

LJMU Research Online

Sevgili, C, Bayraktar, M, Seyhan, A and Yuksel, O

Cold Ironing Impact on Voyage Carbon Intensity in Container Shipping: Economic and Regulatory Insights

https://researchonline.ljmu.ac.uk/id/eprint/26620/

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Sevgili, C, Bayraktar, M, Seyhan, A and Yuksel, O (2025) Cold Ironing Impact on Voyage Carbon Intensity in Container Shipping: Economic and Regulatory Insights. Sustainability, 17 (12).

LJMU has developed LJMU Research Online for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

http://researchonline.ljmu.ac.uk/



Article



1

2

3

4

5

6

7

8

9 10

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

Mustafa Nuran¹, Murat Bayraktar^{2,*} and Onur Yuksel^{2,3}

- ¹ Maritime Faculty, Dokuz Eylül University, 35250, İzmir, Türkiye; mustafa.nuran@deu.edu.tr (M.M.)
- ² Maritime Faculty, Zonguldak Bülent Ecevit University, 67300, Zonguldak, Türkiye; bayraktarmurat@beun.edu.tr (M.B.); onur.yuksel@beun.edu.tr (O.Y.)
- ³ Liverpool Logistics Offshore and Marine Research Institute (LOOM), Faculty of Engineering, Liverpool John Moores University, Liverpool, UK, L3 3AF; o.yuksel@ljmu.ac.uk (O.Y.)
- * Correspondence: bayraktarmurat@beun.edu.tr

Abstract: The implementation of hybrid propulsion systems in vessels has gained 11 prominence due to their significant advantages in energy efficiency and the reduction of 12 harmful emissions, particularly during low engine load operations. This study evaluates 13 hybrid propulsion system applications in two different tugboats, focusing on fuel 14 consumption and engine load across eight distinct operational scenarios, including 15 Istanbul Strait crossings, towing and pushing manoeuvres. The scenarios incorporate 16 asynchronous electric motors with varying power ratings, lead-acid and lithium iron 17 phosphate batteries with distinct storage capacities, and photovoltaic panels of different 18 sizes. The highest fuel savings of 72.4% were recorded in the second scenario, which 19 involved only towing and pushing operations using lithium iron phosphate batteries. In 20 contrast, the lowest fuel savings of 5.2% were observed in the sixth scenario, focused on a 21 strait crossing operation employing lead-acid batteries. Although integrating larger-scale 22 batteries into hybrid propulsion systems is vital for extended ship operations, their 23 adoption is often limited by space and weight constraints, particularly on tugboats. 24 Nevertheless, ongoing advancements in hybrid system technologies are expected to 25 enable the integration of larger, more efficient systems, thereby enhancing fuel-saving 26 27 potential.

Keywords: fuel consumption saving rate; hybrid propulsion system; energy efficiency;28tugboat; energy storage system29

30

31

1. Introduction

Global warming represents a critical challenge that must be addressed to achieve a 32 sustainable society. The Paris Agreement, implemented to mitigate climate change, aims 33 to limit global temperature rise by reducing human-sourced carbon dioxide (CO₂) 34 emissions by 45% by 2030 compared to 2010 levels, with the ultimate goal of achieving 35 net zero emissions by 2050 [1]. In alignment with the objectives of the Paris Agreement, 36 the International Maritime Organization (IMO) has introduced and implemented a range 37 of targets and innovative initiatives to advance sustainable development in marine 38 transportation, a sector that significantly contributes to global greenhouse gas (GHG) 39 40 emissions [2].

Academic Editor: Firstname Lastname

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

Citation: To be added by editorial staff during production.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/license s/by/4.0/).

By 2030, the IMO aims to reduce CO₂ emissions by 40% and decrease total GHGs by 41 at least 20%, with a target of 30%. Additionally, a 5% adoption of zero-emission fuels is 42 targeted, with an ambition to reach 10%. Midterm 2040 objectives include a 70% reduction 43 in GHG emissions, striving for 80%, and ultimately achieving net-zero emissions by 2050 44 [3]. In this context, the Energy Efficiency Existing Index and Carbon Intensity Indicator 45 46 have been introduced to enhance the sustainability of the global merchant fleet [4]. 47 Compliance with these metrics requires onboard adaptations such as engine power limitation, hull cleaning, air lubrication, and route optimisation. Integrating Hybrid 48 Propulsion Systems (HPSs) with batteries or fuel cells, alongside the retrofitting of ships 49 with alternative fuels, constitutes a strategic approach to meeting the 2040 and 2050 50 51 emission reduction targets [5].

Hybrid and all-electric propulsion systems have emerged as viable solutions to meet52current and future maritime regulations, integrating electrical and mechanical energy for53enhanced efficiency and flexibility [6]. HPSs enable multiple operating modes, including54diesel drive, generator-assisted propulsion, and energy storage-supported configurations.55Power-Take-Off (PTO) and Power-Take-Home (PTH) modes utilise electric motors to56optimise energy use, reduce emissions, and extend maintenance intervals [7].57

PTO and PTH modes utilise electric motors to optimise energy use, reduce emissions, 58 and extend maintenance intervals. PTO mode operates similarly to generator mode but 59 without energy storage systems [8]. PTH and electric drive modes rely solely on electric 60 motors powered by batteries and optimally loaded generators, reducing engine wear and 61 extending maintenance intervals. PTH mode also enhances onboard comfort with low 62 noise, vibration-free operation, and improved cost-efficiency [9]. Their boost mode 63 combines main engines and electric motors to meet high-power demands [10]. These 64 hybrid propulsion strategies improve manoeuvrability, operational efficiency, and 65 environmental sustainability, aligning with emission reduction targets [11]. 66

For short sea shipping vessels, the adoption of an all-electric ship concept powered 67 by battery systems and supported by a shore-based solar panel charging infrastructure 68 presents a highly promising and sustainable solution [12,13]. In this context, all-electric 69 tugboats and integrating shore-charged battery systems into conventional tugboats have 70 the potential to reduce GHG emissions significantly [14]. 71

The paper's structure is as follows: Section 2 presents a review of relevant literature,72Section 3 details the methodology and case studies, Section 4 discusses the results, and73Section 5 offers concluding remarks.74

2. Literature Review

HPS applications hold substantial potential to advance the adoption of intelligent, 76 environmentally sustainable power solutions, thereby facilitating cost-effective and 77 resilient operations within the maritime sector [11,15]. Therefore, HPS installation studies 78 on different ship types have been investigated based on diversified drive and operation 79 modes. 80

The operational profiles of main engines in HPSs have been extensively studied on 81 different vessel types, reflecting their varying load conditions throughout maritime 82 operations. The examined vessel types can be classified as platform supply vessels (PSVs) 83 [16], diving support vessels [17], offshore and harbour tugboats [15,18], offshore service 84 vessels [6], Ro-Ro ferries [19,20], high-speed ferries [21,22], short-route ferries [6,23-25], 85 fishing vessels [26], patrol vessels [27,28], tourist boats [29], icebreakers [30], mega yachts 86 [31], and research vessels [32]. Additionally, Bui et al. [15] examined HPS-integrated 87 tugboat operations with dynamic positioning (DP) capability across five distinct modes: 88 DP standby, DP loading, harbour loading, cruising, and conventional manoeuvring. 89

Key criteria for HPS applications include operational duration, energy demands,90emissions, efficiency, manoeuvrability, costs, maintenance ease, equipment constraints,91bunkering challenges, life cycle, and cold ironing potential. While ship-specific variations92exist, efficiency remains the primary focus.93

Within this framework, the efficiency of serial, parallel, and combined HPS 94 configurations has been analysed to assess their operational performance and viability. 95 For instance, the case study on a tourist boat demonstrated that HPS implementation 96 resulted in a 2% increase in energy efficiency [29]. Capasso et al. [32] reported up to 12% 97 energy efficiency savings in research vessels. Bui et al. [15] emphasised the necessity of 98 energy management strategies to optimise electrical power and mitigate engine load 99 fluctuations. Chai et al. [17] highlighted moderate to high fuel consumption savings, 100 particularly with DC-powered electric motors in HPS configuration. Kim et al. [26] 101 conducted a life cycle analysis on HPSs in fishing vessels, finding that medium-sized ships 102 (displacement of 9.77 tons) achieve the highest efficiency with a 7.6% reduction in CO₂ 103 emissions. 104

Beyond environmental benefits, HPSs offer notable cost savings, as highlighted in the 105 literature. On a short-route ferry, the implementation of HPS resulted in up to 7% lower 106 operational costs compared to conventional systems [23]. Battery pack size significantly 107 affects economic performance, with larger batteries enabling more stable operation and 108 reduced charging frequency but substantially increasing weight and investment costs 109 [29]. Therefore, the selection of larger battery packs should be based on operational 110 conditions to ensure an optimal balance between performance and trade-offs [22]. The 111 deployment of an advanced energy management strategy, tailored to the specific usage 112 profile, can significantly enhance the benefits of battery packs, further optimising the 113 utilisation of larger systems [21,33]. 114

The integration of hybrid systems in large vessels, such as tankers, bulk carriers, and 115 container ships, has been widely investigated, particularly in the context of auxiliary 116 system implementation. The incorporation of battery storage and waste heat recovery 117 systems into the ship electrification plant of a tanker vessel has demonstrated fuel savings 118 and emission reductions for the plant of up to 18.15% [34]. These reductions can be further 119 enhanced through the implementation of fuel cells, achieving up to a 49.75% reduction 120 when utilising LNG on the case study tanker vessel [35]. The utilisation of green 121 hydrogen-fuelled fuel cells in a case study bulk carrier can achieve a 91.79% reduction in 122 GHG emissions from its electrification plant [36]. Furthermore, onboard hydrogen 123 production from pink ammonia can enhance this reduction to 95.66% [37]. The 124 implementation of hybrid systems in the propulsion plants of bulk carriers has been 125 demonstrated in smaller inland vessels. Energy efficiency optimisation of a parallel HPS 126 resulted in 2.60% and 9.86% reductions in energy consumption on westbound and 127 eastbound voyages, respectively, for an inland bulk carrier [11]. 128

HPSs mitigate ship oscillations and speed fluctuations during energy transitions, 129 with studies demonstrating a 70% reduction using advanced optimisation algorithms [38]. 130 Various energy recovery application integrations to HPSs, such as waste heat recovery 131 and hybrid turbochargers, have been shown to enhance energy efficiency by up to 53% 132 [19]. In addition to fuel efficiency, HPSs improve vibration and noise levels [6,15], load 133 response [32], system reliability [6], and operational flexibility [39]. Given these benefits, 134 HPS is strongly recommended for diverse ship types to enhance sustainability [17,26], 135 with its primary objectives focusing on fuel savings, GHG emissions reduction, and 136 operational cost optimisation [40]. 137

Research papers have explored the implementation of HPSs across various vessel 138 types, focusing on optimising energy management, and integrating advanced energy 139 recovery systems. Studies emphasise the benefits of hybrid configurations in reducing 140 emissions, enhancing energy efficiency, and improving vessel performance through 141 battery storage, waste heat recovery, and fuel cell technologies. Additionally, adaptive 142 optimisation strategies have been investigated to minimise fluctuations in speed and 143 stability while maximising system reliability. 144

This study investigates the fuel consumption savings achievable through the 145 implementation of HPSs in tugboats, considering diverse operational modes and profiles. 146 While extensive research has explored HPS applications, the integration of real-time data 147 for tugboat installations remains an underexamined area. To address this gap, eight HPS 148 scenarios have been developed using different electric motors, batteries, and solar panels 149 based on operational data from tugboats. The analysis employs a numerical simulation 150 model developed using real-time data to evaluate the potential fuel consumption 151 reduction. Given the spatial and weight constraints of tugboats, a 1% limitation has been 152 applied to account for installation feasibility. Achieving substantial fuel savings through 153 these scenarios would provide valuable insights and contribute to meeting the 2030 and 154 2050 global decarbonisation targets for shipowners, operators, and stakeholders. 155

A key contribution of this work is the development of a practical decision-making 156 framework supporting maritime stakeholders during the early stages of hybrid system 157 selection and evaluation for tugboats. Rather than relying on complex methodologies, the 158 framework prioritises accessibility and ease of use. This makes it particularly valuable for 159 operators and decision-makers who may not have access to advanced modelling tools or 160 expertise. 161

3. Materials and Methods

Table 1. Technical specifications of tugboats [41].

Operational data for the HPS simulation were collected from three tugboats 163 operating in the Strait of Istanbul. Their dimensional and power characteristics, which are 164 critical for HPS integration, are shown in Table 1. Two of the tugboats share the same 165 dimensions, general arrangement, capacity plan, and structural design. These sister ships 166 are referred to collectively as Tugboat I. The third vessel, with different specifications, is 167 identified as Tugboat II. 168

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, 171 irreversible, turbocharged, and intercooled, generates roundly 350 kW of power per 172 cylinder. Nominal specific fuel oil consumption is 191.5 g/kWh at engine load of 85%. The 173 main engine generating 1140 kW fuel consumption of the Tugboat II varies between 50 174

162

169

and 300 (l/h) depending on the engine speed, torque, and power output. The Tugboat I 175 and II main engines meet the emission limitation of IMO Tier II. 176

Sea trial data and acquisition of actual speed-power curves are significant for fuel 177 efficiency calculations [42], and while ship main engine loads demonstrate the 178 environmentally benign use of HPSs [26]. The speed-power and power-fuel consumption 179 curves for the main engine were sourced from the engine catalogue. Additionally, to 180 accurately determine the power-fuel consumption characteristics at low load conditions, 181 the required data were derived from load tests conducted on the diesel engine [43]. The 182 main engine quickly wears out and operates inefficiently at low loads [27,43]. Therefore, 183 the mode of HPS, in which the electric motor operates to compensate for low-load power 184 conditions, was applied throughout the analysis. Data on service speed, main engine 185 loads, and RPMs were collected through real-time measurement and monitoring during 186 tugboat operations. Due to the advanced technological outfitting and integrated sensor 187 systems, operational data were directly accessible and recordable from the bridge. These 188 are defined as primary data. Additionally, secondary data were obtained from the 189 propulsion system interface, which recorded operational parameters. Detailed 190 information on tugboat operations is provided in Table 2. 191 192

Operation	Data Trimo	Varial Cada	Operation time (min)	Installed Power of Main	The type of turbest corrise	
No.	Data Type	vesser Coue	Operation time (min)	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	
07	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	

Table 2. Operation of tugboats.

193

209

To simplify the representation of HPS scenarios, unique codes were assigned to each 194 operation and piece of equipment. For example, O1 refers to the strait crossing operation 195 of Tugboat I, which lasts 204.5 minutes. Tugboats I and II provided support to marine 196 vessels during both strait crossing and towing/pushing operations. Additionally, 197 environmental factors such as air temperature, current speed, humidity, wind speed, and 198 wind force influence fuel consumption rates. The thrust power generated by the propeller 199 is affected by weather, hull fouling, and loading conditions [27]. 200

In this study, total fuel consumption is derived from instantaneous engine power 201 output and operational hours. While these estimates generally align with the daily fuel 202 consumption figures reported in noon reports, minor discrepancies are observed. These 203 variations are primarily attributed to environmental influences such as sea state, weather 204 conditions, and strait currents. As noted in the assumptions section, these external factors 205 are not explicitly accounted for in the analysis. Operations O1 to O4 for Tugboats I and II 206 are illustrated in Figure 1, which was generated using the Marine Traffic application that 207 displays the real-time positions of vessels. 208







Figure 2. Tugboat engine load and operation time

7 of 19

The type and duration of the tugboat's operation are critical factors for HPS 218 installation. Tugboats are generally equipped with high-power propulsion systems, and 219 they are operated at low loads considering all operations [35]. The main engine loads of 220 tugboats can occasionally reach 100% in the towing/pushing operation; however, these 221 intervals constitute a very short period considering the total duration of the operations. 222 Tugboat II was operated at relatively low loads throughout the O2 and O3 operations 223 compared to other operations. Therefore, the PTH mode was suitable for HPS applications 224 on O2 and O3. Two different curves were highlighted on the O2 and O3 graphs because 225 the data were recorded instantly on two main engines. For the remaining operations 226 involving Tugboat I, only the load data from the first main engine were available. The 227 load profile of the second main engine was assumed to be identical to that of the first. 228

Tugboat I supported the marine vessel throughout the strait crossing during229operations O1 and O4. As a result, main engine loads remained relatively stable, typically230ranging between 40% and 60%. In contrast, during operations O5 to O8, Tugboat I231performed both towing and pushing tasks, like Tugboat II, leading to higher main engine232load levels.233

Tugboats are equipped with relatively powerful marine engines to facilitate their 234 operations and provide support to large-scale ships. However, they are quite inefficient 235 and consume high amounts of fuel per unit of power because high-power engines are 236 operated at low loads. The installation of an HPS for tugboats is suggested in this paper 237 to reduce this high fuel consumption and accompanying harmful emissions. Despite the 238 low emissions and fuel savings of HPS, it causes complexity in power systems [21]. The 239 planned HPS system, which includes electric motors, energy storage systems, renewable 240 energy sources, and an existing main engine system, is shown in Figure 3. 241



Figure 3. Fundamental components of the proposed hybrid propulsion system for tugboats244Utilising batteries for standby operations offers several advantages over auxiliary245engines [7]. Therefore, in this study, batteries are used to power electric motors during246low-load operations. Each tugboat is equipped with two electric motors rated at 500 kW247and 250 kW, respectively, to meet energy demands under such conditions. The technical248specifications of these motors are presented in Table 3.249Table 3. Technical specifications of the electric motors250

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 252 are 3-phase 400 V (Δ) 50 Hz asynchronous electric motors. They have the "S1" operation 253 type that provides continuous operation, and they have an IP55 protection class that is 254 dust-resistant and water sprays. They were manufactured in the B35 type, which defines 255 the type of construction with feet and flanges. The number of poles is 4 pieces. In terms of 256 efficiency, they are in the class of high efficiency (IE2) and premium efficiency (IE3), 257 ranging from 95.1% to 96.1%. 258

Batteries were evaluated based on several key performance indicators, including 259 energy density, efficiency, cost, life cycle, operating temperature range, volume-to-weight 260 ratio, and suitability for specific application areas. Among the available technologies, 261 lead-acid and lithium iron phosphate (LiFePO4) batteries emerged as the most appropriate 262 options for HPSs, given current technological capabilities. Lead-acid (Pb-Ac) batteries are 263 known for their robustness and ability to function effectively across a wide range of 264 temperatures. Accordingly, two distinct battery types with varying capacities were 265 selected to meet the energy demands of the electric motor, ensuring operational flexibility 266 and reliability in diverse conditions [44]. Therefore, the battery types are selected as 267 LiFePO₄ and Pb-Ac as their technical specifications are described in Table 4. 268 Table 4. Technical specifications of the energy storage systems [45–48] 269

1		0, 0 ,		
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)	<mark>~3</mark> .	- <mark>3.4</mark>	<mark>~11.8</mark>	<mark>3-12.8</mark>
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, 271 and life cycle, provide convenience in choosing the most suitable one. Table 4 clearly 272 shows that lithium-based batteries have a high value in terms of specific energy and cycle 273 life based on 80% depth of discharge (DOD). On the other hand, Pb-Ac batteries stand out 274 in terms of their robust structure, operation at high-temperature ranges, and low cost. 275 However, Pb-Ac batteries are not suitable for large-scale applications, especially due to 276 their low energy density and limited capacity. In addition, low performance and more 277 batteries cause costs and losses of volume and total weight increment on board [32]. On 278 the other hand, lithium-based batteries have a battery life of approximately 3.75 years 279 when used throughout the ship 's navigation, and this lifespan period can be extended up 280 to 11.62 years when batteries are not used constantly [34]. 281

Li-ion batteries offer a significant benefit in terms of weight and energy density for 282 marine vessels equipped with HPS [6,22] because their size is very critical on ships [39]. 283 Lithium-based batteries are determined to be one of the best battery type with existing 284 technologies to operate optimally [39,49]. However, further safety measures must be 285 followed in the case of an explosion or overheating. Sodium-based batteries are described 286 as an alternative [22] because of their high energy density but operating them at high 287 temperatures requires expanded safety measures [39]. The state of charge of batteries is 288

limited 90% [21] to prevent overcharging and over-discharging [15]. Therefore, 80% of the 289 battery's energy was used in the analysis. Moreover, onshore solar panels and rectifiers 290 were evaluated for recharging. The solar panels and their technical specifications are 291 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 294 shown in Table 5, and their power densities are 10 W/kg and 15.97 W/kg respectively. As 295 an alternative to photovoltaic solar panels, batteries can be charged via generators. 296 However, in HPS, shore-based charging lowers emissions and costs compared to the 297 overnight charging of batteries via diesel generators [23]. Shore-based charging rectifiers 298 that operate between 20°C and 50°C are used in several energy distribution applications 299 including power systems, electric cars, and marine vessels [52]. In addition, they have a 300 structure that can be operated in dust-free dry areas, with an IP20 protection class and 301 high efficiencies exceeding 85% [53,54]. 302

Bayraktar [55] developed a MATLAB GUI for HPS analysis, based on a 303 comprehensive literature review and power and transmission-based formulas. This 304 interface includes equations regarding with the main engine, electric motor, batteries and 305 solar panels. Ship diesel main engine power calculation is performed on the basis of 306 cylinder diameter, stroke length, engine speed, indicated mean effective pressure, number 307 of cylinders, two or four stroke. Ship diesel main engine power calculation equations: 308 $IHP = p_i * l * \frac{\pi * D^2}{4} * \frac{n}{60} * z * k$ (1) 309

Where, IHP stands for Indicated Horsepower (kW). This power refers to the total power 310 generated in the ship main engine cylinders before mechanical losses such as friction and 311 heat loss. p_i is the indicated mean effective pressure (bar), l is the stroke length (mm) of 312 engine, D is the cylinder diameter (mm), n is the ship engine speed (rpm), k is the number 313 of power stroke in each cycle, z is the number of cylinders. Since the marine engines 314 analysed in this study are 4-stroke engines, k value is taken as 0.5. 315

The electric motor power is calculated by considering the electric motor phase state, motor 316 efficiency, voltage value, current value, torque value and motor speed. Equations used in 317 the calculation of electric motor power: 318

 $P_{\rm m} = V * I * \cos \varphi * \eta_{\rm m} (2)$

 $P_{\rm m} = \sqrt{3} * V * I * \cos\varphi * \eta_{\rm m} (3)$

Equation 2 and equation 3 refer to single phase and three phase induction motor power 321 calculation equations respectively. Where P_m is the generated power of electric motor, V 322 is the voltage (V), I is the current (A), $\cos \phi$ is the power factor and $\eta_{\rm m}$ is the efficiency of 323 electric motor. The equation used during the utilisation of energy from batteries by electric 324 motors: 325

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

Eused refers to the energy (kWh) drawn from the battery, Pmotor refers to the power 327 demand (kW) of the electric motors calculated as specified in equation 3. t_m refers to the 328

292 293

319

320

340

341

342

electric motors operation time (h), η_{system} refers to the efficiency during the energy 329 transfer from the battery to the electric motor. Discharge current from battery is calculated 330 based on equation 5. 331

at Vhat*Nevstern (C)	_{at} =	$\frac{P_{motor}}{V_{hat*\eta_{system}}}$ (5)
----------------------	-----------------	---

Where, I_{bat} and V_{bat} are refers to Battery discharge current (A) and Nominal battery333voltage (V) respectively. Additionally, equation 6 is used to calculate the state of charge334of the batteries after energy drawn from the batteries.335

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

Eused indicates the energy drawn from the batteries and Ebattery indicates the amount337of energy at %100 battery charge. Equation 7 is used in the stage of charging the batteries338from solar panels.339

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

 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 343 and low-load fuel consumption, low-load energy consumption, battery requirements for 344 electric motor operation, battery volume and weight, total fuel savings, and limited fuel 345 savings. During the analysis, a 1% increase in weight and volume was permitted for both 346 tugboats based on gross tonnage. This corresponds to 5.46 tons for Tugboat I and 2.72 tons 347 for Tugboat II. 348

Initailly, the load/fuel consumption curves were derived from the load tests on the 349 diesel engine conducted by Bayraktar and Nuran [56]. In this way, the fuel consumption 350 curves of the tugboat main engines were estimated, especially for low loads, since specific 351 fuel consumption rates at loads was not specified in the main engine catalogues. The 352 instantaneous and recorded tugboats' main engine's load rates data and fuel consumption 353 curve data were used in the interface for the analyses. The assumptions made throughout 354 the analysis process are outlined as follows. 355

- The low load was defined as the utilisation of less than 20% of the power output of the main engine [57].
 357
- 80% of the battery energy was used in the analysis for safety.
- o 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 368 following the installation of the HPS.
 369
- The weather and sea conditions during data collection remained consistent 370 throughout the installation and analysis of the HPS.
 371

4. Results and Discussion

The required power and energy to meet low loads were calculated based on the 373 described assumptions. The selection of the electric motor, which was the main drive at 374 low loads, was performed as M1-Tugboat I and M2-Tugboat II. Batteries providing the 375 necessary energy for the electric motor and solar panels were randomly selected for each 376 operation. After all, the selections, the number of batteries, battery weight and volume, 377

372

358

359

360

361

362

363

364

365

366

Scenario no Op. Code

Operation time (s)

Low load operation time (s)

Total amount of fuel consumption (l) Amount of low load fuel consumption (l)

Amount of low load energy consumption (Wh)

required panel area, energy and fuel consumption at low loads, and total and limited fuel 378 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 380 consumption for the 8 different scenarios.

158411

									382
Γable 6. Hybrid propulsion system scenarios for eight cases.									383
	Ι	II	III	IV	V	VI	VII	VIII	
	O1M1B1	O2M2B3	O3M2B2	O4M1B4	O5M1B1	O6M1B4	O7M1B2	O8M1B3	
	P1	P2	P1	P2	P1	P2	P1	P2	
	12267	1965	2475	8400	26100	23220.2	39425.6	3001.93	
	3575.3	1895	1987	2528	18892.4	6304.2	22567.2	1492.2	
1)	1007.7	29.2	64.6	778.3	1704.5	2145.2	2552.4	257.1	
on (l)	151.7	21.1	24.3	113.1	901	110.7	525.5	101.3	

120268

1238

127101

645169

830

162173



209707

19403.2

80

23165.5

30

Total amount of fuel saving rate (%) _ — Limited amount of fuel saving rate (%) Energy supplied from batteries during the operation (kWh)

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 387 panel no 2 have been used throughout the analysis. The towing/pushing operation of 388 Tugboat II with the code "O2M2B3P2" yielded the highest fuel saving of 72.4%. This 389 scenario was followed by "O5M1B1P1" and "O8M1B3P2". "O3M2B2P1" and their 390 efficiencies were 52.9%, 39.4%, and 37.7%, respectively. Nevertheless, "O6M1B4P2", 391 "O4M1B4P2", and "O1M1B1P1" had the lowest fuel-saving efficiency outputs at 5.2%, 392 14.5%, and 15.1%, respectively. A total of 80 and 1238 batteries were needed to cover the 393 energy consumption at low loads in "O2M2B3P2" and "O5M1B1P1" operations. These 394 two scenarios were ranked first and second among all scenarios when there is no weight 395 and volume limitation. The duration of these operations affected the number of batteries. 396 Although the operation time of the "O3M2B2P1" scenario was longer than "O2M2B3P2", 397 it required fewer batteries due to battery type and capacity. The "O5M1B1P1" scenario 398 was ranked 2nd in fuel efficiency and needed 1238 batteries to drive the electric motor 399 throughout the low loads. 1238 batteries caused 28.5 tons of added weight and about 24 400 m³ of volume loss. The implementation of such a scenario appears impractical under real-401 world conditions. Accordingly, weight and volume constraints were applied across all 402 scenarios, resulting in limited fuel savings. 403

384

385 386

LiFePO4 batteries emerged as a prominent option due to their performance in 404 scenarios with limited fuel savings. These batteries offer high energy density and long 405 cycle life. However, their performance declines significantly in low-temperature 406 environments, where they may lose up to 50% of their capacity. Additionally, their cost 407 per unit of energy remains higher compared to other battery technologies. 408

The second highest fuel saving was obtained from the "O5M1B1P1" scenario, but the 409 saving rate regressed to 7.5% when weight and volume limitations were applied. The 410 added weights of 5.46 tons and 2.72 tons, along with volume reductions of 5.327 m³ and 411 2.654 m³, constituted the limitations for Tugboats I and II, respectively. As a result, fuel 412 savings decreased by nearly a factor of four in the O6M1B4P2, O7M1B2P1, and O8M1B3P2 413 scenarios. Nevertheless, the use of batteries in the maritime industry has continued to 414 expand due to technological progress, particularly in reducing battery weight and cost 415 [13]. These advancements are expected to prevent significant reductions in fuel savings 416 across all scenarios. 417

Installing solar panels directly on tugboats presents significant spatial constraints, as 418 effective battery charging requires panel areas ranging from 13 m² to 531 m². Tugboats I 419 and II do not have sufficient space to support this. Therefore, our strategy focuses on land-420 based solar panel charging stations, which can accommodate the necessary area without 421 affecting vessel design or operations. Small-scale onboard installations may still be used 422 for auxiliary purposes, but the primary energy supply will come from shore-based 423 infrastructure. 424

HPS on tugboats present considerable potential for fuel savings, even within the 425 constraints of limited space and weight for battery integration. Given the inherently 426 variable and demanding energy profiles associated with tugboat operations, there is a 427 compelling case for evaluating the retrofitting of conventional engines with dual-fuel 428 alternatives. However, retrofitting a tugboat with an engine capable of operating on 429 cleaner fuels such as biofuels, methanol or LNG can be both costly and time-consuming 430 compared to the integration of battery systems into a conventional system [59].

While LNG systems offer substantial reductions in fuel and lubrication oil costs, they432are also associated with increased maintenance requirements and higher capital costs [60].433On the other hand, methanol and biofuels especially first generations do not achieve the434desired level of GHG emission reductions necessary to meet the long-term climate targets435[61,62]. These limitations highlight the need for more practical and scalable solutions that436can bridge the gap between current technologies and long-term decarbonisation goals.437

In this context, integrating optimised battery systems into conventional propulsion 438 setups emerges as a practical solution for reducing fuel consumption across tugboat fleets, 439 offering a straightforward implementation compared to full engine retrofits [63]. It also 440 allows operators to begin decarbonising their fleets without the immediate need for largescale infrastructure changes. 442

Despite its advantages, deciding battery size and optimising energy management 443 efficiently remain significant challenges in battery-supported hybrid systems [63]. In 444 addition to onboard load distribution, the operational profile and navigational challenges 445 specific to tugboats must be considered. Incorporating these factors into optimisation 446 strategies enhances overall operational efficiency and contributes to extending battery 447 lifespan. This, in turn, improves the economic performance of battery-supported hybrid 448 configurations [64].

Our approach investigates various hybrid configurations selected based on the 450 specific operational profiles of the tugboats, aiming to provide practical decision support 451 for maritime stakeholders without relying on complex optimisation strategies in the initial 452 selection and evaluation stages. These preliminary assessments focus on estimating 453

Looking ahead, zero-carbon tugboats, utilising either fully electric plug-in 456 configurations or hybrid systems combining hydrogen fuel cells and batteries, are 457 regarded as the ultimate solution in achieving net-zero emission targets [14,65]. These 458 vessels offer numerous advantages, including zero emissions during operation, lower 459 operating and maintenance costs, higher energy efficiency, and reduced noise pollution. 460 They also support long-term cost savings, improved air quality, and operational flexibility 461 in environmentally sensitive areas, while enhancing resilience to fuel price volatility 462 [14,66]. 463

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. 466 Additional concerns, such as infrastructure demands, cold weather performance, 467 regulatory uncertainty, and operational limitations, must also be addressed to enable broader implementation [66]. 469

Considering these merits and drawbacks, battery-integrated hybrid propulsion 470 systems can serve as an effective transitional solution toward achieving zero-emission 471 tugboats. They can address current limitations such as range, charging time, and 472 infrastructure demands. Eventually, these systems can progressively unlock the 473 environmental and operational advantages of zero-carbon tugboats [67]. 474

Charging batteries using renewable energy sources significantly enhances the 475 environmental performance of hybrid systems [14]. The operational area examined in the 476 case study demonstrates strong potential for solar energy utilisation. While the results 477 indicate that tugboats are not well-suited for onboard solar panel installation due to 478 spatial constraints, their operational profiles are highly compatible with battery charging 479 on a shore-based station. Consequently, the use of land-based solar charging facilities has 480 been adopted as the primary strategy for battery charging in this study. Similar studies 481 support the viability of solar-powered charging infrastructure located on shore or offshore 482 facilities for short-sea maritime vessels [13,68,69]. 483

5. Conclusion

The use of HPS resulted in fuel savings on tugboats and can contribute to achieving 485 the Sustainable Development Goals and the IMO's future decarbonisation targets. The 486 fuel savings varied between 5.2% and 72.4%, depending on the operational modes and 487 the equipment used in the HPS. Based on the results and discussions, the major findings 488 of the study are outlined as follows: 489

- HPS is well-suited for tugboats engaged in towing and pushing operations, as their 490 main engines often operate at low loads for extended periods prior to vessel 491 engagement, allowing for significant fuel consumption savings. 492
- Fuel consumption savings are comparatively lower for tugboats performing straitcrossing operations, since their main engines typically operate at optimal load levels, reducing the potential benefit of HPS integration.
 493
 494
 495
- Installing long-range HPS using current technologies significantly increases weight 496 and volume, making LiFePO₄ batteries a more suitable choice than Pb–Ac types due 497 to their higher energy density. 498
- Fuel consumption savings decrease when volume and weight limitations are applied, 499 particularly in long-range and low-load operations. However, increasing the 1% 500 allowance for added weight and volume could enhance fuel consumption savings. 501
- Larger electric motors can yield higher fuel consumption savings, but their selection 502 must balance cost and operational functionality to ensure practical implementation. 503

526

527 528

533

534

535

- Land-based solar panel charging systems are currently more viable than onboard 504 installations, given the limited space on tugboats. Onboard solar integration requires 505 careful planning to maintain operational efficiency. 506
- The broader adoption of HPS is currently limited by technological maturity and 507 insufficient incentives. However, regulatory developments such as carbon taxation 508 and the expansion of emission control areas are expected to drive wider 509 implementation across the maritime sector. 510

Consequently, HPS installations are viable options for tugboats to reduce fuel 511 consumption and harmful emissions and to meet new regulations and restrictions set by 512 the IMO. In future research, HPS applications can be evaluated and applied for other 513 vessel types, such as ferries and PSVs, particularly those that operate under low load 514 conditions for a significant portion of their operational time and require a high degree of 515 operational flexibility and resilience. This paper will be a resource for academics, experts, 516 and industry stakeholders who will work on HPS, diesel-electric system, and other 517 alternative propulsion systems in the phase of comparison. 518

Author Contributions: Conceptualization, M.N. and M.B.; methodology, M.N., M.B., 520 and O.Y.; software, M.B.; validation, M.B. and O.Y.; formal analysis, M.B. and O.Y.; 521 investigation, M.N., M.B., and O.Y.; data curation, M.N. and M.B.; writing—original draft 522 preparation, M.N., M.B., and O.Y.; writing—review and editing, M.N., M.B., and O.Y.; 523 visualization, M.B. and O.Y. All authors have read and agreed to the published version of 524 the manuscript. 525

Funding: This research received no external funding

Acknowledgments: During the preparation of this manuscript/study, the author(s) used529PHD thesis data presented by Bayraktar [38] under the supervision of Mustafa NURAN530for the purposes of efficiency analysis. The authors have reviewed and edited the output531and take full responsibility for the content of this publication.532

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

References

- 1.
 United Nations For a Livable Climate: Net-Zero Commitments Must Be Backed by Credible Action Available
 536

 online: https://www.un.org/en/climatechange/net-zero-coalition (accessed on 10 June 2025).
 537
- UNCTAD Review of Maritime Transport Navigating Maritime Checkpoints Available online: 538 https://unctad.org/system/files/official-document/rmt2024_en.pdf (accessed on 20 May 2025). 539
- 3. IMO IMO's Work Cut GHG Emissions Ships Available 540 to from online: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx (accessed on 10 June 541 2025). 542
- Bayraktar, M.; Yuksel, O. A Scenario-Based Assessment of the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) Regulations. *Ocean Engineering* 2023, 278, doi:10.1016/j.oceaneng.2023.114295.
- Tadros, M.; Ventura, M.; Guedes Soares, C. Review of the Decision Support Methods Used in Optimizing Ship 545 Hulls towards Improving Energy Efficiency. *Journal of Marine Science and Engineering* 2023, 11, 546 doi:10.3390/jmse11040835.
- Inal, O.B.; Charpentier, J.-F.; Deniz, C. Hybrid Power and Propulsion Systems for Ships: Current Status and Future 548 Challenges. *Renewable and Sustainable Energy Reviews* 2022, 156, doi:10.1016/j.rser.2021.111965. 549

- Chin, C.S.; Tan, Y.-J.; Kumar, M.V. Study of Hybrid Propulsion Systems for Lower Emissions and Fuel Saving on Merchant Ship during Voyage. *Journal of Marine Science and Engineering* 2022, 10, 393, doi:10.3390/jmse10030393.
- MAN MAN HyProp ECO Fuel-Efficient Hybrid Propulsion System Available online: https://manes.com/docs/default-source/document-sync/man-hyprop-eco-eng.pdf?sfvrsn=9790dc3e (accessed on 10 June 553 2025).
- Zhao, T.; Xiang, D.; Zheng, Y. Control Strategy to Start a Shaft Generator System Employing DFIM under Power 555 Take Me Home Mode. *CPSS Transactions on Power Electronics and Applications* 2019, 4, 119–127, 556 doi:10.24295/CPSSTPEA.2019.00012. 557
- 10.ZFHybridPropulsionTechnologyAvailableonline:https://www.zf.com/public/org/Brochure_Hybrid-558propulsion-technology_72413.pdf (accessed on 10 June 2025).559
- He, Y.; Fan, A.; Wang, Z.; Liu, Y.; Mao, W. Two-Phase Energy Efficiency Optimisation for Ships Using Parallel 560 Hybrid Electric Propulsion System. *Ocean Engineering* 2021, 238, 109733, doi:10.1016/j.oceaneng.2021.109733.
- Kolodziejski, M.; Michalska-Pozoga, I. Battery Energy Storage Systems in Ships' Hybrid/Electric Propulsion 562 Systems. *Energies* 2023, *16*, 1122, doi:10.3390/en16031122.
- Yüksel, O.; Göksu, B.; Bayraktar, M. Propulsion and Photovoltaic Charging System Parameter Computation for an All-Electric Boat. *Ships and Offshore Structures* 2024, *19*, 580–593, doi:10.1080/17445302.2023.2195239.
- Acomi, N.; Stanca, C.; Raicu, G.; Surugiu, G.; Popa, E.M. Advantages and Disadvantages of Using Electric 566 Tugboats: A Systematic Review. *journal of eta maritime science* 2025, 13.
- Bui, T.M.N.; Dinh, T.Q.; Marco, J.; Watts, C. An Energy Management Strategy for DC Hybrid Electric Propulsion 568 System of Marine Vessels. In Proceedings of the 2018 5th International Conference on Control, Decision and 569 Information Technologies (CoDIT); April 2018; pp. 80–85. 570
- Pham, V.V.; Hoang, A.T. Analyzing and Selecting the Typical Propulsion Systems for Ocean Supply Vessels. In Proceedings of the 2020 6th International Conference on Advanced Computing and Communication Systems (ICACCS); March 2020; pp. 1349–1357.
- Chai, M.; Bonthapalle, D.R.; Sobrayen, L.; Panda, S.K.; Wu, D.; Chen, X. Alternating Current and Direct Current-Based Electrical Systems for Marine Vessels with Electric Propulsion Drives. *Applied Energy* 2018, 231, 747–756, doi:10.1016/j.apenergy.2018.09.064.
- Jeong, B.; Oguz, E.; Wang, H.; Zhou, P. Multi-Criteria Decision-Making for Marine Propulsion: Hybrid, Diesel 577 Electric and Diesel Mechanical Systems from Cost-Environment-Risk Perspectives. *Applied Energy* 2018, 230, 1065– 1081, doi:10.1016/j.apenergy.2018.09.074.
- Altosole, M.; Campora, U.; Vigna, V. Energy Efficiency Analysis of a Flexible Marine Hybrid Propulsion System.
 In Proceedings of the 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM); June 2020; pp. 436–441.
 582
- Yuksel, O.; Pamik, Murat; Bayraktar, M. The Assessment of Alternative Fuel and Engine Power Limitation 583 Utilisation in Hybrid Marine Propulsion Systems Regarding Energy Efficiency Metrics. *Journal of Marine* 584 *Engineering & Technology* 2025, 1–15, doi:10.1080/20464177.2025.2479319. 585
- Oo, T.Z.; Ren, Y.; Kong, A.W.-K.; Wang, Y.; Liu, X. Power System Design Optimization for a Ferry Using Hybrid-Shaft Generators. *IEEE Transactions on Power Systems* 2022, *37*, 2869–2880, doi:10.1109/TPWRS.2021.3128239.
- Ruggiero, V.; Morace, F. Innovative Use of Hybrid Propulsion System in Fast Passenger Ferries over 300 588 Passengers and 20 Knots. In *HSMV 2020*; IOS Press, 2020; pp. 207–215. 589
- Jeong, B.; Wang, H.; Oguz, E.; Zhou, P. An Effective Framework for Life Cycle and Cost Assessment for Marine 590 Vessels Aiming to Select Optimal Propulsion Systems. *Journal of Cleaner Production* 2018, 187, 111–130, 591 doi:10.1016/j.jclepro.2018.03.184.

- Alami, A.H.; Jansson, K.; Alashkar, A.; Mahmoud, M.; Yasin, A.; Khuri, S. A Techno-Economic-Environmental 593 Investigation of Replacing Diesel Engines with Pneumatic Motors for Ferry Boats. *Energy Conversion and 594 Management* 2025, 327, 119613, doi:10.1016/j.enconman.2025.119613. 595
- Maloberti, L.; Zaccone, R. An Environmentally Sustainable Energy Management Strategy for Marine Hybrid 596 Propulsion. *Energy* 2025, 316, 134517, doi:10.1016/j.energy.2025.134517.
- 26. Kim, S.; Jeon, H.; Park, C.; Kim, J. Lifecycle Environmental Benefits with a Hybrid Electric Propulsion System 598
 Using a Control Algorithm for Fishing Boats in Korea. *Journal of Marine Science and Engineering* 2022, 10, 1202, 600
 600
- Vasilikis, N.I.; Geertsma, R.D.; Visser, K. Operational Data-Driven Energy Performance Assessment of Ships: The Case Study of a Naval Vessel with Hybrid Propulsion. *Journal of Marine Engineering & Technology* 2023, 22, 84–100, doi:10.1080/20464177.2022.2058690.
- Maydison; Zhang, H.; Han, N.; Oh, D.; Jang, J. Optimized Diesel–Battery Hybrid Electric Propulsion System for Fast Patrol Boats with Global Warming Potential Reduction. *Journal of Marine Science and Engineering* 2025, 13, 1071, doi:10.3390/jmse13061071.
- Barelli, L.; Bidini, G.; Gallorini, F.; Iantorno, F.; Pane, N.; Ottaviano, P.A.; Trombetti, L. Dynamic Modeling of a 607 Hybrid Propulsion System for Tourist Boat. *Energies* 2018, *11*, 2592, doi:10.3390/en11102592.
- 30. Li, L.; Yi, P.; Wu, S.; Huang, S.; Li, T. Analysis of Impact of Control Strategies on Integrated Electric Propulsion 609 System Performance During Icebreaking Process. *Journal of Marine Science and Engineering* 2024, 12, 1888, 610 doi:10.3390/jmse12101888.
- Di Bernardo, R.; Di Cecca, B.; Coppola, T.; Spazzafumo, G.; Speranza, D. Preliminary Design of a 75 m Mega Yacht 612 with Diesel - Electric Hybrid Propulsion Powered with Hydrogen FCs. *International Journal of Hydrogen Energy* 613 2025, 137, 917–924, doi:10.1016/j.ijhydene.2024.06.412.
- 32. Capasso, C.; Veneri, O.; Notti, E.; Sala, A.; Figari, M.; Martelli, M. Preliminary Design of the Hybrid Propulsion 615 Architecture for the Research Vessel "G. Dallaporta." In Proceedings of the 2016 International Conference on 616 Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation 617 Electrification Conference (ESARS-ITEC); November 2016; pp. 1–6. 618
- Martinić-Cezar, S.; Jurić, Z.; Assani, N.; Račić, N. Controlling Engine Load Distribution in LNG Ship Propulsion 619 Systems to Optimize Gas Emissions and Fuel Consumption. *Energies* 2025, *18*, 485, doi:10.3390/en18030485.
 620
- Yuksel, O.; Koseoglu, B. Numerical Simulation of the Hybrid Ship Power Distribution System and an Analysis of
 Its Emission Reduction Potential. *Ships and Offshore Structures* 2023, *18*, 78–94, doi:10.1080/17445302.2022.2028435.
- Korkmaz, S.A.; Erginer, K.E.; Yuksel, O.; Konur, O.; Colpan, C.O. Environmental and Economic Analyses of Fuel
 Cell and Battery-Based Hybrid Systems Utilized as Auxiliary Power Units on a Chemical Tanker Vessel.
 International Journal of Hydrogen Energy 2023, 48, 23279–23295, doi:10.1016/j.ijhydene.2023.01.320.
- Yuksel, O.; Blanco-Davis, E.; Spiteri, A.; Hitchmough, D.; Shagar, V.; Di Piazza, M.C.; Pucci, M.; Tsoulakos, N.;
 Armin, M.; Wang, J. Optimising the Design of a Hybrid Fuel Cell/Battery and Waste Heat Recovery System for
 Retrofitting Ship Power Generation. *Energies* 2025, *18*, 288, doi:10.3390/en18020288.
- Yuksel, O.; Blanco-Davis, E.; Hitchmough, D.; Shagar, G.V.; Spiteri, A.; Di Piazza, M.C.; Pucci, M.; Tsoulakos, N.;
 Armin, M.; Wang, J. Integrated Approach to Ship Electrification Using Fuel Cells and an Ammonia Decomposition
 System. *Journal of Marine Science and Engineering* 2025, *13*, 977, doi:10.3390/jmse13050977.
- Sun, X.; Yao, C.; Song, E.; Yang, Q.; Yang, X. Optimal Control of Transient Processes in Marine Hybrid Propulsion 632 Systems: Modeling, Optimization and Performance Enhancement. *Applied Energy* 2022, 321, 119404, 633 doi:10.1016/j.apenergy.2022.119404.

- Damian, S.E.; Wong, L.A.; Shareef, H.; Ramachandaramurthy, V.K.; Chan, C.K.; Moh, T.S.Y.; Tiong, M.C. Review
 on the Challenges of Hybrid Propulsion System in Marine Transport System. *Journal of Energy Storage* 2022, *56*, 636
 105983, doi:10.1016/j.est.2022.105983.
- Bayraktar, M.; Cerit, G.A. An Assessment on the Efficient Use of Hybrid Propulsion System in Marine Vessels.
 World Journal of Environmental Research 2020, *10*, 61–74, doi:10.18844/wjer.v10i2.5346.
- 41. DGCS Directorate 640 General of Coastal Safety Marine Vessels Available online: https://kiyiemniyeti.gov.tr/Data/1/Files/Document/Documents/fW/pB/CH/c7/DEN%C4%B0Z%20VASITALARI 641 MIZ%202022-1.pdf (accessed on 10 September 2024). 642
- Kalajdžić, M.; Vasilev, M.; Momčilović, N. Power Reduction Considerations for Bulk Carriers with Respect to 643 Novel Energy Efficiency Regulations. *Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike* 2022, 73, 79–92. 644
- Bayraktar, M.; Nuran, M. Multi-Criteria Decision Making Using TOPSIS Method for Battery Type Selection in
 Hybrid Propulsion System. *Transactions on Maritime Science* 2022, *11*, 45–53, doi:10.7225/toms.v11.n01.w02.
- 44. Brasil, C.F.; Melo, C.L.S. A Comparative Study of Lead-Acid Batteries and Lithium Iron Phosphate Batteries Used 647 in Microgrid Systems. In Proceedings of the 2017 Brazilian Power Electronics Conference (COBEP); November 648 2017; pp. 1–7. 649
- Lee, S.; Cherry, J.; Safoutin, M.; McDonald, J. Modeling and Validation of 12V Lead-Acid Battery for Stop-Start 650 Technology; SAE International: Warrendale, PA, 2017; 651
- 46. Dong, G.; Wei, J.; Zhang, C.; Chen, Z. Online State of Charge Estimation and Open Circuit Voltage Hysteresis 652 Modeling of LiFePO4 Battery Using Invariant Imbedding Method. *Applied Energy* 2016, 162, 163–171, 653 doi:10.1016/j.apenergy.2015.10.092.
- 47. ODYSSEY Batteries for Marine Applications | ODYSSEY® Battery. ODYSSEY Battery 2025.
- 48. Outdo DS-LiFePO4 Energy-OUTDO BATTERY Available online: https://www.huawei-battery.com/lxtl_xq/2.html
 656 (accessed on 17 June 2025).
- 49. Sciberras, E.A.; Norman, R.A. Multi-Objective Design of a Hybrid Propulsion System for Marine Vessels. *IET* 658 *Electrical Systems in Transportation* 2012, 2, 148–157, doi:10.1049/iet-est.2011.0011.
- 190 Watt Monokristal Güneş Paneli Available 660 50. Lexron Yakens Depo online: https://www.yakensdepo.com/index.php?route=product/product&product_id=208&srsltid=AfmBOopGTbhzj5G 661 F_iG2tufBdafZDZrY0FFstX5Ak137qdMRzWgK4NCt (accessed on 12 June 2025). 662
- 51. Gesper 80 W Watt Polikristal Güneş Paneli 85 W A Grade Solar Panel 12V Fiyatları ve Özellikleri Available online: 663 https://www.n11.com/urun/80-w-watt-polikristal-gunes-paneli-85-w-a-grade-solar-panel-12v-13227795 664 (accessed on 12 June 2025). 665
- 52. Baliga, J. Advanced Power Rectifier Concepts; Springer: Berlin, 2009; ISBN 978-0-387-75589-2.
- 53. Hamzi, I.; Bakkali, M.E.; Aghoutane, M.; Touhami, N.A. Conversion Efficiency Study of the Bridge Rectifier at 667
 2.4GHz. *Procedia Manufacturing* 2020, 46, 771–776, doi:10.1016/j.promfg.2020.04.003.
- 54. Enel Redresör 24-48-110-220V 10-100A 1 Faz | Enel Enerji 2019.
- 55. Bayraktar, M. Efficiency Analysis of Hybrid Propulsion System for Marine Vessels. PhD, Dokuz Eylul University: 670
 İzmir, 2021. 671
- Bayraktar, M.; Nuran, M. Load Test on Electric Motor and Diesel Engine to Energy Saving of Alternative Marine
 Propulsion Systems. *World Journal of Environmental Research* 2022, *12*, 43–49, doi:10.18844/wjer.v12i1.7733.
- 57. MAN Service Letter SL09-511/MTS Available online: https://www.man-es.com/docs/default-source/service 674

 letters/sl2009-511.pdf?sfvrsn=fe02e64c_4 (accessed on 12 June 2025).
 675
- Yagi, K.; Sioshansi, R.; Denholm, P. Evaluating a Concentrating Solar Power Plant as an Extended-Duration 676 Peaking Resource. *Solar Energy* 2019, 191, 686–696, doi:10.1016/j.solener.2019.08.008.

666

59.	Pu, YH.; Debue, F.; Vandermeeren, P.; Christianen, K.; De Wilde, E.; Sorrentino, A.; Devalapalli, R.; Schröder, D.;	678
	Pedgrift, A.; Lee, YS.; et al. The FASTWATER Demonstrator: Retrofitting a Harbor Tug Boat to Methanol/Marine	679
	Gas Oil Dual-Fuel Operation. Transportation Research Procedia 2023, 72, 3664–3671, doi:10.1016/j.trpro.2023.11.554.	680
60.	Karaçay, Ö.E.; Özsoysal, O.A. Techno-Economic Investigation of Alternative Propulsion Systems for Tugboats.	681
	Energy Conversion and Management: X 2021, 12, 100140, doi:10.1016/j.ecmx.2021.100140.	682
61.	Bayraktar, M.; Yuksel, O.; Pamik, M. An Evaluation of Methanol Engine Utilization Regarding Economic and	683
	Upcoming Regulatory Requirements for a Container Ship. Sustainable Production and Consumption 2023, 39, 345-	684
	356.	685
62.	Bayraktar, M.; Pamik, M.; Sokukcu, M.; Yuksel, O. A SWOT-AHP Analysis on Biodiesel as an Alternative Future	686
	Marine Fuel. Clean Technologies and Environmental Policy 2023, 25, 2233–2248, doi:10.1007/s10098-023-02501-7.	687
63.	Laryea, H.; Schiffauerova, A. A Novel Standalone Hybrid Renewable Energy Systems Onboard Conventional and	688
	Autonomous Tugboats. Energy 2024, 303, 131948, doi:10.1016/j.energy.2024.131948.	689
64.	Gao, J.; Lan, H.; Cheng, P.; Hong, YY.; Yin, H. Optimal Scheduling of an Electric Propulsion Tugboat Considering	690
	Various Operating Conditions and Navigation Uncertainties. Journal of Marine Science and Engineering 2022, 10,	691
	1973, doi:10.3390/jmse10121973.	692
65.	Chen, Z.S.; Lam, J.S.L. Life Cycle Assessment of Diesel and Hydrogen Power Systems in Tugboats. Transportation	693
	Research Part D: Transport and Environment 2022, 103, 103192, doi:10.1016/j.trd.2022.103192.	694
66.	Elis, E. ADVANTAGES AND DISADVANTAGES OF USING ELECTRIC TUGBOATS. Journal of Marine	695
	Technology & Environment 2025 , 1, 44–51.	696
67.	Liu, TK.; Chen, YS. Assessing Sustainable Decarbonization Strategies for Green Shipping Using Tugboat Owner	697
	Investment in Hybrid Power Systems in Ports in Taiwan. Sustainable Development 2024, 32, 4440-4454,	698
	doi:10.1002/sd.2908.	699
68.	Karimi, S.; Zadeh, M.; Suul, J.A. Shore Charging for Plug-In Battery-Powered Ships: Power System Architecture,	700
	Infrastructure, and Control. IEEE Electrification Magazine 2020, 8, 47–61, doi:10.1109/MELE.2020.3005699.	701
69.	Nazir, C.P. Offshore Electric Ship Charging Station: A Techno-Economic Analysis. International Journal of Marine	702
	Engineering Innovation and Research 2021 , 6, doi:10.12962/j25481479.v6i4.10763.	703
		704