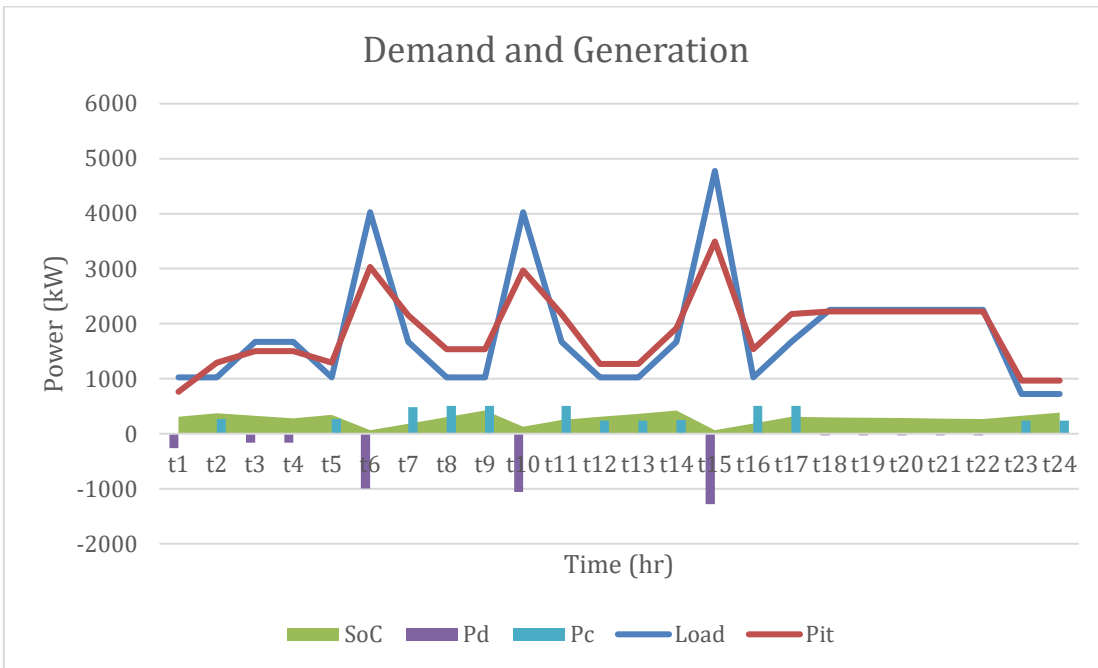


Figure 10: Battery Peak Shaving and Spinning Reserve During Generation and Demand.

5.1.1.2 50% SoC at the Start and End of Voyage

The results below in Figure 11 - Figure 13 shows the battery and generator's behaviours when the battery SoC is 50% at the beginning and end of the voyage. In Figure 12 and Figure 13, the battery charges at times t1 and t2, while only the SG, the SG and AG2 supply power to the loads, respectively; at t3-t4, the SG and the ESS are the power sources; at t5, the SG are the only power source while charging the ESS. During the peak at t6, all three gensets and the ESS supply power to the loads. When the load reduces at t7-t9, the SG, AG1 and AG2 supply power while charging the ESS. Due to a further reduction in the load at t8-t9, AG2 is switched OFF while AG1 and SG are ON. The manoeuvring at t10 and t15 increases the power demand; hence, AG1, AG2, SG and ESS are utilised. The ESS is then charged when the load reduces at t11-t14, with the AG1, AG2 and SG running at t11, then only SG and AG1 at t12-t13 until the demand gradually increases at t14, requiring the starting of AG2. The ESS is then charged when the load is reduced at t16-t17 while the AG1 and SG and AG1, AG2, and SG supply the required power, respectively. During loading and unloading at t18-t20, the ME is switched OFF; hence, the SG cannot be used. Therefore, AG1, AG2, and the ESS supply the power. It is expected that only one AG will operate during harbouring at t23-t24; hence, AG1 supplies the power while the ESS charges. Charging the ESS at the end of the voyage is important so that the ESS can be used for manoeuvring when leaving the port. This optimal EMS strategy ensures that none of the generators operate below its minimum loading values, as shown in Figure 11, and prioritises the SG as the most used power source to meet the power demand except at the harbour during load, unloading, and harbouring, as seen in Figure 12. Figure 11 shows the battery's load optimisation ability and Figure 13 shows the battery's peak shaving and spinning reserve function during peak loads at t6, t10, and t15. Instead of starting additional AGs at t1, t3, t4, and t18 - t22, the battery is discharged to provide power.

As in the first scenario, the calculated SFC is 2092.9MT and higher than the fuel consumption when the SoC is 30% at the beginning and end of the voyage. Also, comparing this scenario with the scenario without a battery has fuel savings of 1.42%.

The cumulative start and stop of the generators, as well as the battery charge and discharge cycle, are recorded in Table 5.

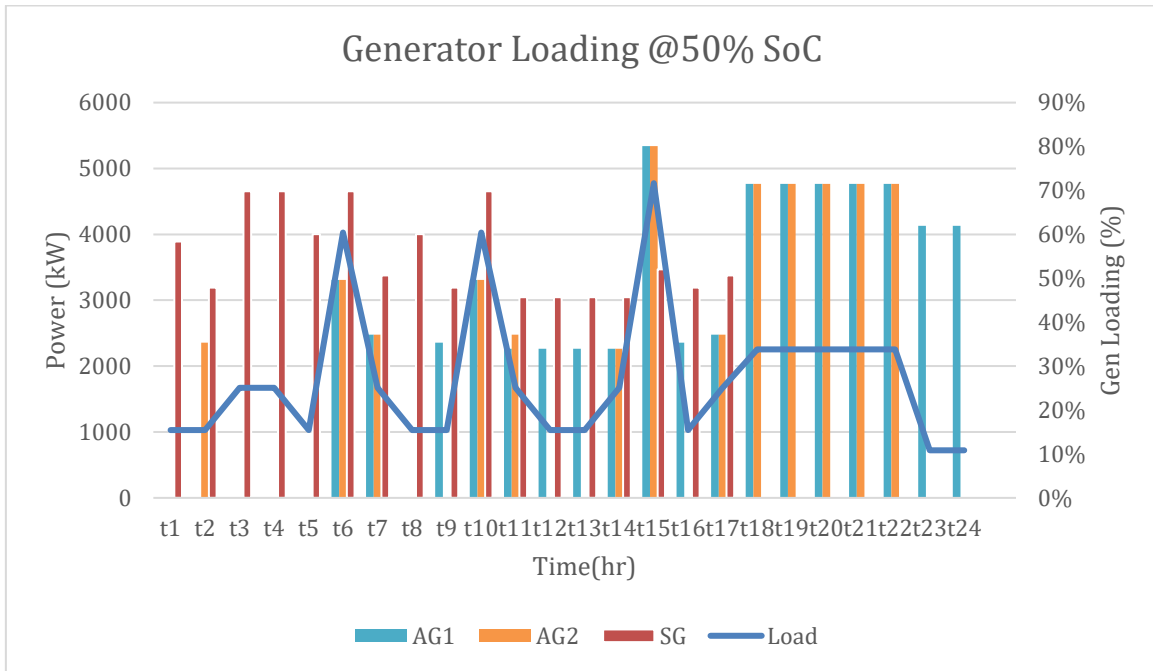


Figure 11: Load Optimization and EMS Strategy

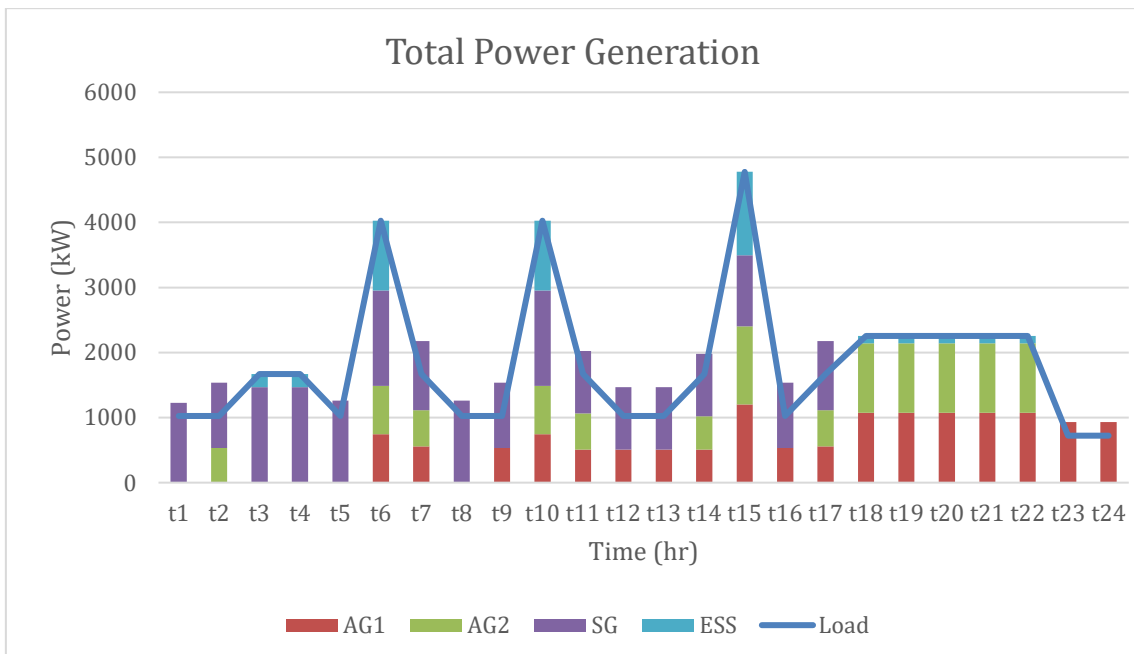


Figure 12: Total Power Generation from All Sources.

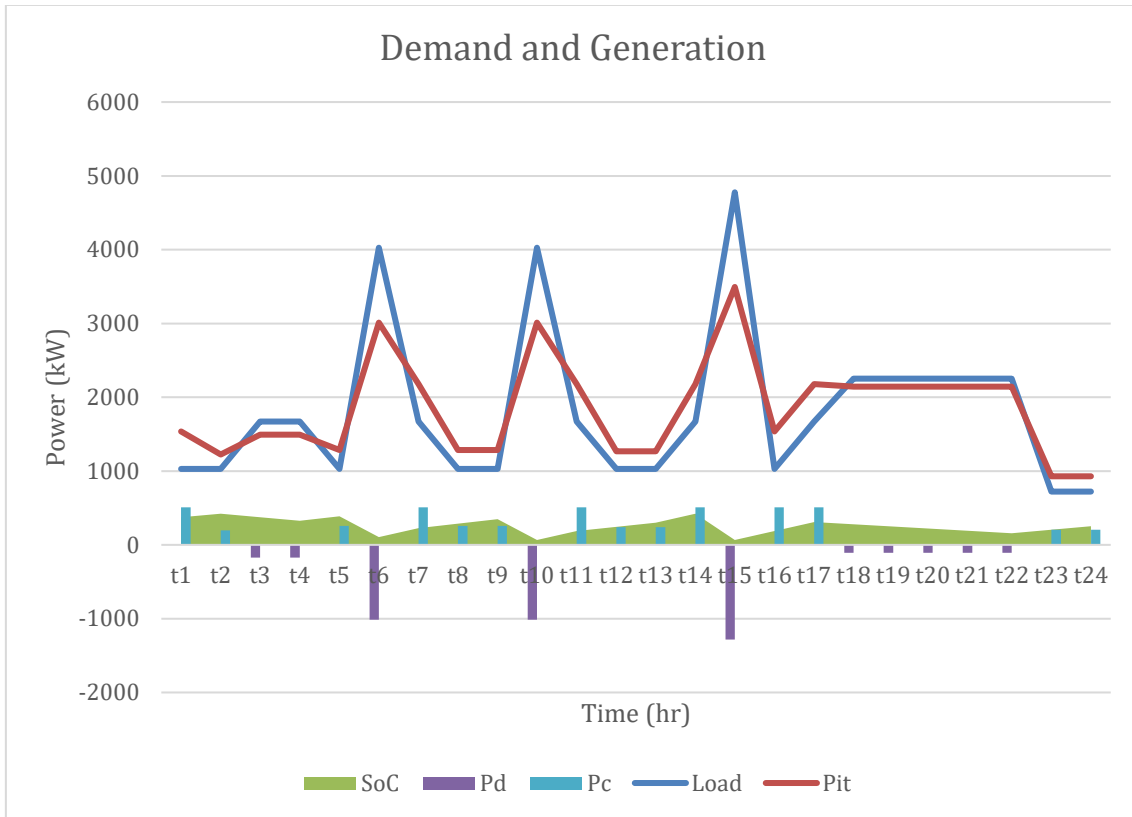


Figure 13: Battery Peak Shaving and Spinning Reserve During Generation and Demand

5.1.1.3 30% SoC at Start and End of Voyage

The results below in Figure 14 - Figure 16 shows the battery and generator's behaviours when the battery SoC is 30% at the beginning and end of the voyage. The results analysis is similar to that of the first two scenarios, with the key differences being in the ESS availability and utilisation. Due to the low initial SoC, the battery is unavailable for use until t6, as shown in Figure 15 and Figure 16; also, all generators are evenly utilised.

As in the previous two scenarios, the calculated SFC is 2060.3MT, which is lower than the previous two. Comparing this scenario with the scenario without a battery, we see that it has fuel savings of 3.03%. The cumulative start and stop of the generators, as well as the battery charge and discharge cycle, are recorded in Table 5.

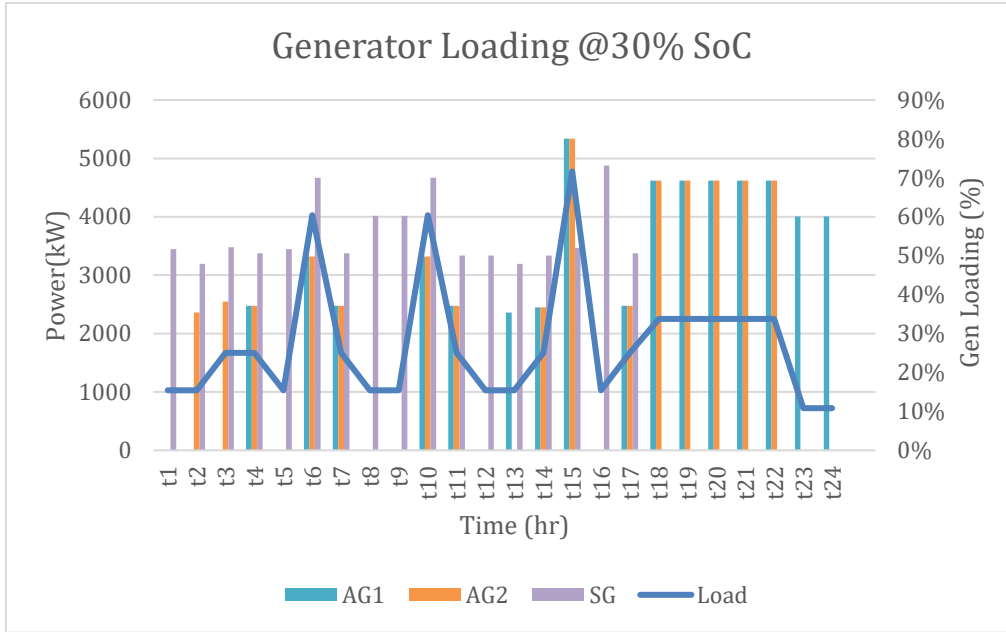


Figure 14: Load Optimization and EMS Strategy

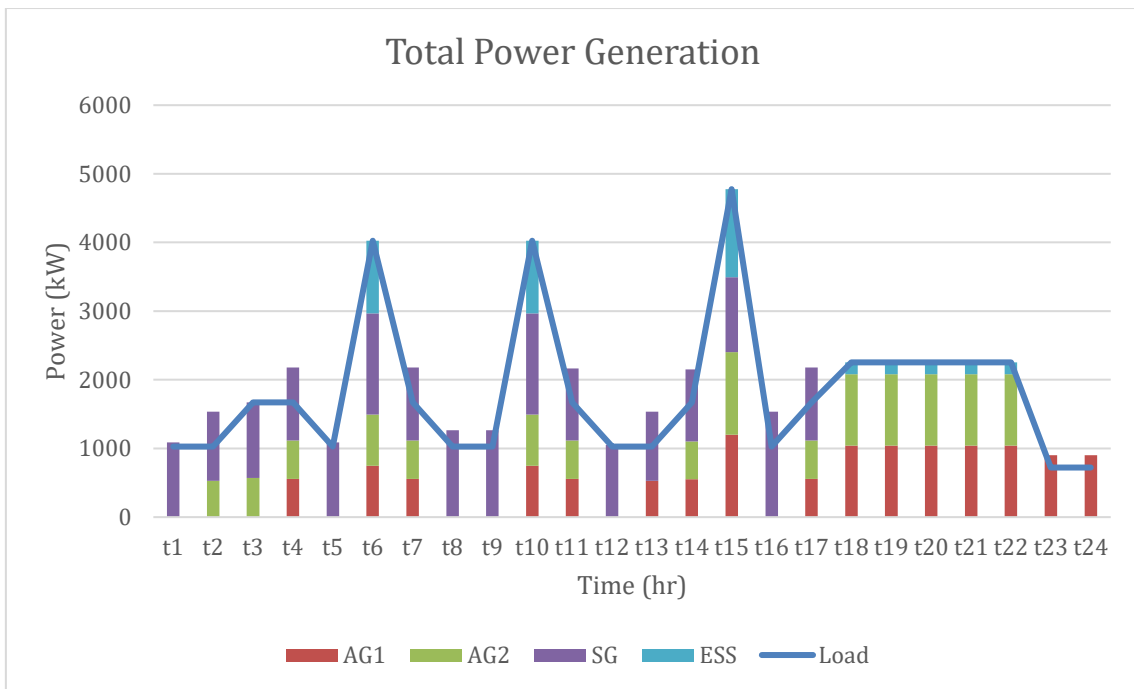


Figure 15: Total Power Generation from All Sources.

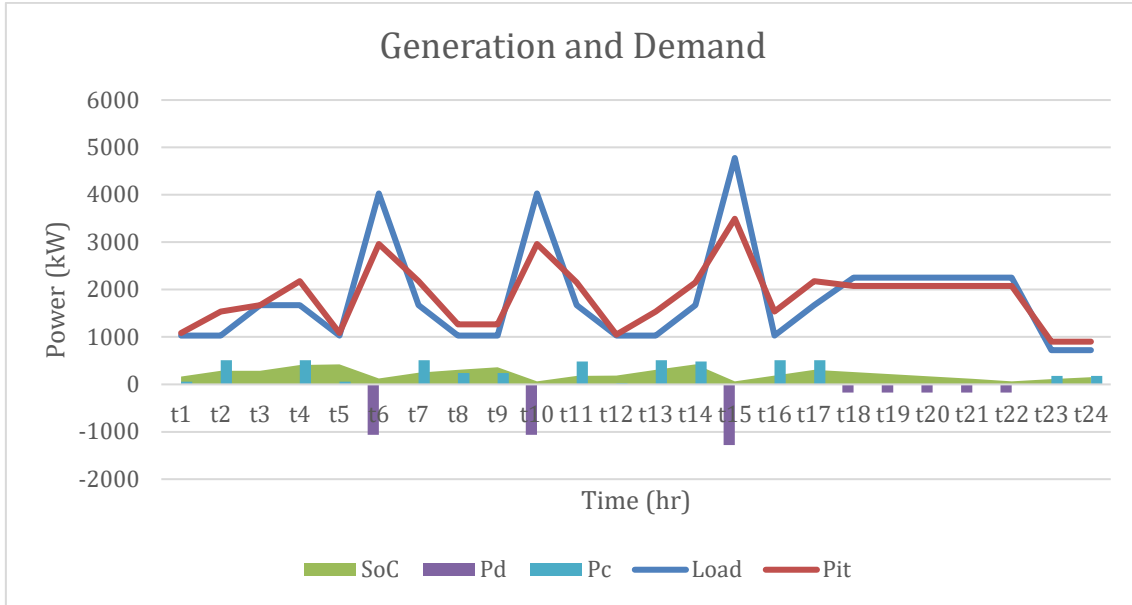


Figure 16: Battery Peak Shaving and Spinning Reserve During Generation and Demand

5.1.1.4 50% SoC Only at the Beginning of Voyage

The results below in Figure 17 - Figure 20 shows the battery and generator's behaviours when the battery SoC is 50% only at the beginning of the voyage. The results analysis is similar to that of the previous scenarios, with the key differences being in the ESS utilisation. Because there is no requirement to charge the battery at the end of the voyage, the battery is charged and optimised for use at t6, t10 and t15. The power discharged from the ESS at these times is 1282.176kW compared to the previous scenarios, where 1282.176kW was only dispatched at time t15.

As calculated in the previous scenarios, the SFC is 1847.7MT, which is the lowest compared to the previous scenarios. Comparing this scenario with the scenario without a battery, we see that it has fuel savings of 15%. The reason for the reduced SFC and high savings is that the battery was not charged at the end of the voyage. The cumulative start and stop of the generators, as well as the battery charge and discharge cycle, are recorded in Table 5.

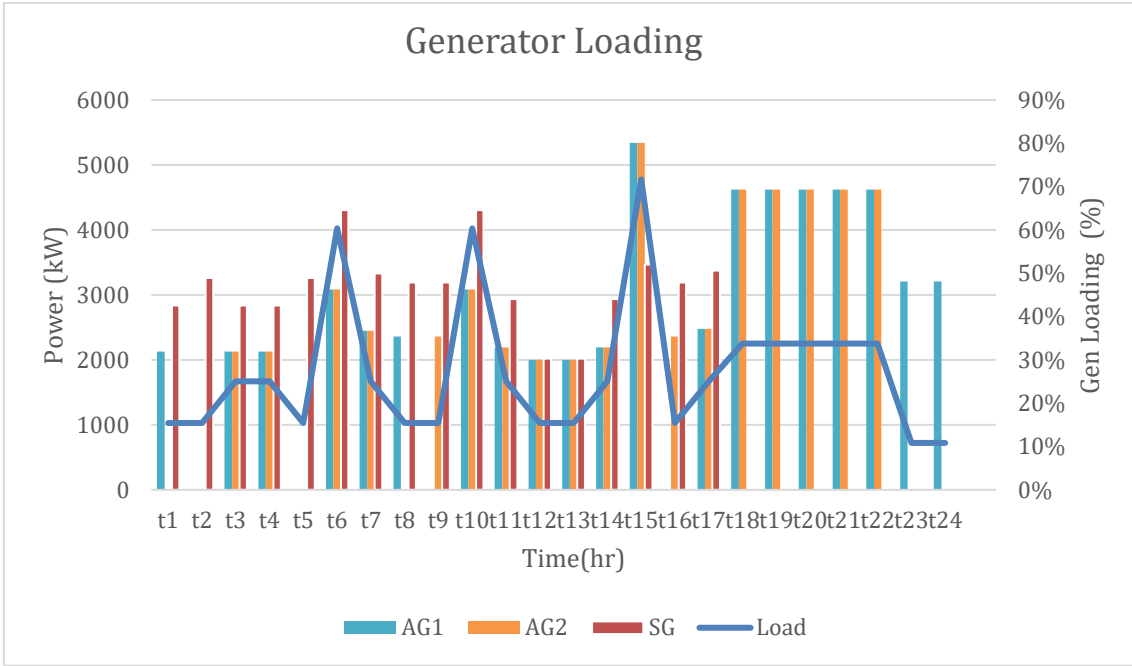


Figure 17: Load Optimization and EMS Strategy

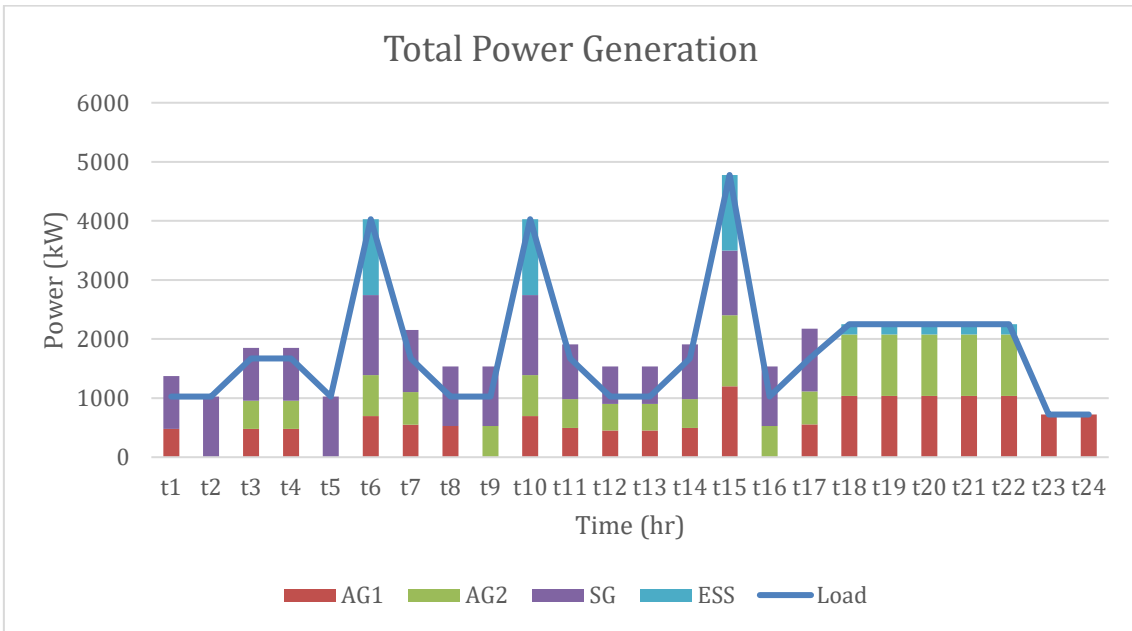


Figure 18: Total Power Generation from All Sources.

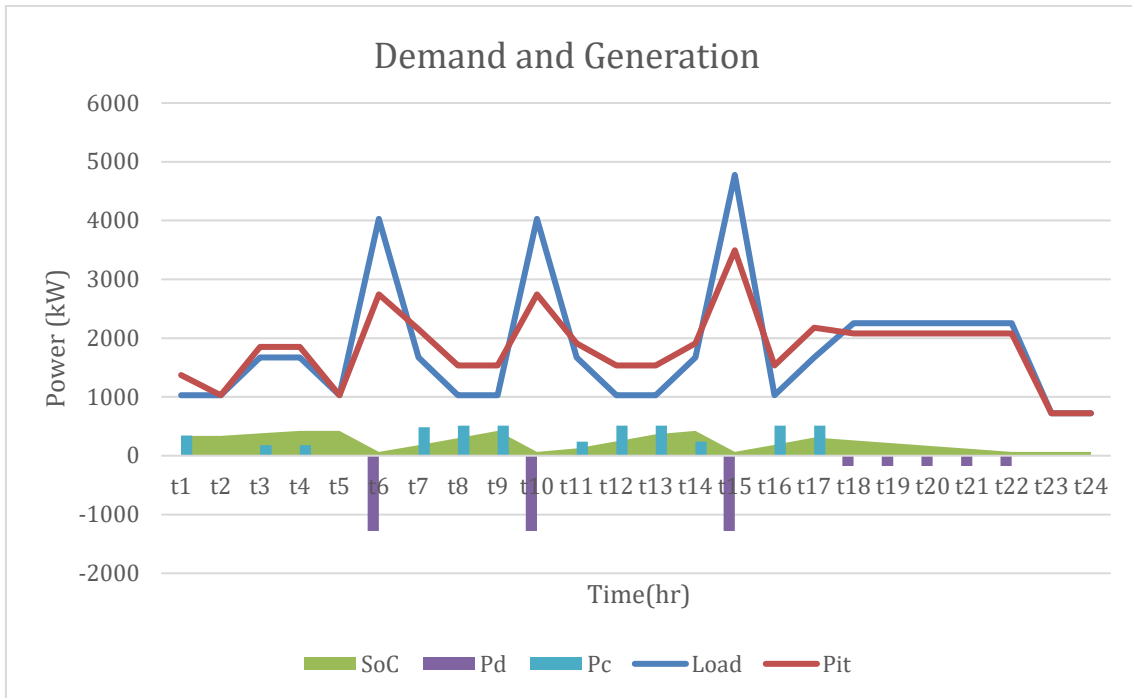


Figure 19: Battery Peak Shaving and Spinning Reserve During Generation and Demand

5.2 EMS Strategy and Vessel Optimization Without ESS

Without batteries, the ship would operate three auxiliary generators and one shaft generator to meet the load demand. Without batteries and optimisation, the generator would be ramped up and down to meet the fluctuating load demand during manoeuvring, which increases the wear and tear of the units. Also, there will be scenarios where the generators operate below 30% of their total capacity, thereby increasing fuel consumption and emissions. Figure 20 shows the four generators' optimised generator loading, and the EMS strategy ensures that none of the generators operate below 30%. Although the SG is prioritised, AGs are seldom used during normal seagoing conditions, showing that the units are oversized and underutilised. The total fuel consumed in the 25 years' operating time without batteries is 2122.7MT. Using batteries at the recommended battery levels of 50%, as in 5.1.1.2 and 5.1.1.4, saves 1.4% - 13% on fuel consumption depending on the ESS usage.

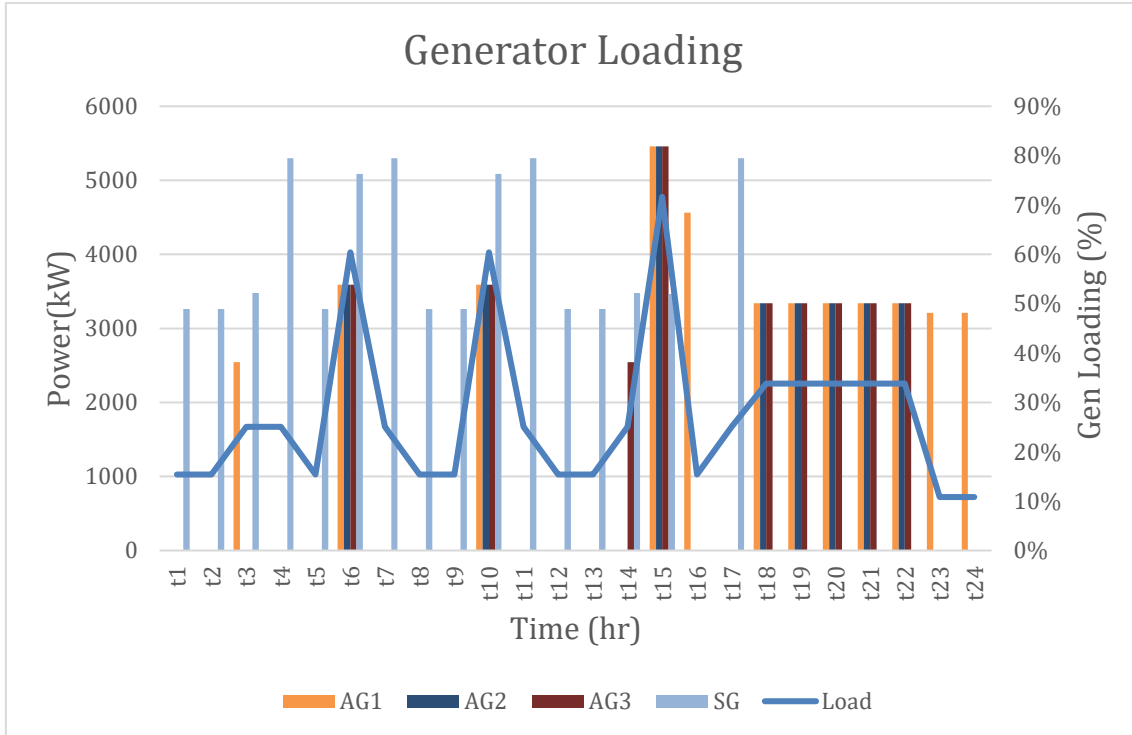


Figure 20: Optimised Generator Loading

5.3 ESS Sizing Optimisation

The last stage of the simulation is to find the optimal size of the energy storage that minimises fuel consumption. Here, the battery size is set as a variable and the additional constraints in Equation (21) – (24) are used to derive the optimal size from GAMS. The optimal ESS size calculated by GAMS using Equation (20) is 390.873kWh, and the SFC throughout the 25-year operating lifespan is 2191.5MT. Comparing this with the fuel consumption in 5.1.1.1 using the actual size BESS size of 508.8kWh shows a 2.2% increase in fuel consumption. With the optimised ESS, the AGs are loaded up to 90% of their installed capacity, as shown in Figure 21 at which fuel efficiency is poor, hence the increase in fuel consumption. Such generator loading can also increase the generator run hours, which directly affects the maintenance costs and wear and tear. Figure 22 shows that the battery's peak shaving and load optimisation capability is reduced.

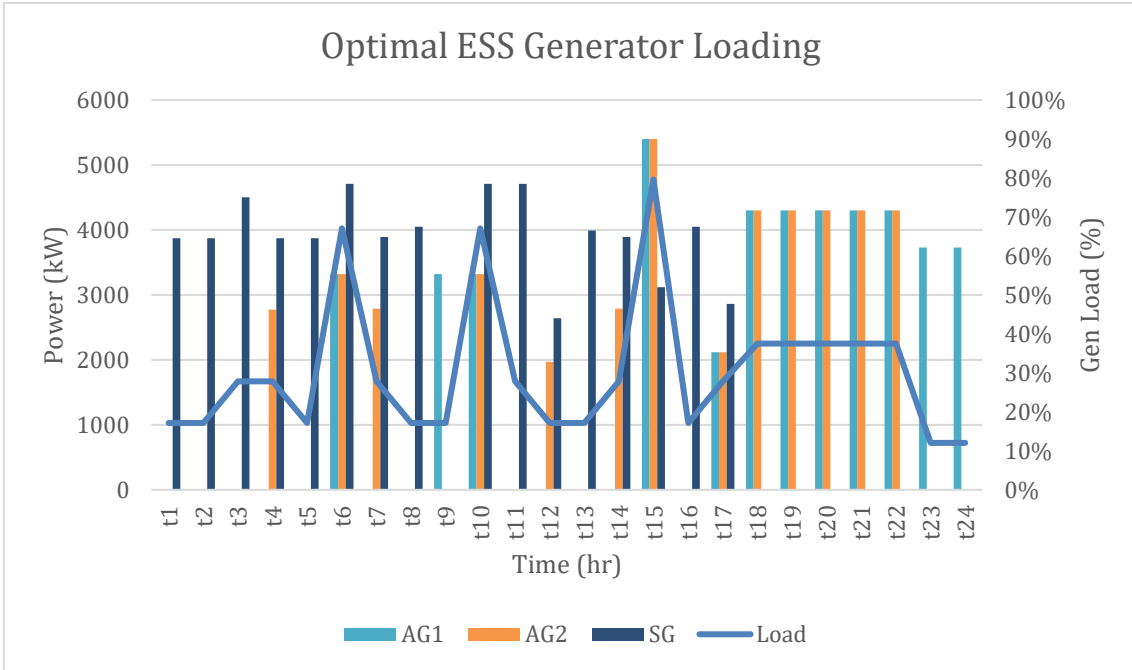


Figure 21: Generator Loading using Optimal ESS Size

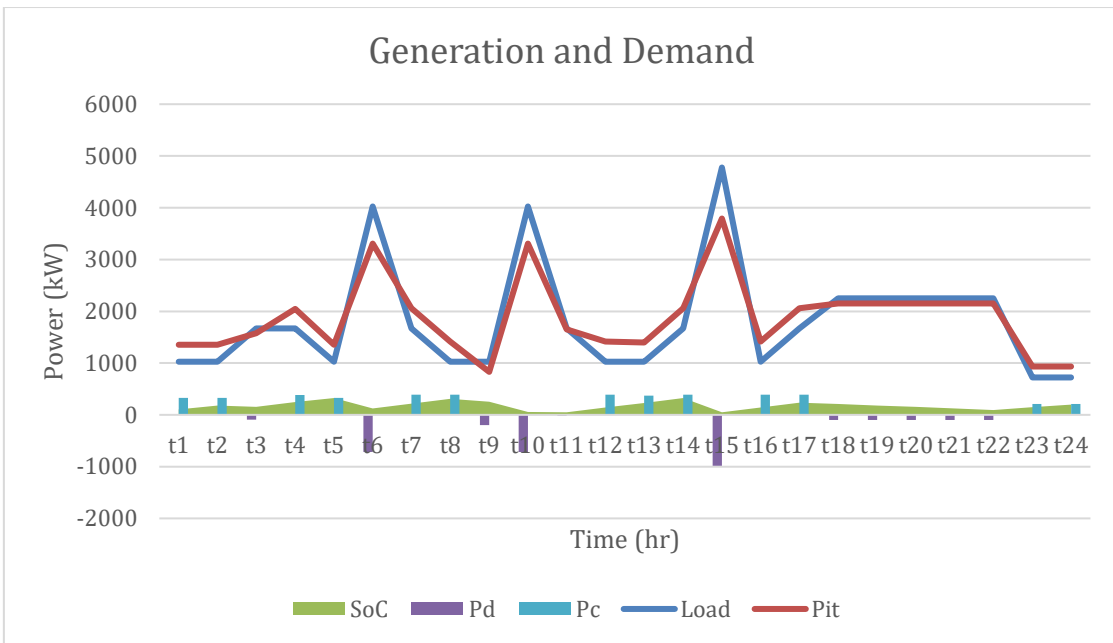


Figure 22: Battery Peak Shaving and Spinning Reserve During Generation and Demand

5.4 Conclusion

In this chapter, the proposed algorithm is applied to the case study, and the results are presented and analysed. A sensitivity analysis is done to study the effect of varying the SoC, optimising the ESS, and replacing the ESS with an AG on fuel consumption.

The SoC level at the start and end of the voyage is directly proportional to the fuel consumption. If the batteries are not charged at the end of the voyage, as seen in Figure 19, the fuel savings become more significant, but this scenario is not recommended as the batteries need to be charged to assist in manoeuvring when leaving the port. The fuel saving achieved when using batteries compared to without batteries can easily be eroded due to this change in SoC. The objective function of this optimisation is to minimise the total operating cost of the vessel by finding the optimal ESS size; hence, the resulting optimal size, as provided by GAMS, is 390.873kWh. Due to the objective function being minimisation and the battery having the most expensive cost, 390.873kWh is the minimum ESS size that can provide technical and economic benefits. At this size, the generators are operating outside the optimal fuel efficiency limits, and their fuel consumption has increased by 4.5%. It is important to note that, due to the high price of shore electricity, €0.2847 per kWh, compared to the MGO price of € 0.15 per kWh, the model could not use shore power during loading /unloading and harbouring. From EMS strategy in the result summary presented in Table 5, we can see that the generator use increases as the SoC decreases but is reversed for the BESS.

The unavailability of generator capital and operation costs affected the accuracy of the cost savings calculation, as only the BESS costs were used. Therefore, cost savings values were omitted from the results.

| | | | | | | |
|-------------------------|-------------------------------|-------------------------------|-------------------------------|--------------------|-------------------------------|--------------|
| ESS size | 508.8kWh | | | | 390.873kWh | N/A |
| SoC | 75% @ start and end of voyage | 50% @ start and end of voyage | 30% @ start and end of voyage | 50% @ start voyage | 50% @ start and end of voyage | N/A |
| Voyage fuel consumption | 2144.2MT | 2092.9MT | 2060.3MT | 1847.7MT | 2191.5MT | 2122.7 MT |
| Voyage fuel savings | -1% | 1.42% | 3.03% | 15% | -3.14% | N/A |
| EMS Strategy | (Start/Stop) | (Start/Stop) | (Start/Stop) | (Start/Stop) | (Start/Stop) | (Start/Stop) |
| AG1 | 18/4 | 14/10 | 16/8 | 20/4 | 12/12 | 12/12 |
| AG2 | 11/13 | 13/11 | 15/9 | 18/4 | 13/11 | 8/16 |
| SG | 16/8 | 17/7 | 17/7 | 17/7 | 16/8 | 16/8 |
| BESS (discharge/charge) | 11/14 | 10/14 | 8/13 | 8/12 | 11/13 | N/A |

Table 5-Results Summary

6 Conclusion and Future Work

There is an urgent need to decarbonise transportation, and the marine sector is not left out. This thesis has provided a detailed analysis of the impact of integrating Energy Storage Systems (ESS) with existing power-generating units on a short-distance merchant vessel equipped with auxiliary generators that exhibit weak load ramping capabilities. By implementing advanced simulation techniques and optimisation using the General Algebraic Modelling System (GAMS), the study has highlighted the potential of ESS to significantly enhance operational efficiency, reduce environmental impact, and optimise fuel consumption. By decreasing reliance on fuel and reducing the frequency of generator startups, ESS implementation contributes to lower emissions, thus supporting compliance with stringent international maritime environmental regulations. The key findings of utilising ESS in this study include:

- I. **Enhanced Fuel Efficiency:** The integration of ESS in the SMG shows substantial improvements in fuel efficiency by allocating generator operations within their optimal efficiency load points. This was particularly evident in the load optimisation function of the ESS, where the generators were operated at optimal points compared to their idle times without ESS. It is important to note that the fuel saving derived can be increased or decreased depending on the battery and the battery SoC at the start and end of the voyage. The fuel savings recorded were between 1.42% - 15%, and the battery contributed about 27% of the total power required during manoeuvring.
- II. **Increased Operational Flexibility:** ESS integration allowed for greater operational flexibility of the SMG through the EMS strategy. The AGs' starts and stops were reduced and limited to periods when the load increased or when the battery required charging, thus utilising the battery for peak shaving, load optimisation and spinning reserve. In addition to minimising the auxiliary generator starts and stops, the generators were optimally loaded during short transient load fluctuation, thus preventing quick ramps, reducing the mechanical stress and extending the generators' operational lifespan. Also, the use of batteries reduces the generator run hours, which affects the maintenance frequency and costs. For

peak shaving, the battery provided 27% of the power required, and 5-12% was reserved for times when the start of an additional AG was required. For load optimisation, the integration of the ESS ensured that the AGs were optimally loaded and utilised.

- III. Reduction in Total Costs: The developed economic dispatch model effectively minimised total operational costs by dynamically allocating the batteries, auxiliary generators, and shaft generator based on load demands and operational and capital costs. Without ESS, the generators were oversized and underutilised due to the predominant steady nature of the loads. Although this thesis did not consider generator capex and other OPex, such as maintenance cost, battery charge and discharge costs, in the cost calculation, ESS utilisation can save 1.44% on the operational cost depending on the start and end SoC.

The promising results obtained from the simulation studies of ESS on maritime vessels pave the way for several future research opportunities. To further extend the work covered in this thesis and to address the practical challenges of real-world application, a few improvements are suggested:

- I. Exploration of Advanced ESS Technologies and DC Power Sources: Future studies should explore emerging battery technologies that promise higher efficiencies, better energy densities, and reduced costs. Such technologies could further enhance the economic and operational viability of ESS in maritime applications. Hybrid energy storage systems can also be explored to improve flexibility.

Other DC power sources, such as fuel cells and solar panels, have been proposed for ferries and other short-distance passenger vessels thereby increasing the usability of the DC bus. Although these technologies are yet to be implemented in merchant shipping, ESS integration is an enabling technology for their utilisation.

- II. Operational Validation: This study was carried out at the beginning of the vessel construction. It is crucial to validate the model with actual operational data for a longer duration. This would provide valuable data on the practical challenges and

performance dynamics of ESS. Assessing the impact of ESS on the overall maintenance, operational costs, and lifespan of the vessel's power systems would provide deeper insights into their lifecycle benefits and cost-effectiveness. This assessment should also consider the generator capex to improve the accuracy of the result.

The outcomes of this thesis firmly establish the potential of an optimal EMS strategy and ESS in enhancing energy delivery in merchant vessels. Without the EMS strategy, generators and batteries will not be effectively utilised. Continued research and development in this field are essential to overcome existing challenges and realize the full potential of ESS in promoting a sustainable and economically efficient maritime industry.

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Appendixes

Appendix 1- GAMS Code

```

sets
t 'time' /t1*t24/
i 'generator index' /g1*g3/;
Alias (t,h);

Table gendata (i,*) generator cost characteristics and limits
      a      b      c      Pmin  Pmax  UT  DT
g1  0.0086  -1.5018  261.65  450  1500  4  3
g2  0.0086  -1.5018  261.65  450  1500  4  3
g3  0.004   -0.42    170      600  2100  4  0;

Parameter load(t)/t1 1027,t2 1027,t3 1027,t4 1669,t5 1669,t6 4027
           t7 1669,t8 1027,t9 1027,t10 4027,t11 1669,t12 1027
           t13 1027,t14 1669,t15 4777,t16 1027,t17 1669,t18 2253
           t19 2253,t20 2253,t21 2253,t22 2253,t23 722,t24 722/;

Variables TC          Total Cost
           p(i,t)     Power generated by DG
           SFC        Fuel Consumption
           SOC(t),Pc(t),Pd(t), Eess;

binary variable U(i,t), y(i,t), z(i,t);
p.lo(i,t) = 0*gendata(i,"Pmin");
p.up(i,t) = 0.9*gendata(i,"Pmax");
p.up('g3', 't15') = 0.52*gendata('g3',"Pmax");
p.up('g3', 't18') = 0*gendata('g3',"Pmax");
p.up('g3', 't19') = 0*gendata('g3',"Pmax");
p.up('g3', 't20') = 0*gendata('g3',"Pmax");
p.up('g3', 't21') = 0*gendata('g3',"Pmax");
p.up('g3', 't22') = 0*gendata('g3',"Pmax");
p.up('g3', 't23') = 0*gendata('g3',"Pmax");
p.up('g3', 't24') = 0*gendata('g3',"Pmax");
p.up('g2', 't23') = 0*gendata('g2',"Pmax");
p.up('g2', 't24') = 0*gendata('g2',"Pmax");

Scalar SOC0/254.4/,SOCmax/422.304/,eta_c/0.95/,eta_d/0.9/,Eessnom/508.8/,Cinst_ess/676.547/, Nrep/1/,Cinst_inv/23000/,Dt/0.25/,FC/806.83/;
SOC.up(t)=SOCmax; SOC.lo(t)=0.13*eessnom;
Pc.up(t)=1*Eessnom; Pc.lo(t)=0; Pd.up(t)=3*Eessnom; Pd.lo(t)=0;
*SoC.fx('t24')= SOC0;

equations Genconst3, Genconst4, TCcalc,SFCcalc, balance, ESSconst1,uptime,Dntime;
TCcalc.. TC=e*sum((t,i),(gendata(i,'a')* sqr(p(i,t))+gendata(i,'b')*p(i,t)+gendata(i,'c')*u(i,t))*FC*power(10,-6))*11*25*30+ Cinst_ess*ess*(Nrep+1)+Cinst_inv;
SFCcalc..SFC=e*sum((t,i),(gendata(i,'a')* sqr(p(i,t))+gendata(i,'b')*p(i,t)+gendata(i,'c')*u(i,t))*11*25*30);
Genconst3(i,t) .. p(i,t)=1-U(i,t)*0.9*gendata(i,"Pmax");
Genconst4(i,t) .. p(i,t)=g*U(i,t)*gendata(i,"Pmin");
ESSconst1(t) .. SOC(t) =e= soc05*(ord(t)=1) + SOC(t-1)*(ord(t)>1) + dt*(Pc(t)*eta_c - Pd(t)/eta_d);
Uptime(i,t)..u(i,t)=g*sum(h,gendata(i,"UT")* y(i,t));
Dntime(i,t).. 1-U(i,t) =g= sum(h,gendata(i,"DT")*z(i,t));
balance(t)..sum(i,p(i,t))+ Pd(t) =g= load(t)+Pc(t);
Model OptimalESS /all/;
option limrow=3;
Solve OptimalESS us miqcp min TC;

Parameter report(t,*);
report(t, 'Load') = load(t);
report(t, 'Pit') = sum (i,p.l(i,t));
report(t, 'SoC') = SOC.l(t);
report(t, 'Pd') = Pd.l(t);
report(t, 'Pc') = Pc.l(t);
display report;
execute_unload 'OptimalESS.gdx' P.l
execute 'gdxrw.exe OptimalESS.gdx var=P rng=P TC!al'
execute_unload 'OptimalESS.gdx' report
execute 'gdxrw.exe OptimalESS.gdx par=report rng=report!al'

```

Appendix 2- Interview question list

- i. What are the technology drivers for ESS integration? What is the most prominent ESS technology requested by the SY or owner?
- ii. Does the SY have specific space or technology requirements for the ESS?
- iii. What are the owner's expectations with ESS integration? Cost reduction, fuel efficiency, spinning reserve, backup power, etc.?
- iv. Is the cost reservation for ESS integration a significant consideration for the SY and owners?
- v. What percentage of CAPEX and OPEX impacts (equipment + shipyard additions) does ESS have on the vessel? What's the expected Return on Investment (ROI) period?
- vi. What methods and tools are currently being used for sizing?
- vii. What does the future outlook of ESS on ships look like?