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Simulation of a Hybrid Propulsion System on Tugboats Operating in the Strait of Istanbul

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Abstract: The implementation of hybrid propulsion systems in vessels has gained prominence due to their significant advantages in energy efficiency and the reduction of harmful emissions, particularly during low engine load operations. This study evaluates hybrid propulsion system applications in two different tugboats, focusing on fuel consumption and engine load across eight distinct operational scenarios, including Istanbul Strait crossings, towing and pushing manoeuvres. The scenarios incorporate asynchronous electric motors with varying power ratings, lead-acid and lithium iron phosphate batteries with distinct storage capacities, and photovoltaic panels of different sizes. The highest fuel savings of 72.4% were recorded in the second scenario, which involved only towing and pushing operations using lithium iron phosphate batteries. In contrast, the lowest fuel savings of 5.2% were observed in the sixth scenario, focused on a strait crossing operation employing lead-acid batteries. Although integrating larger-scale batteries into hybrid propulsion systems is vital for extended ship operations, their adoption is often limited by space and weight constraints, particularly on tugboats. Nevertheless, ongoing advancements in hybrid system technologies are expected to enable the integration of larger, more efficient systems, thereby enhancing fuel-saving potential.

Keywords: fuel consumption saving rate; hybrid propulsion system; energy efficiency; tugboat; energy storage system

Academic Editor: Firstname Lastname

Received: date
Revised: date
Accepted: date
Published: date

Citation: To be added by editorial staff during production.

1. Introduction

Global warming represents a critical challenge that must be addressed to achieve a sustainable society. The Paris Agreement, implemented to mitigate climate change, aims to limit global temperature rise by reducing human-sourced carbon dioxide (CO_2) emissions by 45% by 2030 compared to 2010 levels, with the ultimate goal of achieving net zero emissions by 2050 [1]. In alignment with the objectives of the Paris Agreement, the International Maritime Organization (IMO) has introduced and implemented a range of targets and innovative initiatives to advance sustainable development in marine transportation, a sector that significantly contributes to global greenhouse gas (GHG) emissions [2].

https://doi.org/10.3390/xxxxx

By 2030, the IMO aims to reduce CO_2 emissions by 40% and decrease total GHGs by at least 20%, with a target of 30%. Additionally, a 5% adoption of zero-emission fuels is targeted, with an ambition to reach 10%. Midterm 2040 objectives include a 70% reduction in GHG emissions, striving for 80%, and ultimately achieving net-zero emissions by 2050 [3]. In this context, the Energy Efficiency Existing Index and Carbon Intensity Indicator have been introduced to enhance the sustainability of the global merchant fleet [4]. Compliance with these metrics requires onboard adaptations such as engine power limitation, hull cleaning, air lubrication, and route optimisation. Integrating Hybrid Propulsion Systems (HPSs) with batteries or fuel cells, alongside the retrofitting of ships with alternative fuels, constitutes a strategic approach to meeting the 2040 and 2050 emission reduction targets [5].

Hybrid and all-electric propulsion systems have emerged as viable solutions to meet current and future maritime regulations, integrating electrical and mechanical energy for enhanced efficiency and flexibility [6]. HPSs enable multiple operating modes, including diesel drive, generator-assisted propulsion, and energy storage-supported configurations. Power-Take-Off (PTO) and Power-Take-Home (PTH) modes utilise electric motors to optimise energy use, reduce emissions, and extend maintenance intervals [7].

PTO and PTH modes utilise electric motors to optimise energy use, reduce emissions, and extend maintenance intervals. PTO mode operates similarly to generator mode but without energy storage systems [8]. PTH and electric drive modes rely solely on electric motors powered by batteries and optimally loaded generators, reducing engine wear and extending maintenance intervals. PTH mode also enhances onboard comfort with low noise, vibration-free operation, and improved cost-efficiency [9]. Their boost mode combines main engines and electric motors to meet high-power demands [10]. These hybrid propulsion strategies improve manoeuvrability, operational efficiency, and environmental sustainability, aligning with emission reduction targets [11].

For short sea shipping vessels, the adoption of an all-electric ship concept powered by battery systems and supported by a shore-based solar panel charging infrastructure presents a highly promising and sustainable solution [12,13]. In this context, all-electric tugboats and integrating shore-charged battery systems into conventional tugboats have the potential to reduce GHG emissions significantly [14].

The paper's structure is as follows: Section 2 presents a review of relevant literature, Section 3 details the methodology and case studies, Section 4 discusses the results, and Section 5 offers concluding remarks.

2. Literature Review

HPS applications hold substantial potential to advance the adoption of intelligent, environmentally sustainable power solutions, thereby facilitating cost-effective and resilient operations within the maritime sector [11,15]. Therefore, HPS installation studies on different ship types have been investigated based on diversified drive and operation modes.

The operational profiles of main engines in HPSs have been extensively studied on different vessel types, reflecting their varying load conditions throughout maritime operations. The examined vessel types can be classified as platform supply vessels (PSVs) [16], diving support vessels [17], offshore and harbour tugboats [15,18], offshore service vessels [6], Ro-Ro ferries [19,20], high-speed ferries [21,22], short-route ferries [6,23–25], fishing vessels [26], patrol vessels [27,28], tourist boats [29], icebreakers [30], mega yachts [31], and research vessels [32]. Additionally, Bui et al. [15] examined HPS-integrated tugboat operations with dynamic positioning (DP) capability across five distinct modes: DP standby, DP loading, harbour loading, cruising, and conventional manoeuvring.

Key criteria for HPS applications include operational duration, energy demands, emissions, efficiency, manoeuvrability, costs, maintenance ease, equipment constraints, bunkering challenges, life cycle, and cold ironing potential. While ship-specific variations exist, efficiency remains the primary focus.

Within this framework, the efficiency of serial, parallel, and combined HPS configurations has been analysed to assess their operational performance and viability. For instance, the case study on a tourist boat demonstrated that HPS implementation resulted in a 2% increase in energy efficiency [29]. Capasso et al. [32] reported up to 12% energy efficiency savings in research vessels. Bui et al. [15] emphasised the necessity of energy management strategies to optimise electrical power and mitigate engine load fluctuations. Chai et al. [17] highlighted moderate to high fuel consumption savings, particularly with DC-powered electric motors in HPS configuration. Kim et al. [26] conducted a life cycle analysis on HPSs in fishing vessels, finding that medium-sized ships (displacement of 9.77 tons) achieve the highest efficiency with a 7.6% reduction in CO_2 emissions.

Beyond environmental benefits, HPSs offer notable cost savings, as highlighted in the literature. On a short-route ferry, the implementation of HPS resulted in up to 7% lower operational costs compared to conventional systems [23]. Battery pack size significantly affects economic performance, with larger batteries enabling more stable operation and reduced charging frequency but substantially increasing weight and investment costs [29]. Therefore, the selection of larger battery packs should be based on operational conditions to ensure an optimal balance between performance and trade-offs [22]. The deployment of an advanced energy management strategy, tailored to the specific usage profile, can significantly enhance the benefits of battery packs, further optimising the utilisation of larger systems [21,33].

The integration of hybrid systems in large vessels, such as tankers, bulk carriers, and container ships, has been widely investigated, particularly in the context of auxiliary system implementation. The incorporation of battery storage and waste heat recovery systems into the ship electrification plant of a tanker vessel has demonstrated fuel savings and emission reductions for the plant of up to 18.15% [34]. These reductions can be further enhanced through the implementation of fuel cells, achieving up to a 49.75% reduction when utilising LNG on the case study tanker vessel [35]. The utilisation of green hydrogen-fuelled fuel cells in a case study bulk carrier can achieve a 91.79% reduction in GHG emissions from its electrification plant [36]. Furthermore, onboard hydrogen production from pink ammonia can enhance this reduction to 95.66% [37]. The implementation of hybrid systems in the propulsion plants of bulk carriers has been demonstrated in smaller inland vessels. Energy efficiency optimisation of a parallel HPS resulted in 2.60% and 9.86% reductions in energy consumption on westbound and eastbound voyages, respectively, for an inland bulk carrier [11].

HPSs mitigate ship oscillations and speed fluctuations during energy transitions, with studies demonstrating a 70% reduction using advanced optimisation algorithms [38]. Various energy recovery application integrations to HPSs, such as waste heat recovery and hybrid turbochargers, have been shown to enhance energy efficiency by up to 53% [19]. In addition to fuel efficiency, HPSs improve vibration and noise levels [6,15], load response [32], system reliability [6], and operational flexibility [39]. Given these benefits, HPS is strongly recommended for diverse ship types to enhance sustainability [17,26], with its primary objectives focusing on fuel savings, GHG emissions reduction, and operational cost optimisation [40].

Research papers have explored the implementation of HPSs across various vessel types, focusing on optimising energy management, and integrating advanced energy recovery systems. Studies emphasise the benefits of hybrid configurations in reducing emissions, enhancing energy efficiency, and improving vessel performance through battery storage, waste heat recovery, and fuel cell technologies. Additionally, adaptive optimisation strategies have been investigated to minimise fluctuations in speed and stability while maximising system reliability.

This study investigates the fuel consumption savings achievable through the implementation of HPSs in tugboats, considering diverse operational modes and profiles. While extensive research has explored HPS applications, the integration of real-time data for tugboat installations remains an underexamined area. To address this gap, eight HPS scenarios have been developed using different electric motors, batteries, and solar panels based on operational data from tugboats. The analysis employs a numerical simulation model developed using real-time data to evaluate the potential fuel consumption reduction. Given the spatial and weight constraints of tugboats, a 1% limitation has been applied to account for installation feasibility. Achieving substantial fuel savings through these scenarios would provide valuable insights and contribute to meeting the 2030 and 2050 global decarbonisation targets for shipowners, operators, and stakeholders.

A key contribution of this work is the development of a practical decision-making framework supporting maritime stakeholders during the early stages of hybrid system selection and evaluation for tugboats. Rather than relying on complex methodologies, the framework prioritises accessibility and ease of use. This makes it particularly valuable for operators and decision-makers who may not have access to advanced modelling tools or expertise.

3. Materials and Methods

Operational data for the HPS simulation were collected from three tugboats operating in the Strait of Istanbul. Their dimensional and power characteristics, which are critical for HPS integration, are shown in Table 1. Two of the tugboats share the same dimensions, general arrangement, capacity plan, and structural design. These sister ships are referred to collectively as Tugboat I. The third vessel, with different specifications, is identified as Tugboat II.

Table 1. Technical specifications of tugboats [41].

Vessels	Tugboat I	Tugboat II
Length Over All	32 m	26 m
Breadth Moulded	11.8 m	9.5 m
Depth Moulded	5.55 m	4.65 m
Vessel Draft	4.25 m	~4 m
Gross/Net Tonnage	546/164	272/-
Speed	13 knots	12 knots
Daily Diesel Consumption	25.84m^3	9.57 m^3
Total capacity (m^3)	127 m^3	32.269 m^3
Fire Pomp	FIFI-1 3000 m^3/h	-
Range	-	500 mil
Bollard Pull	75.4 ton	30 ton
Main Engine	2 * 2100 kW–1000 rpm	2 * 1140 kW
Generators	2 * 269 kW	2 * 120 kW
Propellers	2 * WST-CP 2800 mm	2 * SRP 1012

The main engine of Tugboat I, which has direct fuel injection, four strokes, irreversible, turbocharged, and intercooled, generates roundly 350 kW of power per cylinder. Nominal specific fuel oil consumption is 191.5 g/kWh at engine load of 85%. The main engine generating 1140 kW fuel consumption of the Tugboat II varies between 50 and 300 (l/h) depending on the engine speed, torque, and power output. The Tugboat I and II main engines meet the emission limitation of IMO Tier II.

Sea trial data and acquisition of actual speed-power curves are significant for fuel efficiency calculations [42], and while ship main engine loads demonstrate the environmentally benign use of HPSs [26]. The speed-power and power-fuel consumption curves for the main engine were sourced from the engine catalogue. Additionally, to accurately determine the power-fuel consumption characteristics at low load conditions, the required data were derived from load tests conducted on the diesel engine [43]. The main engine quickly wears out and operates inefficiently at low loads [27,43]. Therefore, the mode of HPS, in which the electric motor operates to compensate for low-load power conditions, was applied throughout the analysis. Data on service speed, main engine loads, and RPMs were collected through real-time measurement and monitoring during tugboat operations. Due to the advanced technological outfitting and integrated sensor systems, operational data were directly accessible and recordable from the bridge. These are defined as primary data. Additionally, secondary data were obtained from the propulsion system interface, which recorded operational parameters. Detailed information on tugboat operations is provided in Table 2.

Table 2. Operation of tugboats.

Operation No.	Data Type	Vessel Code	Operation time (min)	Installed Power of Main Engines and Generator Sets	The type of tugboat service
O1	Primary data	Tugboat I	204.5	4200 kW/538 kW	Strait Crossing
O2	Primary data	Tugboat II	32.75	2280 kW/240kW	Towing/Pushing operation
O3	Primary data	Tugboat II	41.25	2280 kW/240kW	Towing/Pushing operation
O4	Secondary Data	Tugboat I	140	4200 kW/538 kW	Strait Crossing
O5	Secondary Data	Tugboat I	435	4200 kW/538 kW	Towing/Pushing operation
O6	Secondary Data	Tugboat I	387	4200 kW/538 kW	Strait Crossing and Towing/Pushing operation
O7	Secondary Data	Tugboat I	657.1	4200 kW/538 kW	Strait Crossing and Towing/Pushing operation
O8	Secondary Data	Tugboat I	50	4200 kW/538 kW	Towing/Pushing operation

To simplify the representation of HPS scenarios, unique codes were assigned to each operation and piece of equipment. For example, O1 refers to the strait crossing operation of Tugboat I, which lasts 204.5 minutes. Tugboats I and II provided support to marine vessels during both strait crossing and towing/pushing operations. Additionally, environmental factors such as air temperature, current speed, humidity, wind speed, and wind force influence fuel consumption rates. The thrust power generated by the propeller is affected by weather, hull fouling, and loading conditions [27].

In this study, total fuel consumption is derived from instantaneous engine power output and operational hours. While these estimates generally align with the daily fuel consumption figures reported in noon reports, minor discrepancies are observed. These variations are primarily attributed to environmental influences such as sea state, weather conditions, and strait currents. As noted in the assumptions section, these external factors are not explicitly accounted for in the analysis. Operations O1 to O4 for Tugboats I and II are illustrated in Figure 1, which was generated using the Marine Traffic application that displays the real-time positions of vessels.

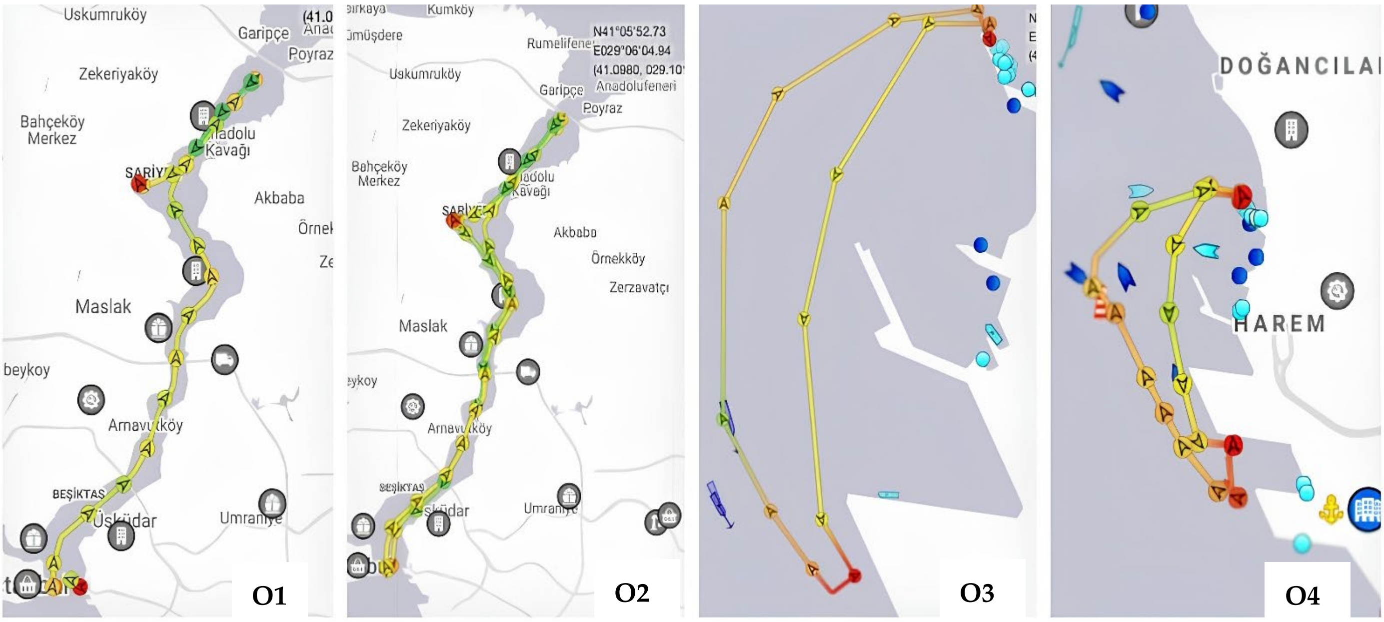

Figure 1. Tugboat Routes of (O1), (O2), (O3) and (O4).

The operations were performed by tugboats which operates the Strait of Istanbul region. The engine loads and operating times of these routes are described in Figure 2 with eight different engine load/time curves based on the operation code.

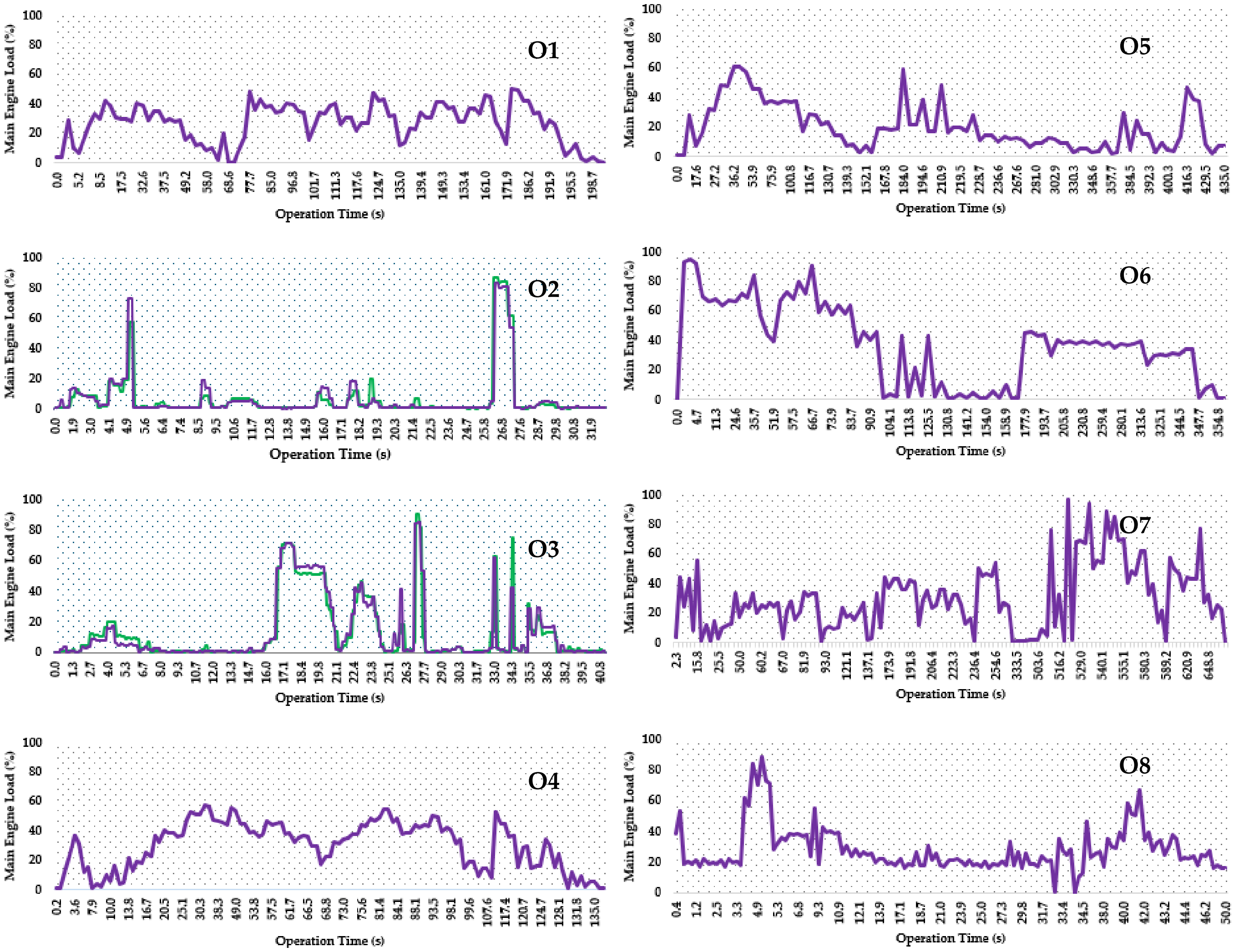

Figure 2. Tugboat engine load and operation time

The type and duration of the tugboat's operation are critical factors for HPS installation. Tugboats are generally equipped with high-power propulsion systems, and they are operated at low loads considering all operations [35]. The main engine loads of tugboats can occasionally reach 100% in the towing/pushing operation; however, these intervals constitute a very short period considering the total duration of the operations. Tugboat II was operated at relatively low loads throughout the O2 and O3 operations compared to other operations. Therefore, the PTH mode was suitable for HPS applications on O2 and O3. Two different curves were highlighted on the O2 and O3 graphs because the data were recorded instantly on two main engines. For the remaining operations involving Tugboat I, only the load data from the first main engine were available. The load profile of the second main engine was assumed to be identical to that of the first.

Tugboat I supported the marine vessel throughout the strait crossing during operations O1 and O4. As a result, main engine loads remained relatively stable, typically ranging between 40% and 60%. In contrast, during operations O5 to O8, Tugboat I performed both towing and pushing tasks, like Tugboat II, leading to higher main engine load levels.

Tugboats are equipped with relatively powerful marine engines to facilitate their operations and provide support to large-scale ships. However, they are quite inefficient and consume high amounts of fuel per unit of power because high-power engines are operated at low loads. The installation of an HPS for tugboats is suggested in this paper to reduce this high fuel consumption and accompanying harmful emissions. Despite the low emissions and fuel savings of HPS, it causes complexity in power systems [21]. The planned HPS system, which includes electric motors, energy storage systems, renewable energy sources, and an existing main engine system, is shown in Figure 3.

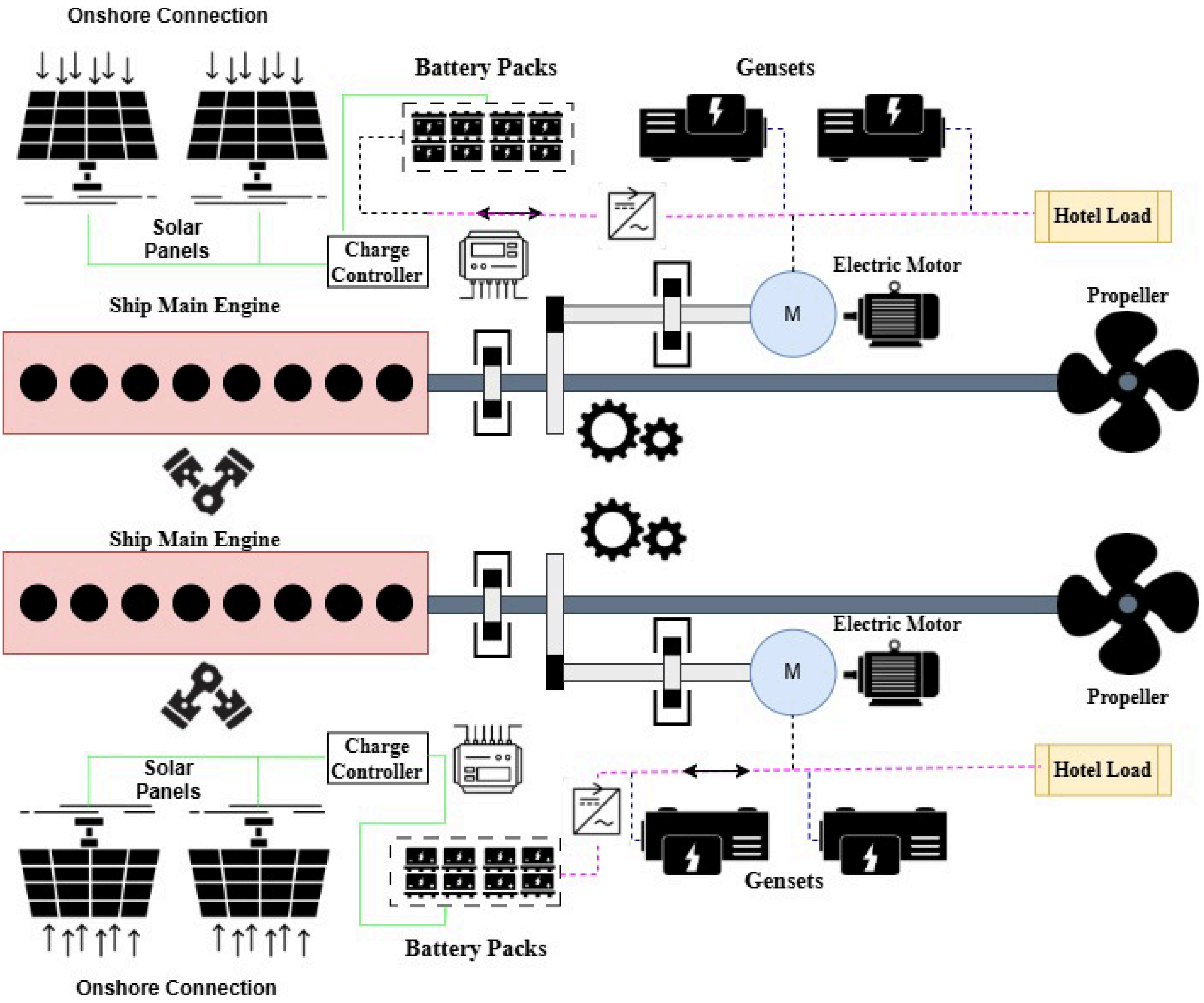

Figure 3. Fundamental components of the proposed hybrid propulsion system for tugboats

Utilising batteries for standby operations offers several advantages over auxiliary engines [7]. Therefore, in this study, batteries are used to power electric motors during low-load operations. Each tugboat is equipped with two electric motors rated at 500 kW and 250 kW, respectively, to meet energy demands under such conditions. The technical specifications of these motors are presented in Table 3.

Table 3. Technical specifications of the electric motors

Motor No	M1	M2
Output power (kW)	500	250
Rated speed (rpm)	1490	1490
Rated Current (A)	890	430
Rated Torque (Nm)	3204.7	1602.3
Power Factor (Cos φ)	0.88	0.87
*Efficiency	0.951	0.96
Weight (kg)	1850	1400
Volume (l)	867.6	802.3

*Efficiency values obtained because of 75% loading of asynchronous electric motors

Unique codes were assigned on electric motors as in the operations. Both M1 and M2 are 3-phase 400 V (Δ) 50 Hz asynchronous electric motors. They have the “S1” operation type that provides continuous operation, and they have an IP55 protection class that is dust-resistant and water sprays. They were manufactured in the B35 type, which defines the type of construction with feet and flanges. The number of poles is 4 pieces. In terms of efficiency, they are in the class of high efficiency (IE2) and premium efficiency (IE3), ranging from 95.1% to 96.1%.

Batteries were evaluated based on several key performance indicators, including energy density, efficiency, cost, life cycle, operating temperature range, volume-to-weight ratio, and suitability for specific application areas. Among the available technologies, lead-acid and lithium iron phosphate ($LiFePO_4$) batteries emerged as the most appropriate options for HPSs, given current technological capabilities. Lead-acid (Pb-Ac) batteries are known for their robustness and ability to function effectively across a wide range of temperatures. Accordingly, two distinct battery types with varying capacities were selected to meet the energy demands of the electric motor, ensuring operational flexibility and reliability in diverse conditions [44]. Therefore, the battery types are selected as $LiFePO_4$ and Pb-Ac as their technical specifications are described in Table 4.

Table 4. Technical specifications of the energy storage systems [45–48]

No	B1	B2	B3	B4
Battery Type	$LifePO_4$	$LifePO_4$	Pb-Ac	Pb-Ac
Capacity (Ah)	200	50	50	71.5
Dimension (l*b*h) (mm)	460*173*240	199*188*147	229*138*210	330*173*239
Volume (l)	19.1	5.6	6.6	13.6
Weight (kg)	23	7	18.2	35.3
Operating Temperature	-20°C to 60°C		-40°C to 55°C	
Open Circuit Voltage (change as state-of-charge)	~3-3.4		~11.8-12.8	
Energy (Wh)	2560	640	642	918.1
Wh/l	134	116.4	96.8	67.4
Specific energy (Wh/kg)	111.3	91.4	35.3	26
Cost ($/kWh)	272.1	1273.4	208.7	435.7
Life Cycle (80% DOD)	2000	2500	360	400

Technical specifications of batteries, which include capacity, volume, weight, cost, and life cycle, provide convenience in choosing the most suitable one. Table 4 clearly shows that lithium-based batteries have a high value in terms of specific energy and cycle life based on 80% depth of discharge (DOD). On the other hand, Pb-Ac batteries stand out in terms of their robust structure, operation at high-temperature ranges, and low cost. However, Pb-Ac batteries are not suitable for large-scale applications, especially due to their low energy density and limited capacity. In addition, low performance and more batteries cause costs and losses of volume and total weight increment on board [32]. On the other hand, lithium-based batteries have a battery life of approximately 3.75 years when used throughout the ship ’s navigation, and this lifespan period can be extended up to 11.62 years when batteries are not used constantly [34].

Li-ion batteries offer a significant benefit in terms of weight and energy density for marine vessels equipped with HPS [6,22] because their size is very critical on ships [39]. Lithium-based batteries are determined to be one of the best battery type with existing technologies to operate optimally [39,49]. However, further safety measures must be followed in the case of an explosion or overheating. Sodium-based batteries are described as an alternative [22] because of their high energy density but operating them at high temperatures requires expanded safety measures [39]. The state of charge of batteries is limited 90% [21] to prevent overcharging and over-discharging [15]. Therefore, 80% of the battery's energy was used in the analysis. Moreover, onshore solar panels and rectifiers were evaluated for recharging. The solar panels and their technical specifications are described in Table 5.

Table 5. Photovoltaic solar panel technical specifications [50,51].

Solar Panel Code	P1	P2
Output power (W)	80	190
Open-circuit voltage Voc(V)	21.76	22.80
Short-circuit current Isc(A)	5.12	10.30
Peak voltage Vmp(V)	17.80	18.6
Peak Current Imp(A)	4.48	9.95
Dimension (mm)	780*675*28	1480*670*30
Weight (kg)	8	11.9
Operating and storage temperature	–40 to +85 °C	
Normal Operating Cell Temperature	45°C (±2°C)	
Efficiency	~ 20%	

Two different photovoltaic solar panels with power outputs of 80 W and 190 W are shown in Table 5, and their power densities are 10 W/kg and 15.97 W/kg respectively. As an alternative to photovoltaic solar panels, batteries can be charged via generators. However, in HPS, shore-based charging lowers emissions and costs compared to the overnight charging of batteries via diesel generators [23]. Shore-based charging rectifiers that operate between 20°C and 50°C are used in several energy distribution applications including power systems, electric cars, and marine vessels [52]. In addition, they have a structure that can be operated in dust-free dry areas, with an IP20 protection class and high efficiencies exceeding 85% [53,54].

Bayraktar [55] developed a MATLAB GUI for HPS analysis, based on a comprehensive literature review and power and transmission-based formulas. This interface includes equations regarding with the main engine, electric motor, batteries and solar panels. Ship diesel main engine power calculation is performed on the basis of cylinder diameter, stroke length, engine speed, indicated mean effective pressure, number of cylinders, two or four stroke. Ship diesel main engine power calculation equations:

$$IHP = p_i * l * \frac{\pi * D^2}{4} * \frac{n}{60} * z * k \quad (1)$$

Where, IHP stands for Indicated Horsepower (kW). This power refers to the total power generated in the ship main engine cylinders before mechanical losses such as friction and heat loss. p_i is the indicated mean effective pressure (bar), l is the stroke length (mm) of engine, D is the cylinder diameter (mm), n is the ship engine speed (rpm), k is the number of power stroke in each cycle, z is the number of cylinders. Since the marine engines analysed in this study are 4-stroke engines, k value is taken as 0.5.

The electric motor power is calculated by considering the electric motor phase state, motor efficiency, voltage value, current value, torque value and motor speed. Equations used in the calculation of electric motor power:

$$\mathrm{P_m} = \mathrm{V} * \mathrm{I} * \cos\varphi * \eta_\mathrm{m} \quad (2)$$

$$\mathrm{P_m} = \sqrt{3} * \mathrm{V} * \mathrm{I} * \cos\varphi * \eta_\mathrm{m} \quad (3)$$

Equation 2 and equation 3 refer to single phase and three phase induction motor power calculation equations respectively. Where $\mathrm{P_m}$ is the generated power of electric motor, V is the voltage (V), I is the current (A), cosφ is the power factor and η_m is the efficiency of electric motor. The equation used during the utilisation of energy from batteries by electric motors:

$$\mathrm{E_{used}} = \frac{\mathrm{P_{motor}} * \mathrm{t_m}}{\eta_\mathrm{system}} \quad (4)$$

$\mathrm{E_{used}}$ refers to the energy (kWh) drawn from the battery, $\mathrm{P_{motor}}$ refers to the power demand (kW) of the electric motors calculated as specified in equation 3. $\mathrm{t_m}$ refers to the electric motors operation time (h), η_{system} refers to the efficiency during the energy transfer from the battery to the electric motor. Discharge current from battery is calculated based on equation 5.

$$I_{bat} = \frac{P_{motor}}{V_{bat} * \eta_{system}} \quad (5)$$

Where, I_{bat} and V_{bat} are refers to Battery discharge current (A) and Nominal battery voltage (V) respectively. Additionally, equation 6 is used to calculate the state of charge of the batteries after energy drawn from the batteries.

$$SOC\ (\%) = \frac{E_{battery} - E_{used}}{E_{battery}} * 100 \quad (6)$$

E_{used} indicates the energy drawn from the batteries and $E_{battery}$ indicates the amount of energy at %100 battery charge. Equation 7 is used in the stage of charging the batteries from solar panels.

$$E_{battery} = P_{panel} * t_p * \eta_p \quad (7)$$

P_{panel} is power output of the solar panel, t_p is effective charging time of panels, and η_p is the panel efficiency.

The interface evaluates parameters such as operation time, low-load durations, total and low-load fuel consumption, low-load energy consumption, battery requirements for electric motor operation, battery volume and weight, total fuel savings, and limited fuel savings. During the analysis, a 1% increase in weight and volume was permitted for both tugboats based on gross tonnage. This corresponds to 5.46 tons for Tugboat I and 2.72 tons for Tugboat II.

Initailly, the load/fuel consumption curves were derived from the load tests on the diesel engine conducted by Bayraktar and Nuran [56]. In this way, the fuel consumption curves of the tugboat main engines were estimated, especially for low loads, since specific fuel consumption rates at loads was not specified in the main engine catalogues. The instantaneous and recorded tugboats' main engine's load rates data and fuel consumption curve data were used in the interface for the analyses. The assumptions made throughout the analysis process are outlined as follows.

- The low load was defined as the utilisation of less than 20% of the power output of the main engine [57].
- 80% of the battery energy was used in the analysis for safety.
- Batteries were only charged on land, and they were not charged during operation.
- The second main engine load profile of Tugboat I was assumed to be the same as the first one.
- Transmission efficiencies of auxiliary equipment were taken as 95% unless stated otherwise.
- The onshore facility is assumed to harness solar energy for 8 hours each day [58].
- 1% weight and volume increase were allowed in the calculation of limited fuel efficiency. However, there was no limitation for the total fuel efficiency in terms of weight and volume.
- The propeller types, sizes, and efficiencies of the tugboats remained unchanged following the installation of the HPS.
- The weather and sea conditions during data collection remained consistent throughout the installation and analysis of the HPS.

4. Results and Discussion

The required power and energy to meet low loads were calculated based on the described assumptions. The selection of the electric motor, which was the main drive at low loads, was performed as M1-Tugboat I and M2-Tugboat II. Batteries providing the necessary energy for the electric motor and solar panels were randomly selected for each operation. After all, the selections, the number of batteries, battery weight and volume, required panel area, energy and fuel consumption at low loads, and total and limited fuel savings were acquired for the 8 different scenarios described in Table 6. Figure 4 highlights the analysis results considering fuel consumption saving rates and energy consumption for the 8 different scenarios.

Table 6. Hybrid propulsion system scenarios for eight cases.

Scenario no	I	II	III	IV	V	VI	VII	VIII
Op. Code	O1M1B1P1	O2M2B3P2	O3M2B2P1	O4M1B4P2	O5M1B1P1	O6M1B4P2	O7M1B2P1	O8M1B3P2
Operation time (s)	12267	1965	2475	8400	26100	23220.2	39425.6	3001.93
Low load operation time (s)	3575.3	1895	1987	2528	18892.4	6304.2	22567.2	1492.2
Total amount of fuel consumption (l)	1007.7	29.2	64.6	778.3	1704.5	2145.2	2552.4	257.1
Amount of low load fuel consumption (l)	151.7	21.1	24.3	113.1	901	110.7	525.5	101.3
Amount of low load energy consumption (Wh)	209707	19403.2	23165.5	158411	120268	127101	645169	162173
Number of batteries	216	80	30	456	1238	366	830	666
Volume of batteries (l)	4125.4	530.9	346.9	6214.9	23644.8	4988.3	9597.9	4419.4
Weight of batteries (t)	5	1.5	0.6	16.1	28.5	12.9	16.6	12.1
Area of solar panel (m^2)	173	13	19	103	99	83	531	106
Total amount of fuel saving rate (%)	15.1	72.4	37.7	14.5	52.9	5.2	20.6	39.4
Limited amount of fuel saving rate (%)	7.9	38.5	25.1	3.3	7.5	1.4	4.6	11.3

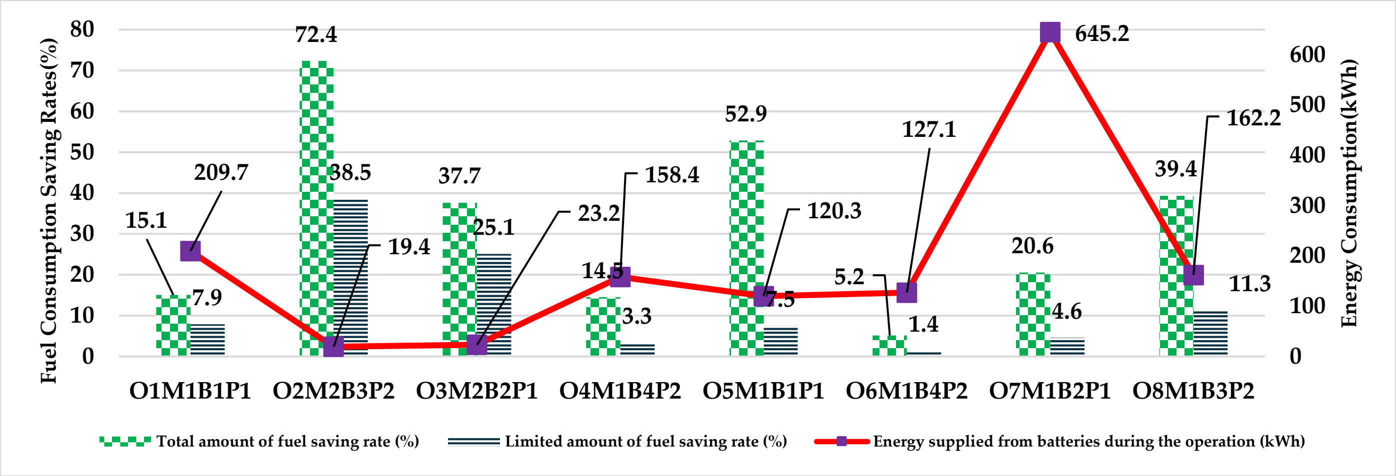

Figure 4. Total and limited fuel saving rates with energy supplied from batteries during each scenario.

O8M1B3P2 refers to the eighth scenario in which motor no 1, battery no 3, and solar panel no 2 have been used throughout the analysis. The towing/pushing operation of Tugboat II with the code "O2M2B3P2" yielded the highest fuel saving of 72.4%. This scenario was followed by “O5M1B1P1” and “O8M1B3P2”. “O3M2B2P1” and their efficiencies were 52.9%, 39.4%, and 37.7%, respectively. Nevertheless, “O6M1B4P2”, “O4M1B4P2”, and “O1M1B1P1” had the lowest fuel-saving efficiency outputs at 5.2%, 14.5%, and 15.1%, respectively. A total of 80 and 1238 batteries were needed to cover the energy consumption at low loads in “O2M2B3P2” and “O5M1B1P1” operations. These two scenarios were ranked first and second among all scenarios when there is no weight and volume limitation. The duration of these operations affected the number of batteries. Although the operation time of the “O3M2B2P1” scenario was longer than “O2M2B3P2”, it required fewer batteries due to battery type and capacity. The “O5M1B1P1” scenario was ranked 2nd in fuel efficiency and needed 1238 batteries to drive the electric motor throughout the low loads. 1238 batteries caused 28.5 tons of added weight and about 24 m^3 of volume loss. The implementation of such a scenario appears impractical under real-world conditions. Accordingly, weight and volume constraints were applied across all scenarios, resulting in limited fuel savings.

$LiFePO_4$ batteries emerged as a prominent option due to their performance in scenarios with limited fuel savings. These batteries offer high energy density and long cycle life. However, their performance declines significantly in low-temperature environments, where they may lose up to 50% of their capacity. Additionally, their cost per unit of energy remains higher compared to other battery technologies.

The second highest fuel saving was obtained from the "O5M1B1P1" scenario, but the saving rate regressed to 7.5% when weight and volume limitations were applied. The added weights of 5.46 tons and 2.72 tons, along with volume reductions of 5.327 $m^3$and 2.654 m^3, constituted the limitations for Tugboats I and II, respectively. As a result, fuel savings decreased by nearly a factor of four in the O6M1B4P2, O7M1B2P1, and O8M1B3P2 scenarios. Nevertheless, the use of batteries in the maritime industry has continued to expand due to technological progress, particularly in reducing battery weight and cost [13]. These advancements are expected to prevent significant reductions in fuel savings across all scenarios.

Installing solar panels directly on tugboats presents significant spatial constraints, as effective battery charging requires panel areas ranging from 13 m^2 to 531 m^2. Tugboats I and II do not have sufficient space to support this. Therefore, our strategy focuses on land-based solar panel charging stations, which can accommodate the necessary area without affecting vessel design or operations. Small-scale onboard installations may still be used for auxiliary purposes, but the primary energy supply will come from shore-based infrastructure.

HPS on tugboats present considerable potential for fuel savings, even within the constraints of limited space and weight for battery integration. Given the inherently variable and demanding energy profiles associated with tugboat operations, there is a compelling case for evaluating the retrofitting of conventional engines with dual-fuel alternatives. However, retrofitting a tugboat with an engine capable of operating on cleaner fuels such as biofuels, methanol or LNG can be both costly and time-consuming compared to the integration of battery systems into a conventional system [59].

While LNG systems offer substantial reductions in fuel and lubrication oil costs, they are also associated with increased maintenance requirements and higher capital costs [60]. On the other hand, methanol and biofuels especially first generations do not achieve the desired level of GHG emission reductions necessary to meet the long-term climate targets [61,62]. These limitations highlight the need for more practical and scalable solutions that can bridge the gap between current technologies and long-term decarbonisation goals.

In this context, integrating optimised battery systems into conventional propulsion setups emerges as a practical solution for reducing fuel consumption across tugboat fleets, offering a straightforward implementation compared to full engine retrofits [63]. It also allows operators to begin decarbonising their fleets without the immediate need for large-scale infrastructure changes.

Despite its advantages, deciding battery size and optimising energy management efficiently remain significant challenges in battery-supported hybrid systems [63]. In addition to onboard load distribution, the operational profile and navigational challenges specific to tugboats must be considered. Incorporating these factors into optimisation strategies enhances overall operational efficiency and contributes to extending battery lifespan. This, in turn, improves the economic performance of battery-supported hybrid configurations [64].

Our approach investigates various hybrid configurations selected based on the specific operational profiles of the tugboats, aiming to provide practical decision support for maritime stakeholders without relying on complex optimisation strategies in the initial selection and evaluation stages. These preliminary assessments focus on estimating economic and environmental benefits, while further implementation may require more advanced optimisation techniques for system refinement.

Looking ahead, zero-carbon tugboats, utilising either fully electric plug-in configurations or hybrid systems combining hydrogen fuel cells and batteries, are regarded as the ultimate solution in achieving net-zero emission targets [14,65]. These vessels offer numerous advantages, including zero emissions during operation, lower operating and maintenance costs, higher energy efficiency, and reduced noise pollution. They also support long-term cost savings, improved air quality, and operational flexibility in environmentally sensitive areas, while enhancing resilience to fuel price volatility [14,66].

However, despite these benefits, electric tugboats face several challenges that may hinder widespread adoption. These include limited range, high upfront costs, long charging times, and reduced power output compared to diesel-powered counterparts. Additional concerns, such as infrastructure demands, cold weather performance, regulatory uncertainty, and operational limitations, must also be addressed to enable broader implementation [66].

Considering these merits and drawbacks, battery-integrated hybrid propulsion systems can serve as an effective transitional solution toward achieving zero-emission tugboats. They can address current limitations such as range, charging time, and infrastructure demands. Eventually, these systems can progressively unlock the environmental and operational advantages of zero-carbon tugboats [67].

Charging batteries using renewable energy sources significantly enhances the environmental performance of hybrid systems [14]. The operational area examined in the case study demonstrates strong potential for solar energy utilisation. While the results indicate that tugboats are not well-suited for onboard solar panel installation due to spatial constraints, their operational profiles are highly compatible with battery charging on a shore-based station. Consequently, the use of land-based solar charging facilities has been adopted as the primary strategy for battery charging in this study. Similar studies support the viability of solar-powered charging infrastructure located on shore or offshore facilities for short-sea maritime vessels [13,68,69].

5. Conclusion

The use of HPS resulted in fuel savings on tugboats and can contribute to achieving the Sustainable Development Goals and the IMO’s future decarbonisation targets. The fuel savings varied between 5.2% and 72.4%, depending on the operational modes and the equipment used in the HPS. Based on the results and discussions, the major findings of the study are outlined as follows:

- HPS is well-suited for tugboats engaged in towing and pushing operations, as their main engines often operate at low loads for extended periods prior to vessel engagement, allowing for significant fuel consumption savings.
- Fuel consumption savings are comparatively lower for tugboats performing strait-crossing operations, since their main engines typically operate at optimal load levels, reducing the potential benefit of HPS integration.
- Installing long-range HPS using current technologies significantly increases weight and volume, making $LiFePO_4$ batteries a more suitable choice than Pb–Ac types due to their higher energy density.
- Fuel consumption savings decrease when volume and weight limitations are applied, particularly in long-range and low-load operations. However, increasing the 1% allowance for added weight and volume could enhance fuel consumption savings.
- Larger electric motors can yield higher fuel consumption savings, but their selection must balance cost and operational functionality to ensure practical implementation.

- Land-based solar panel charging systems are currently more viable than onboard installations, given the limited space on tugboats. Onboard solar integration requires careful planning to maintain operational efficiency.
- The broader adoption of HPS is currently limited by technological maturity and insufficient incentives. However, regulatory developments such as carbon taxation and the expansion of emission control areas are expected to drive wider implementation across the maritime sector.

Consequently, HPS installations are viable options for tugboats to reduce fuel consumption and harmful emissions and to meet new regulations and restrictions set by the IMO. In future research, HPS applications can be evaluated and applied for other vessel types, such as ferries and PSVs, particularly those that operate under low load conditions for a significant portion of their operational time and require a high degree of operational flexibility and resilience. This paper will be a resource for academics, experts, and industry stakeholders who will work on HPS, diesel-electric system, and other alternative propulsion systems in the phase of comparison.

Author Contributions: Conceptualization, M.N. and M.B.; methodology, M.N., M.B., and O.Y.; software, M.B.; validation, M.B. and O.Y.; formal analysis, M.B. and O.Y.; investigation, M.N., M.B., and O.Y.; data curation, M.N. and M.B.; writing—original draft preparation, M.N., M.B., and O.Y.; writing—review and editing, M.N., M.B., and O.Y.; visualization, M.B. and O.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Acknowledgments: During the preparation of this manuscript/study, the author(s) used PHD thesis data presented by Bayraktar [38] under the supervision of Mustafa NURAN for the purposes of efficiency analysis. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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