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Battery Energy Storage Systems for Emission Reduction: A Roadmap for Strategic Loading of Naval Ships

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Abstract. Battery Energy Storage Systems (*BESS*) stand as a cutting-edge solution for reducing emissions and improving the resilience of naval hybrid power systems. However, their effectiveness depends on several factors, including operational and reliability requirements, power system configuration and electrification level, load profiles, and the chosen Energy Management Strategy (*EMS*). Strategic loading (*SL*), a core function of modern *EMS*, plays a key role in optimising energy use, enhancing performance, reducing costs, and ensuring reliability during mission-critical scenarios. However, comprehensive analyses on *BESS* integration to address the actual operational needs of naval ship energy infrastructures are often insufficiently explored in the literature. This paper presents an optimisation-based *SL* approach for integrating *BESS* into naval ships through performance assessment. A range of *BESS* configurations was evaluated based on power and energy specifications to minimise fuel consumption, improve generator load balancing, and enhance redundancy. Real-world load data from a conventionally propelled naval vessel were used to validate the approach. Results show that properly sized *BESS* systems significantly reduce fuel use and increases overall electric load stability and availability. The proposed method supports model-based *EMS* design and enables future retrofitting of conventional naval ships.

Keywords. Battery Energy Storage System, Optimisation, Strategic Loading, Fuel Efficiency, Sustainability

1. Introduction

The International Maritime Organization (IMO) has outlined a roadmap to reduce the environmental impact of the maritime industry by 2050 [1,2]. Key strategies include transitioning to low-carbon fuels [3,4,5], and improving energy efficiency through better design practices [6]. Naval vessels are expected to align with this decarbonisation path by adopting innovative technologies to meet multi-role and high-performance requirements [7,8,9].

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While designed for Minimum Generator Operation (*MGO*), naval power systems often require additional generators for redundancy, thus reducing efficiency and increasing fuel consumption. They also face highly dynamic load profiles due to the intermittent and concurrent use of propulsion and onboard equipment, requiring robust and flexible power management to ensure supply continuity in mission-critical scenarios. In this context, loading strategies are essential to modern naval electric plant design [10,11]. However, realistic load profiles are rarely available during early-stage ship design, highlighting the need for reliable estimation or simulation methods.

Battery technologies are increasingly viable for hybrid ship power systems, as they offer high energy density, rapid response and long life cycles [12,13,14]. Improvements in thermal management and safety standards further enhance their reliability [15,16]. As a result, Battery Energy Storage Systems (*BESS*) are emerging as viable solutions [17,18] for enhancing power system resilience and reducing emissions [9,19].

However, most studies and applied research involving *BESS* in naval vessels rely on conventional sizing methodologies and often overlook dynamic control strategies or load-sharing approaches suited to military operations. Performance validation is often limited, and sizing is often underestimated in simulation. Furthermore, system behavior is typically evaluated using statistic load profiles due to scarce full-scale operational data.

This paper presents an optimisation-based load sharing strategy to enhance reliability and fuel efficiency of naval ship power systems operating in *MGO* mode. The approach integrates a *BESS* sizing under dynamic load conditions and mission constraints. Each configuration is assessed for generator usage, battery contribution, and system redundancy. Leveraging real-world load data, the framework enables meaningful comparisons across *BESS* setups and supports early-stage design of resilient, energy-efficient shipboard power architectures.

The rest of the paper is structured as follows: section 2 formulates the power system model; section 3 details the optimisation framework; section 4 introduces the case study and real load data; section 5 presents simulation results and section 6 concludes the paper.

2. Power system model

Naval ship power systems typically rely on multiple generator sets to meet dynamic load demands and redundancy. In the hybrid configuration studied here, the generators are enhanced by a *BESS*.

A steady-state modelling approach is used for both combustion engines and batteries, prioritising computational efficiency and physical relevance over detailed dynamic fidelity [20]. Generators are characterised by their required fuel consumption $m_{fuel,req}(t)$ and total power output $P_{gen,tot}(t)$, with fuel usage estimated using a black-box model based on Specific Fuel Oil Consumption (*SFOC*) and load demand.

In this hybrid architecture the total load $P_{load}(t)$ is shared between generators and the *BESS*. Battery behaviour is controlled by a load allocation factor $\alpha_{BESS}(t)$, which governs the power $P_{BESS}(t)$ exchanged with the system over the maximum power available

$$\alpha_{BESS}(t) = \frac{P_{BESS}(t)}{P_{BESS,\ max}}.$$

The optimisation-driven loading strategy dynamically adjusts $\alpha_{BESS}(t)$ to minimise fuel consumption while respecting operational constraints.

The dynamic behaviour of the *BESS* is captured through its State of Charge (*SoC*), which evolves according to the following expression $\forall t \in (0, T)$:

$$SoC(t) = SoC(0) - \frac{\beta}{E_{BESS,\ max}} \int_0^t P_{BESS}(\tau) d\tau \tag{1}$$

Here, $SoC(0)$ is the initial state of charge, $E_{BESS,\ max}$ is the rated energy of the battery, and $P_{BESS}(t)$ is the instantaneous power exchange of the *BESS* [21]. The coefficient β accounts for efficiency losses during charge and discharge, defined as:

$$\beta = \begin{cases} \eta_{charge} & \text{if } P_{BESS} \leq 0 \\ \dfrac{1}{\eta_{discharge}} & \text{if } P_{BESS} > 0 \end{cases}$$

where η_{charge} and $\eta_{discharge}$ are the respective efficiencies during charging and discharging phases. To preserve battery health, operational limits are typically imposed, maintaining *SoC* within a range of 20% to 80%. Within this range, the *BESS* is assumed to operate at a near-constant voltage, allowing voltage fluctuations to be neglected for the purposes of steady-state modelling. This modelling framework enables the evaluation of how variations in *BESS* sizing impact generator load sharing, system efficiency, and overall performance across different configurations.

3. Optimised Strategic Loading approach

This section outlines the *BESS* technical specification range of variation and the numerical optimisation algorithm. The *BESS* design space is shaped by converter limits and backup time requirements, defined by power ($P_{BESS,max}$) and energy ($E_{BESS,max}$). Series-parallel configurations based on manufacturer specifications define the feasible sizing range.

3.1. Optimisation algorithm for strategic loading

The proposed load sharing strategy is formulated as a constrained optimisation problem aimed at minimising fuel consumption during mission operations. A Genetic Algorithm (GA), previously described in [7], is used to solve this problem.

The decision variables are the time-dependent *BESS* load allocation factors α^j_{BESS}, defined at each discrete time step t_j, with $j = 0, \ldots, T-1$, and a candidate solution is defined as $\alpha = \left\{\alpha^j_{BESS}\right\}_j$. Total mission time is $\sum_{j=0}^{T-1} \left(t_{j+1} - t_j\right)$. Each solution is evaluated using the cost function:

$$f(\alpha = \left\{\alpha^j_{BESS}\right\}_j) = \sum_{j=0}^{T-1} \sum_{i=1}^{N_{active}} P^j_{gen,i} SFOC^j_i \Delta t_j \tag{2}$$

where $\Delta t_j = t_{j+1} - t_j$, $P^j_{gen,i}$ is the power supplied by generator i at time t_j, and $SFOC^j_i$ is its specific fuel oil consumption.

The total generator power required at each step is $P^j_{gen,tot} = P^j_{load} - P^j_{BESS}$. In real-world operation, the *MGO* condition is often not satisfied for the sake of maintining high reliability. Load demand is distributed among the number of generators specified by the operational mode set by the predefined Energy Management Strategy (*EMS*). With the integration of a *BESS*, the total power $P^j_{gen,tot}$ is evenly distributed among the active, minimum number of generators N^j_{active} required to support the load at time step j, e.g. without an additional generator.

Eventually, the optimisation problem combines the cost function defined in equation 2 with power balance and mission-related constraints, and is parameterised by each selected *BESS* configuration:

$$\left\{\begin{aligned}
&\min_{\left\{\alpha^j_{BESS}\right\}_j} \sum_{j=0}^{T-1} \sum_{i=1}^{N_{active}} P^j_{gen,i} SFOC^j_i \Delta t_j \\
&s.t.: \\
&\alpha_{BESS,min} \leq \alpha^j_{BESS} \leq \alpha_{BESS,max} \\
&P^j_{gen,i} = 0 \quad \vee \quad P_{gen,i,min} \leq P^j_{gen,i} \leq P_{gen,i,max} \\
&\sum_{i=1}^{N_{active}} P^j_{gen,i} + \alpha^j_{BESS} P_{BESS,\ max} = P^j_{load} \\
&SoC_{min} \leq \frac{1}{E_{BESS,\ max}} \left(E_0 - \beta \sum_{p=1}^{j} P_{BESS_p} \Delta t_p \right) \leq SoC_{max} \\
&SoC(0) = SoC(T) \\
&m_{MDO} = \sum_{j=0}^{T-1} \sum_{i=1}^{N_{active}} \dot{m}^j_{i,MDO} \Delta t_j \leq MDO_{onboard}
\end{aligned}\right. \tag{3}$$

4. Case study

This section describes the power system under study, introducing the battery-enhanced plant configuration. Onboard load data are analysed to validate the optimisation approach and identify optimal *BESS* sizing for improved generation performance.

The case study involves a conventionally propelled naval ship with separate power generation and propulsion systems. Six diesel generators supply a 660 V, 50 Hz main network. Quadratic approximation at rated speed of *SFOC* data provided by manufacturer was used to speed simulations in MATLAB/Simulink. The automation algorithm of the shipboard electric plant is based on a predefined matrix that considers 18 different configurations of operational modes and available generators to meet the load demand. Table 1 shows the minimum number of active generators and the calculated, as-built load balance expressed in per unit (PU), based on the rated power of one generator.

As shown in Table 1, the ship is designed to operate under the *MGO* loading strategy. However, recorded load profiles reveal that actual power demand is often significantly lower than the design assumptions, even under high-load conditions. In real-world this

Table 1. Required online sources in each operational mode

Mode	Number of online generators	Calculated load (PU)
Port	2 - 3	1.520
Manoeuvre	4	3.320
Navigation	3	2.550
Combat	4	3.070

results in keeping an excessive number of generators online to maintain high reliability, resulting in inefficient operation. Integrating a *BESS* could close the gap between real and expected load conditions, ensuring reliability together with the *MGO* mode, without the use of an additional generator.

In this study, 25 *BESS* configurations were sampled and tested from the following ranges of variation of the couple $(P_{BESS,\ max}, E_{BESS,\ max})$

$$[0.4;0.8]PU \times [0.4;0.8]PUh \subseteq \mathbb{R}^2.$$

The *BESS* is designed for a projected 10-year lifespan, and sizing is evaluated following the approach in [22] to account for long-term performance degradation. It interfaces with the main power grid via a 1 kV converter.

4.1. Actual load profiles

This section presents the onboard load profile measurements from the case study. In early-stage ship design, load scenarios are often uncertain, typically relying on statistical assumptions from legacy vessels. This study utilises real operational data to enhance accuracy and validate design choices, facilitating more reliable simulations for *BESS* sizing and fuel consumption analysis.

Load profiles were obtained using the ship's automation system, which gathers real-time data from sensors connected to main switchboards, generators and the propulsion control system. Active and reactive powers are measured at the generator switchboards, while Speed Over Ground (*SOG*) and propulsion commands are monitored via GPS and telegraph lever positions. Additional signals such as manoeuvre readiness selectors and shaft speeds are used to identify operational modes. Data were recorded during various navigational phases, including manoeuvring and deep-sea operations, across different seasons. Figure 1 illustrates representative manoeuvring phases, highlighting peak transients during thruster-intensive operations.

5. Results and performance evaluation

Simulations were carried out in MATLAB R2024b on a computer equipped with a 24 cores, 32 threads processor operating at 2.20 GHz and with 16 GB DDR4-SDRAM. Manoeuvres are tested systematically using a reduced number of time array points to enable efficient batch simulations, as shown in the red box of figure 1. Average outcomes in fuel consumption and battery usage remain consistent across different manoeuvre segments. Load distributions between generators and the *BESS* have been evaluated using the parameter set listed in Table 2.

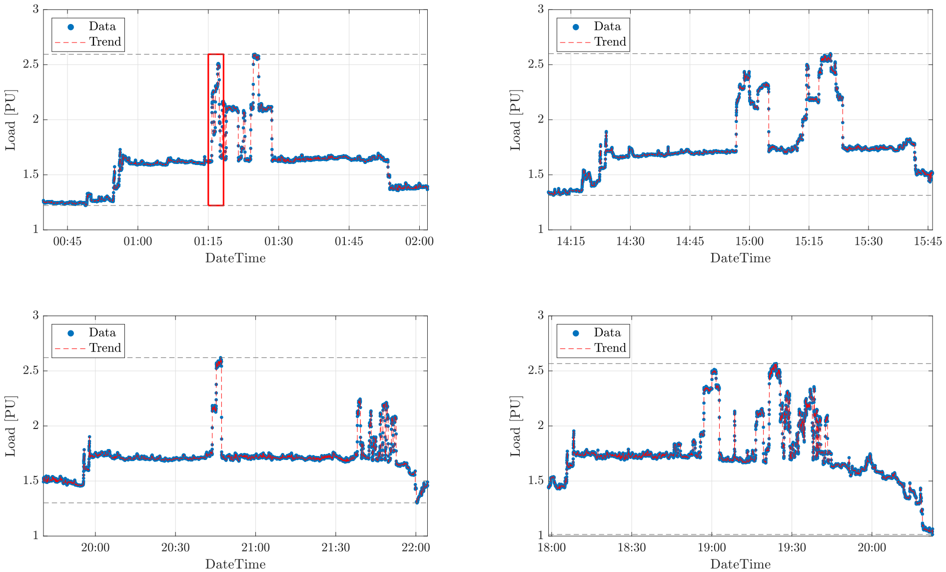

Figure 1. Power demand recordings across different manoeuvre scenarios.

Table 2. Simulation parameters adopted for the case study.

$P_{gen,min}$	$P_{gen,max}$	$\alpha_{BESS,min}$	$\alpha_{BESS,max}$	η_{charge}	$\eta_{discharge}$	$\%SoC_{min}$	$\%SoC_{max}$
$0.20P_{gen,MCR}$	$0.95P_{gen,MCR}$	-1	1	0.94	0.97	20%	80%

Figure 2 compares generator and battery usage across the 25 *BESS* configurations defined in Section 4. Each subplot illustrates the cumulative time spent by each energy source (generators and batteries) at specific power level intervals as stacked bars, with colours representing usage intensity in the same interval. The left colour bar indicates battery loading (green for charging, red for discharging), while the right colour bar represents generator loading from low to high output. The results highlight that the balance between power and energy ratings in the *BESS* sizing significantly affects load sharing and system efficiency. Low-power configurations (top rows) exhibit limited use, typically below 40% of rated capacity, reducing their ability to handle transients and increasing reliance on a third generator, along with fuel consumption and mechanical wear. As battery power increases, the *BESS* supports a broader operating range, stabilising generator loads and improving efficiency. However, insufficient energy capacity leads to high discharge rates that can shorten endurance and occasionally require a fourth generator, especially during recharging. Configurations with high power and energy deliver the most balanced performance, smoothing both transient and sustained demands. Conversely, low energy setups, exhibit frequent charge-discharge cycling under heavy loads, even with high power.

Figure 3 shows violin plots of *BESS* C-rates across the tested power and energy configurations.

The distribution shapes reflect how the battery is used during load sharing. Configurations with low power ratings exhibit narrow distributions concentrated at low C-rates. High power and low energy setups show wider distributions with higher peaks, revealing

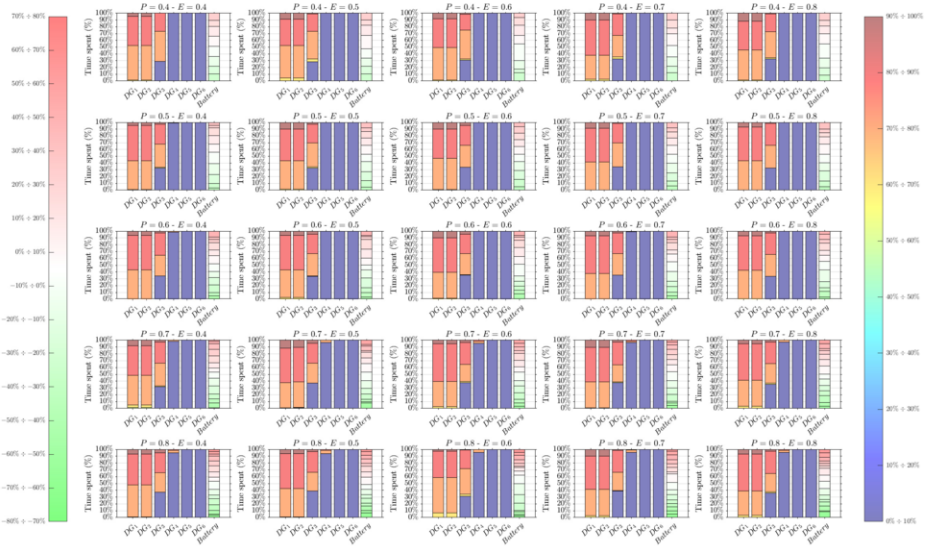

Figure 2. Stacked time at generators and battery percentage load levels for different *BESS* configurations.

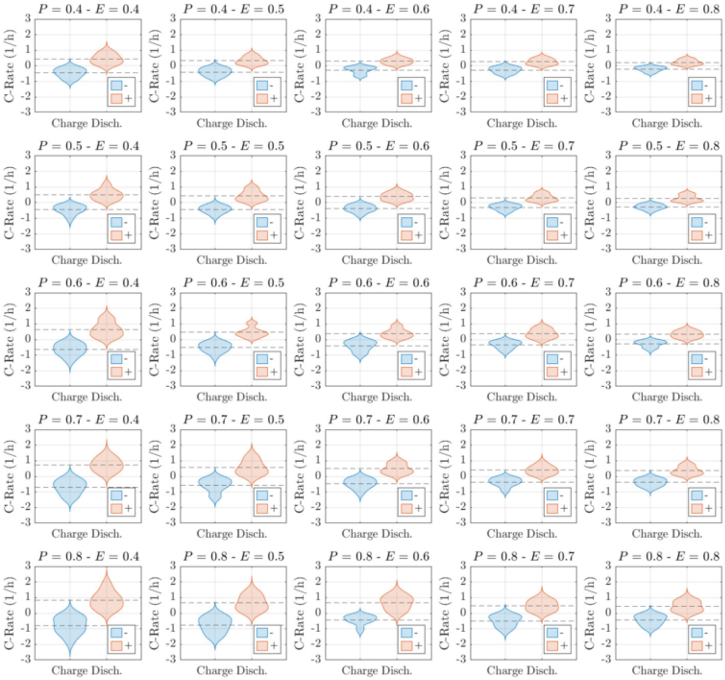

Figure 3. Violin plots of C-rates for each *BESS* configuration over the load profile time history.

more frequent cycling per unit time, higher usage rates and higher currents, potentially impacting the *BESS* lifespan of modules. In contrast, high power and high energy configurations provide more balanced distributions, supporting short-term and sustained loads while avoiding excessive C-rate peaks. These results confirm that increasing power alone intensifies battery usage, while matching it with sufficient energy ensures more reliable performance.

Figure 4 displays violin plots of the *SoC* across various *BESS* configurations. These distributions reflect the energy fraction utilised by the battery during load sharing over the mission profile.

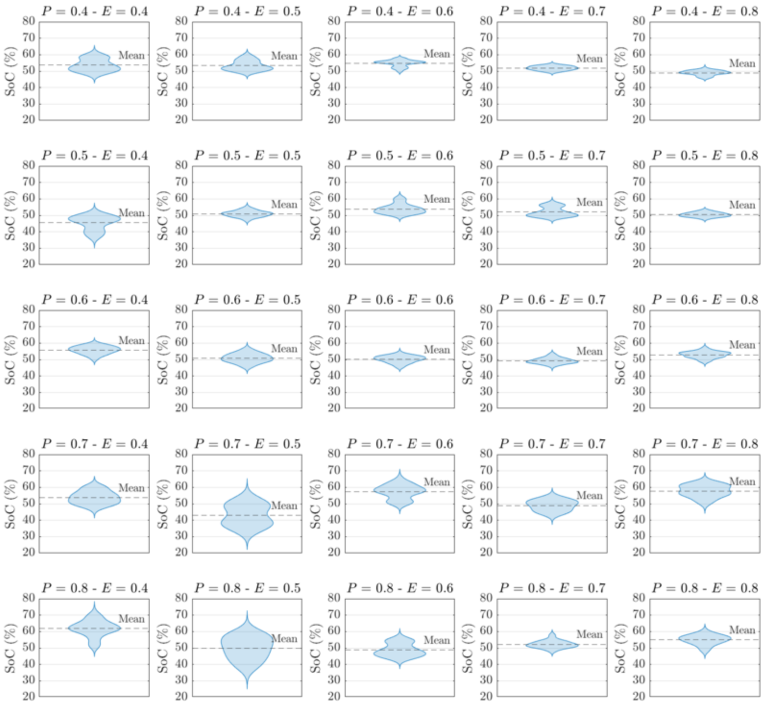

Figure 4. Violin plots of *SoC* experienced by each *BESS* configuration during the load profile time history.

Low energy configurations show broader *SoC* ranges and greater variability, indicating deeper cycling. This behaviour may reduce battery lifespan due to increased stress from deeper Depth Of Discharge (*DoD*). In contrast, high energy batteries maintain *SoC* within a narrower band around the initialising value $SoC(0)$. This effect benefits battery health and supports the preservation of long-term capacity.

The visualisations highlighted in this section underline how load sharing dynamics evolve with changing battery characteristics and support data-driven decisions for energy-efficient and reliable naval ship operations.

6. Conclusions

This paper addresses the need for emission reduction and operational resilience in naval onboard power systems by integrating Battery Energy Storage Systems (*BESS*) through a strategic loading optimisation approach. Using real onboard load profiles and assessing multiple storage configurations, the proposed method aligns design with operational needs, enhancing the efficiency and reliability of naval electrical systems. The study highlights the importance of properly sizing power and energy ratings of *BESS* to optimise load sharing and performance. Small batteries offer minimal support, especially those with limited power, leading to greater generator reliance. In contrast, larger batteries with balanced power and energy ratings enable efficient and stable generator operation. Findings are validated by real-world load profiles, with analyses presented in relation to a representative load profile window. Violin plots of C-rates and *SoC* quantitatively confirm that inadequate sizing results in either underutilisation or excessive stress of the *BESS*, while appropriately sized configurations provide more effective load handling and enhance battery longevity. The results underscore the value of an optimisation approach in hybrid naval power system design. By ranking *BESS* configurations based on generator and battery usage patterns, designers can assess the trade-offs between efficiency, reliability, cost, and integration complexity. Overall, this framework supports optimal *BESS* selection based on real load data.

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