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Review

Challenges and Solutions of Ship Power System Electrification

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Abstract: Growing environmental concerns have prompted the shipping industry to adopt stringent measures to address greenhouse gas emissions, with fuel-powered ships being the primary source of such emissions. Additionally, alternative forms of ship propulsion, such as internal combustion engine hybridization, low-carbon fuels, and zero-carbon fuels, face significant challenges either in terms of cost or emission-reduction capability at present. In order to decarbonize navigation, countries are focusing the maritime industry's transition towards low-carbon alternatives on transforming energy consumption, with widespread attention on the electrification of ships. Therefore, this paper provides a comprehensive review of the feasibility of fully electrifying ships, covering aspects such as technological prospects, economic viability, and emission-reduction capabilities. Firstly, the current state of research on ship electrification technology is summarized; the applicability of different battery types to electric ship technology is compared. Subsequently, the economic viability and emission-reduction capabilities of five different electric ship lifecycles are discussed separately. The results indicate that ship electrification is a key pathway to achieving zero-emission shipping, with lithium-ion batteries being the most suitable battery technology for maritime use currently. Short-to-medium-range electric ship types have demonstrated economic advantages over traditional diesel ships. As battery costs continue to decline and energy density keeps improving, the economic feasibility of ship electrification is expected to expand.

Keywords: all-electric ships; battery technology; electric ship economy; shipping industry

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1. Introduction

Shipping is one of the most significant modes of transportation in global trade, transporting around 11 billion tons of goods annually, and accounting for approximately 90% of the total global trade volume [1,2]. However, the shipping industry has also emerged as one of the major contributors to global greenhouse gas emissions, increasingly becoming a significant factor in air pollution [3] and global warming [4], and leading to considerable damage including marine eutrophication, ecological toxicity, air pollution, and climate change [5,6].

The International Maritime Organization (IMO) reports that greenhouse gas emissions from the entire shipping industry increased from 977 million tons in 2012 to 1.076 billion tons in 2018 [7], According to a recent study, carbon dioxide (CO_2) emissions from the maritime sector account for approximately 3.3% of global anthropogenic greenhouse gas (GHG) emissions, as shown in Figure 1 [8]. It is projected that by 2050, emissions from maritime shipping will constitute 17% of the global carbon dioxide emissions [9]. Emission Control Areas (ECAs) impose stricter requirements for the control of SO_x and NO_x than other areas [10], as approximately 15% of global anthropogenic emissions of nitrogen oxides (NO_x) and sulfur oxides (SO_x) come from the shipping industry [11].

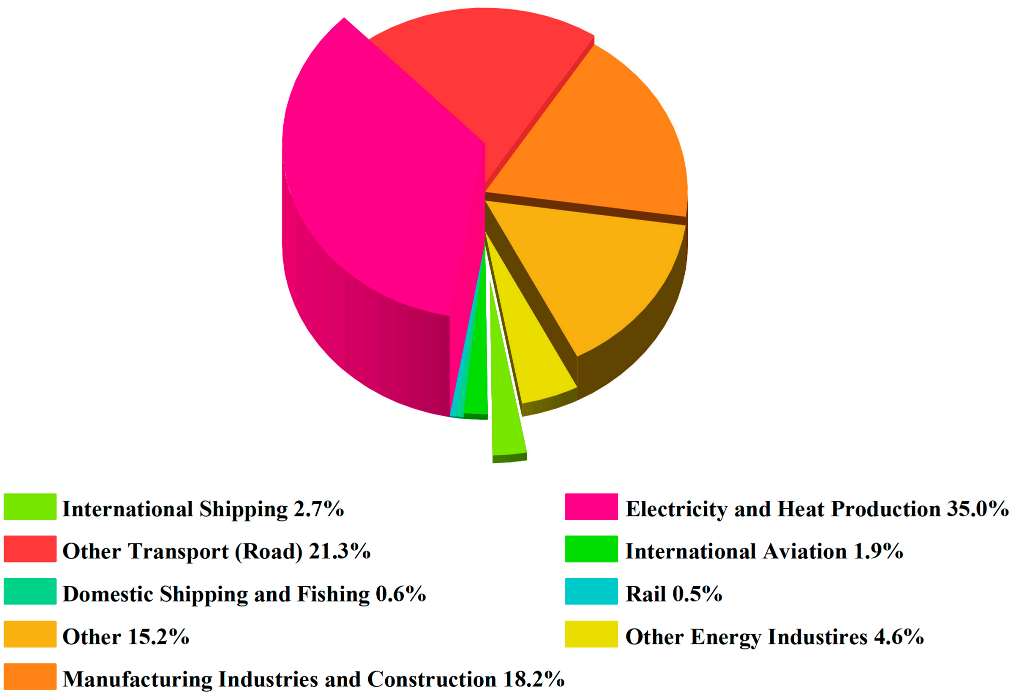

Figure 1. The proportion of CO_2 emissions from the shipping industry as a percentage of global total emissions.

In order to prevent further increases in greenhouse gas emissions from shipping, the International Maritime Organization has released the International Maritime Strategy to reduce emissions of greenhouse gases in line with the Paris Agreement. The latest strategy was formulated in July 2023, with the International Maritime Organization adopting the "2023 Ship Greenhouse Gas Emission Reduction Strategy" at the 80th session of the Marine Environment Protection Committee (MEPC 80). The strategy sets forth ambitious goals, including peaking international shipping greenhouse gas emissions as soon as possible and achieving net-zero emissions around 2050, taking into account different national circumstances. This demonstrates IMO's ambitious efforts in addressing global climate challenges [12]. The introduction of IMO regulations aims to tightly regulate ship emissions and guide the maritime industry towards significant reductions in fossil fuel consumption and pollutant emissions in the future.

In the short term, most ship operators have turned to energy-saving measures such as slow steaming (intentionally reducing the cruising speed of vessels to decrease fuel consumption), route optimization, and hull fouling management to comply with maritime organization regulations [13]. However, the emission reductions achieved through these measures, typically ranging from 10% to 15%, are insufficient to meet the forthcoming IMO efficiency regulations [14,15]. To achieve the greenhouse gas emission-reduction goals in shipping, the industry is currently exploring and applying feasible technological measures in areas such as clean energy, power devices, energy efficiency technologies, and onboard carbon capture. Energy efficiency technology measures are widely applied but have limited potential, while onboard carbon capture technology is not yet mature, lacking relevant regulations and sufficient industrial support; therefore, it is not conducive to large-scale implementation. In this context, the primary pathway to achieve greenhouse gas emission reduction in shipping will be through the use of low-carbon/zero-carbon alternative fuels and clean energy. Hybrid battery technology has been explored as a feasible short-term solution to reduce (though not eliminate) emissions from fossil fuel sources. One study indicates that the optimal scenario for hybrid systems results in emissions reductions of only 14% for bulk carriers (constituting 2% of global fleet emissions) [16], which is not significantly better than existing energy efficiency measures. The use of liquefied petroleum gas, liquefied natural gas, methanol, and their bio-derivatives as medium-to-long-term alternative fuels has garnered significant attention. However, recent studies have raised doubts about whether these fuels have the potential to achieve cost parity and substantially reduce lifecycle greenhouse gas emissions [17–19]. Clean energy sources, such as blue hydrogen (produced by capturing and storing carbon from natural gas) are expected to reduce greenhouse gas emissions by only 20% compared to liquefied natural gas [20]. While renewable ammonia and hydrogen offer feasible emission reductions, their inefficient production processes make them unlikely to be cost-competitive enough to replace fossil fuels compared to heavy fuel oil [21,22]. Against this backdrop, electrification of ships has garnered significant attention, replacing traditional internal combustion engine propulsion systems with battery-powered electric propulsion systems, namely battery-powered electric vessels [23,24].

Electrification of ships is a practical and significant research topic, with some researchers focusing on the optimization of electric power systems for ships [25] and the energy management of these systems [26], while others primarily investigate the advantages of electric propulsion. Reference [27] provides an overview of the design of all-electric ships and the components of onboard electrical systems. Reference [28] summarizes the applicability of control strategies used in hybrid and electric ships. One survey focused on highlighting research and development efforts in all-electric ships, particularly emphasizing power service quality, onboard protection, and thermal management [29]. However, this study provides a review of battery technology for electric ships, as well as the economic viability and emission-reduction capabilities of electric ships, rather than focusing on a single approach. This work will be of significant guiding importance for future research on new energy ships.

The purpose of this article is to present the challenges and solutions of electrifying ship propulsion systems. The main objectives of this paper are as follows:

(1) Based on the requirements of ships, the most suitable battery types for maritime use are identified. Considering the diversity of battery technologies, this paper reviews the characteristics of selected batteries in accordance with the demands of electric vessels, including battery power, durability, and safety, to determine the most feasible solution capable of meeting the power supply requirements of all-electric ships;
(2) This article selects five different types of vessels, including cruise ships, transport ships, inland operation vessels, nearshore tugboats, and dry bulk carriers, to conduct a full lifecycle economic evaluation, validating the economic feasibility of these five different types of short-to-medium-range vessels;
(3) The study compares the greenhouse gas emission-reduction capabilities of selected electric vessels relative to diesel vessels, summarizing previous research on the emission-reduction capabilities of electric vessels.

The structure of the remaining parts of this study is as follows: Section 2 introduces maritime energy storage technologies and identifies the optimal type of maritime batteries. Section 3 conducts an economic analysis of the selected five different vessel types. Section 4 discusses the emission-reduction capabilities of electric vessels. Section 5 presents the conclusions.

2. Ship Electrification Technology

Electric vessels are ships that utilize electrical energy as their power source, converting it into mechanical energy on the propulsion system through electric motors. In terms of layout, they replace traditional shaft systems with propulsion motors to drive the vessel forward. Their outstanding emission-reduction capabilities and more flexible interior layout are driving the development of fully electric ships.

2.1. The Development History of Electric Propulsion Technology

The earliest attempts to apply electric propulsion technology to ships can be traced back to the 1830s [30], as shown in Figure 2, where batteries were used to power DC motors installed experimentally on small boats. In 1836, Jacobi installed an electric motor on a 28-foot-long rowboat, which successfully crossed the Neva River in September 1838 with 14 passengers on board, marking the first recorded launch of an electrically powered vessel. In 1882, the first batch of commercial inland electric boats produced by the Electrical Power Storage Company operated on the River Thames in England, marking the first successful commercial electrification of vessels. At that time, the vessels were equipped with a DC distribution system.

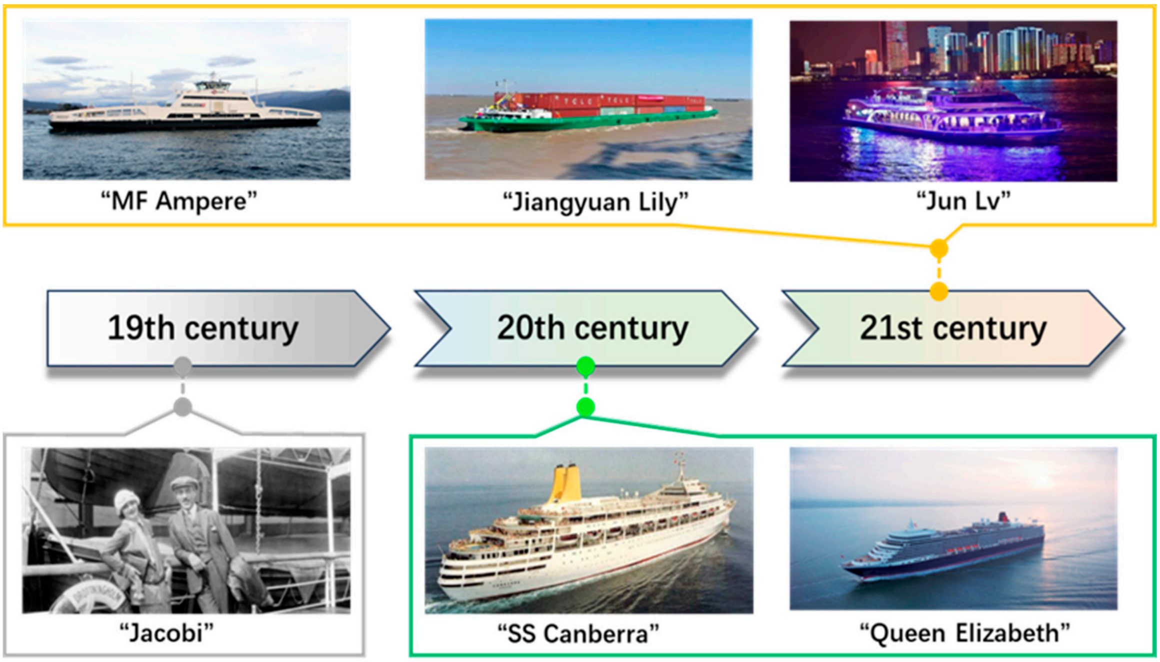

Figure 2. The development history of electric propulsion ships.

During the 20th century, the introduction of internal combustion engines slowed down the development of electric propulsion technology. The first diesel–electric propulsion system was successfully installed on the merchant ship Selandia in 1903 [31]. In 1960, SS Canberra became the first cruise ship to utilize alternating current (AC) generators to supply electrical power to propulsion engines. In the early 1980s, advancements in power electronics and variable frequency drives led to new concepts in shipboard electrical system design, resulting in a significant breakthrough in electric propulsion technology known as Integrated Power Systems (IPS). The IPS architecture was first applied to the Queen Elizabeth 2, a converted ocean liner equipped with nine diesel generators to provide power for ship services and propulsion loads.

As we enter the 21st century, against the backdrop of global efforts toward decarbonization, the importance of electric propulsion systems has become increasingly pronounced, rapidly displacing fuel-based propulsion systems. Electric propulsion technology has made breakthroughs in areas such as maneuverability, reliability, operational efficiency, and propulsion power, with its applications continually expanding. In 2015, the world's first battery-powered passenger ship, the MF Ampere, began operations, heralding the era of zero-emission electric vessels [32]. Subsequently, electric vessels have gradually penetrated various sectors such as ferries, cargo ships, and cruise ships.

2.2. Electric Propulsion System

The ship electric propulsion system is a modernized vessel power system that utilizes electricity as its primary propulsion energy source. Compared to traditional internal combustion engine propulsion systems, electric propulsion systems offer a higher efficiency and lower environmental impact. As shown in Figure 3, the ship electric propulsion system mainly consists of the following components:

- Power Source: The power source of the ship's electric propulsion system can be generators, battery packs, or other renewable energy devices such as solar panels, wind turbines, etc. These power sources convert energy into electricity to provide power to the electric propulsion system.
- Power Conversion Equipment: The power conversion equipment is used to convert the direct current (DC) generated by the power source into alternating current (AC) required for ship propulsion. This typically includes inverters and frequency converters.
- Propulsion Motor: The propulsion motor is the core component of the electric propulsion system, responsible for converting electrical energy into mechanical energy and driving the ship's propeller or other propulsion devices. Propulsion motors are typically alternating current (AC) motors, and their types and specifications vary depending on the size and purpose of the vessel.
- Propulsion Device: This includes propellers or other forms of propulsion devices, which convert the mechanical power of the electric motor into thrust to propel the ship forward.
- Auxiliary Equipment: The ship's electric propulsion system may also include some auxiliary equipment such as cooling systems, power transmission systems, safety systems, etc., to ensure the safe and reliable operation of the system.

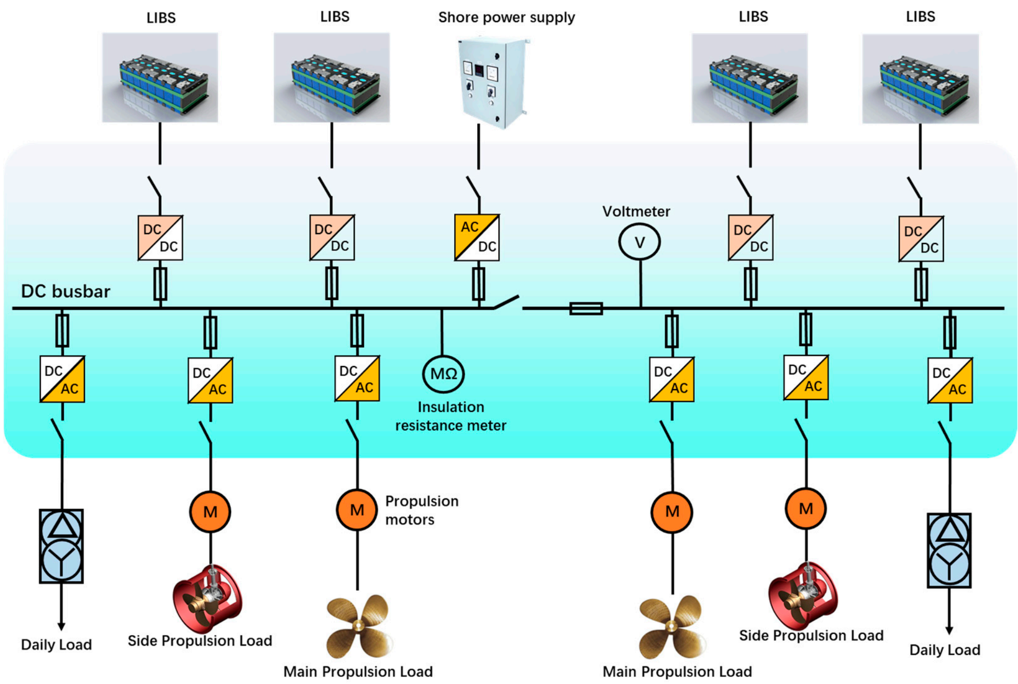

Figure 3. The principle single-line diagram of pure electric power propulsion system.

The pure electric propulsion system is powered by a lithium-ion battery (LIB) pack, converting the chemical energy in the batteries into mechanical energy to drive the ship forward through the propellers. Its energy-saving feature lies in the pure electric propulsion system depicted in Figure 3, where all power loads derive their power from the LIB pack. Integrated electric propulsion is established by installing generators driven by diesel engines or gas turbine generators to produce electrical power at standard frequency and voltage levels. This electrical power is fed into the main distribution board and distributed throughout the ship via cables and power converters to accommodate propulsion motors and all service loads. As electrical power typically operates at a constant voltage and fixed frequency, variable speed drives adjust the speed of the propulsion motors to produce the appropriate frequency corresponding to the desired speed. Compared to traditional propulsion systems, the integrated electric propulsion architecture offers significant opportunities in efficiency improvement and ship design [28,33], as illustrated in Figure 4.

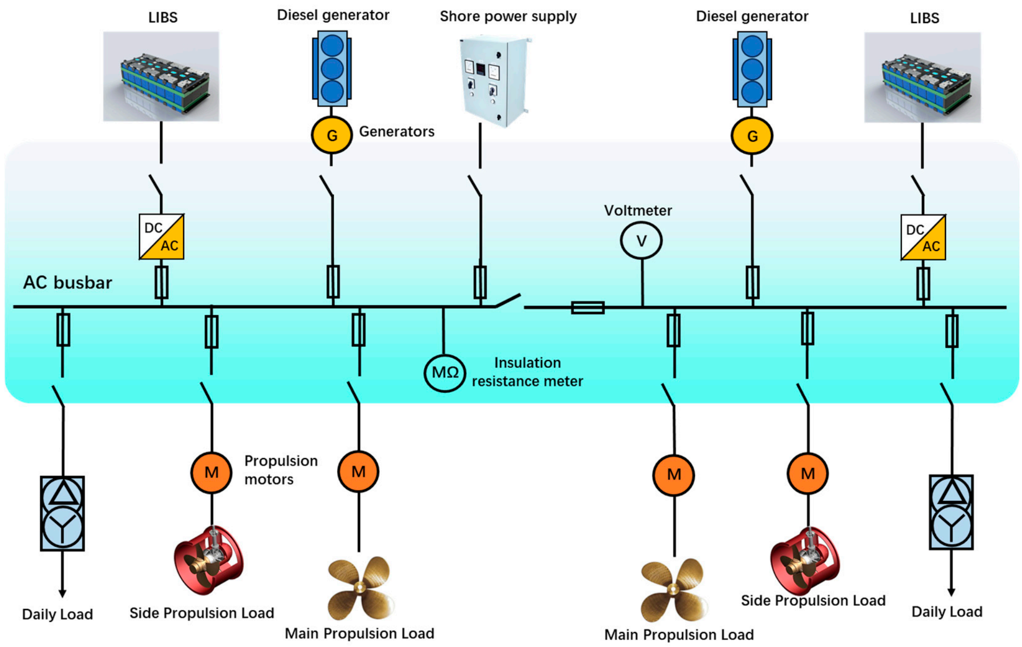

Figure 4. Schematic diagram of integrated electric propulsion system.

The voltage level, current rating, power rating, and frequency of a ship's electric propulsion system parameters are closely related to the ship's electric propulsion system, collectively determining the design, performance, and operational characteristics of the power system. In marine electric propulsion systems, different voltage levels are commonly used for transmitting and distributing electrical power. Common voltage levels include 440 V, 230 V, and 110 V, while larger ships may utilize higher voltage levels such as 6.6 kV, 11 kV, or even higher, as shown in Table 1. The current rating depends on the load and transmission capacity of the power system. In marine electric propulsion systems, various current ratings are typically used for different electrical equipment and systems, such as propulsion motors, auxiliary equipment, etc. The power rating refers to the power that the electrical system can transmit or generate. In marine electric propulsion systems, power ratings can involve generators, propulsion motors, auxiliary equipment, etc. Common power ratings can range from tens of kilowatts to several megawatts. The frequency of marine electric power systems is typically 50 Hz or 60 Hz, depending on the electrical standards of the region where the vessel operates.

Table 1. The key technical specifications of the electric propulsion system.

The Name of the Ship	Voltage Rating	Current Type	Rated Propulsion Power	Ship Parameters	References
"Shen Kuo"	-	DC	2300 kW	Length: 63 m Width: 23 m Depth: 9.4 m Displacement: approximately 2194 tons	[34]
"Fincantieri"	11 kV	DC	78 MW	Length: 330 m Width: 38.4 m Maximum draft: 8.55 m	[27]

Table 1. *Cont.*

The Name of the Ship	Voltage Rating	Current Type	Rated Propulsion Power	Ship Parameters	References
"Dianchi Harmony"	750 V	DC	150 kW	Length: 39.8 m Width: 10 m Passenger capacity: 150 people	[35]
"Jiazhou 07"	-	DC	400 kW	Length: 34.9 m Width: 7 m Designed draft: 0.8 m	[35]
"Guangzhou Star"	750 V	DC	420 kW	Length: 43.5 m Width: 13.5 m Depth: 3.2 m	[35]

The advantages of marine electric propulsion systems include higher efficiency, lower noise and vibration, reduced emissions, better flexibility, and controllability. With increasing demands for environmental protection and energy conservation, the application of marine electric propulsion systems is becoming increasingly widespread in commercial and public maritime sectors.

2.3. Marine Energy Storage Systems for Electric Ships

As a newly emerging type of vessel in recent years, the main feature of electric vessels is the adoption of Integrated Power Systems (IPS) onboard to supply energy to various ship loads (such as propulsion, radar, anchors, air conditioning, etc.), effectively reducing redundancy in ship equipment and improving vessel operational efficiency [36]. The energy storage system, due to its ability to absorb/release energy, can serve as an energy/power buffer to achieve energy balance between the generation and load sides of the onboard IPS, thus offering promising applications in the full-time scale management of all-electric vessels [37–39]. Energy storage systems comprise various types, each with distinct technical characteristics, and their application varies across different scenarios. The core component of an energy storage system is the energy storage device, which currently includes the battery, flywheel, and supercapacitor, among others; refer to Table 2 for more information.

Table 2. Basic parameters of the selected battery technology [40–52].

Battery Type	Specific Energy [Wh/kg]	Specific Power [W/kg]	Lifetime [Years]	Cycle Life [Cycles]	Operating Temperature Range [°C]	Efficiency [%]	Response Time
Pb-H_2SO_4	30–50	75–300	5–15	500–1000	−20 to +75	70–90	ms
Ni-MH	40–80	300–333	10–15	500–2000	−10 to +60	70–90	ms
Li-ion	75–250	200–2000	5–15	400–9000	−25 to +60	85–90	ms
Flywheel	10–30	400–1500	15–20	20,000+	-	93–95	<ms
Supercapacitor	2.5–15	500–5000	4–12	100,000+	−40 to +65	90–95	<ms

2.3.1. Marine Energy Storage Technology

Just like in the automotive industry, batteries are the primary storage medium used on ships because they offer relatively high energy density and a cost-effective solution compared to other storage mediums. The characteristic of maintaining high efficiency under actual discharge currents is also attractive for marine applications that require continuous operation.

A flywheel is an electromechanical device used to store energy in the form of kinetic energy by accelerating a rotating rotor. The stored energy is released by decelerating the torque over a relatively short period of time. Significant advantages of flywheels include a high power density and high cycling capability. However, in terms of long-term applications, they do not offer any advantages over batteries. Due to these characteristics, flywheels are particularly suitable for mitigating power fluctuations and providing propulsion over time frames ranging from milliseconds to several minutes [49].

Supercapacitors, also known as ultracapacitors or double-layer capacitors, operate on the same fundamental principles as traditional capacitors. They store energy in the form of an electric field and are renowned for their high symmetric charge–discharge rates. Typically, supercapacitors have relatively low equivalent series resistance, allowing them to efficiently deliver power. They are commonly used in applications requiring higher power over shorter durations, such as camera flashes, filter applications, and reactive power compensation. The key characteristics of supercapacitors include higher power density, faster charge and discharge rates due to lower internal resistance, longer lifespan, lower voltage, and higher cost per watt-hour (up to 20 times higher compared to lithium-ion batteries). One of the main drawbacks of supercapacitors is their high sensitivity to overvoltage and overcharging. Other disadvantages include relatively lower energy density, linear discharge voltage, high self-discharge, and low cell voltage [53].

However, single-energy storage systems (ESS) still face critical issues such as the inability to simultaneously achieve high power density and energy density, incompatible high-temperature and low-temperature performance, and lack of synergy between operational rate and cycle life. Hybrid-energy storage systems (HESS), leveraging the endurance of energy-based storage and the rapid response of power-based storage, significantly enhance the overall performance and cost-effectiveness of energy storage systems. They provide an important solution for applications with complex operating conditions. Typically, hybrid-energy storage systems are composed of devices with a high power density and high energy density, thereby satisfying both energy and power demands. One challenge faced by electric ship propulsion systems is the large fluctuations in propulsion loads, which can be effectively addressed using the characteristics of hybrid-energy storage. Jun Hou et al. studied a novel configuration of hybrid-energy storage systems, specifically combining batteries with flywheels, to assess the feasibility and effectiveness of mitigating load fluctuations in ships. They compared this configuration with combinations involving batteries and supercapacitors. Simulation results demonstrate that the battery/flywheel hybrid-energy storage system is feasible and effective in mitigating load fluctuations in all-electric ships, particularly under harsh sea conditions [54]. Jun Hou et al. investigated a hybrid-energy storage system (HESS) combining battery packs and supercapacitor packs, considering two real-time electromagnetic strategies: separating power demands and treating HESS as a single entity. Simulation results indicate substantial benefits of internal coordination within HESS in reducing fluctuations and losses [37]. Kyaw Hein et al. focused on optimizing the range and multi-objective energy management of fully electric ships with hybrid-energy storage systems, aiming to optimize vessel routes, operating costs, emissions, and degradation of energy storage. Simulation results demonstrate that considering sea conditions in navigation planning strongly influences the path and speed of fully electric ships, thereby affecting propulsion power requirements [39].

Ships, due to their inherent characteristics, operate in different work environments compared to land-based applications, with the main distinctions being as follows:

(1) The mobility characteristics of ships. The swaying and vibrations caused by movement can introduce uncertainties in the operation of energy storage systems and render some energy storage technologies unsuitable for maritime applications. For example, flow batteries are not suitable for operation in environments with swaying and vibrations.
(2) The isolated nature of ships. This characteristic brings about diverse and adaptable load requirements for shipboard energy storage. For instance, due to the lack of a main power grid support system like on land, energy storage systems on ships need to play multiple roles during voyages, including but not limited to providing direct propulsion power and assisting various operational loads. This necessitates shipboard energy storage systems to possess both energy and power characteristics.

(3) The operating environment of ships. Ships operate in environments characterized by high temperatures, humidity, and salinity, and their operating ranges are wide. This starkly contrasts with the excellent environmental control capabilities of land-based energy storage systems. Consequently, higher reliability requirements are imposed on shipboard energy storage systems.

With advances in battery technology, battery energy storage systems are increasingly capable of meeting power and energy demands in a wide range of scenarios. In summary, under current technological conditions, batteries serve as the primary means for supporting the basic load of ships. Batteries possess high energy density, a wide temperature operating range (0 to 35 °C), and relatively reliable safety management methods [55]. Therefore, the subsequent sections of this paper primarily discuss battery energy storage systems.

2.3.2. The Types of Batteries Used in Electric Ships

Regarding the use of batteries onboard, there are three different types of electric vessels: plug-in hybrid electric vessels, hybrid electric vessels, and fully electric vessels [56]. Plug-in hybrid and hybrid electric vessels both combine traditional diesel engines with batteries. In hybrid electric vessels, the batteries are charged by the surplus energy from the engine and are used to absorb load fluctuations [16], whereas in plug-in hybrid electric vessels, the batteries are charged from the grid and are fully utilized for specific conditions such as port berthing [57]. Fully electric vessels solely rely on batteries as their power source, charged by connecting to the grid. They do not have internal combustion engines and require no fossil fuels during operation, resulting in no direct carbon emissions, making them completely zero-emission [58].

Electric ships can also utilize batteries to replace traditional ballast tanks. Conventional ships with internal combustion engines use ballast systems to distribute weight and offset buoyancy by filling and draining water tanks according to cargo loads. Case studies on fully electric or hybrid propulsion systems suggest that by distributing battery modules throughout existing voids, machinery, and ballast water tanks, it is possible to partially or entirely replace ballast systems with battery energy storage systems without significant impacts on symmetry (trim) and balance [16]. Furthermore, battery systems can be installed in various locations on the vessel to achieve more flexible and precise weight distribution adjustments, thereby enhancing the stability of the ship [59,60]. When electric ships utilize batteries, real-time adjustment and control of the batteries can be achieved through a battery management system to meet various navigation requirements, whereas adjusting ballast water is comparatively difficult and requires more time and labor. In terms of environmental protection, the use of battery systems can reduce the environmental impact of ships as they do not emit wastewater or other pollutants, aligning with the modern shipping industry's environmental requirements and trends. Below, an analysis is provided on the characteristics of different types of batteries and their suitability onboard ships.

Technical Characteristics

Over the past decade, extensive research on batteries has rapidly improved their characteristics [61,62]. The selection of batteries suitable for navigation is based on energy density and power density since batteries need to ensure relatively long distances of travel and manage necessary accelerations [49]. However, other characteristics of batteries, such as lifespan, cycle count, operating temperature range, efficiency, safety, and cost, also impact the sustainability of ships and require further research [63]. Table 3 compares the characteristics of the selected lead–acid batteries (Pbacid), nickel–metal hydride batteries (Ni-MH), and lithium-ion batteries (Li-ion).

Table 3. Characteristics of different battery technologies [64–67].

Battery Type		Advantages	Disadvantages
$Pb–H_2SO_4$		Inexpensive; Lead is easily recyclable; Low self-discharge (2–5% per month); Short cycle life.	Shorty cycle life; Cycle life is affected by depth of charge; Low energy density.
Ni-MH		Tolerant of low temperatures; With memory effect; High self-discharge rate.	High degradation; High cost; Toxicity of cadmium metal.
Li-ion	LFP	High safety; Long cycle life; Lower cost.	Low energy density; Poor performance at low temperatures; High self-discharge rate.
	NCM	High energy density; Good performance at low temperatures; High charging efficiency.	High cost; Risk of TR; Capacity degradation.

The lead–acid battery was first proposed in 1890 and is currently the most mature and longest-used energy storage technology [68]. It is commonly used in internal combustion engine vehicles to provide rapid high-current pulses for starting, buffer electrical energy during vehicle operation, and supply power to the electrical system when the engine is not running. The lead–acid battery is a mature technology known for its relatively stable performance, low manufacturing cost, high operational safety, high specific power, and ability to withstand large charge/discharge rates [69,70]. However, its main drawbacks include relatively low specific energy, energy density, and cycle life (50–110 Wh/L), which can lead to significant volume and weight in large-scale energy storage applications. Therefore, lead–acid batteries are widely used in small-scale energy storage scenarios where investment sensitivity is a concern [71,72].

Nickel–metal hydride batteries have been continuously evolving over the years. Due to their higher specific energy, specific power, and cycle life compared to lead–acid batteries, they are more suitable for navigation. In addition, nickel–metal hydride batteries exhibit good electrical performance at low temperatures compared to other types of battery technologies [52]. On one hand, this type of battery increases energy density in terms of volume (140–420 Wh/L) and weight, enhances high-rate power capabilities, and increases tolerance to over-discharge [73,74]. On the other hand, the release of hydrogen gas and the generation of explosive gases during charging are among the main drawbacks of this battery technology [50]. Additionally, nickel-based batteries also exhibit significant memory effects, which can affect battery lifespan if subjected to prolonged shallow charging and discharging. At room temperature, the charging efficiency of nickel–metal hydride batteries is relatively low, with a self-discharge rate of 12.5% per day, which increases with rising ambient temperatures [74]. To meet the energy requirements of ship navigation, further improvements are needed in energy density, specific power, faster charging capabilities, and cost.

Lithium-ion batteries (LIBS) are considered the most advanced technology for electric ships. Compared to lead–acid and nickel–metal hydride batteries, LIBS offer a superior combination of high energy density (200–700 Wh/L), high power density, high cycle life, fast charging capabilities, and low self-discharge rates [75,76]. They exhibit no significant memory effects and are currently the most extensively researched battery technology. The main drawbacks of LIBS lie in their high investment costs and safety concerns. With the advancement of LIB technology and the promotion of large-scale and integrated production of LIBS, the price of LIBS is rapidly decreasing. This means that in the future, investment cost will no longer be the primary limiting factor for the application of LIBS. Regarding the safety issues of LIBS, marine batteries not only serve the short-term power needs of sea voyages but also need to withstand the impacts of mechanical [77] and thermal [78,79] accidents [80,81]. LIBS mainly consist of a cathode, an anode, electrolyte, and separator. The types of LIBS are named after their cathode chemistry, with lithium iron phosphate (LFP) and nickel cobalt manganese (NCM) being the two main technological pathways for marine LIBS. LFP batteries exhibit excellent electrochemical performance and thermal stability. Their main advantages include high safety and long cycle life, as well as lower cost. Nickel cobalt manganese (NCM) batteries, on the other hand, offer advantages in energy density, low-temperature performance, and charging efficiency.

System Design

The design of battery energy storage systems in electric ships involves several critical aspects, with the choice of battery type determining the design of the onboard battery storage system. Below, we discuss the most suitable battery type for onboard use based on three aspects: the space and weight occupied by the battery system on the ship, battery lifespan, and battery safety. This paper discusses the most suitable types of batteries for onboard use based on the requirements of electric vessels for batteries in terms of power, lifespan, and safety. Battery-powered all-electric vessels are typically small vessels, with electric-powered river passenger boats being their classic representatives. For example, the 'Yangtze Three Gorges 1' is a vessel propelled solely by battery power, with a total capacity of 7.5 MWh, equivalent to the total battery capacity of over 100 pure electric cars. It is currently the largest in terms of battery capacity and passenger capacity among all-electric passenger ships designed and built worldwide. With a single charge, it can sail for 100 km. The parameters of the vessel are listed in Table 4.

Table 4. Technical data of the "Changjiang Sanxia 1".

Basic Technical Parameters	Numerical Values
Total Length/m	100
Total width/m	15.8
Depth/m	4
Total battery power/kW	1050
Battery capacity/kWh	7500
Range/km	100

In terms of battery energy density, the 'Yangtze Three Gorges 1' has a total power of 1050 kW and a battery capacity of 7500 kWh. According to the parameters of the three types of batteries in Table 2, if this vessel were to achieve a power of 1050 kW using lead–acid batteries and nickel–metal hydride batteries, the battery weights would be approximately 10 tons and 5 tons, respectively. Under the same power, lithium-ion batteries would require less than 1 ton. If the onboard battery capacity is 7.5 MWh, the weights of lead–acid batteries and nickel–metal hydride batteries on the ship would be approximately 250 tons and 125 tons, respectively, with volumes of about 94 m^3 and 28 m^3. Under the same battery capacity, lithium-ion batteries would only require about 46 tons and 16 m^3, as shown in Figure 5. The key technological constraints of battery-powered vessels lie in the volume occupied by the battery system and electric motors relative to the existing volume occupied by ship engines, fuel storage, and mechanical spaces [82]. If the volume occupied by the battery system is too large, it can increase the difficulty of cabin layout. In commercial vessels such as cargo ships and transport ships, it can encroach upon cargo space, reducing economic returns. The weight of the batteries increases the ship's draft, leading to higher resistance. Consequently, more power is required to achieve the same speed. Therefore, electric vessels need smaller battery volumes and weights. In these respects, lithium-ion batteries demonstrate superior performance.

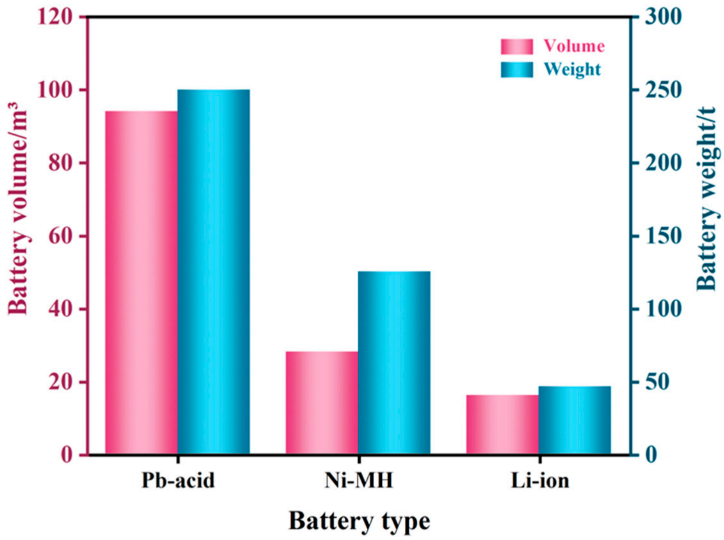

Figure 5. Volume and weight of three types of batteries at the same capacity.

In terms of lifespan, the calendar lifespan of the three types of batteries is similar. However, concerning cycle life, assuming the 'Yangtze Three Gorges 1' electric vessel undergoes one charge per day and operates for 200 days per year, with the average lifespan of vessels currently standing at 20 years, it would require at least 4000 cycles. According to the data in Table 2, it can be observed that the cycle life of lead–acid and nickel–metal hydride batteries is insufficient, only lithium-ion batteries can meet this requirement. If marine batteries are lead–acid or nickel–metal hydride, they would need to be replaced during the vessel's lifespan, resulting in higher cost inputs.

In terms of safety, prevention of lithium-ion battery safety incidents is currently approached from three aspects: intrinsic battery safety, proactive ship protection, and passive ship protection. Intrinsic battery safety focuses on enhancing the inherent safety of battery cells, modules, and cabinets through explosion-proof and heat-dissipating designs to prevent thermal runaway (TR).

To ensure stable operation of lithium-ion batteries in marine environments, they should have a minimum protection rating of at least IP67 to prevent ingress of water and dust. The battery casing and connectors should be made from corrosion-resistant materials such as stainless steel or special coatings. The battery management system should be capable of monitoring battery temperature and adjusting as necessary to prevent overheating or excessive cooling. By implementing these measures, the reliability and safety of lithium-ion batteries in marine environments can be significantly enhanced, necessitating careful consideration of these factors in both design and usage. Cheng Siong Chin and colleagues analyzed the challenges faced by lithium-ion batteries in maritime and offshore applications, including corrosion from seawater, high water pressure (subsea applications), and extreme environmental temperatures (near polar climates). They emphasized that for lithium-ion batteries to function safely and effectively at sea, extensive design considerations are necessary. These include understanding the effects of external pressure and temperature on the performance of lithium-ion batteries and power electronic circuits. The battery power systems must not be exposed to water and require adequate mechanical sealing such as O-rings and marine-grade connectors to prevent seawater from leaking into the battery power modules. Mechanical housings are made from marine-grade materials including carbon steel and alloy steel (DH36, AH36, EH36), stainless steel (grade 316), aluminum (5052, 5083, and 6061-T6 grades), galvanized steel, marine-grade high-density polyethylene, and titanium metal [83]. Proactive ship protection involves using smoke detectors to detect fires, thereby improving the ship's monitoring and suppression capabilities against battery thermal runaway fires. Passive ship protection involves improving the layout of ships and battery compartments to enhance the ship's ability to contain the spread of battery fires. Du Rui et al. researched feasible safety design measures for lithium-ion batteries, including requirements for battery cells, battery packs, and battery management systems. They also studied the layout and ventilation schemes of battery compartments on ships, as well as the design of fire suppression systems. According to relevant regulations, they performed calculations and verification for fixed heptafluoropropane fire extinguishing systems. Finally, they pointed out limitations in the design schemes and drawbacks of using fire suppression agents [84]. Increasing safety protections for lithium-ion battery systems on ships may involve certain cost investments [77]. Thomas L. Fantham et al. considered safety laboratory testing for commercial high-capacity single-cell and multi-cell battery packs, proposing appropriate control measures such as fuses, contactors, and system design. They also recommended the use of suitable enclosures and fire suppression systems if these measures fail. Implementing these mitigation measures would entail additional costs for the battery systems, with costs around GBP 100 for high-current contactors and fuses. However, fire suppression and enclosures are more expensive. The cost of an automatic fire suppression system is approximately GBP 1000 per canister, and GBP 120 per square meter for enclosures. Large lithium-ion battery-specific fire extinguishers (9 L) cost GBP 400. It is evident that achieving maximum safety comes at a cost [85]. Currently, the cost of fire safety measures on electric ships appears relatively high. However, with ongoing technological advancements and the expansion of the industry, these costs are expected to gradually decrease.

Considering the requirements of ships for batteries in terms of energy density, lifespan, and safety, lithium-ion batteries emerge as the preferred choice for marine applications. Based on the high safety requirements and relatively moderate space and weight constraints in practical applications, lithium iron phosphate batteries have become the mainstream choice for marine battery power in recent years. They are suitable for vessels with shorter, more frequent journeys, lower power requirements, and fewer charging time constraints. However, nickel cobalt manganese batteries will play a role in the field of vessels with longer journeys, lower battery cycle frequencies, and higher energy density requirements.

2.3.3. Electric Ship Energy Replenishment Technology

Currently, factors such as long charging times, limited cruising ranges, high acquisition costs, and inadequate infrastructure hinder the widespread adoption of electric vessels. The key to promoting the use of electric vessels lies in the improvement of electric vessel charging/swapping stations. The main method for replenishing electric power in electric vessels is through shore power systems. When ships are not loading or unloading cargo, the lengthy charging time during port stops and the resultant pressure on port services can lead to excessively high time and operating costs for electric vessel transport. This situation is not conducive to the long-distance transportation of electric vessels.

The energy replenishment modes for electric vessels primarily consist of charging and battery swapping. In the charging mode, shipowners initially need to purchase marine batteries, which adds to their initial investment pressure. Additionally, charging times are lengthy, and there are high requirements for port charging facilities. When cargo handling is unnecessary, the time costs are high, thus increasing port operational pressures. In contrast, in the battery swapping mode, users do not need to purchase marine batteries initially [86]; instead, batteries are leased, effectively addressing the issue of high initial investment. Moreover, battery swapping is faster, effectively alleviating range anxiety. Comparing these two energy replenishment modes, in terms of initial investment costs, the cost of power batteries typically accounts for 30–40% of the construction cost of electric vessels. The battery swapping mode significantly reduces the initial investment pressure on shipowners. In terms of replenishment time, battery swapping is faster, reducing both the time and operational costs of electric vessel transport. Therefore, this paper considers the battery swapping mode to be the key solution to addressing end-user concerns. However, the battery swapping electric vessel industry in China is currently in its infancy stage, with missing standards and simultaneous construction of swapping facilities. As for charging facilities, different types of electric vessels equipped with rechargeable batteries have varying charging facilities, and the industry has not yet established unified technical standards. Standardized marine charging stations have yet to be established and promoted.

According to the operational characteristics of electric vessels, there are currently three main energy replenishment schemes for electric vessels [87], as shown in Figure 6, as follows:

- For vessels with high charging demands and total battery storage energy of up to 1000 kWh, it is more suitable to adopt a supercapacitor charging mode or a containerized power swapping mode. These types of vessels are primarily passenger ferries and roll-on/roll-off passenger ferries.
- For vessels with high charging demands and total battery storage energy exceeding 4000 kWh, it is more suitable to adopt a containerized power swapping mode. These types of vessels are primarily long-haul freighters and regional operation vessels.
- Ships with charging demands occurring once every one to two days and total battery storage energy under 4000 kWh are more suitable for adopting the lithium-ion battery compartment charging mode. These types of ships primarily include tour boats and short-to-medium-haul freighters.

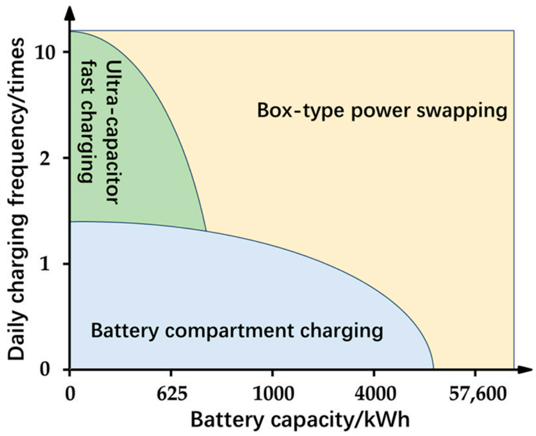

Figure 6. Suggestions for different electric ship energy replenishment modes.

3. Analysis of the Economic Viability of Electric Ships

The economic viability of electric vessels is closely tied to their application scenarios and ship types. Below, we discuss five different types of short-to-medium-haul vessels in scenarios such as inland waterways, lakes, and nearshore areas. These include large commercial tourist boats, cargo ships, inland operation vessels, nearshore tugboats, and bulk cargo ships.

3.1. Typical Cases of Electric Ships

The paper selects five different types of vessels for various purposes [88], as shown in Figure 7. Below is an introduction to the selected vessel types, with typical vessel parameters listed in Table 5.

Table 5. Technical data of the analyzed ships.

Typical Ships	Average Main Engines (s) Power (kW)	Speed (km/h)	Battery Capacity (kWh)	Range (km)
A	150	17	1000	100
B	240	10	1500	110
C	30	9	250	90
D	3000	23	5000	200
E	370	18	2200	120

Figure 7. Typical ship to be analyzed.

3.1.1. Fully Electric Large-Scale Commercial Tourist Ship—"Shanshui Green Source"

"Shanshui Green Source" is an inland lake tourist ship completed and launched in September 2020. With a total length of 32.65 m and a width of 8 m, it is divided into two decks and can accommodate up to 182 passengers. The vessel employs a dual-engine, dual-propeller, and dual-rudder propulsion system, providing flexible operation and high safety standards. Powered by two 75 kW AC main engines, it can achieve a maximum speed of 17 km/h. The total capacity of the vessel is 1000 kWh, equivalent to the full charge capacity of 30 electric cars. It is equipped with a DC 120 kW fast charger, which can be fully charged in 7 h, with a maximum range of 100 km.

3.1.2. Thousand-Ton Electric Transport Ship—"Zhongtian Electric Transport 001"

"Zhongtian Electric Transport 001" is a river transport ship completed and launched in May 2020. The vessel has a total length of 49.8 m, a beam of 10.6 m, a depth of 3.9 m, and a draft of 3.1 m. It has a carrying capacity of 1000 tons and a designed cruising speed of 10 km/h. Propulsion is provided by two 120 kW electric motors, utilizing a dual-energy system comprising lithium-ion batteries and supercapacitors. The battery capacity is 1500 kWh, providing a range of 50 km, with an additional 100 km achievable using mobile power sources for extended range. The vessel is equipped with both high-voltage (6.6 kV/11 kV) and low-voltage (440 V) shore power, along with fast-charging capabilities.

3.1.3. Electric Work Ship—"Taihu Electric 001"

"Taihu Electric 001" is primarily used for salvaging blue-green algae in the Taihu Basin. It was completed and put into operation in March 2021. The vessel has a total length of 19 m and a width of 2.9 m, equipped with a '2 + 1' set of 10 kW electric thrusters. Its operational cruising speed ranges from 8 to 10 km/h, with a battery life exceeding 10 h. The ship adopts 'oil-to-electric' technology, utilizing lithium-ion batteries with a capacity of 250 kWh for propulsion.

3.1.4. Pure Electric Tugboat—"Yunport Electric Tugboat No. 1"

"Yunport Electric Tugboat No. 1" serves as a harbor tugboat, delivered for use on 16 August 2021. This vessel has a total length of 35.5 m, a width of 10 m, a draft of 3.5 m when fully loaded, with a minimum cruising speed of 13 knots and a minimum working duration of 8 h. It is powered by a 5000 kWh lithium iron phosphate battery pack, providing propulsion of 3000 kW, equivalent to the performance of a conventional tugboat with 2984 kW. It is equipped with a 6930 kVA high-voltage shore power system, capable of fully replacing traditional high-power fuel-powered tugboats.

3.1.5. Three Thousand Ton Pure Electric Bulk Carrier—"Ship Union No. 1"

"Ship Union No. 1" is an inland river bulk cargo vessel, with its official launching ceremony held on 22 February 2022, followed by its official commissioning. This vessel has a carrying capacity of 3000 tons and a rated power of 370 kW. It is powered by two 1100 kWh movable container-type lithium iron phosphate battery packs, making it the first large-scale ship power battery pack in China to be compatible with both charging and swapping. It has a range of 120 km and is supported by four shore-based DC charging facilities, consisting of two 360 kW and two 180 kW chargers.

3.2. The Economic Analysis Results

3.2.1. Initial Investment Cost

The initial investment cost of a vessel primarily comprises the construction cost. Additionally, for electric vessels, it includes the cost of ship batteries and the construction cost of supporting shore-based electrical infrastructure. Refer to Table 6 for the analysis of electric vessel construction costs in the aforementioned typical cases. Electric boats currently do not have a cost advantage in terms of hull construction costs. Batteries represent 30% to 60% of the manufacturing cost of electric vessels. The average cost of power batteries for the aforementioned electric vessels is 2000 RMB per kWh. Based on existing power battery technology and material conditions, the lifespan of power batteries is approximately 10 years, with an annual equivalent usage cost of around 200 RMB per kWh The lifespan of the vessel is set at 20 years [89]. This paper analyzes the full 20-year lifecycle of the vessel; thus, electric vessels require one battery replacement during their lifespan. The battery cost in Table 6 represents the total cost of batteries after one replacement. The construction cost of shore-based electrical infrastructure mainly includes the cost of grid expansion and charging stations.

Table 6. Initial investment cost of the analyzed ships.

Typical Ships	Battery Capacity (kWh)	Battery Type	Total Battery Cost (¥10 K)	Total Construction Cost (¥10 K)	Shore Power Construction Cost (¥10 K)	The Construction Cost If Traditional Vessels Are Used (¥10 K)	Cost Difference (¥10 K)
A	1000	LIBs	400	1200	100	800	500
B	1500	LIBs	600	900	150	350	700
C	250	LIBs	100	150	4.2	35	119.2
D	5000	LIBs	2000	3000	900	1600	2300
E	2200	LIBs	880	1274	200	400	1074

3.2.2. Operation Cost

The annual operating costs of the vessel mainly include the annual electricity cost for electric vessels and the annual fuel cost for diesel vessels, as well as their respective annual labor and maintenance costs. Refer to Table 7 for the analysis of the average annual operating costs of electric vessels in the aforementioned typical cases. The unit price of electricity for vessel usage is calculated at 1 RMB/kWh, based on the comprehensive service fee of the Jiangsu Provincial Electric Power Company's shore-based facilities. The labor and maintenance costs are obtained through research. Electric boats, by using electricity instead of traditional fuel, demonstrate significant operational cost benefits. From the perspective of energy consumption costs, the price difference between electricity and fuel is significant. In terms of labor and maintenance costs, due to the higher level of electrification and intelligence of electric boats, the labor and maintenance costs of electric vessels are generally lower than those of traditional vessels. Considering the overall operating costs (energy consumption + labor and maintenance), electric boats exhibit significantly better economic efficiency compared to traditional vessels.

Table 7. Annual operating cost of the analyzed ships.

Typical Ships	Annual Electricity Consumption (10 K kWh)	Electricity Unit Price (¥/kWh)	Annual Electricity Cost for Electric Ships (¥10 K)	Electric Ship Maintenance and Operation Labor Costs (¥10 K)	Annual Diesel Consumption for Diesel Ships (10 K L)	Fuel Unit Price (¥/L)	Annual Fuel Cost for Diesel Ships (¥10 K)	Diesel Ship Maintenance and Operation Labor costs (10 K L)	Operational Cost Difference (¥10 K)
A	20	1	20	20	9	6.75	60.75	47.25	−68
B	45	1	45	20	20	5.6	112	41.92	−88.92
C	3	1	3	0.06	1.8	6	10.8	0.6	−8.34
D	60	1	60	160	34.95	6.75	235.9125	223	−239
E	65	1	65	36	35	6.5	227.5	90	−217

3.2.3. Discussion and Analysis

As shown in Figure 8, considering the initial investment and operating costs of five different types of vessels operating in the context of short-to-medium-distance river and lake scenarios, electric vessels exhibit higher initial investment costs compared to diesel vessels due to the expensive battery and recharging infrastructure costs. However, due to higher fuel prices and maintenance expenses for diesel vessels, electric boats demonstrate advantages in terms of energy consumption and maintenance costs, resulting in lower overall operating costs compared to diesel vessels. In terms of the full 20-year lifecycle cost of vessels, for ship types A and B, it takes approximately 7 to 8 years to break even with diesel vessels. Ship type C reaches parity with diesel vessels around 14 years, while ship type D takes nearly 10 years to break even. Ship type E is expected to break even with equivalent diesel vessels in 5 years. On the whole, all five types of short-to-medium-distance electric vessels are expected to break even within the 20-year lifespan of the vessel. Vessel types reaching the breakeven point earlier will save costs, and the speed of reaching breakeven is related to initial investment costs and annual electricity consumption. In simple terms, short-to-medium-distance electric vessels currently demonstrate economic cost advantages.

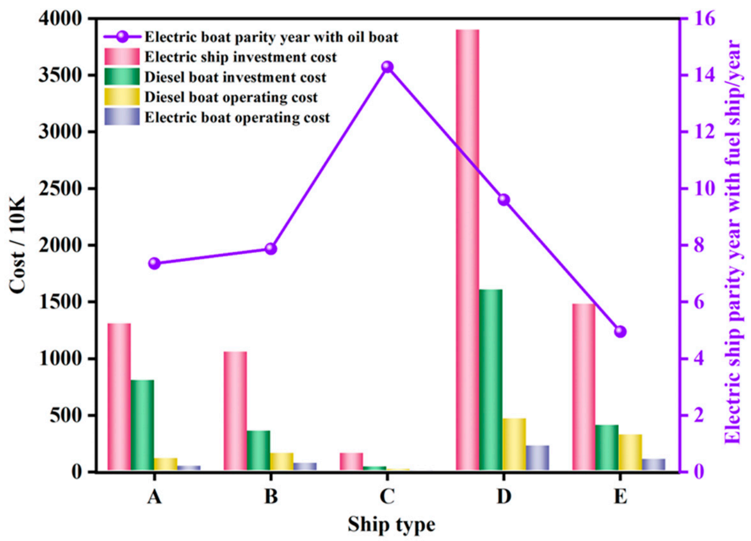

Figure 8. Economic results analysis of electric ships.

This conclusion aligns with the findings of many existing studies on the economic viability of electric vessels. For example, Jessica Kersey et al. [82], calculated and compared the fuel, operational, and maintenance costs of electric container ships and low-speed two-stroke fuel oil (LSFO) ICE ships, as well as the environmental costs of NO_x, SO_2, and CO_2 emissions from direct combustion or grid electricity generation. They found that under the current battery technology scenario, battery-powered electric ships have lower costs than existing ICE ships, applicable to vessel sizes larger than 8000 TEU and voyages shorter than 1000 km [9,90–94]. However, when considering the environmental costs of

NO_x, SO_2, and CO_2, and taking into account the high emission rates of heavy fuel oil compared to the emissions intensity of the U.S. grid, the cost-effectiveness range extends to voyages of 5000 km for all size categories. Without a significant increase in heavy fuel oil prices, the range is expected to increase to 2000 km in the near future. This indicates that electrification is currently the preferred option for short-to-medium-distance vessels [82]. Maja Perčić et al. analyzed the economic viability of electric ferries in coastal shipping in Croatia. They considered three Croatian ferries operating on relatively short, medium, and relatively long routes, comparing the lifecycle costs of electric ships using traditional diesel engines and three different types of batteries (lead–acid, nickel–hydrogen, and lithium-ion). The analysis indicates that electrification using lithium-ion batteries is the optimal solution for decarbonizing the coastal shipping sector in Croatia. Electrification with lithium-ion batteries is more cost-effective, especially for small vessels operating on shorter routes, primarily due to the investment costs associated with the required battery capacity and average vessel power [89].

4. Greenhouse Gas Emissions from Ships

The greenhouse gas emissions from traditional diesel vessels mainly stem from the combustion of ship fuel, such as the burning of fossil fuels (such as heavy oil, diesel, etc.) to generate power in ship engines. Electric vessels do not directly emit greenhouse gases during operation because they typically use electricity as their power source instead of burning fossil fuels. Therefore, the greenhouse gas emissions of electric vessels primarily depend on the source of electricity. If the electricity comes from renewable sources such as wind, solar, or hydroelectric power, then the operation of electric vessels will generate minimal greenhouse gas emissions. Conversely, if the electricity comes from fossil fuel power plants such as coal, natural gas, or oil, then carbon dioxide (CO_2) and other greenhouse gases will be produced during the electricity generation process. The carbon emission factor of the grid represents the total carbon emissions produced by the power grid over its lifecycle, considering all forms of electricity generation including renewable and conventional sources. This article selects typical locations in Jiangsu Province for analysis of the emission-reduction potential of electric ships, using Jiangsu Province's grid carbon emission factor for calculations. Although China's renewable energy generation is growing rapidly, its share in the energy consumption increment remains relatively low, with coal still being the primary source of power generation. The European Union leads globally in the development of clean energy, with renewable energy accounting for 39% of electricity generation in the EU in 2022, providing favorable conditions for the development of clean synthetic fuels, as shown in Figure 9.

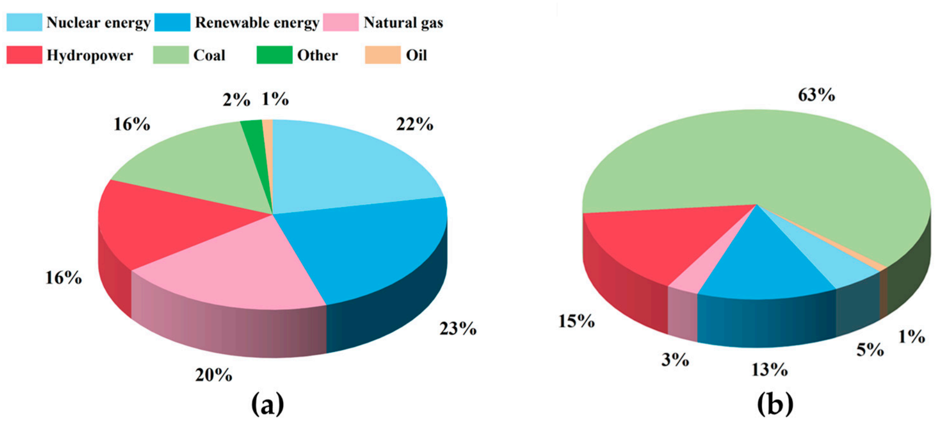

Figure 9. Electricity structure map between China and Europe in 2022. (**a**) The 2022 European electricity structure chart; (**b**) the 2022 Chinese electricity structure chart [87].

4.1. The Process of Greenhouse Gas Emissions from Ships

The emission process of diesel-powered vessels involves the recovery of crude oil, transportation of petroleum to refineries, production processes, transportation of diesel to fuel stations, and ultimately, the combustion of diesel in ship engines. Reference [89] analyzed the entire process of sourcing fuel for diesel-powered vessels in Croatia. It assumed that crude oil is imported only from the Middle East, with the transportation process starting from the extraction site to the port (approximately 500 km). From there, crude oil is transported via oil tankers (4000 km) to Croatian ports and then further transported via pipelines to local refineries (7 km). At the refinery, diesel is produced and transported to fuel stations via tanker trucks. The emission process of electric vessels primarily involves the mining of battery raw materials, the manufacturing of batteries, the generation of electricity for charging battery-powered vessels, and the operation of vessels resulting in zero exhaust emissions, as shown in Figure 10.

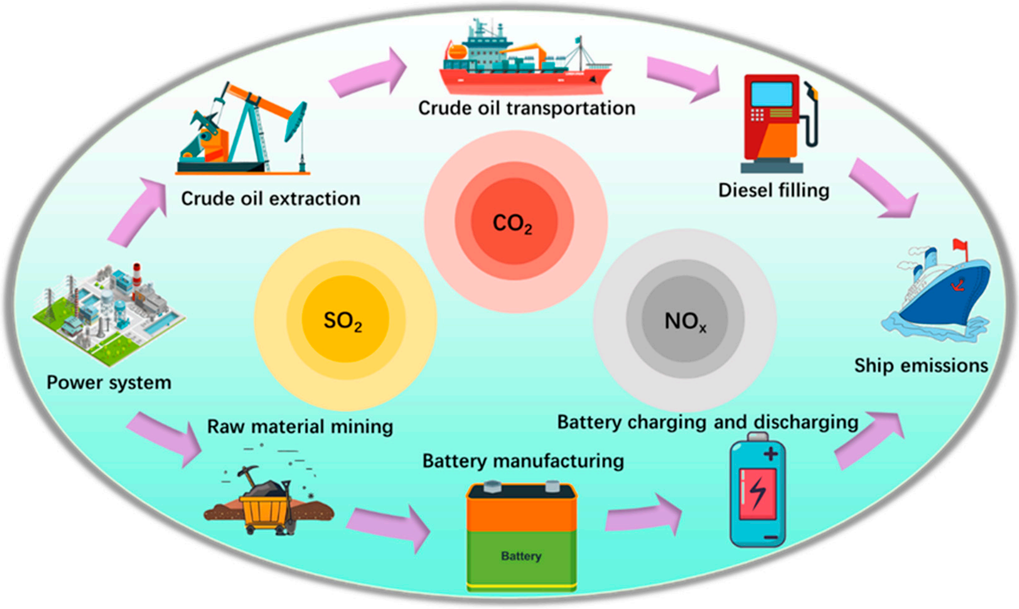

Figure 10. Schematic diagram of the life cycle greenhouse gas emissions process for diesel and electric ships.

4.2. The Emission-Reduction Capability of Electric Ships

For the analysis of emission-reduction capabilities of the five selected electric vessels in Section 3 of this paper, comparisons are made with equivalent diesel vessel types. Only fuel emissions are considered, such as the carbon emissions from diesel fuel for diesel vessels and the grid carbon emissions for charging electric vessels, as shown in Figure 11. The coal equivalent coefficient for diesel is 1.457 kg ce/kg, and for electricity is 0.1229 kg ce/kWh [95]. The conversion efficiency of diesel generators is approximately 31%, meaning that 10,000 kWh of electricity consumption is equivalent to the consumption of 2.724 tons of diesel. According to the International Maritime Organization (IMO) Voluntary Energy Efficiency Operational Indicator (EEOI) Guidelines, every ton of diesel emits 3.206 tons of CO_2. The typical marine batteries selected for this study are all LFP (lithium iron phosphate). Without considering future advancements in battery manufacturing and recycling technologies, the carbon footprint for producing LFP in China is 56 kg CO_2/kWh [96]. Battery recycling technologies generally fall into two main categories: physical methods and chemical methods. Physical methods include cascading utilization, while chemical methods encompass three specific techniques: wet metallurgical recycling, pyrometallurgical recycling, and pyro-hydrometallurgical combined recycling. Cascading utilization refers to batteries that are not damaged but have degraded (capacity below 80%), making them unsuitable for continued use in electric ships but viable for applications like energy storage systems and backup power for communication base stations at similar or lower levels. This approach extends battery life and maximizes its residual value, making it the most suitable method for battery recycling in maritime applications [97]. The carbon footprint for cascading utilization recycling of lithium iron phosphate batteries is 0.624 kg (CO_2)/kg, which is calculated based on dividing battery capacity by the energy density of lithium iron phosphate batteries as shown in Table 2 [98]. According to the latest data from the Ministry of Ecology and Environment's notice on key tasks related to the management of corporate greenhouse gas emissions reporting in 2022, the carbon emission factor for grid electricity is 0.5810 tons of CO_2 per MWh, equivalent to 5.81 tons of CO_2 emissions for every 10,000 kWh of electricity consumed. Building upon the established targets in Jiangsu Province's power development plan and carbon peak strategies, and incorporating assessments of future renewable energy technology development potential by the Environmental Planning Institute of the Ministry of Ecology and Environment, the overall trend of Jiangsu Province's grid emission factors shows a decline from 2022 to 2035. Specifically, the emission factors for Jiangsu Province are projected to be 0.512 t CO_2/MWh in 2030 and 0.411 t CO_2/MWh in 2035 [99]. This study uses the power emission factors for Jiangsu Province in 2022, 2030, and 2035 to calculate the carbon emissions during the charging process of typical electric ships.

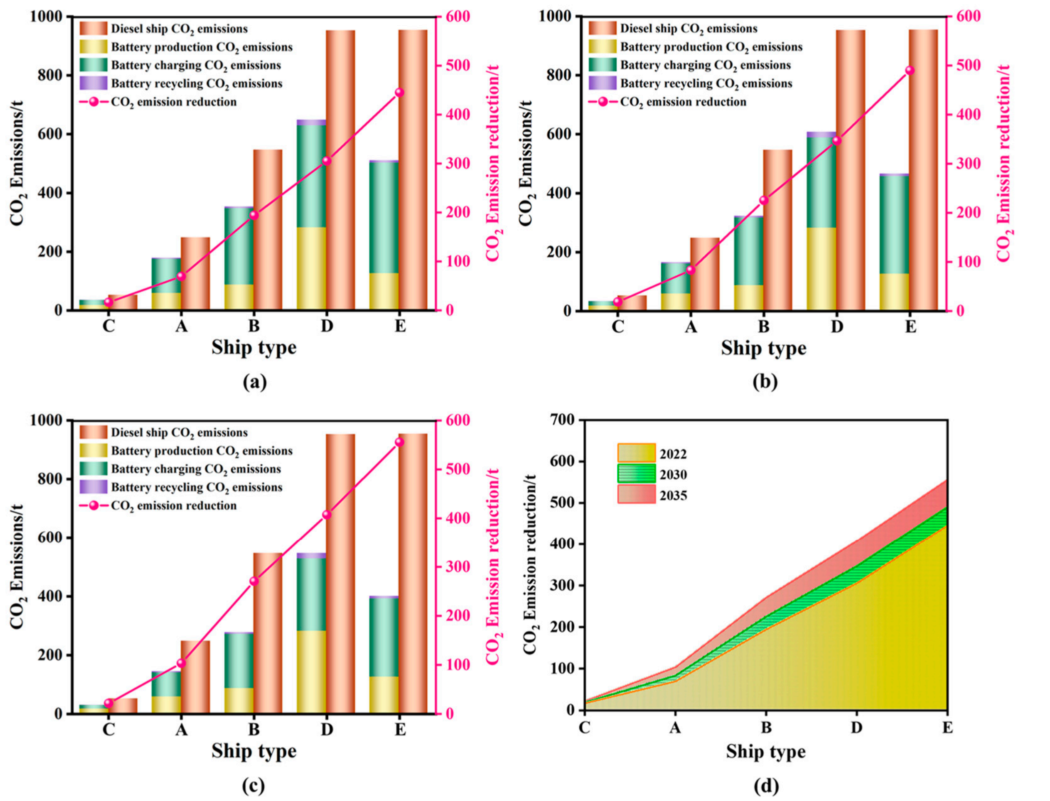

Figure 11. Analysis of emission-reduction capabilities of electric ships across different years. (**a**) In 2022. (**b**) In 2030. (**c**) In 2035. (**d**) CO_2 emission reduction from electric ships.

Reference [89] conducted a life cycle assessment to study the environmental impacts of electric vessels in Croatia and compared them with the environmental impacts of diesel vessels. The study considered three battery systems: lithium-ion batteries, nickel–hydrogen batteries, and lead–acid batteries. The results indicate that the greenhouse gas emissions from electric vessels mainly stem from the electricity production process, with lower emissions associated with higher proportions of renewable energy generation in the grid structure. Among the battery types, electrification using lithium-ion batteries is the most environmentally friendly option for replacing diesel-powered vessels, resulting in a reduction of approximately 46% in carbon dioxide emissions and approximately 98% in nitrogen oxide emissions. Reference [82] compared the CO_2, NO_x, and SO_2 emission intensities of battery-powered and traditional diesel engine small-scale New Panamax container ships. The results show that in the United States, electrification using batteries reduces sulfur dioxide emissions per kilometer by 86% compared to low sulfur fuel oil, but only by 4% in China [100]. For vessels charged at ports in the United States and China, nitrogen oxide emissions are reduced by approximately 83% and 42%, respectively, compared to low sulfur fuel oil. These findings suggest the need to integrate charging infrastructure with renewable energy generation to fully harness the emission-reduction potential of battery charging [101]. Achieving zero emissions in the shipping industry may be more challenging than imagined. This is because shipping is not a singular and isolated operation but rather interconnected with various activities, particularly those in the energy sector.

5. Conclusions

The consumption of fossil fuels and the environmental impact of greenhouse gases are gradually prompting the shipping industry to implement decarbonization measures outlined in greenhouse gas emission-reduction regulations. One feasible measure for reducing fuel consumption and shipping emissions in the future of maritime transportation is to replace traditional mechanical propulsion with electric propulsion. Fully electric vessels powered solely by batteries are receiving significant attention for achieving zero emissions in shipping. This paper summarizes the research progress in the electrification of ship propulsion systems. It discusses marine battery energy storage technologies and concludes that lithium-ion batteries are currently the preferred choice for electric vessel energy storage. The paper provides replenishment recommendations based on the operational characteristics of electric vessels. Furthermore, a further study is conducted on five different types of electric vessels from both economic and environmental perspectives, comparing the economic viability and emission-reduction capabilities of electric vessels with diesel vessels. The evaluation results can be summarized as follows:

- Among different battery technologies (lithium-ion, nickel–hydrogen, lead–acid), lithium-ion batteries are considered the most prominent technology for ship electrification, based on the energy density, lifespan, and safety requirements of ships for batteries. To meet the high demands of ships for batteries, extensive research efforts are focused on utilizing advanced technologies and processes of emerging energy technologies to enhance existing battery systems.
- Through a lifecycle cost analysis of ships, it is concluded that electrification of short-to-medium-distance cruise ships, transport ships, work boats, tugboats, and dry bulk cargo ships in inland, lake, and near-shore scenarios has demonstrated economic advantages. The economic benefits are associated with initial investment costs and annual electricity consumption. Although electric vessels incur higher initial investment costs, their lower operational costs in the long run result in overall economic viability. As the cost of power batteries gradually decreases, the economic advantages of electric vessels will become increasingly apparent.
- Through comparing the carbon emission intensity of selected electric vessel models with traditional diesel vessels and reviewing previous studies on the emission reduction of electric vessels, electrification emerges as a crucial means to achieve emissions reduction in shipping, demonstrating commendable performance in greenhouse gas emission reduction. The carbon emissions of electric vessels are closely linked to the cleanliness of the grid, with lower emissions associated with higher proportions of renewable energy in the power mix. It is imperative to integrate charging infrastructure with renewable energy generation to fully leverage the emission-reduction potential of battery electrification.

Utilizing existing battery technology to achieve full electrification is feasible for vessels operating in short-distance scenarios, as demonstrated by the case studies presented. Additionally, further advancements in energy storage technology will pave the way for comprehensive electrification of vessels operating on longer routes. However, the shipping industry faces complex factors hindering the development of vessel electrification. Efforts are ongoing to address these issues even for cost-effective measures, thus enhancing the feasibility of practical applications. This review lays the groundwork for further research into the electrification of ship propulsion systems. Given that energy consumption contributes significantly to global environmental issues, the sustainable concept of fully electric propulsion will help substantially reduce emissions and serve as part of the transition towards extremely low-carbon or zero-emission shipping.

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