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Energy Storage Systems - Possible Impacts on Maritime Sector

S. Thangalakshmi[1]*, V. Ganeshram[2]

Faculty, Electrical, School of Marine Engineering and Technology, Indian Maritime University, Chennai Campus[1]*

Lecturer, Chemistry, School of Marine Engineering and Technology, Indian Maritime University, Chennai Campus[2]

Abstract: Typical marine vehicles either use diesel or diesel-electric power, which produces toxic pollutants that impact the health of those who live near the harbour. The use of the Battery-operated Electric Propulsion (pure-electric) technology would decrease hazardous pollutants emitted by sea vehicles to zero. Concerns over critical environmental degradation and fossil fuel usage have captivated the automotive market, particularly in maritime vessels, in recent times. The oscillations generated by strong dynamic loads serve as an additional difficulty in ships. To improve stability in shipboard power systems, many generators are now maintained online at far lower than their efficient point. So, to increase the fuel mileage of shipboard power systems, a simple option, a compromise between fuel savings and durability, might be presumed: minimal generator operation with ensured safety. In contrast to previous systems in which propulsion and service loads are powered by distinct generators, propulsion and service loads are linked into a shared network in pure-electric ships to achieve reduced fuel economy with lower emissions. Integration of an energy storage system (ESS) is said to be a useful strategy for increasing the reliability of the shipboard power system. Batteries, ultra-capacitors, flywheels, and fuel cells are examples of energy storage technologies that are now employed in a variety of applications. Marine batteries are particularly developed for sea transport, having larger plates and more resilient structure to handle the stress and hammering that might arise on any powerboat. These batteries have been designed specifically to suit the prospective and future demands of marine transportation applications. This study examines many types of maritime energy storage devices that have been widely employed to enhance the overall efficiency of sea transport.

Keywords: energy storage system, carbon neutral, decarbonisation, marine batteries, fuel cell

I. INTRODUCTION

With the world's energy and environmental challenges becoming more serious, governments have passed a slew of restrictions to curb ship emissions. As a result of the advantages of zero emissions and zero pollution, pure electric ships are viewed as a significant future direction for ship development [1]. Over the last several decades, pure-electric ships with all on-board systems powered by electricity have grown increasingly widespread. Although direct driven propulsion systems remain the preferable choice for certain types of ships, the enhanced design flexibility and prospects for fuel savings afforded by all electric ship designs have limited the number of ships built using direct driven propulsion systems [2]. AC-based power systems have dominated, but DC-based power systems are becoming increasingly common due to the advancement of improved power electronic converters and power electronic-based protective relays capable of breaking large potential DC currents [3]. It is typical for DC-based systems to use the option to enable diesel engines to change engine rpm to current loading in order to save fuel usage. This adaptability is not available in traditional AC-based systems. On-board energy storage is an emerging option for reducing fuel usage, particularly in AC-based systems. On-board electrical energy storage has become widespread practise in vehicles such as automobiles, taxis, and tankers to reduce fuel use. The similar tendency, as outlined in, is now occurring in the marine industry. Battery energy storage systems are currently being installed as a complement to diesel engine generating sets in new constructions and retrofits. There are other examples of plug-in vessels that charge in port, comparable to Plugin Hybrids on land. Moreover, a growing number of vessels, particularly short-distance ferries, are sailing with batteries as their only on-board source of electricity [4]. The use of renewable energy, as well as the growing number of electric vehicles and electronic devices, is boosting demand, which contributes to the cheap cost of electrochemical storage. At the moment, lithium and lead-acid batteries play an important part in daily life for sustainable development. Because of their high current capacity and small weight, lithium ion batteries are becoming increasingly popular. Lithium batteries are used in a range of merchandise. This includes the ability to power transportation, vape systems, laptops, and smart phones. The advantages comprise lightweight materials and the capacity to charge and recharge to high densities at a faster pace than other battery systems. Simply said, one can accomplish more with less when it comes to weight and dimensions. It is normal for any ship designer or operator to pursue technologies to minimise weight and expenses as vessels are developed and economies are sought [5].

The single line diagram of a shipboard microgrid explains the utilisation of an Energy Storage System. Shipboard microgrids have evolved dramatically during the last few decades as a result of their complicated power topology, power electronics interface-based high power sources, and loads. As a result, current shipboard microgrids are strikingly analogous to terrain islanded microgrids, however the existence of large dynamic loads, complicated controls, and power administration significantly challenge shipboard microgrids when matched to land microgrids. Conventional power systems employ a radial configuration with separate generators for utility and propulsion loads. Conversely, as power electronics-based modern devices have advanced, the utilisation of common power systems for both propulsion and service loads has increased significantly in recent years. The progress of shipboard power systems is depicted in Figure 1 as a one-line diagram.

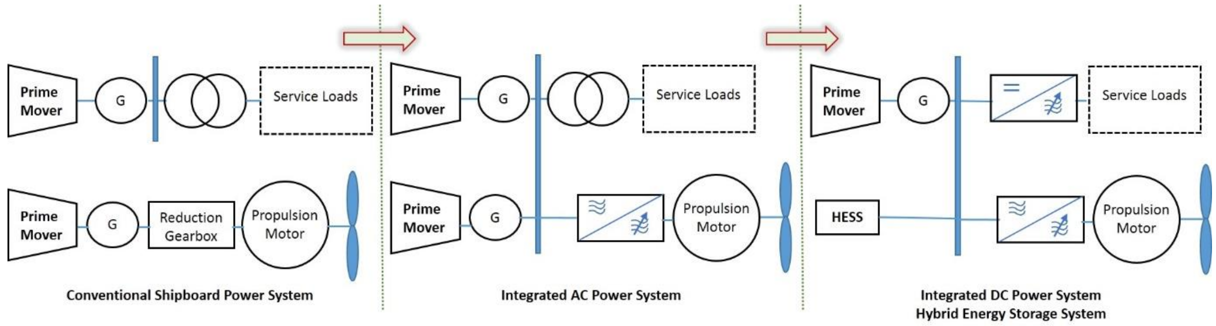

Figure 1. Shipboard Power System Evolution [3]

II. BATTERIES – IN A NUTSHELL

Every battery is a device that generates electrical power from a chemical energy source. Two reactive materials competent of impulsive oxidation–reduction reactions must be present in the energy source. If the reactants are made to conduct the chemical reaction in an electrochemical cell, the 'free energy' of the process is turned into electrical energy, and the electron transfer occurs through an external circuit [6].

A battery is an electrochemical cell or set of cells that generates an electric current. In theory, every galvanic cell might be utilised as a battery [7]. A perfect battery would never run out of power, generate constant voltage, and be resistant to external fluctuations such as heat and humidity. Real batteries find a mix between ideal qualities and practical constraints. An automobile battery, for instance, weighs roughly 18 kg, or about 1% of the mass of a typical car or light-duty truck. This sort of battery would provide practically endless energy if placed in a smartphone, however it would be rejected for this use due to its size. As a result, really no battery is "best," and batteries are chosen for a specific application while considering factors such as battery mass, affordability, reliability, and current capacity. Batteries are classified into two types: primary and secondary [8-11].

A primary cell is a battery that is intended to be utilised once and then discarded, as opposed to being recharged and reused like a secondary cell. In general, the electrochemical process that occurs in the cell is irreversible, leaving the cell non-rechargeable. Primary cells possess high density and discharge gradually. Because there is no fluid within these cells, they are often referred to as dry cells. The chemical reaction is irrevocable, and the internal resistance is substantial. Its upfront costs are minimal, and primary cells are simple to employ [12]. Secondary cells are composed of molten salts and damp cells and exhibit a low energy density. Internal resistance is minimal, and the chemical process can be reverted. When comparing to the primary cell, it has a high capital cost and is more difficult to utilise [13].

Energy storage is an unavoidable component of electric mobility, and batteries remain the most popular kind of energy storage. Batteries are essentially a storage media comprised of two electrodes immersed in an electrolyte. An electric-vehicle battery, also known as a traction battery, is a type of battery that is used to power the propulsion of electric vehicles. Deep-cycle secondary batteries are utilised in electric vehicle batteries because they are built to provide power over extended periods of time. They should always be built with a large ampere-hour rating. Electric - vehicle batteries are distinguished by their reasonably high power-to-weight ratio, specific energy, and energy density. In addition, compact, thinner batteries lower vehicle weight and increase efficiency. Several contemporary storage designs have substantially lower specific energy when comparing to liquid fuels, which frequently affects the maximum all-electric range of the Electric Vehicle [14-15].

III. SHIP POWER BATTERIES

Ship batteries can be used for energy storage in hybrid marine power (HMP) and electrical propulsion systems, as standby power in a crisis, or as a component of a renewable energy scheme. In specific circumstances, they can potentially be used to propel life-boats, rescue- boats, and reserve generators. Batteries are indeed an integral part of an all-electric propulsion system. Furthermore, today's batteries are mostly used as backup power, supplying the energy required for shorter voyages or ships cruising close to inhabited regions. Batteries, which are generally used on ferries, tugs, and other small or specialised vessels, are not currently capable of delivering the necessary power for lengthy cruises [16].

Battery power is becoming a more popular pick for the automotive industry, with electric automobiles currently on the road. Taking to the high seas, the maritime sector has attempted to include batteries onto ships in an effort to reduce greenhouse gas (GHG) emissions and expedite the decarbonisation. Previously, the expense of energy and environmental issues were not given much emphasis in naval power systems. The European Commission proposed a unique climate pact (the Paris Protocol) with the long-term objective of reducing worldwide emissions by at least to 60% by 2050 in comparison to 2010 levels [17]. Various strategies have now been offered to conserve fuel and reduce pollution. The most often used techniques to meeting the IMO's environmental criteria include the use of alternative fuels, flue gases after purification, and blended propulsion [18-19]. This type of initiative has increased the prominence of battery utilisation. Nearly 150 ships currently have batteries on board, and yet another 100 are under development.

IV. BATTERY OPTIONS FOR ELECTRIFIED VEHICLES

Lead – Acid Batteries

For more than a decade, the lead-acid battery was a successful and profitable product, and it is still extensively implemented as electrical energy storage in the automobile industry and other uses. Its benefits include inexpensive cost, proven technology, and relatively high power capabilities. These benefits make it appealing for use in HMP where high power is the key focus. When compared to their more modern equivalents, the materials used (lead, lead oxide, and sulphuric acid) are quite inexpensive.

These batteries have a number of drawbacks. They have a low energy density, owing to the large molecular weight of lead. Temperature properties are subpar. Its specific power and energy are sizably reduced below 10°C. This feature severely limits its utility, particularly in cooler environments. The presence of extremely caustic sulphuric acid might endanger vehicle passengers. Another possible threat is hydrogen, which is very explosive even in trace amounts and is emitted by self-discharge processes. Additional concern with hermetically sealed batteries is hydrogen leakage. Indeed, in order to offer adequate safeguards against acid leaks, the battery must be sealed, confining parasitic gases in the case. So, pressure in the batteries may accumulate, inflicting enlargement and mechanical limitations on the casing and sealing. For its toxic effects, lead in electrodes is an issue for the ecosystem. Lead emissions from lead-acid batteries can emerge during the manufacturing process, in the event of a vehicle wreck (pour of electrolyte via fractures), or during disposing at the expiration of battery life [20].

Batteries with a Nickel Base

Nickel is a thinner metal than lead and has excellent electrochemical characteristics that make it suitable for energy storage [21].

Nickel/Iron:

The nickel/iron arrangement became commercially viable in the early twentieth century. Pallet jack trucks, mine locomotives, shuttling vehicles, railcars, and powered hand trucks were among the deployments. A nickel hydroxy-oxide positive electrode and a metallic iron negative electrode are used in the system. The electrolyte is a concentrated solution of potassium hydroxide (usually 240 g/l) with 50 g/l lithium hydroxide. It has a nominal open-circuit voltage of 1.37 volts. Nickel/iron batteries have issues with gassing, oxidation, and self-discharge. The necessity to preserve the level of water and safely dispose of the hydrogen and oxygen liberated during the discharge process makes these batteries problematic. Nickel–iron batteries, like lead-acid batteries, suffer from low temperatures. Lastly, nickel is substantially more expensive than lead. Their key benefits are greater power density in comparison to lead-acid batteries and the capacity to resist 2000 severe discharges [24].

Nickel/Cadmium:

The nickel/cadmium system employs the very same positive electrodes and electrolyte as the nickel/iron system, as well as metallic cadmium negative electrodes. It has a nominal open-circuit voltage of 1.3 volts. These batteries have vast improved features such as high specific power (more than 220 W/kg), long lifecycle (up to 2000 cycles), better resistance of electric and mechanical abuse, a minimum voltage drops for a broad range of discharge currents, fast charge potential (about 40 to 80 percent in 18 minutes), expansive span of operating temperature (40 to 85°C), low self-discharge rate (0.5 percent per day), and outstanding long-term storage due to insignificant corrosion.

Nevertheless, the nickel/cadmium battery has significant drawbacks, along with a high upfront cost, a reduced cell voltage, and cadmium's carcinogenicity and atmospheric threat. The nickel/cadmium battery is broadly classified into two types: vented and sealed. There are several options for vented types. A more contemporary invention, vented sintered-plate, offers a high specific energy but is costlier. It has a flatter discharge voltage profile, as well as exceptional high current rate and low-temperature characteristics. A sealed nickel/cadmium battery has a unique cell design characteristic that prevents pressure accumulation in the cell produced by gassing upon overcharge. As a result, the battery demands no maintenance [22].

Nickel–Metal Hydride (Ni–MH)

Since 1992, nickel-metal hydride batteries have been on the market. Its properties are comparable to those of a nickel/cadmium battery. The primary distinction between them is that hydrogen, absorbed in a metal hydride, is used for the active negative electrode material instead of cadmium. The Ni–MH battery is replacing the Ni–Cd battery due to its better specific energy and lack of toxicity or carcinogenic effects. Ni–MH battery design has a nominal voltage of 1.2 V and a specific power and energy of 200 W/kg and 65 Wh/kg, respectively [23].

Batteries with a Lithium Base

Lithium is the lighter of all metals used in battery technology and has particularly unique electrochemical properties. It does, in fact, permit a very high thermodynamic voltage, resulting in quite a high specific energy and power. Lithium-based batteries are classified into two types: lithium–polymer and lithium–ion.

Lithium–Polymer (Li–P):

For the negative and positive electrodes of lithium–polymer batteries, respectively, lithium metal and a transition metal intercalation oxide are used. It features a layered architecture into which lithium ions may be injected or ejected during discharge and charge, correspondingly. A thinner solid polymer electrolyte (SPE) is utilised, which has the advantages of increased security and design adaptability. Lithium ions produced at the negative electrode move across the SPE and are implanted into the crystal structure at the positive electrode during discharge [25]. The procedure is reversed when charged. The Li/SPE/V6O13 cell is the most appealing among the Li– polymer cells because it uses a lithium foil negative electrode and a vanadium oxide positive electrode. It has a specific energy of 155 Wh/kg and a specific power of 315 W/kg, and it works at a nominal voltage of 3 Volts. The benefits are a very low self-discharge rate (about 0.5 percent per month), the possibility to fabricate in a range of shapes and sizes, and a completely safe structure (reduced activity of lithium with solid electrolyte). Still, because of the temperature dependence of ionic conductivity, it has a relatively poor performance at low temperatures.

Lithium-Ion (Li-Ion):

Since the first presentation of the Li-ion battery in 1991, Li-ion battery development has skyrocketed to become the most intriguing rechargeable battery of the century. Despite being in the early stages of research, the Li-ion battery has already received acceptability for EV and HEV applications. Instead of metallic lithium, the Li-ion battery employs a lithiated carbon intercalation material for the negative electrode, a lithiated transition metal intercalation oxide for the positive electrode, and a liquid organic solution or a solid polymer as the electrolyte. During discharge and charge, lithium ions glide across the electrolyte between the positive and negative electrodes. Lithium ions are emitted from the negative electrode during discharge, move through the electrolyte, and are picked up by the positive electrode. The procedure is inverted when charged. The nominal voltage of a nickel-based Li-ion battery is 4 Volts, the specific energy is 120 Wh/kg, the energy density is 200 Wh/l, and the specific power is 260 W/kg. The cobalt-based kind offers better specific energy and energy density, but at a higher cost and with a large increase in self-discharge rate. The manganese-based kind is the least expensive, and its specific energy and energy density are comparable to those of the cobalt- and nickel-based varieties [26-27].

Table 1. A Reasonable Comparison of Various Lithium Batteries with Nickel Based Battery [29]

Battery Type	Power Density	Energy Density	Life Cycle	Cost	Safety
Nickel manganese cobalt	High	High	Medium	Medium	Medium
Lithium cobalt oxide	Medium	High	Medium	Medium	Low
Lithium titanium oxide	Medium	Low	Long	High	High
Lithium manganese oxide	Medium	Medium	Short	Low	Medium
Lithium iron phosphate	High	Low	Medium	Medium	High

Because of the low expense, availability, and environmental stewardship of manganese-based materials, it is expected that the evolution of the Li-ion battery would eventually shift to the manganese-based kind.

Lead-acid batteries have generally been employed to supply back - up power to ships, and they are bound to hard criterions for setup and operation. Vented Lead Acid Batteries or Valve Regulated Lead Acid Batteries may be found on-board ships; all these types of batteries are prevalent and involve very cheap CAPEX requirements. LEAD batteries are trustworthy and recyclable, serving as backup power systems on various sorts of vessels.

Lithium-ion batteries are the most recent progression of battery power, with several applications for shipping companies. Lithium-ion batteries can be utilised as backup power to support a ship's operational performance, including the maintenance of Dynamic Positioning (DP) systems. They would allow ships to operate in carbon neutral mode, when batteries serve as the only power source. This reduces GHG emissions, allowing ships to meet stringent port regulations and travel in ecologically protected zones. Furthermore, batteries may be employed for "peak shaving," which is when batteries take over from on-board generator units to supply the peak load of energy. Table 1 compares different lithium batteries with that of nickel-based. This table indicates that the power and energy densities for nickel-based batteries are high, but the safety and life cycles are middling. Although the power density and safety of lithium-iron-phosphate are excellent, the energy density is poor. Furthermore, the ship application imposes significant constraints in addition to the fundamental metrics offered for measuring battery performance. The Table 2 gives the comparison among basic batteries.

Table 2. Comparison Among Basic Batteries [15]

Parameters	Lead-Acid	Nickel-Metal	Lithium-Ion
Simple to use/ Budget Friendly	✔	✗	✔
Energy Efficiency	✔	✔	✔
Temperature Performance	✗	✗	✔
Weight	✔	✔	✔
Life Cycle	✔	✗	✔

Table 2 shows that the Lithium Ion battery is a superior choice for ship batteries.

V. SHIP BATTERIES - SPECIFICATIONS AND NEEDS

The performance of absolute neutrally buoyant battery sections, provided a certain usable volume and a design depth, is typically compared when selecting a power source for a specific maritime application with a definite energy need [28].

There are four types of electrochemical power sources for maritime vehicle applications:

a) conventional batteries operating at normal pressure inside a pressure hull;

b) pressure-compensated batteries that operate at atmospheric pressure but are electrically isolated from seawater;

c) batteries made of seawater;

d) fuel cells

Lead/acid batteries operating at normal pressure in conventional submarines, pressure compensated batteries in the deep-sea rescue vehicle (DSRV), and magnesium/silver chloride seawater batteries in torpedoes are classic examples for the first three categories mentioned above. Seawater is utilised as the battery electrolyte in the magnesium/silver chloride battery, and the internal pressure of the battery is equivalent to the exterior (ambient) pressure, which is determined by water depth and density. The DSRV battery is built on silver/zinc cells, with the gaps in the cell filled with oil and the electrolyte pressure kept equal to the external pressure by a flexible member between the oil and the seawater [4].
When comparing battery systems, various elements should be examined in addition to the exact energy content and power capabilities, with common criteria being affordability, battery life, service needs, and safety. This also applies to marine batteries. Furthermore, the flotation of pressure-compensated batteries may vary with depths or extent of discharge. For seawater batteries, buoyancy invariably fluctuates with depth of discharge. For shallow dive underwater vehicles (UWV), the overall mean density of the pressure vessel is small, hence the simplest and most economical battery option is to employ a high energy density battery arrangement and combine the battery and electrical systems within the pressure vessel [28].

VI. KEY ISSUE: THE THERMAL RUNAWAY

The safety concern termed as "thermal runaway" is the fundamental hurdle for battery-powered ships. In case a battery is exposed to high temperatures, such as those caused by a high current discharge rate or closeness to external heat sources, then heat, flames, and gas can be released. This might set off a chain reaction, resulting in a large-scale fire that could destroy ships and endanger crew members. Other issues like an overcharged battery, too-high discharge rates, or a short circuit can all lead to thermal runaway. Thermal runaway-prone chemistries like NCA, NMC, and LMO must be utilised in combination with system-level safety mechanisms that either confine or monitor the cells' behaviour. A durable battery box, an efficient cooling system (to minimise thermal runaway in the early phases), and accurate state-of-charge monitoring and cell discharge balance are examples of such approaches. While battery safety is undeniably a serious worry, it's helpful to remember the substantial safety difficulties that the internal combustion engine (ICE) and gasoline storage faced in the past, which were mostly addressed via advancements in design and engineering.

As a result, batteries are tested according to precise norms and standards, and extra safety measures, such as Battery Management Systems (BMS), can be included. A BMS supervises the appropriate connection and disconnection of battery packs and sub-packs by monitoring the electrical and thermal parameters such as, voltage, current, and temperature of battery modules, packs, and sub-packs. BMS helps ship managers to optimise energy consumption and availability, as well as extend battery life, in addition to giving crucial safety information.

VII. OTHER CHALLENGES

Life Cycle:

Battery life duration may be measured in two ways: cycle stability and overall age. The number of times a battery may be fully charged and drained before degrading to 80% of its original capacity at full charge is known as cycle stability. The overall age of a battery is the number of years it may be anticipated to last. Under test conditions, today's batteries fulfil the cycle stability criteria of electric automobiles. Overall age, on the other hand, remains a challenge, owing to the fact that ageing increases at higher ambient temperatures. One option may be to evaluate batteries according to their suitability for specific climes. Batteries intended for cold areas, for instance, would rely on heating and insulation, whilst those made for hot climates would employ electrolytes and materials that can withstand high temperatures.

Specific Energy and Specific Power:

Batteries' specific energy, or ability for storing energy per kilogramme of weight, is still just 1% that of gasoline. Batteries will likely to restrict the cruising range of electric vehicles to short distances between charges until there is a substantial advancement.

Current battery technologies do a good job of addressing specific power, or the proportion of power that batteries can produce per kilogramme of mass. In hybrid vehicles, which release a little quantity of energy fast, specific power is very significant. Specific power is less significant in electric vehicles than specific energy. Currently, the performance of batteries in terms of specific power is on par with or better than that of Internal Combustion Engines.

Charging Time:

Long charging times are both a technical and a business hurdle that really should be overcome. Plugging a 15-kWh battery onto a typical 120-volt socket takes approximately 10 hours to charge. Fast charging solutions that use more advanced charging connections can drastically minimise this time.

While using existing generating units to charge a ship battery is a valid option, it must be done with proper charging controls and without impeding the generators' allowable load.

Cost:

Although if battery manufacturers overcome the technological problems listed above, the cost of batteries may remain higher than the targets. The cost of battery electricity per kwh of energy in 2016 was $227 USD. Obviously, the battery costs will have a significant impact on the economic feasibility of electric vehicles. As production numbers grow, battery costs will drop dramatically. Higher degrees of automation will reduce prices even further by improving quality, decreasing scrap, and lowering labour expenses.

Marine Unique Challenges with Battery Operations:

Shipyards are faced with the issues of on-board integration after an owner has decided to add batteries. Yards must do thorough risk assessments, evaluating ventilation technologies, hazardous regions, and energy storage system spaces, all while adhering to installation rules that guarantee ships cruise safely. Ship design engineers must go to great lengths to eliminate danger and demonstrate to flag authorities that battery-powered ships are safe to dock.

During operations, ships must connect to the electrical grid at port to recharge their batteries. Operators of battery-powered ships must verify that the electricity provided from the grid originates from renewable sources in order to reduce emissions. In order to achieve totally greener operations, ship management will need to analyse whole supply chain responsibility. On-board generator sets may also charge batteries, albeit this energy is not sustainable until ships use alternative decarbonized fuels.

Lastly, there are the dual issues of prolonging battery lifecycles and recycling batteries in a sustainable manner. Battery strength degrades with time; hence batteries must be subjected to persistence testing to guarantee that a particular level of capacity is retained. When batteries could no longer be utilised, shippers must work with shipyards to handle recycling, guaranteeing that the hazardous or polluting constituents of batteries are securely treated.

VIII. CONCLUSION

Batteries are one of an increasing number of options for shipment that is carbon-neutral or zero-emissions. This study examines the various combinations of energy storage devices used in the literature for maritime conditions. Because of its increased energy density, extended service life, and low maintenance requirements, the Li-ion battery is currently the most often utilised battery for marine vehicle applications both on and under the water. For maritime applications, solid-state batteries are also being investigated. Fully electric vehicles that are as convenient as ICE-based vehicles are unlikely to be ready for the mainstream market without a big advance in battery technology. This is especially true in the maritime context, where there are additional limiting factors such as cost, space availability, safety, and the dynamic climate for a seagoing vessel. There will be no single technology that will dominate the whole sector. Power density, capacity, cycle lifespan, energy density, and charging time are all important considerations for different types of electric vehicles. Lithium ion battery technology with solid-state electrolyte advancements are likely to have a huge impact on the future of electric vehicles.

Batteries are one of an increasing number of options for shipment that is carbon-neutral or zero-emissions. While huge ships may not ever run on batteries alone, batteries are still a viable option for smaller ships and may be paired with alternative sources effectively. Batteries can also be used in conjunction with emerging fuel cell technologies to achieve substantially higher standards of efficiency while cutting carbon. In this approach, batteries can help to enhance sustainable shipping while also contributing to the development of a GHG-free maritime ecosystem.

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