Design and Sizing of an Energy Storage System for a Hybrid Tugboat

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***Abstract*—The global maritime industry is increasingly prioritizing sustainability, promoting the adoption of various hybrid and fully electric propulsion systems for different vessel types. This paper presents a design and sizing methodology of an energy storage system for a hybrid tugboat, customized to meet the operational demands while minimizing environmental impact. The proposed framework integrates analysis of load profile, energy storage sizing, battery technologies selection, and propulsion system optimization to achieve an optimal balance between performance, and emissions reduction. The results demonstrate that a well-designed energy storage system for a hybrid tugboat can achieve reductions in fuel consumption and greenhouse gas emissions without compromising the availability and robustness required for towing and transit operations.**

***Index Terms*—Energy Storage Design, Propulsion Optimization, Energy Management.**

I. Introduction

The growing global concern over climate change has significantly pressured industries to adopt sustainable practices. The maritime sector, responsible for approximately 3% of global CO_2 emissions [1], has continuously increased its emissions, as shown in Fig. 1. Addressing emission reduction is critical, as strict regulations on emissions and fuel efficiency aimed at mitigating the environmental impact of maritime activities are being implemented worldwide [2].

One promising approach is adopting electro-mobility technologies in maritime operations. In this context, electro-mobility can be implemented through various strategies [3], from hybrid propulsion systems to fully electric vessels [4]. Hybrid propulsion, in particular, combines the advantages of diesel engines with electric power systems, offering a flexible and efficient solution for reducing emissions without compromising performance [5]. The hybridization of propulsion systems relies on the separate or simultaneous use of different energy sources [1].

Several studies have examined hybrid propulsion systems. A marine hybrid propulsion system, focusing on vector control of the electric motor during different modes and verifying the control feasibility [6]. The optimization of hybrid propulsion system design for a tugboat has been explored, presenting a methodology that streamlines powertrain component sizing and control, minimizing costs for a specific operating profile [7]. A coordinated control strategy for a variable-speed hybrid tugboat have been presented to improve fuel economy. The proposed strategy, validated through simulations and a small-scale experimental testbed, showed reduced costs and lower CO_2 emissions [8].

Among vessel types, tugboats—used for towing and maneuvering large ships—are among the highest emitters per unit of energy due to their highly variable load profiles [3]. Tugboats and ferries are ideal candidates for hybridization due to their operational profiles, which involve prolonged idling, low-speed maneuvering, and frequent speed changes that lead to inefficient fuel consumption [9].

This paper presents the design and sizing of an energy storage system for a hybrid tugboat, based on the real load profile of a Chilean vessel. Although maritime hybrid technologies have advanced [10], a standardized national methodology for tugboat hybridization is still lacking. The proposed approach considers load profiles, energy demand, battery selection, and propulsion optimization. Simulations show reduced emissions while maintaining the robustness needed for towing and transit operations.

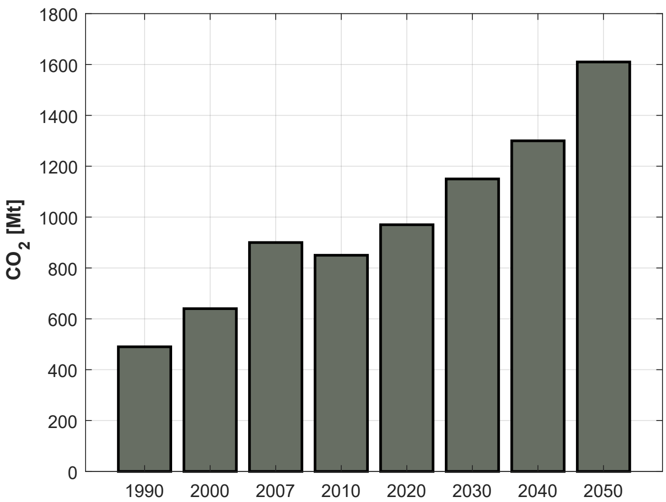

Fig. 1. Estimated CO_2 emissions (in million tonnes per year) from international shipping [1].

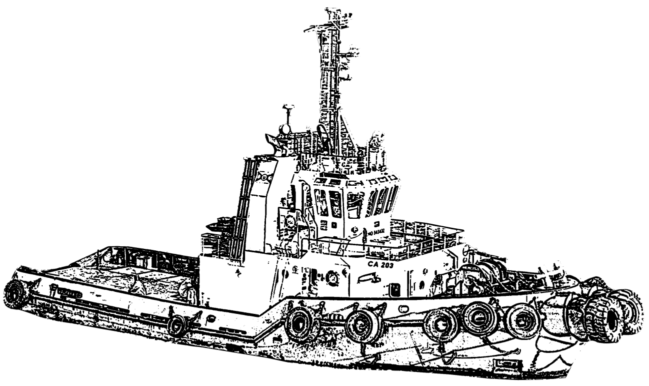

Fig. 2. Typical tugboat structure.

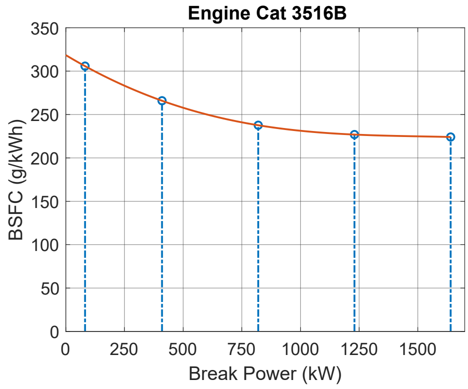

Fig. 3. Brake-specific fuel consumption (BSFC) of the CAT 3516B engine used in tugboats [11].

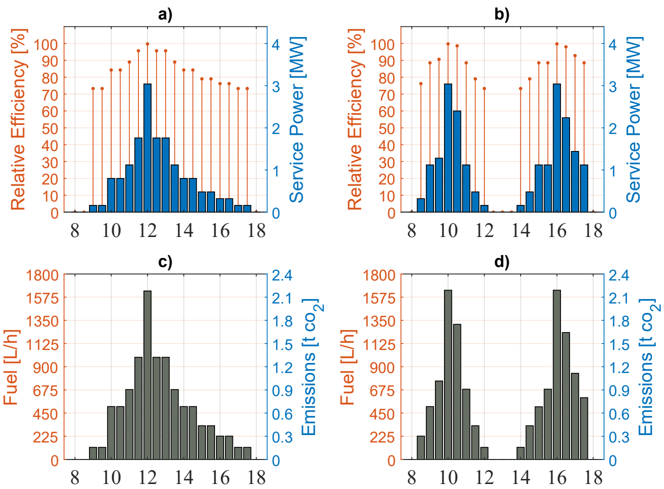

Fig. 4. Load profile of a tugboat operating in a Chilean harbor: a) One service manoeuvre, b) Two service manoeuvres, c) Fuel consumption/emissions generated for a service maneuver, d) Fuel consumption/emissions generated for two service maneuvers.

II. Description of Tugboats and their Requirements

Tugboats play a pivotal role in assisting and maneuvering larger ships, ensuring their safe navigation in harbors, canals, and congested waterways [12]. The primary function of a tugboat is to provide towing and pushing assistance to other vessels, particularly those lacking the maneuverability needed to navigate specific areas, such as container ships in harbor zones [3]. Tugboats are known for their engine capacity, which generates substantial bollard pull—the force required to hold a vessel stationary against external forces such as wind, currents, or water resistance. These vessels are equipped with powerful engines and specialized towing equipment, including towing winches and strong towing lines.

Tugboats come in various designs and sizes to accommodate the diverse needs of maritime shipping, especially as they often operate near urban areas [10]. Their design typically features a distinctive high bow and powerful propellers for enhanced control and stability during operations, as shown in Fig. 2.

The brake-specific fuel consumption (BSFC) indicates how efficiently a combustion engine uses fuel to generate power. The BSFC as a function of output power is illustrated in Fig. 3 for a typical engine used in tugboats [11]. For tugboat engines, BSFC is lower at higher power levels, showing better efficiency. Maximum efficiency occurs at nominal power. At lower power levels, BSFC increases, reducing overall efficiency.

To evaluate the effect of hybridization, the term relative efficiency is employed. This term evaluates how the conventional engine is working taking as a reference the optimal efficiency at the nominal operating point as shown in eq. (1). At this operating point the relative efficiency is 100% reducing its value if the engine works at lower levels of power.

$$\eta_{\text{rel}} = \frac{\text{BSFC}_{\text{nom}}}{\text{BSFC}} \tag{1}$$

To calculate emissions, the following formula relates brake power (P_b), BSFC, usage time (t_u), and a carbon factor (CF):

$$\text{Emissions} = \frac{\text{BSFC} \cdot P_b \cdot t_u \cdot \text{CF}}{10^{-6}} \quad [\text{t } CO_2] \tag{2}$$

The operational profile of a tugboat operating in a Chilean port typically includes one to two maneuvers per day during a 10-hour work shift, as illustrated in Fig. 4. Fig. 4-a) shows the power delivered by the tugboat conventional propulsion system and the relative efficiency of the engines during one service maneuver while b) shows the same information for two maneuvers; c) shows the fuel consumption by the tug and the CO_2 emissions generated by the load of the diesel engines, corresponding to a maneuver, while d) shows the emissions generated by the load of the diesel engines for two service maneuvers.

It can be observed that as the tugboat operates close to the nominal power point of its diesel engines, its relative efficiency improves. This indicates optimal fuel consumption during those periods. Conversely, at lower operating points, the engine consumes more fuel relative to the energy produced.

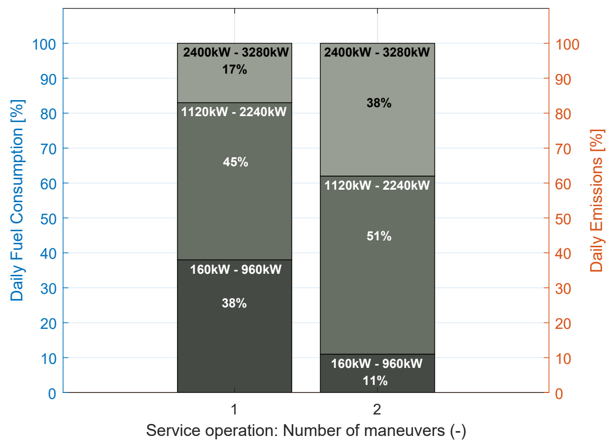

Fig. 5. Percentage of emissions per day based on power ranges.

Fig. 5 shows the accumulated fuel consumption and CO_2 emissions generated for one and two maneuvers. Each service operation is divided into three segments: the lower segments correspond to propulsion system power levels with a relative efficiency below 90%, the middle segments correspond to relative efficiencies ranging from 90% to 98%, and the upper segments represent power levels with the highest relative efficiency, ranging from 98% to 99.8%. At low power levels, fuel consumption can account for up to 38% and 11% of the total daily fuel usage, for one and two maneuvers, respectively. Resulting in high emissions due to the diesel engine operating far from its optimal efficiency point, emphasizing the variability of the load profile of this type of vessel and its impact on fuel consumption and emissions.

III. Hybridization of Tugboats

There are several definitions of vessel hybridization depending on the ENERGY source and the propulsion system [1]. In this paper, the types of hybridization are defined exclusively by the configuration of the propulsion system, while the energy source is defined separately.

Figure 6 illustrates the configurations of different propulsion systems. The hybrid and full electric configurations are considered to be connected directly to the ac bus, independently of the energy source which will be analyzed later.

a) **Conventional Propulsion:** The combustion engine is connected to the propeller using a gearbox.
b) **Series Hybrid Propulsion:** This configuration incorporates an electric machine connected to the same mechanical shaft as the propeller. As a hybrid configuration, it can operate using only the conventional engine, a combination of conventional and electric propulsion, or solely electric propulsion. When operating in combination with the diesel engine, the electrical machine can either add torque (i.e., power) to the transmission system (PTI) or take power from the mechanical axis to supply power to the AC bus (PTO).
c) **Parallel Hybrid Propulsion:** In this configuration, the electric machine is connected to the same gearbox as the diesel engine. Therefore, the gearbox must have two input shafts, and if PTO and PTI modes are required, the gearbox must be designed to provide bidirectional power transfer.
d) **Fully Electric Propulsion:** This configuration uses an electric motor as the sole propulsion source. The motor must be designed to provide full power, and if no gearbox is included, the nominal rotational speed must be low, requiring multipole machines. Using this configuration, if the power provided to the propeller is not obtained from a diesel engine it becomes a fully electric boat.

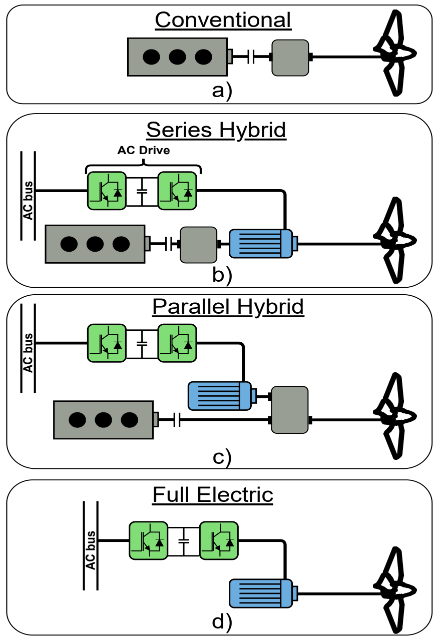

Fig. 6. Propeller propulsion alternatives: a) Conventional, b) Series hybrid, c) Parallel hybrid, d) Full electric.

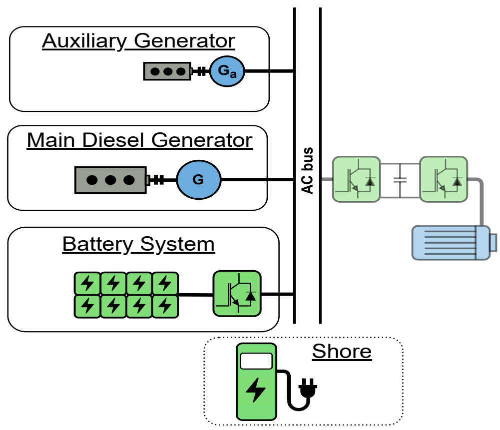

Fig. 7. Power sources for the AC bus, which can operate together.

The energy sources to powered a a hybrid of full electric propulsion system can be concentional dieel generators, batteries, fuel cell etc, or a combination of those. For the analysis in this paper the following main power sources are:

- **Auxiliary Generator:** Supports the vessel's auxiliary

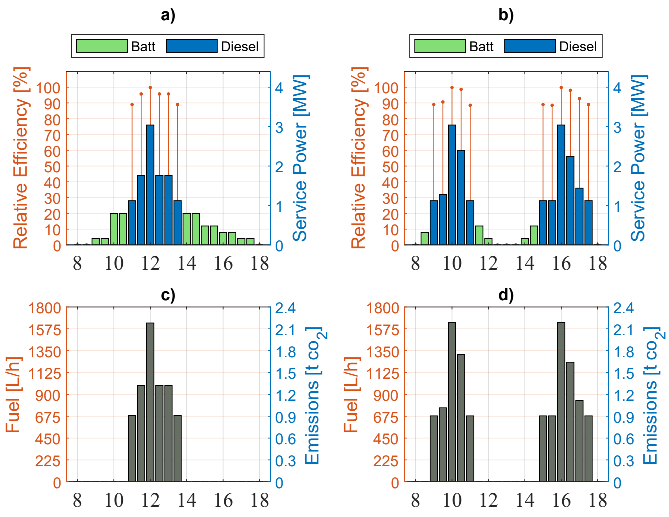

Fig. 8. Load Tug profile using batteries: a) One service manoeuvre, b) Two service manoeuvres, c) Fuel consumption/emissions generated for a service maneuver, d) Fuel consumption/emissions generated for two service maneuvers.

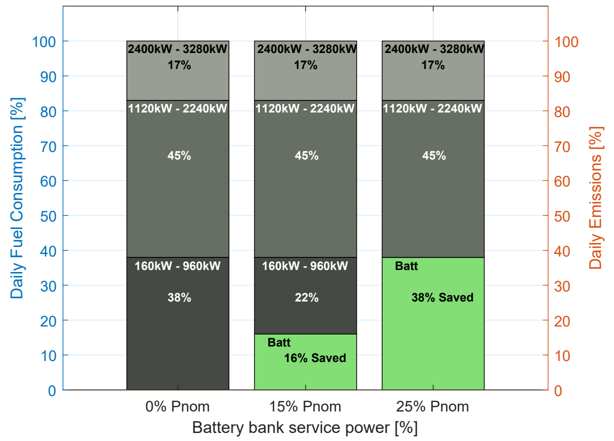

Fig. 9. Comparison of fuel consumption and emissions for a tug boat with a built-in battery bank, considering a service maneuver.

TABLE I
COMPARISON OF FUEL CONSUMPTION AND CO_2 EMISSIONS FOR CONVENTIONAL AND HYBRID PROPULSION SYSTEMS.

Propulsion System	Single Manoeuvre		Two Manoeuvres	
	Fuel [L]	CO_2 [t]	Fuel [L]	CO_2 [t]
Conventional	4600	12.24	8804	15.37
Hybrid	2852	7.59	7836	13.99

loads, ensuring continuity of operations during low-power modes.

- **Main Diesel Generator:** Provides primary propulsion power and can also be used to support the service of a fire pump in emergency scenarios.
- **Battery System:** Supplies power to the electric propulsion system and can be recharged either at port or by the main diesel generator.

Fig. 8 shows the same information of Fig. 4 but incorporate

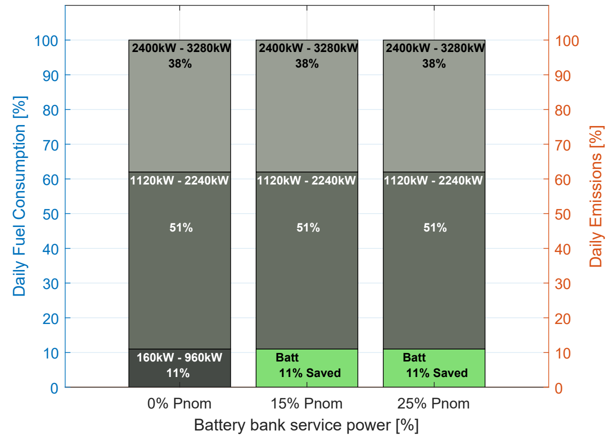

Fig. 10. Comparison of fuel consumption and emissions for a tug boat with a built-in battery bank, considering two service maneuvers.

the use of a battery bank to support the tugboat operation. The purpose of the battery bank is to supply power to the propulsion system when low service power levels are needed i.e., when the diesel engine's relative efficiency is below 85%.

Fig. 9 and Fig. 10 compare fuel consumption and emissions for conventional and hybrid propulsion systems during one and two service maneuvers. The analysis includes systems with 0%, 15%, and 25% of nominal power supplied by a battery bank, aiming to show how increasing battery capacity improves fuel efficiency.

This comparison allows for an analysis of the daily impact of a battery bank with greater capacity that can cover higher service power levels. While no significant reduction is observed for two service maneuvers when increasing the battery bank's capacity, it is evident that for a single service maneuver, a bank capable of delivering up to 25% of the tugboat nominal power can achieve fuel savings and a daily emissions reduction of up to 38%, while improving the minimum relative efficiency up to 90%.

IV. Battery Design Methodology

To begin the design of the battery bank, the total energy requirements for the cases discussed previously must be considered. This analysis provides an estimate of the total energy needed for the worst-case scenario.

A. Battery Technology Selection

Three main technologies are commonly used for maritime electro-mobility applications:

- **Lithium Iron Phosphate (LFP)**: LFP batteries are known for their long life cycle, high thermal stability, and excellent safety performance. They offer lower energy density compared to other lithium-ion technologies but have a higher tolerance to overcharging and overheating.
- **Nickel Manganese Cobalt (NMC)**: NMC batteries have a higher energy density compared to LFP, making them an attractive option for applications that require a compact energy storage solution. NMC technology offers a good

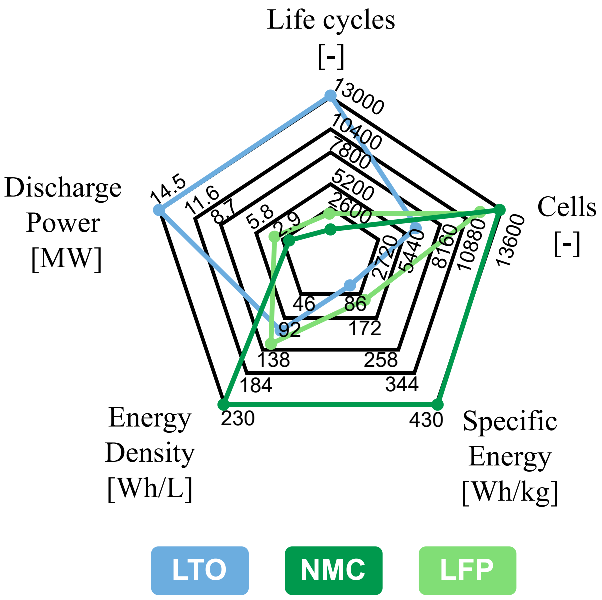

Fig. 11. Battery Technology Options for Maritime Applications

balance between energy density, power output, and cycle life. However, they require more robust thermal management.

- **Lithium Titanate Oxide (LTO)**: LTO batteries are distinguished by their ultra-fast charging capabilities, exceptional cycle life, and superior performance in low-temperature environments. LTO anodes avoid the formation of dendrites, significantly enhancing safety. However, LTO batteries have lower energy density, making them heavier and bulkier for a given energy capacity.

B. Electrical Design

When selecting a battery technology, the parameters of interest for each cell include capacity, voltage, dimensions, and weight. To begin designing the battery bank, it is necessary to define the total energy requirements and the DC voltage of the bank.

These results can be supplemented with data such as the battery current rating. This information allows to determine the total energy and power of the battery bank, as well as the peak power capacity.

C. Mechanical Design

The mechanical design is focused on the calculation of the total weight and volume of the battery bank.

Gross Tonnage (GT) is a measure of the vessel's total internal volume and is calculated by dividing the volume of the vessel's enclosed spaces, in cubic feet, by 100, and is based on two variables: V, the total volume of the vessel in cubic meters (m^3), and K, a multiplier based on the vessel's volume.

Net Tonnage (NT) is the gross tonnage of a vessel minus the space occupied by crew accommodations, machinery, navigation equipment, engine rooms, and fuel storage. Thus, the net tonnage represents the space available for passenger accommodations and cargo storage.

In simple terms, Deadweight Tonnage (DWT) measures how much weight a ship can carry. It includes the combined weight of cargo, fuel, fresh water, ballast water, stores, passengers, and crew. This measurement does not include the ship's empty weight; rather, DWT represents the difference between the ship's displacement in tons when it is "light" and its displacement when submerged to the load line. The load line, located on the ship's hull, indicates the maximum safe submersion depth when the ship is fully loaded.

In summary, once the total energy required by the battery bank is known, the appropriate technology for this application is selected, comparing other technical aspects related to the design for better decision-making, such as cost, life cycle, and performance under various operating conditions. A summary is shown in Fig. 11. The economic cost of the technologies must also be considered for the [7] decision, taking into account that LTO technology has a substantially higher cost than NMC and LFP.

After selecting the battery technology, its mechanical data is used to calculate the required volume and weight. Table II compares the volume and weight of two battery banks, one sized at 15% and the other at 25% of the tug boat nominal power. These values are then checked against the vessel's specifications (GT, NT, and DWT) to ensure the battery bank fits without affecting the vessel's stability or flotation. For the example tug in Table III, the battery bank's size and weight do not pose any installation issues.

TABLE II
DESIGN PARAMETERS FOR BATTERY BANK

Bank Power	Volume [L]	Weight [kg]
15% P_{nom}	6,975.1	11,014.3
25% P_{nom}	16,875.1	26,647.5

TABLE III
MECHANICAL PARAMETERS OF THE CHILEAN TUGBOAT [13]

Gross Tonnage [L]	Net Tonage [L]	Deadweight [kg]
761,808	228,542.4	220,000

V. SIMULATIONS

The battery bank's design parameters are used to select a cell for electrical modeling with a Shepherd model of order 0. Technical details of the chosen cell, U27-36XP from Valence, are used to find model parameters that closely match its real discharge curve. The model shows good similarity to the actual performance, as illustrated in Fig. 12. This enables the extrapolation of results to model a battery bank and predict its behavior across various operating profiles.

The battery bank is simulated for the different load profiles shown in Fig. 8-a) and Fig. 8-b). This will allow to find a model that can be subjected to extreme operating conditions.

The profile of a single service maneuver corresponds to a more aggressive profile for the battery bank, since it causes

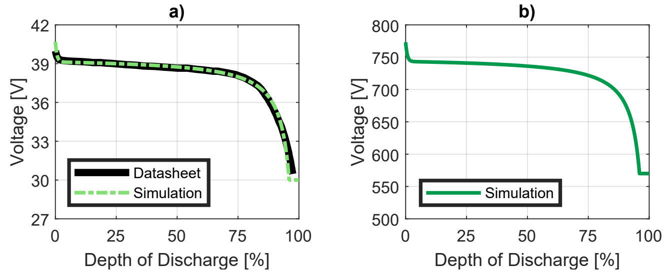

Fig. 12. Battery discharge curve: a) Comparison of cell discharge curve at C/2 from datasheet and curve obtained by means of adjustments to the 0th order Shepherd model, b) Discharge curve of the battery bank (C/2) obtained by means of adjustments to the 0th order Shepherd model.

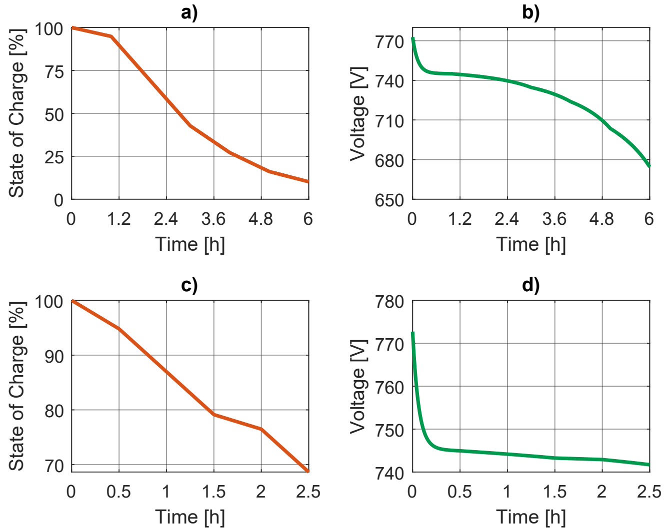

Fig. 13. SOC and Voltage of the battery bank model: a) SOC of the battery bank obtained for a TUG service maneuver, b) Voltages of the battery bank obtained from the operating profile necessary for a TUG service maneuver c) SOC of the battery bank obtained for two TUG service maneuvers, d) Voltages of the battery bank obtained from the operating profile necessary for two TUG service maneuvers.

it to discharge up to 10% of its charge value, whose voltage falls below 700 V, as shown in Fig. 13-a) and Fig. 13-b), respectively. On the other hand, the discharge profile related to two maneuvers considers that it will only be discharged up to 68% of the charge and a voltage greater than 740 V, as shown in Fig. 13-c) y 13-d), respectively.

The chosen cells are designed to handle discharges of almost to 100% of their total capacity, even during maneuvers that significantly discharge the battery bank. However, if the discharge limit is reduced, more batteries would be needed to prevent deep discharges, which would help extend the battery lifecycle [10] .

VI. Conclusions

The integration of hybrid propulsion systems in tugboats shows great potential for reducing fuel consumption and emissions while maintaining operational efficiency. By designing energy storage solutions and optimizing propulsion systems, these systems improve cargo handling, particularly under the variable conditions typical for tugboats. The battery bank design for a tugboat operating in Chilean ports demonstrates its electric functionality and lays the groundwork for other electrical components in the hybrid powertrain, such as the electric motor, propulsion systems, and chargers. The results emphasize hybridization as a key strategy for sustainable maritime operations and offer guidelines for the national hybridization process.

VII. Acknowledgment

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