Battery Energy Storage System Sizing Strategy for Naval Vessels through Multi-Objective Optimisation

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Synopsis

Naval ship design must balance multiple conflicting requirements, including the need for fast response times and high speeds, often leading to large and complex hybrid propulsion systems. At the same time, the decarbonisation of ship operations and the shipping industry has become one of the most concerning topics for the maritime community. Even if the military sector has not been driven yet by this regulatory framework, decarbonisation is also becoming a hot topic for the navies. Additionally, short-term power loads encompass numerous demanding applications. The impact of this type of load on the performance of the shipboard power system influences power quality, and load levelling has been proven to be one of the critical power management strategies for new naval shipboard electric plants. Furthermore, decarbonisation and electric pulse management require pervasive automation systems to balance reduced crew sizes effectively.

In recent years, Battery Energy Storage Systems (*BESS*) have emerged as effective tools for reducing greenhouse gas emissions, as well as for load levelling and peak shaving. These systems support power management strategies, addressing conflicting naval ship design requirements and optimising these critical concerns. *BESS*-based hybrid propulsion is a promising solution for enhancing the energy efficiency of naval ships. It has been proven to be a reliable and flexible design option for improving the power quality of the electric grid. However, *BESS* requires space, weight tolerance, and cost expenditures to match all other military operational requirements in one convenient, optimal shipboard power plant. The paper outlines an optimisation-based approach to size a *BESS*-based hybrid propulsion architecture for naval ships, primarily focusing on reducing environmental footprint, increasing efficiency, and improving power grid reliability. The optimisation aims to minimise the ship exhaust emissions in terms of equivalent CO_2. The frontline ship type case study has been analysed while manoeuvring in restricted waters and deep seas in a given pseudo-random operating condition extracted from actual data, showing potential interest in a new, energy-efficient, and resilient solution. For comprehensive benchmarking, the case study has been further examined and discussed with different sizing configurations, and each case study has been ranked with a set of Key Performance Indicators (KPIs). The study shows that, despite the increasing size and weight of the *BESS* to reduce fuel consumption, analysing different solutions with a model-based strategy for the hybrid plant gives interesting trade-offs during the design phase while leaving space for new research directions.

Keywords: Naval ships; Hybrid Energy Systems; Battery Energy Storage System; Optimisation; Genetic Algorithm; Energy management; Load sharing; Decarbonisation

1 Introduction

The maritime world aims to reduce fuel consumption and environmental impact due to the recent ambitious targets outlined by the International Maritime Organisation (IMO) (IMO, 2023, 2024). The rules aim to drive the maritime industry to reduce Greenhouse Gas emissions and promote sustainable shipping practices.

The formulations of the Energy Efficiency Operational Indicator (EEOI), the Energy Efficiency Design Index (EEDI) and the later introduced Energy Efficiency Existing Ship Index (EEXI) (IMO, 2009, 2013, 2021) have been driving improvements in ship energy efficiency for many years. However, the EEDI formula applies exclusively to commercial vessels (e.g., bulk carriers, tankers, and container ships) and excludes military and other governmental

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Authors' Biographies

Dr. Daniele Belvisi currently is PhD researcher at the University of Genoa on power systems and control strategies for hybrid propulsion systems of naval ships and a Marine Engineering Officer of the Italian Navy. He is currently the Head of the Ship Hull Department of the Italian Aircraft Carrier Cavour, and previously served as the Head of the Energy and Automation Department on the same ship for two years. Earlier experience includes education and training of first-year midshipmen at the Italian Naval Academy.

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Prof. Raphael Zaccone has a BSc, MSc and PhD in Naval Architecture and Marine Engineering. He received his PhD in 2017 from the University of Genoa, Italy. After two years of post-doc, he joined the DITEN Department of the University of Genoa as Assistant Professor in 2019. His main research interests deal with ship autonomous navigation, collision avoidance and route planning, as well as ship propulsion control and simulation. He published over 35 peer-reviewed articles in international scientific journals and conferences.

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vessels. (IMO, 2022b,c). The Initial IMO Strategy on Reduction of Greenhouse gas (GHG) Emissions from Ships (IMO, 2018) outlined the ambitious goal of reducing emissions by at least 50% by 2050 compared to 2008 levels, with a focus on improving energy efficiency, transitioning to low-carbon fuels. This strategy provided a framework for global action, guiding the industry towards sustainable and environmentally responsible practices to combat climate change. One essential framework item is the Ship Energy Efficiency Management Plan (IMO, 2022a), a document describing the company strategy for enhancing vessel performance and reducing environmental impact. Despite the IMO's actions, the maritime industry remains responsible for approximately 3% of global greenhouse gas emissions IMO (2018), and the pace of reduction has yet to keep it on track with the UN Paris Agreement goals. The new GHG reduction paths in shipping also include the transition to alternative, low-carbon fuels, i.e., biodiesel, biomethane, methanol, ammonia, and hydrogen, as well as energy efficiency, operational measures and advice tools (Maloberti et al., 2024). In particular, methanol produced from renewable feedstocks is considered one of the most viable decarbonising options for commercial shipping (Adami and Figari, 2023; Altosole et al., 2021, 2023). Best practices for fuel-efficient operation require assessing and understanding the ship's current energy demand and energy production status. Shipboard automation, particularly the Energy Management System, plays a crucial role in monitoring electrical loads on board and can unveil opportunities for significant efficiency improvements, especially for ships with predominant non-propulsive electric loads. Energy Storage Systems (ESS) have proven their validity to optimise the load factor of the main generating sets (D'Agostino et al., 2023a). The naval sector has yet to embrace the decarbonisation strategy, primarily to uphold substantial and growing operational flexibility across diverse environmental conditions. Naval ship design involves balancing many conflicting requirements, including the need for fast response times and high speeds, which often result in large and complex hybrid propulsion plants (Belvisi et al., 2022), frequently incorporating extensive design frameworks for combined propulsion control systems (Martelli and Figari, 2022). Additionally, demanding combat system applications depend on pulse power loads, which challenge the shipboard power system's power quality and resilience performance. Therefore, load levelling has emerged as a critical power management strategy for new naval shipboard electric plants (D'Agostino et al., 2023b). Both power quality and load levelling must match pervasive automation systems that strive for continuous optimisation of personnel workload. Every alternative solution to fossil-based diesel generation and propulsion systems has peculiarities and critical issues, mainly related to the expected availability, safety measures, maturity of the technologies, and costs (Bao et al., 2021; Maloberti et al., 2022). Despite the numerous advantages of ESS, their high initial investment costs and the constrained space available for ship installation limit their widespread adoption. Therefore, it becomes imperative to tackle the issue of ESS sizing by incorporating considerations of optimal power scheduling. This aspect is closely intertwined with the overall performance of ESS (Kanellos et al., 2014). Additionally, the decision regarding the utilisation levels of different power generation technologies hinges on a variety of factors that have to be tailored to each specific scenario and typically arise from the optimisation of a cost-benefit function and the assurance of the safety and reliability of the power system (Kanellos, 2013). Despite the conflicting requirements of the frontline naval segment, which currently does not leave enough space for a full-scale implementation of ESS-based systems, Governments and Institutions have shown particular interest in multi-purpose ships with low GHG emissions, and this trend will become even more critical. This paper proposes an optimisation-based approach to size a BESS-based hybrid propulsion architecture for naval ships, primarily focusing on increasing operational flexibility, reducing environmental footprint, increasing efficiency, and improving power grid reliability. The goal is to minimise the ship exhaust emissions in terms of equivalent CO_2, thereby achieving a low environmental footprint and cost-effective operation while maintaining high levels of reliability within the specified case study. In this framework, optimising ship electric load sharing over time can enhance hybrid power plant efficiency in response to changes in electric load, providing an additional measure for controlling GHG emissions and reducing operational costs. However, this approach is constrained by factors such as redundancy and reliability, which must be carefully considered over a lifetime study that includes the systemic ageing of machinery and electric plants. The proposed optimisation approach has been tested on a frontline ship case study, considering a mission profile in deep-seas navigation with an assigned speed profile. The simulation approach proposed in this paper aims to address the design challenge of balancing multiple conflicting requirements, such as reducing environmental footprint, increasing efficiency, and improving power grid reliability.

Consequently, ESS-based technologies, while improving power management strategy, could be an interesting tool to advance endurance, reduce environmental footprint, and relax the impact on human workload for maintenance.

2 Hybrid power system modelling

In a typical naval ship electric generation system, multiple gensets, consisting of internal combustion engines coupled with alternators, are employed. A hybrid propulsion system can also integrate a *BESS* with its controller. The systems modelled in this work are the combustion engines and the batteries. The proposed modelling adopts a static approach, neglecting the components' dynamics. It is worth noting that the models used are simplified and well-documented in the literature, integrated to build a system performance model for use in optimisation, such as comparing solutions. The ability of the model to provide accurate performance estimates under specific conditions is therefore secondary to its ability to model the physical behaviour of the system within the computational domain (Martelli, 2015). Combustion engine black-box modelling involves using Brake Specific Energy Consumption (*BSEC*) to represent fuel mass flow rate as a function of power output (Ashok et al., 2018). The specific consumption of the marine diesel oil has been calculated through the following equation:

$$BSEC = SFOC\, LHV_{MDO} \tag{1}$$

Where *SFOC* is the Specific Fuel Oil Consumption and LHV_{MDO} is the lower heating value of Marine Diesel Oil (*MDO*). The fuel mass flow rate of the generator is determined as follows:

$$\dot{m}_{MDO} = P_B\, SFOC \tag{2}$$

Where P_B represents the power delivered by the diesel engine of the generator.

The State of Charge (*SoC*) of the battery is modelled according to the following system of equations:

$$\begin{cases} SoC(t) = SoC(0) - \dfrac{\beta}{E_{BESS}} \displaystyle\int_0^T P_{BESS}(t)dt \\ \beta = \begin{cases} \eta_{charge} & \text{if } P_{BESS} \leq 0 \\ \dfrac{1}{\eta_{discharge}} & \text{if } P_{BESS} > 0 \end{cases} \end{cases} \tag{3}$$

Where $SoC(0)$ is *SoC* at time $t = 0$, $\eta_{charge} = 0,94$ and $\eta_{discharge} = 0,97$ are the battery efficiency during the *BESS* charging and discharging processes, P_{BESS} is the power delivered by the *BESS*, which can be positive or negative depending on whether it is in the discharging or charging phase, and E_{BESS} is the nominal energy stored in the battery. For technological reasons, the State of Charge of the *BESS* should be kept between 30% and 80%.

3 Operational optimisation strategy

This study aims to size a *BESS* by identifying the power split that minimises the environmental impact of the propulsive configurations, using an optimisation approach according to a rule-based procedure that depends on a specific set of performance indicators. A genetic algorithm, i.e. a method based on natural selection that drives biological evolution, is employed to find the optimal solution. The genetic algorithm repeatedly modifies a population of individuals, selecting individuals from the current population as parents at each step and using them to produce the next generation's children. Over successive generations, the population "evolves" toward an optimal solution (Goldberg, 1989). The following subsections describe all the aspects of the problem formulation, from the genetic encoding, i.e., the parametrisation of the problem, to the set-up of the cost function and constraints, based on the steady-state modelling of the ship's propulsion system (Zaccone et al., 2021).

3.1 Genetic encoding

Defining the genetic encoding is crucial when using a genetic approach to solve optimisation problems.

The inputs to the problem are the required mission power profile and the propulsive system configuration. The mission power profile is defined in discrete time, at time instants t_j, $j = 0...T$. The variables identifying the optimal solution are the powers delivered by the *BESS*, expressed as a fraction of its maximum power through an appropriate load factor α. The encoding takes the following form:

$$\mathbf{X} = \left\{\alpha^0_{BESS}, \alpha^1_{BESS}, \cdots, \alpha^{T-1}_{BESS}\right\} \tag{4}$$

Where α^j_{BESS} are the battery load factor for each time instant. The power delivered by the generators at each time instant is calculated as the difference between the load and the power delivered by the BESS, according to the following equation:

$$P^j_{DG,tot} = P^j_{load} - P^j_{BESS} \quad ; \quad j = 0, \cdots, (T-1) \tag{5}$$

This power is then equally shared among the active generators, as they are identical and the time span considered during the simulation is large, meaning its order of magnitude is greater than the variations in electrical measures and generator loading ramps:

$$P^j_{DG,i} = \frac{P^j_{DG,tot}}{N^j_{active}} \tag{6}$$

Where N_{active} represent the number of active generators at each time instant j, which are the minimum number of generators required to support the load, and i represents the i^{th} generator.

3.2 Cost function

In the presented application, the solution ranking after each generation in a genetic algorithm is performed using a cost function. The optimisation objective is to minimise the equivalent CO2 emissions of the power generation plant. Thus, the following function has to be minimised:

$$f(\mathbf{X} = \alpha_{BESS}^{j}) = EF_{fuel} \sum_{j=0}^{T} \sum_{i=1}^{N_{active}} P_{DG,i}^{j} SFOC_{i}^{j} \Delta t_{j} \tag{7}$$

Where EF_{fuel} is the equivalent CO_2 emission factor for the MDO, $\Delta t_j = t_j - t_{j-1}$, and $SFOC_i^j$ is the specific fuel oil consumption of the i^{th} generator at the j^{th} time.

3.3 Constraints

Clearly defining constraints is an essential step in the proposed approach to ensure precise outcomes. First, the bounds of the solutions need to be defined:

$$\alpha_{BESS,min} \leq \alpha_{BESS}^{j} \leq \alpha_{BESS,max} \tag{8}$$

Where $\alpha_{BESS,min}$ and $\alpha_{BESS,max}$ represent the maximum load that can be absorbed by the battery in the charging phase and the maximum load that can be delivered by the battery in the discharging phase, depending on the C-rate of the battery, assumed to be different for the different propulsive configurations considered.

Each generator's generated power must always be non-negative and never exceed its maximum load. Furthermore, for operational reasons, it has been decided that active generators must operate at a minimum output of 20% and a maximum of 95% of their maximum load. The lower limit ensures that diesel generators operate only within an optimal range of load factors, thereby preventing irregular functioning of the diesel engine, while the maximum load limit is set for the start of an additional diesel generator. Therefore, each generator can be kept off or on with power between 20% and 95% of their maximum power. The power balance constraint, therefore, takes the following form:

$$P_{DG,i}^{j} = 0 \quad \vee \quad 0.2 P_{DG,i,max} \leq P_{DG,i}^{j} \leq 0.95 P_{DG,i,max} \tag{9}$$

Where $P_{DG,i}^{j}$ is the i^{th} generator power at each time instant j, and $P_{DG,i,max}$ is the maximum power of the i^{th} generator. A constraint has been implemented on the power balance such that, at each time instant, the power demanded by the load equals the power supplied by the system components:

$$\sum_{i=1}^{N_{active}} P_{DG,i}^{j} + \alpha_{BESS}^{j} P_{BESS} = P_{load} \tag{10}$$

Where P_{BESS} indicates the nominal power of the BESS. Furthermore, two Battery Storage System constraints need to be set. Firstly, the SoC of the $BESS$ is is constrained to remain within specified minimum (SoC_{min}) and maximum (SoC_{max}) limits to preserve the battery state of health:

$$SoC_{min} \leq SoC_{j} \leq SoC_{max} \tag{11}$$

The SoC_j at time t_j obtained by discretizing Equation 3 , is given by:

$$SoC_{j} = \frac{1}{E_{max}} \left(E_{0} - \beta \sum_{p=0}^{j} P_{BESS_{p}} \Delta t_{p} \right) \tag{12}$$

Where $\Delta t_p = t_p - t_{p-1}$. Secondly, the battery energy balance constraint is required to keep the results consistent:

$$SoC_{0} = SoC_{T} \tag{13}$$

Eventually, the fuel consumption must not exceed the fuel available on board:

$$m_{MDO} = \sum_{j=0}^{T} \sum_{i=1}^{N_{active}} \dot{m}_{i,MDO}^{j} \Delta t_{j} \leq MDO_{on\,board} \tag{14}$$

Calculations have been performed using MATLAB R2023b and the parallel computing toolbox. The average computational time to calculate six configurations ranged from around 33 minutes, performing a series calculation. The analysis has been conducted using a MacBook Pro 16 equipped with an Intel Core i7 processor running at 2,667 GHz, featuring 6 cores and 12 threads, along with 16 GB of DDR4-SDRAM.

3.4 *Optimisation problem*

To determine the optimal generator load sharing and, consequently, the optimal propulsion plant configuration, the following optimisation problem, which combines Equations 7, 8, 9, 10, 11, 13 and 14, needs to be solved:

$$\begin{cases} \min\limits_{\alpha^j_{BESS}} \; EF_{fuel} \sum\limits_{j=0}^{T} \sum\limits_{i=1}^{N_{active}} P^j_{DG,i} SFOC^j_i \Delta t_j \\ s.t.: \\ \alpha_{BESS,min} \leq \alpha^j_{BESS} \leq \alpha_{BESS,max} \\ P^j_{DG,i} = 0 \quad \vee \quad 0.2 P_{DG,i,max} \leq P^j_{DG,i} \leq 0.95 P_{DG,i,max} \\ \sum\limits_{i=1}^{N_{active}} P^j_{DG,i} + \alpha^j_{BESS} P_{BESS} = P_{load} \\ SoC_{min} \leq SoC_j \leq SoC_{max} \\ SoC_0 = SoC_T \\ m_{MDO} = \sum\limits_{j=0}^{T} \sum\limits_{i=1}^{N_{active}} \dot{m}^j_{i,MDO} \Delta t_j \leq MDO_{onboard} \end{cases} \tag{15}$$

4 Simulation methods and experiments

This paper aims to select the configuration of the electrical generating system on board and examine its performance under specific operating conditions using the simulation experiments outlined below. The mission time for sampling the time-speed profile ranges from a few hours to a day to accurately capture the load sharing trend on a daily basis. Ultimately, the time step is longer than the time required to distribute load power among diesel generators to match the power demand, and transient effects in load distribution among generators are therefore disregarded.

4.1 *Case study ship*

The case study is a new-generation Destroyer with an overall length of 165 meters, a maximum width of 21.80 meters, and a depth of 12.60 meters. The full-load displacement is 9170 metric tons, with a full-load draught of 5.86 meters. The operating profile necessitates steaming at low speeds for much of the vessel's lifetime.

A Combined diesel or gas or electric (CODOGOL) hybrid propulsion plant has been designed, incorporating two gas turbines and two diesel engines to ensure the required speed range, operational flexibility, power projection, survivability, and efficiency.

This configuration allows for a maximum speed of 29 knots and a cruise speed of 18 knots at the end-of-life displacement, with an operational range of 7000 nautical miles at the cruising speed. Two electric propulsion motors (EPMs) provide patrol speed. Four identical diesel generators power the electric plant. Following the "$n+1$" redundancy principle, three out of four generators provide the necessary electric power at cruising speed. A *BESS* has been proposed as a backup to meet redundancy requirements and reduce fuel consumption. The *BESS* has been initially sized to provide the required electric power in emergency conditions, acting as a spinning reserve when one of the generators fails. Specifically, the initial *BESS* sizing delivers the necessary power for 20 minutes, allowing sufficient time to start up another generator in emergency conditions. The *BESS* is divided into four Energy Storage Modules (*ESM*s) to enhance redundancy and reduce vulnerability.

The described architecture ensures high efficiency across a wide range of speeds, using the Lithium-ion battery pack to maintain the Minimum Generator Operation (*MGO*) mode at low speeds. Figure 1 illustrates the architecture, showing only the starboard shaft line, with the port side being conceptually similar. The main technical data of the machinery are reported in Table 1.

This paper introduces an alternative approach to the static sizing of the *BESS* for hybrid propulsion plants of naval ships during the design phase, leveraging a rule-based software. This model works as a decision support system that evaluates different generation plant configurations against a given set of KPIs. The proposed model-based approach offers a novel perspective for *BESS* sizing, addressing Strategic Loading (SL) or Spinning Reserve (SR) requirements.

4.2 *Scenarios*

The ship's mission profile has been derived from databases of a frontline ship currently in active service by scaling the measurements of time-speed trends during a typical mission. Firstly, to evaluate a typical speed range for this case study, the operating profile of the ship must be considered, as shown in Figure 2.

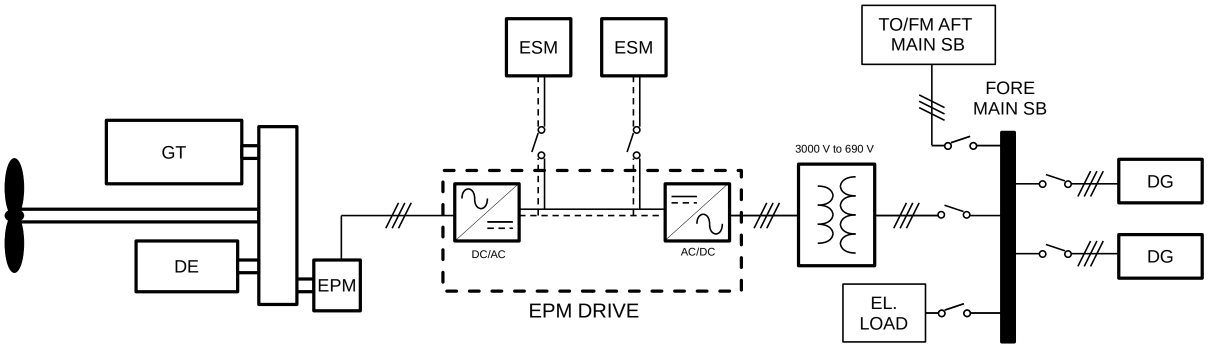


Figure 1: Layout of the proposed propulsion scheme (only the starboard shaftline is shown).

Table 1: Initial sizing of the main propulsion and generation machinery

Gas turbines	$2 \times 30600\,kW$ @ $3600\,rpm$, $220\,g/kWh$ min.
Prop. Diesel engines	$2 \times 7280\,kW$ @ $1150\,rpm$, $188\,g/kWh$ min.
EPM	$2 \times 1120\,kW$ @ $880\,rpm$
Diesel generators	$4 \times 2240\,kW\,/\,2150\,kWe$ @ $1800\,rpm$, $188\,g/kWh$ min.
BESS	$4\times$ ESM $(3240\,Ah$ @ $972\,V)$
ESM	$18(s) \times 54(p)$ modules $(60\,Ah$ @ $54\,V)$

According to the operating profile relationship, the ship primarily operates at low and medium speeds, using electric propulsion to achieve optimal performance at cruising and patrolling speeds. The propulsion system's efficiency in electric mode depends on the running load factor of the diesel generators. Therefore, optimising low and medium speed ranges is crucial for this propulsion plant configuration, and a typical mission profile for appropriate *BESS* dimensioning is selected accordingly.

Next, the ship's active power absorption has been analysed referring to a similar naval vessel equipped with mechanical propulsion. Consequently, the electric load of the reference ship pertains to non-propulsive loads, while for the case study, diesel generators also provide the necessary propulsion load to the electric motors. Let T be a given observation time matching a fixed mission time for the case study. Assuming $P_{ref,k}(t)$ represents a k-measured trend sample of the electric power for non-propulsive loads (e.g., hotel loads, combat systems, navigation devices, radars, and auxiliary generation plants, but excluding propulsion and ship services loads), the load factor of the generation plant of the reference ship is given by:

$$\gamma_{ref,T,k} = \frac{P_{ref,k}(t)}{P_{ref,balance}} \tag{16}$$

Where $P_{ref,k}(t)$ is a k-measured trend observed and measured from the automation plant of the reference ship, $P_{ref,balance}$ is the active power calculated from the load balance of the ship for the same type of loads as $P_{ref,k}(t)$, and T is the reference mission time. It is noteworthy that, given the mission profile and duration, $\gamma_{ref,T}$ is not significantly dependent on the specific sample analysed. At this stage of the work, fixing the mission profile (i.e. assuming $\gamma_{ref,T} = \gamma_{ref,T,k}$) implicitly neglects the stochastic nature of $\gamma_{ref,T} = \gamma_{ref,T}(t,m)$, where t is time and m is a specific, continuous variable that identifies the mission. Furthermore, in this context the stochastic nature of the electric power load over time with respect to the mean load is also disregarded.

Finally, the load profile is obtained by adding a propulsive load, which is calculated based on a typical speed-time relationship sampled from the case study's operating profile. In other words, it is assumed that the active power $P(t)$ provided by the generation plant of the case study is calculated from the load factor mentioned earlier, as expressed by the following relationship:

$$P(t) = P_{prop}(t) + \gamma_{ref,T}\, P_{balance} \tag{17}$$

Where $P_{prop}(t)$ is the active power required by the electric propulsion motors (EPMs) to ensure the necessary speed, and $P_{balance}$ is the electric load of non-propulsive loads calculated from the load balance.

A representative sample in the lower speed ranges for the time-speed relationship according to the operating profile shown in Figure 2 is illustrated in Figure 3.

4.3 Rule-based sizing strategy

The sizing strategy is based on a set of KPIs evaluated as follows in this section.

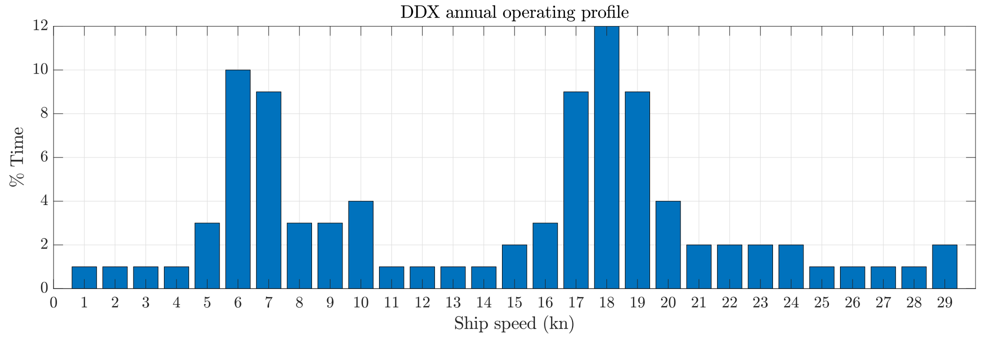


Figure 2: A typical operating profile of a new generation Destroyer with the stated mission requirements

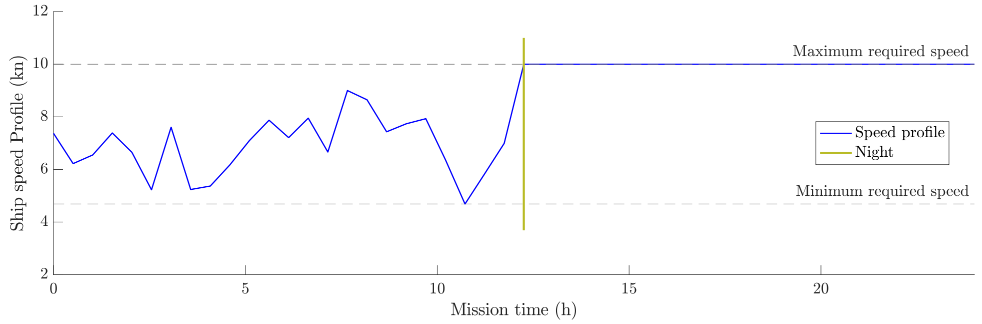


Figure 3: A sample for the speed profile of a new generation Destroyer with the stated mission requirements

The total amount of equivalent CO_2 emissions over one year of operation, representing the environmental footprint of the chosen generation plant configuration, is calculated according to the following equation:

$$CO_{2,\,eq}^{tot} = DAS\ EF_{fuel} \sum_{j=0}^{T} \sum_{i=1}^{N_{active}} P_{DG,i}^{j}\, SFOC_i^j\, \Delta t_j \tag{18}$$

Where DAS is the number of days at sea in one year calculated from the the ship's annual operational availability, i.e. 292 days.

The mean Depth of Discharge (DoD) of the battery is calculated over the mission time as follows:

$$DoD_{mean} = \frac{\sum_{i=1} \left(\boldsymbol{SoC}_{max} - \boldsymbol{SoC}_{min}\right)_i}{n_{peaks}} \tag{19}$$

where $\boldsymbol{SoC}_{max}$ is the vector of local maxima, $\boldsymbol{SoC}_{min}$ is the vector of local minima and n_{peaks} is the number of peaks of the SoC over the mission time. DoD_{mean} ranks, together with the year-based number of charge-discharge cycles of the $BESS$ (N_{cycles}), the battery system usage rate, and is related to its life cycle and duration.

The installed power for generation is strictly related to the necessary space on board the ship and the mean available power over time and is considered through the generator's rated power ($P_{DG,\,max}$).

The mean available power over the mission time T is given by:

$$P_{av,\,mean} = \sum_{i=1}^{N_{DG}} P_{DG,i,max} + P_{BESS} - \frac{\sum_{j=0}^{T} \left(\sum_{i=1}^{N_{active}} P_{DG,i}^{j} + \theta^j \alpha_{BESS}^{j} P_{BESS} \right)}{T} \tag{20}$$

in the way that the optimal load balance is satisfied with the term $\sum_{i=1}^{N_{active}} P_{DG,i}^{j} + \alpha_{BESS}^{j} P_{BESS}$ and θ^j is a Heaviside step function type

$$\theta^j = \begin{cases} 1 & \text{if } \alpha_{BESS}^{j} > 0 \\ 0 & \text{if } \alpha_{BESS}^{j} \leq 0 \end{cases}$$

In the equation 20, N_{DG} is the number of installed generators. P_{av} represents the availability and redundancy of the electric plant in case of shutdown of the main generators with the given load profile in a specific mission time.

The last indicator is the battery system volume, V_{BESS}, calculated by dimensioning the $BESS$ given the technical data of the battery modules. This volume represents the space on board the $BESS$ requires, directly proportional to its weight and cost.

Once the *KPIs* have been chosen, the sizing strategy involves the selection of a hybrid plant configuration in terms of three main parameters: the nominal power of the generators ($P_{DG,max}$), the maximum power deliverable by the battery system (P_{BESS}), and the capacity of the battery system (E_{BESS}). The rule-based sizing strategy can be outlined as follows:

Step 1: The initial configuration of the hybrid plant features diesel generators with a rated power sufficient to meet the electric load balance. For the case study, a *BESS* was then sized to ensure the necessary SR capabilities in case of a diesel generator shutdown, maintaining the same availability in *MGO* mode. This initial sizing was determined using static considerations and was supported and tested by dynamic simulations. At the same time, the *BESS* achieves the *MGO* mode, providing even better fuel consumption performance than the same system without a battery, as already highlighted in Belvisi et al. (2022). The first simulation is conducted with the proposed approach on the initial hybrid plant configuration to determine if the initial *BESS* sizing is adequate to ensure SL capabilities for load sharing;

Step 2: The three main parameters are systematically varied one at a time, beginning with the size of the diesel generator. Each hybrid plant configuration derived from these parameter combinations is assessed using the selected KPIs. All configurations must adhere to the static considerations established during the design phase, which include available space and weight, electric load balance, and the provision of spinning reserve to ensure *MGO* conditions;

Step 3: The configurations tested in the previous step are characterised by the best load sharing in terms of fuel consumption. Typically, this results in load sharings with a high rate of battery usage over the mission time or good load sharings but with frequent start and stop cycles of the diesel generators within specific speed ranges;

Step 4: The battery dimensions are refined and tested based on the previous steps to achieve both optimal load sharing and moderate battery usage, ensuring a reliable life cycle;

Step 5: The configurations achieved are tested with other speed profiles to test typical operating conditions for the fixed mission and robustness of the design solution.

4.4 Results and discussion

This section applies the proposed method to the case study to evaluate the hybrid propulsion system configuration, representing an advantageous trade-off for the specific set of KPIs chosen in Section 4.3. Given the initial configuration of the hybrid plant, in which $P_{DG,max} = 2240\ kW$, $P_{BESS} = 2240\ kW$ and $E_{BESS} = 778\ kWh$, the main parameters are modified according to the strategy described in Section 4.3, and the following configurations are analysed:

- Configuration A: $P_{DG,max} = 2400\ kW$, $P_{BESS} = 2240\ kW$ and $E_{BESS} = 1556\ kWh$, which doubles the energy of the *BESS* and increases the maximum rating of diesel generators by 7%;
- Configuration B: $P_{DG,max} = 2400\ kW$, $P_{BESS} = 2240\ kW$ and $E_{BESS} = 1167\ kWh$, which increases the energy of the *BESS* by 50% and increases the maximum rating of diesel generators by 7%;
- Configuration C: $P_{DG,max} = 2240\ kW$, $P_{BESS} = 2240\ kW$ and $E_{BESS} = 1556\ kWh$, which doubles the energy by *BESS*;
- Configuration D: $P_{DG,max} = 2240\ kW$, $P_{BESS} = 2240\ kW$ and $E_{BESS} = 1167\ kWh$, which increases the energy of the *BESS* by 50%;
- Configuration E: $P_{DG,max} = 2240\ kW$, $P_{BESS} = 1120\ kW$ and $E_{BESS} = 778\ kWh$, that decreases the power of the *BESS* by 50%;
- Configuration F: corresponding to the initial sizing to ensure enough SR for 20 minutes and the *MGO* mode for the hybrid plant;

In order to rank the differences between the six configurations, Figure 4 represents the normalised values of the chosen performance indicators according to the following relationship:

$$KPI_{i,norm} = \frac{KPI_i - KPI_{i,min}}{KPI_{i,max} - KPI_{i,min}} \tag{21}$$

where KPI_i represent the performance indicators described in Section 4.3.

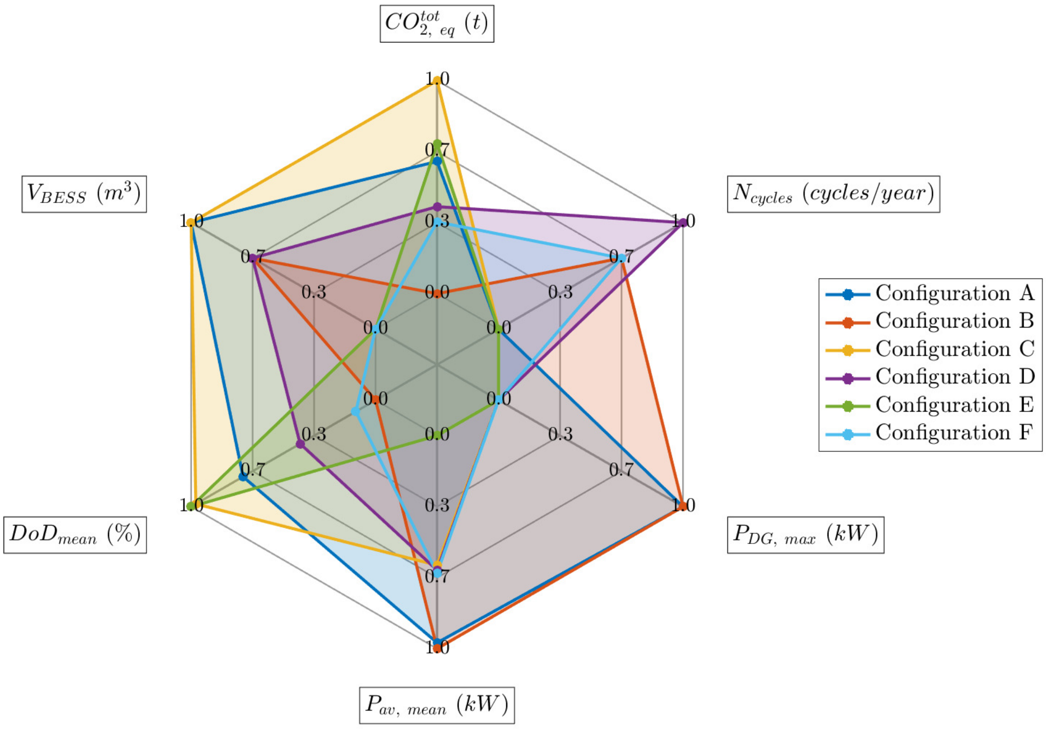
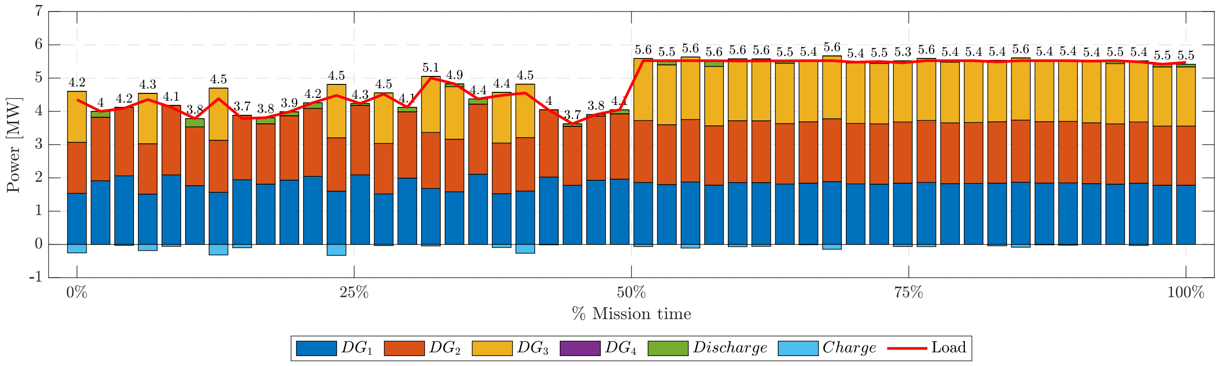


Figure 4: Normalised KPIs for the considered configurations of the *BESS* and diesel generators size

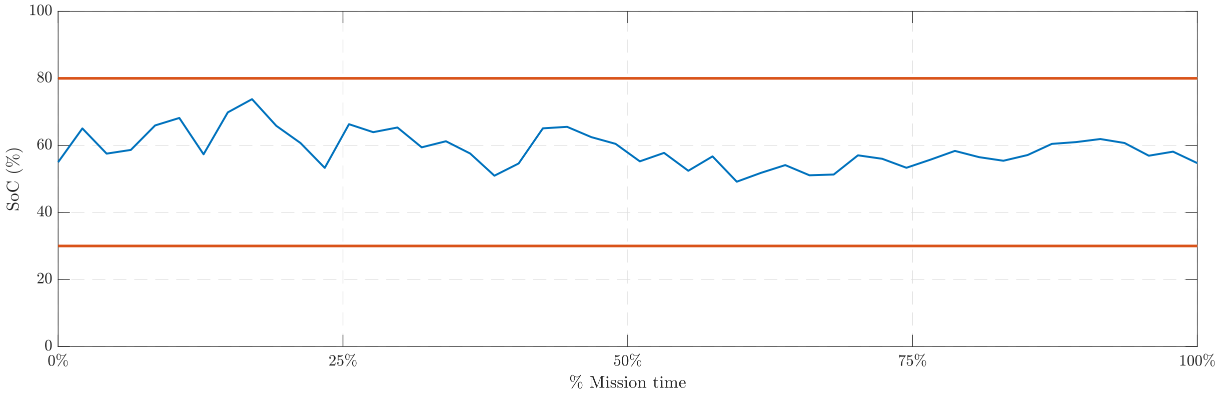
As shown in Figure 4, Configuration B provides the lowest annual-based $CO_{2\,eq}$ emissions, which are about 828 t, as calculated from the selected speed profile over a 24-hour period. Configuration B achieves a $0,4\%$ reduction in $CO_{2,\ eq}$ emissions per SL compared to Configuration C, which performs less efficiently in these respects. On the other hand, this configuration increases the volume of the *BESS* and diesel generators because of the higher energy and maximum power achievable compared to the Configuration F. The volume increase of the *BESS* is about 51% with respect to Configuration F, and with it comes an increase in weight and costs. Furthermore, Configuration C is slightly more reliable regarding SR capabilities, with a mean available power over time increased by 10% compared to Configuration F, as calculated from the load sharing with the chosen time-speed profile. This increased reliability is primarily due to the higher maximum power rating of the diesel generators. However, the predicted usage rate of the *BESS* is poor due to the low calculated Depth of Discharge with this time-speed profile.

Another interesting solution arises from Configuration D. Despite a marginal rise in annual $CO_{2\,eq}$ emissions with respect to Configuration B, Configuration D diminishes the maximum rated power of the diesel generators, albeit at the expense of a slightly higher utilisation rate of the Battery Energy Storage System compared to the optimal configuration in terms of annual cycles (up by 7%). Moreover, the DoD experiences an increase, although the average value remains approximately at 5%. Hence, Configuration D emerges as an optimal solution due to the lower volume of diesel generators and good overall performance. This is further supported by the load sharing illustrated in Figure 5a and the consistent trend observed in Figure 5b, which depicts the corresponding SoC over the mission duration. Additionally, Figure 4 shows that Configuration F has a good overall performance in terms of volume and $CO_{2\,eq}$ emissions. The genetic algorithm used in this study effectively balances conflicting objectives like minimising $CO_{2,eq}$ emissions while optimizing *BESS* volume and diesel generator performance. It consistently produces robust and reliable solutions across different configurations. However, in cases involving oversized generators or *BESS* capacities, the algorithm's performance may diverge. For oversized generators, it prioritizes reliability and power output over efficiency, leading to higher $CO_{2,eq}$ emissions. For large *BESS* capacities, it may overestimate the benefits of reduced generator use, resulting in increased costs and volume without proportional emissions or performance gains.

These observations underscore the need for well-defined bounds, constraints, and power ratings to ensure



(a) Load sharing



(b) State of Charge

Figure 5: Calculated results for Configuration D obtained trough the CO_{2eq} emissions optimisation

balanced solutions. Overall, the algorithm performs well in preliminary design evaluations, essential for practical *BESS* sizing strategies in naval vessels.

5 Conclusions and further research

The proposed method enhances the conceptualisation phase of a *BESS* with a rule-based optimisation strategy, aiming to maintain high levels of efficiency, sufficient spinning reserve, and inherent reliability. This method offers a coherent framework for selecting the optimal configuration tailored to specific design needs by systematically analysing various configurations and their impact on key performance indicators. The method pushes the idea of *BESS* integration on board of naval ships, giving a coherent method of choice of the correct configuration concerning specific design needs, leveraging the concept of spinning reserve and strategic loading for diesel generators and ensuring optimal performance across various operational scenarios. By favouring *BESS* with strategic loading for diesel generators, the method inherently reduces diesel generator running hours under the *MGO* condition. This reduction improves operational efficiency and minimises environmental impact and maintenance requirements, contributing to overall cost savings and sustainability. A significant side effect of implementing this method is its potential to revolutionise life cycle assessment and to reduce operational workload.

While the method presented here represents a significant advancement in *BESS* integration on naval ships, there are several avenues for further research and improvement. Firstly, the dependency on the speed profile could be mitigated by conducting stochastic analyses of the ship's operating profile. By evaluating the relationship between sizing requirements and varying operating conditions, the method could be more robust and adaptable to real scenarios. Furthermore, ongoing research should explore new configurations and operational strategies to maximise *BESS* utilisation while ensuring reliability and performance standards. Although initial sizing constraints are influenced by available space on board, the choice of configuration can be generalised and applied to a broader range of *BESS* configurations, thanks to the inherent modularity of the technology. Lastly, optimisation methods should be refined to enhance calculation precision, reduce computational time, and optimise computational resources by employing advanced optimisation techniques, such as dynamic programming, metaheuristic algorithms or machine learning approaches.

In conclusion, the method outlined in this study represents a step forward in integrating *BESS* on naval ships, offering a systematic approach to configuration selection and optimisation, driving progress towards a cleaner,

https://doi.org/10.24868/11140

more efficient, and resilient maritime fleet. As the maritime industry strives to meet ambitious emission reduction targets set by organisations like the International Maritime Organization, adopting innovative technologies and optimisation strategies will play a crucial role in shaping the future of naval propulsion systems.

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