EMERGING
BATTERY TECHNOLOGIES
IN THE MARITIME INDUSTRY

VOLUME 2

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INTRODUCTION

As the International Maritime Organization regulations continue to evolve, driving the shipping industry toward reduced emissions, industry leaders are increasingly evaluating hybrid and all-electric systems[1] for their potential to help meet compliance targets. Among the myriad technologies shaping the future of marine and offshore operations, battery technology stands out as a potentially transformative solution. Researchers and developers are working on a range of efficient and sustainable battery technologies capable of delivering the required power without compromising the safety of personnel and assets.

Beyond reducing emissions, advanced battery technologies also have the potential to support the adoption of alternative fuels by improving efficiency and reducing fuel costs. For example, peak-shaving in hybrid systems can optimize engine loading and enhance efficiency.

This publication examines the latest advancements in rechargeable battery technology, including lithium-ion (Li-ion) and six next-generation batteries, from different perspectives. It begins by comparing the working mechanisms and technological maturity of different battery types. This study also explores the benefits and challenges of current and emerging energy storage systems for marine and offshore applications.

The initial evaluation indicates that most next-generation batteries require further technological advancements for widespread adoption. In addition to enhancing battery design, the industry needs to develop effective strategies for fire prevention, mitigation and rapid response to support safe operations. This study examines the severity of battery fires from two perspectives: thermal runaway (TR) and gas emissions.

Thermal runaway characteristics depend highly on battery chemistry, state of charge (SoC) and capacity. Consequently, the risks and consequences of battery fires are anticipated to increase significantly with the use of high-energy-density next-generation batteries. During TR, Li-ion batteries emit a mixture of gases, including flammable hydrogen and hydrocarbons, and highly toxic and corrosive gases like hydrogen fluoride (HF) and carbon monoxide (CO). Next-generation batteries pose additional risks, releasing gases such as silicon tetrafluoride (SiF_4) from silicon anode batteries and hydrogen sulfide (H_2S) from lithium-sulfur (Li-S) batteries.

[1] Refer to the definition of hybrid and all-electric vessel in ABS *Requirements for Hybrid and All-Electric Power Systems for Marine and Offshore Applications.*

CURRENT TECHNOLOGIES

A rechargeable (secondary) battery is an electrochemical device consisting of two electrodes that are isolated by a separator and soaked in electrolyte to promote the movement of ions, storing chemical energy and releasing electrical energy [1]. Their ability to be recharged and reused multiple times makes them a sustainable and economical energy solution. Secondary batteries are available in a variety of chemistries, including Li-ion, nickel-cadmium (NiCd), nickel-metal hydride (NiMH) and lead-acid. They are becoming increasingly essential in the marine industry by powering a wide range of systems. Batteries, specifically Li-ion, are widely used in portable electronic devices. They can also serve as the main source of power for all-electric vessels and can be installed in hybrid vessels to support both propulsion and auxiliary systems.

BATTERY APPLICATIONS

Batteries offer tangible benefits in marine operations, supporting advancements in efficiency, regulatory compliance and emission reduction in key areas, including:

- **Zero-emission applications** enable ships to operate with full or partial battery-electric propulsion. This can include cold ironing, which is where ships connect to shore power while docked to eliminate local emissions, contributing to environmental benefits and improved air quality in port areas.
- **Hybrid applications** optimize the use of traditional engines or fuel cells, leading to reduced fuel consumption, emissions and operational costs. Batteries function as a spinning reserve for redundancy safety, facilitate load leveling and enable cyclic operations for greater efficiency.
- **Dynamic applications** utilize batteries for immediate and backup power needs, enhancing safety and enabling dynamic load transitions and peak shaving for optimized efficiency.
- **Energy harvest applications** allow batteries to store energy from onboard or shore-based systems, promoting operational efficiency and sustainability. The harvested energy can be utilized for various purposes, including powering cranes or onboard systems.

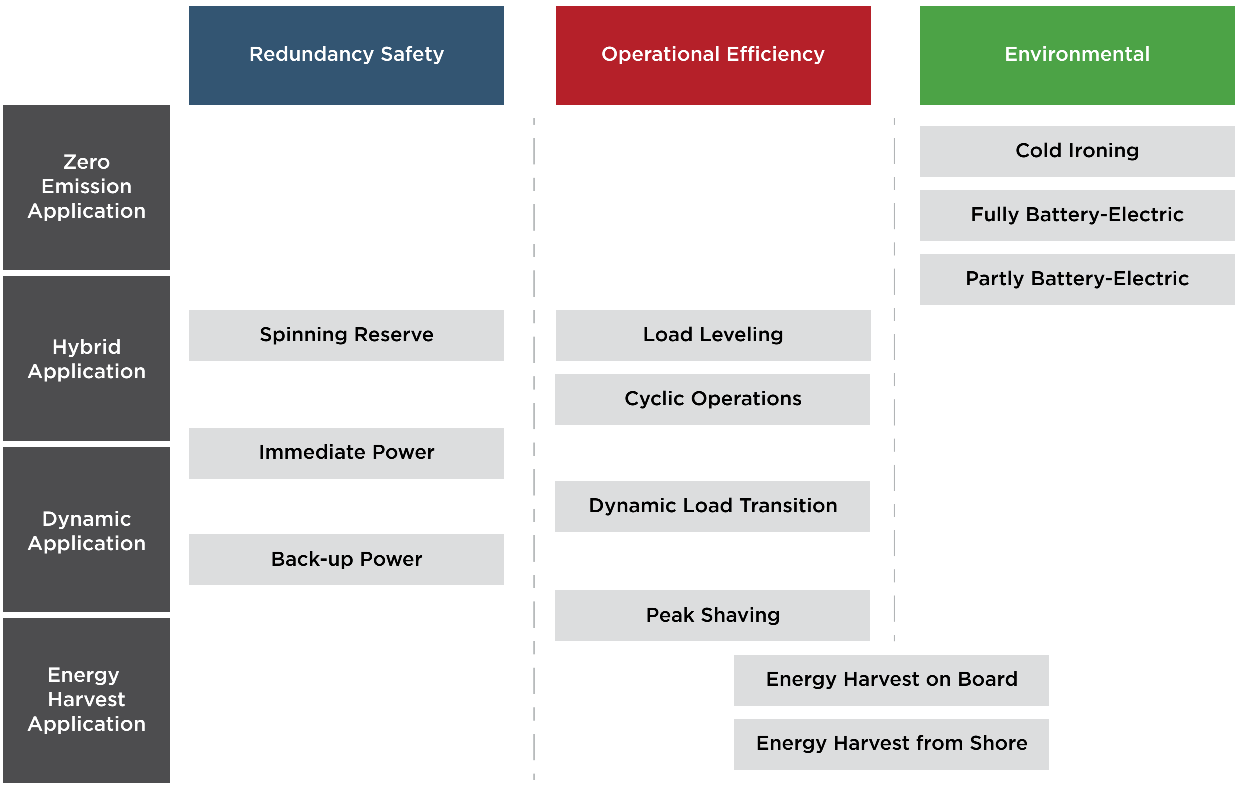


Figure 1: Battery applications [2].

LITHIUM-ION BATTERY

Lithium-ion batteries are gradually replacing lead-acid, NiCd and NiMH batteries as the leading energy storage technology for maritime applications. Lithium-ion batteries feature superior energy density, low self-discharge rate, and cycle life for electrical energy systems and distribution on vessels (see Figure 2 and Table 1).

Despite their advantages, safety risks remain the biggest challenge for Li-ion batteries. To maintain safe operations in marine and offshore environments, complex battery management systems (BMS) are needed to monitor and control their operating ranges for voltage, current, temperature, SoC, state of health and more. Moreover, Li-ion batteries use flammable organic electrolytes, making them prone to fire or explosion during TR.

Thermal runaway is a condition where an internal or external factor triggers a self-sustaining chemical reaction, raising the temperature uncontrollably and potentially leading to battery failure and fires. These factors include thermal abuse (e.g., heating), electrical abuse (e.g., overcharging), and mechanical abuse (e.g., punctures causing internal short circuits). Other factors, such as degradation due to dendrite formation, internal short circuits (due to poor design), toxic and flammable gas generation and the propagation of TR between cells and modules, pose a risk to the safe usage of Li-ion batteries.

Internal protection devices, chemistries less prone to TR, insulation/cooling methods, battery management, control, monitoring and fire protection systems are essential to mitigate risks associated with the use of Li-ion batteries.

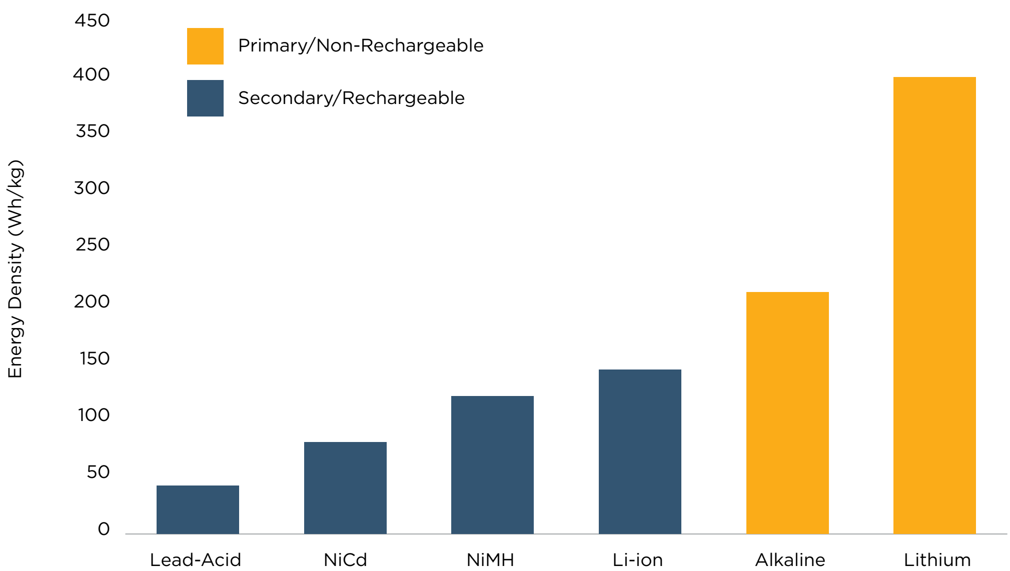


Figure 2: Specific energy comparison of secondary and primary batteries [3].

Specifications	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific Energy in Watt-Hour per Kilogram (Wh/kg)	30-50	45-80	60-120	150-250	100-150	90-120
Internal Resistance	Very Low	Very Low	Low	Moderate	Low	Very Low
Cycle Life	200-300	1,000	300-500	500-1,000	500-1,000	1,000-2,000
Charge Time	8-16h	1-2h	2-4h	2-4h	1-2h	1-2h
Overcharge Tolerance	High	Moderate	Low	Low		
Self-Discharge/Month (Room Temperature)	5%	20%	30%	Less 5%		
Cell Voltage (V) (Nominal)	2 V	1.2 V	1.2 V	3.6 V	3.7 V	3.2-3.3 V
Charge Cutoff Voltage (V/Cell)	2.4 Float 2.25	Full charge Detection by voltage signature		4.2 V		3.6 V
Discharge Cutoff Voltage (V/Cell, 1C)	1.75 V	1 V		2.5-3 V		2.5 V
Peak Load Current Best Result	5C 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge Temperature	-20-50˚ C	0-45˚ C		0-45˚ C		
Discharge Temperature	-20-50˚ C	0-65˚ C		-20-60˚ C		
Maintenance Requirements	3-6 months	Full discharge every 90 days when in full use		Maintenance free		
Safety Requirement	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory		
Used Since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic Efficiency	~ 90%	~ 70% slow charge ~ 90% fast charge		99%		

Table 1: Characteristics of commonly used commercial rechargeable batteries [4].

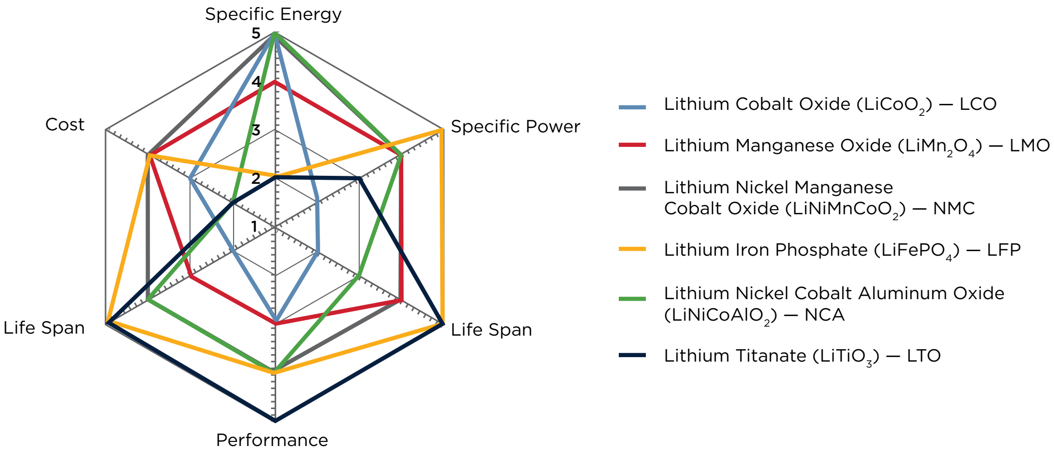


Figure 3: Materials have critical roles in battery performance [5].

Lithium-ion battery technology includes diverse types such as Li-ion cobalt oxide, Li-ion manganese oxide, Li-ion nickel manganese cobalt oxide, Li-ion nickel cobalt aluminum oxide, Li-ion iron phosphate and Li-ion titanate. Figure 3 provides the differences in characteristics between these Li-ion chemistries. The relative merit of various chemistries is provided with a value from one to five, with one representing the lowest level of performance and five representing the highest level of performance for individual characteristics.

Type Composition	Lithium Cobalt Oxide (LCO): $LiCoO_2$ Cathode (~60% Cobalt), Graphite Anode	Lithium Manganese Oxide (LMO): $LiMn_2O_4$ Cathode, Graphite Anode	Lithium Nickel Manganese Cobalt (NMC) Oxide: $LiNiMnCoO_2$, Cathode, Graphite Anode	Lithium Iron Phosphate (LFP): $LiFePO_4$ Cathode, Graphite Anode	Lithium Nickel Cobalt Aluminum (NCA) Oxide: $LiNiCoAlO_2$ Cathode (~9% Cobalt), Graphite Anode	Lithium Titanate (LTO) Oxide: Cathode Lithium Manganese Oxide or NMC; Li_2TiO_3 (Titanate) Anode
Year Invented	1991	1996	2008	1996	1999	2008
Nominal Voltage	3.6 V	3.7 V (3.8 V)	3.6 V, 3.7 V	3.2, 3.3 V	3.6 V	2.4 V
Operating Voltage/Cell	3.0–4.2 V	3.0–4.2 V	3.0–4.2 V, or higher	2.5–3.65 V/cell	3.0–4.2 V/ cell	1.8–2.85 V/cell
Specific Energy (Capacity)	150–240 Wh/kg	100–150 Wh/kg	150–220 Wh/kg	90–120 Wh/kg	200–300 Wh/kg	50–80 Wh/kg
Volumetric Energy Density	500–700 Wh per liter (L)	350 Wh/L	500–700 Wh/L	300–350 Wh/L	700–800 Wh/L	50–177 Wh/L
Charge (C-rate)	• 0.7–1C, charge current above 1C shortens battery life	• 0.7–1C, 3C maximum	• 0.7–1C, charge current above 1C shortens battery life	• 1C typical, 3h charge time typical	• 0.7C, 3h charge typical, fast charge possible with some cells	• 1C typical • 5C maximum

Table 2: Detailed characteristics of current Li-ion battery chemistries [5].
(Continued on next page)

Charging Cutoff Voltage	4.2 V	4.2 V	4.2 V	3.65 V	4.2 V	2.85 V
Discharge (C-rate)	• 1C; 2.50 V cutoff • Discharge current above 1C shortens battery life	• 1C • 10C possible with some cells, 30C pulse (5s)	• 1C • 2C is possible on some cells	• 1C • 25C on some cells • 40A pulse (2s)	• 1C is typical • High discharge rate shortens battery life	• 10C possible • 30C 5s pulse
Discharging Cutoff Voltage	2.5 V	2.5 V	2.5 V	2.5 V (lower than 2 V causes damage)	2.7V–3.0 V	1.8 V
Cycle Life[2]	500–1,000 cycles	300–700 cycles	1000–2,000 cycles	2,000 and higher	500 cycles	Up to 2,000 cycles
Thermal Runaway	• 150° C (302° F) • Full charge promotes thermal runaway	• 250° C (482° F) typical. • High charge promotes thermal runaway	• 210° C (410° F) typical • High charge promotes thermal runaway	• 270° C (518° F) • Lower risk of thermal runaway, even if fully charged	• 150° C (302° F) typical • High charge promotes thermal runaway	• One of the batteries with the lowest risk of thermal runaway
Comments	• Very high specific energy • Limited specific power • Cobalt is expensive • Market share has stabilized	• High power but less capacity • Safer than Li-cobalt • Commonly mixed with NMC to improve performance • Less relevant now; limited growth potential	• Provides high capacity and high power • Serves as a hybrid cell • Market share is increasing • Leading system; dominant cathode chemistry	• Flat voltage discharge curve but low capacity • One of the safest Li-ions • Elevated self-discharge • Used primarily for energy storage • Moderate growth	• Shares similarities with Li-cobalt	• Long life, fast charge • Good temperature tolerance (-30°–60° C), but low specific energy and expensive • Among the safest Li-ion batteries • Ability to ultra-fast charge

Table 2: Detailed characteristics of current Li-ion battery chemistries [5].

LITHIUM-ION BATTERY OUTLOOK FOR MARINE APPLICATION

Lithium-ion batteries have demonstrated their effectiveness and reliability in powering all-electric and hybrid vessels, from small harbor crafts like tugboats to electric ferries. Several companies and organizations have successfully implemented Li-ion battery systems in marine applications. A technology readiness level (TRL)[3] of 8–9 for the Li-ion battery technology for hybrid and all-electric vessels is relatively high, indicating that the technology is sufficiently mature for regular commercial use [6].

The deployment of battery vessels (hybrid and all-electric) is rapidly expanding. ABS classes many hybrid vessels with all-electric modes that can be entirely propelled by battery power and carry the ESS-LiBATTERY notation [1]. However, the onshore charging infrastructure should be carefully planned to meet the operational needs of fully electric vessels. The amount of onboard storage required may be dictated by the availability of the local shore charging infrastructure.

[2] Related to depth of discharge, load and temperature.
[3] TRL: Technology readiness level is a method used to assess the maturity of a particular technology. It provides a consistent point of reference for evaluating how developed a technology is, ranging from basic principles to fully operational systems. TRLs are measured on a scale from 1 to 9, with 1 being the least mature and 9 being the most mature.

Spining Reserve

Backup power to running generators

Benefits include:
- Improved safety
- Reduced fuel consumption and engine maintenance

Peak Savings

Level power seen by engines and offset need to start new engines

Benefits include:
- Reduced fuel consumption and engine maintenance

Enhanced Dynamic Performance

Instant power in support of running engines

Benefits include:
- Reduced fuel consumption
- Enable for "slower" sources like LNG and fuel cells

Enhanced Ride Through

Short time backup power to running generators

Benefits include:
- Improved safety
- Reduced fuel consumption and engine maintenance

Strategic Loading

ESS used to charge or discharge with the aim of optimizing engine operating point

Benefits include:
- Reduced fuel consumption

Zero Emission Operation

Power system is fully powered by ESS

Benefits include:
- Quiet engine room
- Zero emission operation

Figure 4: Benefits of utilizing Li-ion energy storage systems.

In addition to the different applications discussed in Section 2.1, Li-ion batteries offer several additional advantages, including reduced emissions since they do not produce any direct emissions during normal operation. This makes their environmental impact lower than that of conventional power sources like fossil fuels (see Figure 4). However, it is important to consider the full life cycle of these batteries to understand their environmental impact.

Lithium-ion also provides improved performance and lower operating costs, offering a consistent and reliable power source that enhances vessel performance. Although initially more expensive than traditional internal combustion type engines, they have lower operating costs because they do not require expensive fuel, have fewer moving parts and require less maintenance. The costs of Li-ion batteries have been decreasing over the last decade and are expected to continue decreasing as the price of their raw materials becomes less of a barrier. However, shoreside infrastructure and power electronics needed for battery charging remain significant cost drivers for future projects.

Additionally, there are several regulations and standards governing the use of Li-ion batteries in marine applications. The batteries pass through various safety tests like overcharge, forced discharge, high charging rate, external short circuit, impact, thermal abuse, altitude simulation and vibration following the necessary codes and standards (e.g., International Electrotechnical Commission (IEC) 62619, IEC 62620, UL 1973, UL 9540, UL 9540A and GB 38031). Also, class societies like ABS have developed specific Rules for the use of Li-ion batteries for marine and offshore applications, covering aspects such as battery design, installation and testing [1].

CHALLENGES AND LIMITATIONS OF LI-ION BATTERIES

Research indicates that Li-ion batteries are nearing their theoretical limits in energy and power density, which can create space and weight challenges for larger battery systems needed to meet higher electrical load requirements, such as the electrical energy needed for ocean-going vessels (Figure 5). Therefore, the stability and maneuverability of a vessel should be evaluated, particularly considering the weight of a large battery system.

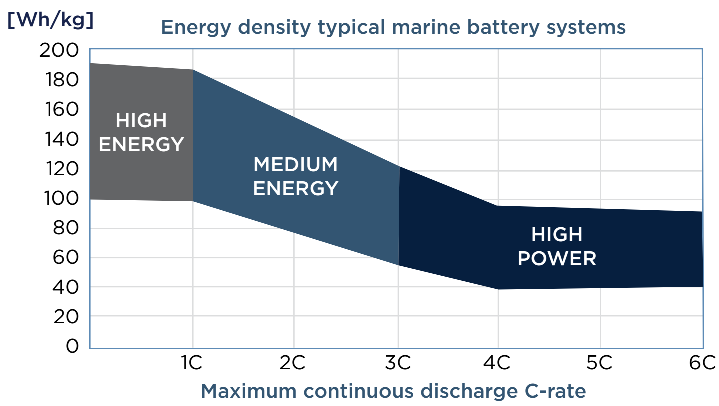
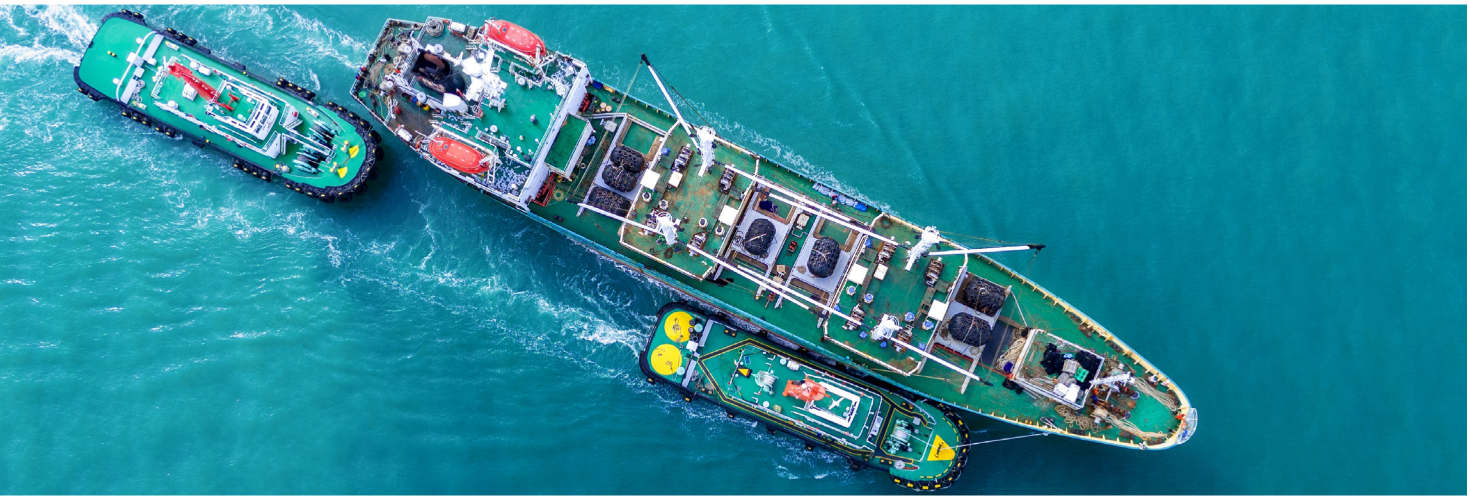


Figure 5: Battery performance — energy/power density [7].



Furthermore, the manufacturing and disposal processes associated with Li-ion batteries can produce indirect emissions that impact the environment as well as pose health and safety risks. The manufacturing process involves the extraction, processing and transportation of raw materials such as lithium, cobalt, nickel and other metals, which can result in greenhouse gas (GHG) emissions, air pollution and water pollution. According to a study by the Swedish Environmental Research Institute, the production of a typical Li-ion battery with a capacity of 20 kilowatt-hour (kWh) can result in GHG emissions of between 61 and 106 kilograms (kg) of carbon dioxide (CO_2) equivalent per kWh of capacity, meaning the total GHG emissions during the fabrication process of a 20 kWh Li-ion battery can range from 1.22 to 2.12 metric tons of CO_2 equivalent [8]. Additionally, the transportation of raw materials and finished products can result in emissions from fossil fuel-powered vehicles.

If not properly disposed of, Li-ion batteries can release toxic substances such as heavy metals, contaminating soil, water and air. The recycling process for Li-ion batteries can be energy-intensive and produce emissions if not done correctly. Overall, while Li-ion batteries for marine applications do not produce direct emissions during operation, their indirect emissions from the manufacturing and disposal processes should be considered to understand their full environmental impact.

Given these considerations, the importance of recycling and repurposing batteries becomes clear. These processes can provide significant benefits, including alternative uses for onshore applications, waste reduction and the recovery of valuable materials. This makes battery recycling and repurposing a promising area for further research and development. However, there are challenges to overcome, such as the economic feasibility of the process, since the costs of collecting, testing and repurposing batteries can be substantial.

Lithium-ion batteries can pose safety risks due to their chemical composition and the potential for TR, a chain reaction that can occur if a battery overheats, causing it to release heat and potentially ignite nearby materials. This can happen if the battery is damaged, overcharged or exposed to elevated temperatures, leading to a fire or explosion that can be dangerous and difficult to control. Mitigating the fire safety risks requires complex monitoring systems to keep the Li-ion battery within the proper operating range for temperature and voltage.

Offshore charging infrastructure for batteries is still in the preliminary stages of development, meaning vessels may need to return to shore frequently for charging, limiting their operating range.

The upfront cost to install Li-ion batteries is higher than implementing traditional fuel-powered engines, posing an economic barrier for some vessel owners who may not have the financial resources to invest in a new power system. As of 2024, the estimated average cost to produce 1 kWh of energy from Li-ion batteries per module is around $115 [9].

For instance, reducing or eliminating emissions for an entire fleet of tugboats will necessitate retrofitting, as a tugboat's lifespan can surpass 30 years. This poses challenges for hybrid and all-electric technologies, as retrofitting existing conventional vessels to hybrid or full battery power is challenging.

Alongside the difficulties in selecting the best battery chemistry for a vessel's operational profile and the limited market options, batteries have a limited lifespan and will need to be replaced periodically. Replacements can be expensive and impact the vessel's long-term operating costs. Therefore, it is crucial to evaluate these factors thoroughly when planning a Li-ion battery retrofit or newbuild.

EMERGING LITHIUM-ION BATTERY TECHNOLOGIES

The limitations of the current Li-ion battery technology have heightened the focus on the research, development and commercialization of next-generation batteries.

This study explores the technological advancements of emerging Li-ion batteries, including silicon anode, Li-S and lithium metal, assessing their potential for application in the maritime industry.

SILICON ANODE

Silicon anode cells, with their ultra-high energy density, are among the most promising candidates for commercial use in the next generation of batteries. Silicon anodes have a theoretical specific capacity of approximately 3,600 milliampere-hours per gram (mAh/g), almost 10 times higher than a commercial Li-ion battery with graphite anodes (~350 mAh/g). Silicon anode cells are categorized under the Li-ion battery family due to their similar operating principles to those of commercial Li-ion batteries. A silicon anode replaces the graphite anode of Li-ion battery while the cathode remains the same material (e.g., nickel manganese cobalt [NMC], lithium iron phosphate [LFP], lithium cobalt oxide [LCO]). The electrolyte components include conventional alkyl carbonates (e.g., ethyl carbonate, dimethyl carbonate, etc.) and lithium salt (LiPF6). Furthermore, the electrolyte can be topped with additives like lithium bis(trifluoromethanesulfonic)imide (LiTFSI), lithium perchlorate and fluoroethylene carbonate (FEC) to improve the stability of the solid electrolyte interface (SEI).

In addition, silicon's abundant availability and environmentally friendly nature make it a potential material for large-scale manufacturing of high-energy-density silicon anode cells.

To commercialize silicon anode cells for large-scale and marine applications, several challenges need to be addressed. During the lithiation and delithiation process[4], silicon anodes typically undergo significant volume changes (300–400 percent), which can cause the active materials to break down, leading to uncontrolled SEI growth and battery degradation. Researchers are actively investigating these issues and implementing various modifications to make silicon anode cells viable for commercial use.

Commercial products with silicon anodes are available and can achieve high energy densities of 300–400 Wh/kg [10]. However, they are often very expensive due to the complex manufacturing process. To address some of the challenges associated with silicon anodes, battery manufacturers commonly use a silicon/carbon composite, incorporating 10–50 percent silicon. This approach helps mitigate some difficulties while still improving energy density to around 300 Wh/kg.

LITHIUM-SULFUR BATTERIES

Lithium-sulfur batteries have significant potential for the next generation of energy storage systems due to their high theoretical energy density (2,600 Wh/kg) and specific capacity of sulfur cathodes (1,675 mAh/g). They are expected to achieve practical energy densities several times higher than current Li-ion batteries.

However, despite their potential, Li-S batteries face significant operational challenges and safety risks, which have hindered their widespread commercialization.

Several inherent issues impede the practical use of Li-S batteries:

- The "shuttling effect" caused by soluble lithium polysulfides during cycling, leading to low coulombic efficiency and loss of active materials.
- The complex phase transition from octasulfur (S8) to lithium polysulfides (Li_2S_2/Li_2S) and the insulating nature of these compounds result in slow kinetics and high reduction and oxidation (redox) overpotential.
- Uneven deposition of metallic lithium dendrites on the anode surface, forming an unstable SEI film during charging and discharging, poses safety risks. Additionally, these dendrites can break lithium crystals, creating "dead Li" (Figure 6) that reduces long-term cycling efficiency.

[4] Lithiation and delithiation are key processes in the operation of Li-ion batteries:

1. Lithiation: This occurs during the charging phase. Lithium ions move from the positive electrode (cathode) through the electrolyte and are inserted into the negative electrode (anode). This process stores energy in the battery.
2. Delithiation: This happens during the discharging phase. Lithium ions move back from the anode to the cathode, releasing the stored energy to power a device.

Current research focuses on developing safe electrolytes to form stable SEI layers and prevent gas generation, designing separators to suppress dendrite formation and reduce chemical crosstalk, and modifying electrodes to enhance stability.

Lithium-sulfur battery prototypes demonstrated energy density greater than 400 Wh/kg, showing their promise. However, due to the above mentioned limitations, the cycle life is typically short.

LITHIUM METAL BATTERIES

Lithium metal, with its low density of 0.59 grams per cubic centimeter (g/cm^3), boasts an exceptionally high theoretical specific capacity of 3,860 mAh/g as an anode, making it a highly researched material for rechargeable lithium metal batteries. Figure 6 illustrates the schematic of lithium metal batteries and highlights the challenges for large-scale applications.

Lithium metal batteries utilize pure lithium metal as the anode, paired with various cathode materials such as LFP, Li-S, NMC, LCO and manganese dioxide (MnO_2). The electrolyte composition is tailored to the chosen cathode material. For instance, lithium perchlorate in propylene perchlorate and dimethoxy ethane are used for MnO_2 cathodes. Two primary obstacles hinder the widespread adoption of lithium metal batteries: dendrite growth during charge and discharge cycles, and low coulombic efficiency during operation. Dendrite formation poses safety risks due to internal short circuits and reduces the cycle life of lithium metal batteries. While using excess lithium metal can mitigate low coulombic efficiency, it also accelerates dendrite formation, leading to potential failures and fires.

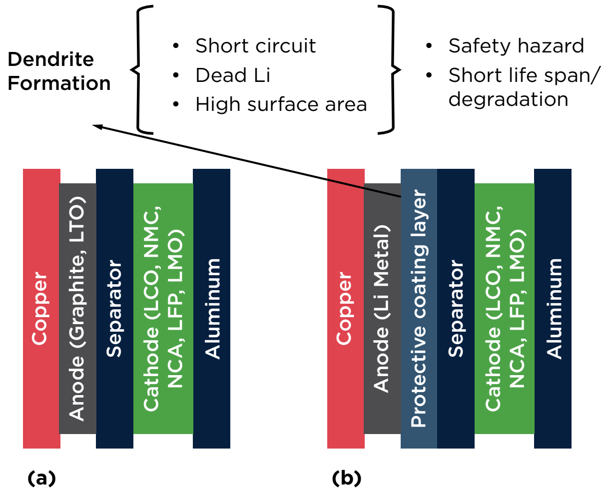


Figure 6: Comparison of (a) conventional lithium-ion battery vs. (b) lithium metal battery.

ADVANCED CATHODE MATERIALS

As the development of Li-ion batteries continues, new cathode chemistries are also being continuously developed. Two recent additions to Li-ion battery chemistry worth mentioning are lithium manganese iron phosphate (LMFP) and lithium manganese-rich (LMR) cathodes.

Lithium manganese iron phosphate is a modified LFP material with some iron ions replaced by manganese ions. The higher stability of $Mn^{2+/3+}$ redox chemistry allows higher oxidation potential, bringing its voltage platform to 4.1 volts (V), on par with NMC chemistry (4.3 V), while still maintaining the thermal stability of LFP. The downside of LMFP is the tendency of manganese ions to distort the lattice. At the cell level, it manifests low power performances and reduced cycle life, like LFP Li-ion batteries [11].

Lithium manganese-rich, for example $Li_{1.2}Mn_{0.6}Ni_{0.2}O_2$, is in fact a mixture of lithium nickel oxide and LMO, which offers a high specific capacity (greater than 250 mAh/g compared to 190mAh/g of NMC) and a high voltage (4.5–4.7 V compared to Li-ion, and 4.3 V of NMC). With an LMR cathode, the energy density of the Li-ion battery cell can be significantly boosted. Its downside is stability, as it shares the instability of layered oxides and manganese redox chemistry. At the cell level, the outcome is thermal stability comparable with NMC Li-ion batteries, which require careful battery management [12].

BEYOND LITHIUM-ION

Extensive research efforts in new energy storage solutions have contributed to implementing battery storage technology in marine applications. Several promising battery technologies are being researched, including redox flow, sodium-ion (Na-ion) batteries and solid-state batteries. Sodium-ion batteries tackle the high costs and resource constraints of Li-ion batteries by using readily available materials. Meanwhile, safety issues associated with the use of organic liquid electrolytes are addressed using solid-state batteries with solid electrolytes. Although these advanced batteries are promising for maritime transportation and offshore energy storage, their safety aspects are still not fully explored.

SOLID-STATE BATTERIES

Solid-state batteries use a solid electrolyte instead of the liquid or gel electrolytes found in conventional Li-ion batteries (see Figure 7). They present a promising solution for overcoming existing challenges by employing nonflammable and electrochemically stable solid electrolytes, including polymers, ceramic and polymer-inorganic composites [13]. These batteries use the same anode and cathode materials as Li-ion batteries, resulting in identical electrochemical reactions. Solid-state batteries offer an energy density of 500–800 Wh/kg.

One significant advantage of solid-state batteries is their improved safety, due to the non-flammable solid electrolyte that minimizes the risk of leaks and fires, making them safer than their liquid counterparts. They also have a longer cycle life, as they can endure more charge and discharge cycles, translating to a longer lifespan. Additionally, solid-state batteries can operate efficiently across a broader range of temperatures, making them suitable for various applications [14]. However, the production of solid-state batteries is currently more expensive due to the complexity of materials and processes involved, and ensuring the stability and longevity of the materials used in these batteries remains a significant challenge.

When it comes to regulations, there are no universally recognized, distinct industry-wide design standards specifically for solid-state batteries. However, several established standards offer guidelines and testing protocols to ensure the safety, reliability and performance of these batteries. These standards, originally developed for conventional Li-ion batteries, are also applicable to solid-state batteries. The standards assess various aspects such as electrical performance, thermal stability, mechanical integrity and safety under diverse conditions.

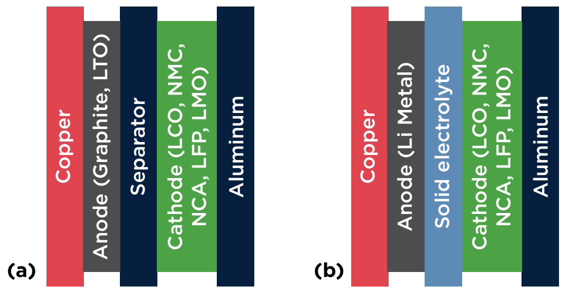


Figure 7: Comparison of (a) conventional lithium-ion battery vs. (b) solid-state battery.

POLYMER SOLID-STATE BATTERIES

The most mature solid-state battery technologies use solid polymer electrolytes (SPE): a lithium metal negative electrode and a metal oxide cathode combined with lithium salt and polymer to form a plastic composite. Polymeric solid electrolytes like polyacrylonitrile (PAN), polyvinyl chloride (PVC), and polyethylene oxide (PEO) are being researched. To be activated, SPE-type solid-state batteries must be heated to 140°-176° F (60°-80° C).

Given the limitations of polymer solid electrolyte — low ionic conductivity at room temperature — a small amount of liquid electrolytes, termed semi-solid or gel electrolyte, is added to polymer solid-state batteries. Adding liquid electrolytes helps improve performance, sometimes significantly, but it does not completely address its flammability. Some of the liquids may be trapped in the polymer matrix, which reduces the risks, but more tests should be conducted to fully evaluate the safety performance.

CERAMIC AND SULFIDE-BASED SOLID-STATE BATTERIES

Ceramic and sulfide-based solid-state batteries represent a promising advancement in energy storage technology. These batteries utilize solid electrolytes, offering a safer alternative to the flammable liquid electrolytes used in conventional Li-ion batteries. Ceramic and sulfide-based solid electrolytes are particularly notable for their high ionic conductivity and robust mechanical properties, making them ideal for solid-state battery applications.

Despite their potential, there are still challenges to overcome, particularly regarding interfacial stability and manufacturing processes.

Current research is exploring various ceramic and sulfides solid electrolytes such as lithium germanium phosphorous sulfide ($Li_{10}GeP_2S_{12}$, LGPS), lithium lanthanum zirconium tantalum oxide ($Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$, LLZTO) and lithium lanthanum zirconium niobium oxide ($Li_{6.75}La_3Zr_{1.75}Nb_{0.25}O_{12}$, LLZNO). Notably, the thermal stability of solid electrolytes can reach up to 1,000° C for lithium lanthanum zirconium oxide ($Li_7La_3Zr_2O_{12}$, LLZO), making it less prone to TR.

SOLID-STATE BATTERIES OUTLOOK

The future of solid-state batteries in marine applications looks promising, with ongoing research and development expected to overcome current challenges and unlock their full potential. The transition to mass production of solid-state batteries is anticipated to occur after 2030, driven by advancements in materials science, manufacturing processes and economies of scale. As these batteries become more commercially viable, they are expected to play a crucial role in the maritime industry's transition to more efficient energy storage solutions.

In summary, solid-state batteries offer a compelling combination of safety, energy density, durability and environmental benefits, making them a promising technology for the future of marine applications. With continued innovation and investment, solid-state batteries are poised to revolutionize energy storage in the maritime sector.

SODIUM BATTERIES

Sodium batteries are emerging as a promising alternative to traditional lithium-based energy storage systems, offering potential advantages in cost, resource availability and safety. Two key types of sodium-based batteries are gaining attention: high-temperature sodium batteries, which operate at elevated temperatures, and Na-ion batteries, which function at room temperature and are structurally similar to Li-ion batteries but use more abundant and less expensive sodium.

HIGH-TEMPERATURE SODIUM BATTERIES

High-temperature sodium batteries, also known as sodium beta or molten salt batteries, are hermetically sealed batteries featuring metallic sodium as the negative electrode and ceramic beta-alumina as the electrolyte. These batteries function at elevated temperatures ranging from 500–698° F (260–370° C), keeping the active materials molten and maintaining ionic conductivity. There are two main types of commercially available high-temperature sodium batteries: sodium sulfur and sodium nickel chloride. Sodium sulfur batteries consist of a sodium negative electrode, beta-alumina electrolyte, and sulfur positive electrode, operating within a temperature range of 590–698° F (310–370° C). On the other hand, sodium nickel chloride batteries feature a sodium negative electrode, beta-alumina electrolyte, and a positive electrode that can be composed of nickel, nickel chloride or sodium chloride, with an operating temperature range of 500–662° F (260–350° C) [15].

These batteries offer an energy density ranging of 90–120 Wh/kg, making them suitable for applications requiring significant power output, and they operate efficiently at elevated temperatures, enabling stable performance in extreme conditions. However, they require high operating temperatures (500–698° F) for optimal performance, which can be energy-intensive and may necessitate specialized equipment, including heaters or furnaces, thermal insulation, heat-resistant materials and robust encapsulation. Additionally, the production and maintenance of these batteries can be costly due to the materials and technology involved. The long-term stability of the materials used also remains a challenge.

High-temperature sodium batteries are rigorously evaluated for performance, safety and reliability, making them suitable for diverse applications, including marine environments. The International Electrotechnical Commission (IEC) 62984 standard outlines the performance requirements and test procedures for high-temperature secondary batteries, including sodium-based batteries, used in mobile and stationary applications. This standard encompasses sodium-based batteries, such as sodium sulfur and sodium nickel chloride batteries, and whose nominal voltage does not exceed 1,500 V.

For instance, ABS has recently granted sodium metal chloride batteries a new technology qualification. The cathode of this battery is composed of metals, primarily nickel and table salt (NaCl), while the anode consists of molten sodium. The anode and cathode are separated by a solid electrolyte made of sodium beta-alumina, a ceramic material that facilitates fast transport of sodium ions at temperatures above 200° C.

This certification confirms that the batteries meet the rigorous standards necessary for the next stage of development, which involves system integration. This step is essential for their future use in the marine and offshore industries, which are increasingly seeking sustainable and reliable energy solutions.

SODIUM-ION BATTERIES

Sodium-ion batteries use sodium ions to store and release energy, similar to how Li-ion batteries use lithium ions. They operate through a liquid electrolyte that facilitates the movement of sodium ions between the anode and cathode during charging and discharging.

As Li-ion battery technology continues to advance, researchers and environmental advocates are increasingly raising concerns about sustainability due to the limited availability of lithium. Sodium, on the other hand, is widely available [16]. Sodium-ion battery technology offers tremendous potential to be a counterpart to Li-ion batteries. However, despite the similarities in electro-chemistry between Na-ion and Li-ion batteries, there are remarkable differences in the physicochemical properties between sodium and lithium that give rise to different behaviors [17].

The cathode materials often used are sodium layered transition metal oxides while the anode materials can include hard carbon or graphite. Na-ion batteries typically have an energy density ranging from 75–200 Wh/kg. This range is similar to that of LFP but lower than the energy density of other types of Li-ion batteries. They offer thousands of charge-discharge cycles, making them durable for long-term use, and the nominal cell voltage is around 3.0–3.1 V. Companies worldwide have been working to develop commercially viable Na-ion batteries. For instance, a 100 megawatt-hour grid battery was installed in China in 2024 for land-based applications [18].

Thanks to their numerous inherent advantages, Na-ion batteries are a promising technology for marine applications. The widespread availability and lower sodium cost make Na-ion batteries appealing for large-scale energy storage solutions needed in marine environments. These batteries can be seamlessly integrated with renewable energy sources such as solar and wind power, offering marine vessels a sustainable energy storage option and helping meet regulatory compliance. Current research is dedicated to enhancing the energy density, cycle life and overall performance of Na-ion batteries. Advances in materials science and battery design are expected to address existing challenges and fully realize the potential of Na-ion batteries for marine applications.

In summary, Na-ion batteries have significant potential as an alternative to traditional Li-ion batteries thanks to their cost-effectiveness, safety benefits and limited environmental impact.

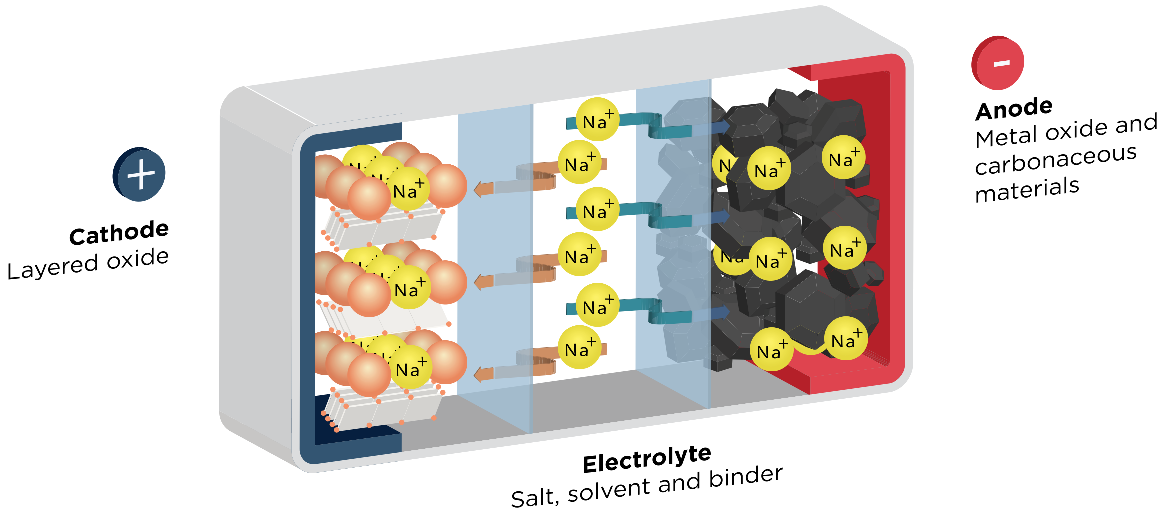


Figure 8: Illustration of Na-ion batteries [19].

AQUEOUS SODIUM-ION BATTERIES

Aqueous Na-ion batteries, which are also referred to as saltwater batteries, consist of a manganese oxide positive electrode, a carbon titanium phosphate composite anode, a saltwater solution electrolyte, and sodium ions that intercalate between the positive and negative electrode during the charge and discharge operation. These sodium batteries operate at ambient temperatures with an optimal range of 23–104° F (–5–40° C).

Aqueous Na-ion batteries are less popular than other types due to several key challenges. One major issue is their lower energy density, which limits their ability to efficiently store and deliver power. Due to these technical hurdles and the focus on improving the more promising solid-state and non-aqueous Na-ion batteries, the development and commercialization of aqueous Na-ion batteries have lagged behind other types.

FLOW BATTERIES

Redox flow batteries (RFBs) operate based on a chemical redox reaction between two liquid electrolytes within the battery cell. These electrolytes are stored in separate tanks and pumped into the cell as required, where they react across an ion-selective membrane, preventing them from mixing. The electrolytes, known as redox pairs, can reversibly react with each other to charge and discharge the battery as needed.

Redox flow batteries come in several types, each with unique characteristics and applications, including:

- Vanadium redox flow batteries (VRFBs)
- Zinc-bromine (Zn-Br) flow batteries
- Iron-chromium (Fe-Cr) flow batteries
- Hydrogen-bromine (H-Br) flow batteries
- Organic redox flow batteries

Flow Batteries		Hybrid Flow Batteries
One-Phase (Liquid Solution)	**Two-Phase (Gas/Liquid Solution)**	96.7%
V/V	H/Br	Zn/Ni
	H/Fe	Zn/Br
	H/Ci	Zn/Cl
Cr/Fe		Fe/Fe
	H/V	Lead (Pb/Pb)
		Copper (Cu/Cu)

Table 3: Example chemistries of flow batteries [20].

Zinc bromine and VRFB are two types of flow battery technologies currently available on the market. Zinc-bromine flow batteries have zinc at the negative electrode and bromide at the positive electrode with an aqueous solution containing zinc-bromide and other compounds contained in reservoirs. During charging, energy is stored as a zinc metal within the cell and polybromide in the cathode reservoir. During discharge, the zinc is oxidized to zinc oxide and the bromine is reduced to bromide. Vanadium redox flow batteries contain vanadium salts in various stages of oxidation in a sulfuric acid electrolyte. Charging and discharging the battery changes the oxidation state of the vanadium in the electrolyte solutions.

One significant challenge of implementing RFB technology in maritime applications is its low energy density. The substantial space required for these systems can be problematic for marine vessels where space and weight are critical factors. However, ongoing research aims to enhance electrolytes and improve energy density, potentially mitigating this concern.

Redox flow batteries should be designed in accordance with recognized industry standards such as the IEC 62932 series. These standards cover various aspects of flow battery design, performance and safety, ensuring that the systems are dependable and meet industry requirements.

	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Nominal Cell Voltage (V)	Energy Efficiency (%)	Cycle Durability (Cycles)	Challenges
VRFBs	10-20	15-25	1.15-1.55	75-90	>1,2000-1,4000	• Highly volatile prices of minerals (i.e., the cost of VRFB energy). • Relatively poor efficiency (compared to Li-ion batteries). Heavy weight of the system, especially the electrolyte. • Relatively poor energy-to-volume ratio compared to standard storage batteries. • Moving parts in the pumps produce the flow of electrolyte solution. • Toxicity of compounds. • Marine/offshore environmental conditions (Inclination, structural integrity, risk of electrolyte leakage).
Zn-Br	60-85	15-65	1.8	75	>6,000	

Table 4: Characteristics of most common redox flow batteries.

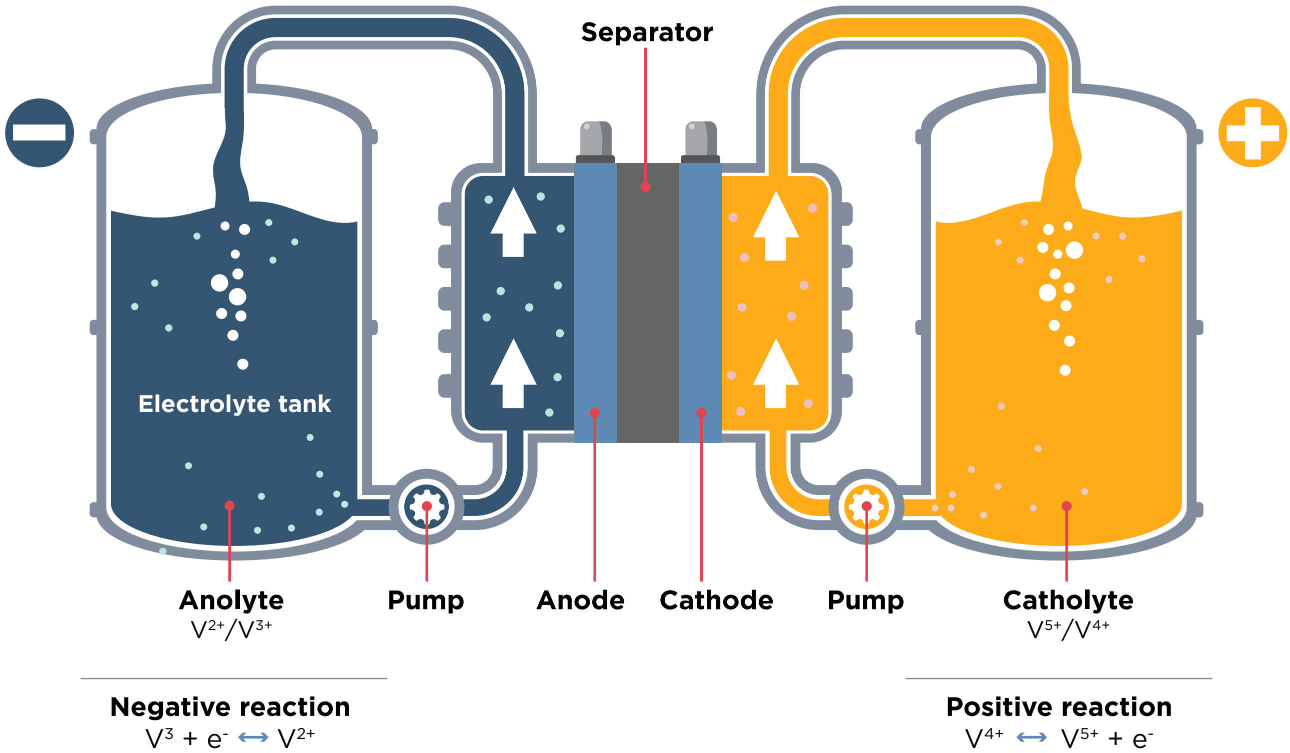


Figure 9: Vanadium redox flow battery [21].

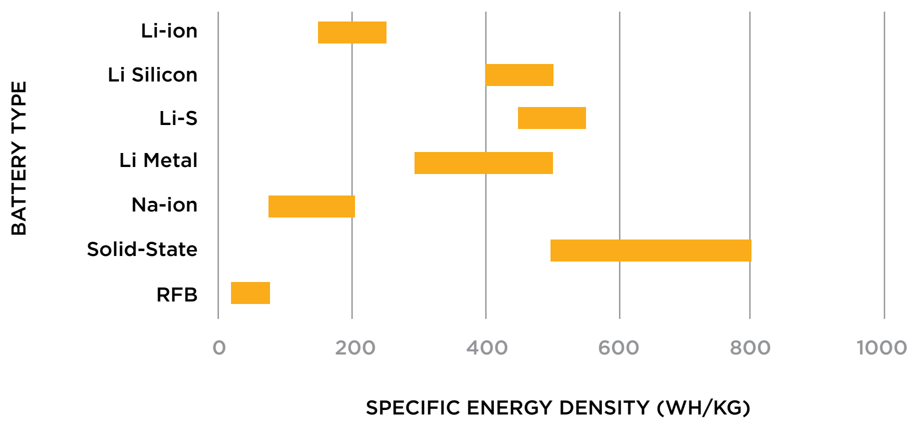


Figure 10: Specific energy density range based on the recent development of various battery types.

Battery Type		Key Components	Working Mechanism/ Salient Feature(s)	Maritime Application	Technology Maturity	Example of Industries Recognized Standard
Li-ion	**Conventional Li-ion**	**Anode:** See Table 2 **Cathode:** See Table 2 **Electrolyte:** Lithium salt (e.g., LiPF$_6$) and organic carbonates solvent (e.g., ethyl methyl carbonate (EMC) and dimethyl carbonate (DMC).	• Recharging involves supplying external electrical power to reverse the cell's electrochemical reactions. • During discharge, lithium ions move from the anode to the cathode via the electrolyte. While charging, the flow reverses.	• Zero-emission applications, • Hybrid applications • Dynamic applications • Energy harvest applications • Refer to Section 2.1	Commercialized (TRL: 8-9) [6]	IEC 62619 IEC 62620 UL 1973
	Silicon Anode	**Anode:** Silicon **Cathode:** Same as **Li-ion batteries** **Electrolyte:** Same as Li-ion batteries with additives	• Similar to Li-ion batteries, but with a silicon anode replacing graphite. • Silicon reacts with lithium to form a lithium-silicon alloy (Li$_x$Si), causing significant volume expansion. • Forms an unstable passivation layer with the electrolyte; additives stabilize this layer. • Currently used in small quantities in graphite-anode batteries.		Research prototype (TRL: 4-5) [22]	
	Li-S	**Anode:** Lithium metal **Cathode:** Sulfur **Electrolyte:** Same as Li-ion batteries (e.g., LiTFSI with ether-based solvents like 1,3-dioxolane (DOL)/ dimethoxyethane (DME) mixtures).	• Similar to Li-ion batteries, but with a silicon anode replacing graphite. • Silicon reacts with lithium to form a lithium-silicon alloy (LixSi), causing significant volume expansion. • Forms an unstable passivation layer with the electrolyte; additives stabilize this layer. • Currently used in small quantities in graphite-anode batteries.		Prototype developed (TRL: 5-6) [23]	
	Lithium Metal	**Anode:** Lithium metal **Cathode:** Metal oxides (e.g., MnO$_2$) **Electrolyte:** Same as Li-ion batteries	• The anode is pure metal, unlike graphite in Li-ion batteries. • Dendrite formation is a major safety concern.		Research prototype (TRL: 4-5)	
Solid-State		**Anode:** Lithium metal **Cathode:** Metal oxides, e.g., MnO2 Electrolyte: Solid inorganic electrolytes (e.g., LGPS)	• Solid-state batteries typically use organic or polymeric electrolytes, unlike the organic electrolytes used in Li-ion batteries.	• Solid-state batteries have the potential to provide high energy density and a safer alternative to current Li-ion batteries, making them an alternative option for the same applications.	Research prototype (TRL: 4-5)	IEC 62619 IEC 62620 UL 1973

Table 5: Comparison of working mechanisms and technological maturity of different battery types.
(Continued on next page)

Battery Type	Key Components	Working Mechanism/ Salient Feature(s)	Maritime Application	Technology Maturity	Example of Industries Recognized Standard
High-Temperature Sodium	**Anode:** Metallic sodium **Cathode:** (e.g., sulfur) **Electrolyte:** Ceramic beta-alumina	• These batteries typically consist of a sodium metal anode, a ceramic beta-alumina solid electrolyte and a cathode made of materials like sulfur or nickel chloride. • During discharging, the sodium ions move back from the anode through the electrolyte to the cathode, where they react with the cathode material to produce electrical energy. • The high operating temperature ensures that the materials remain in a molten state, which is necessary for the ionic conductivity and overall stability of the battery.	These batteries can be integrated into hybrid marine power systems, working alongside other energy sources to optimize fuel efficiency and reduce emissions. They can also serve as a reliable backup power source, helping keep critical systems operational.	Commercialized (TRL: 8-9)	IEC 62984 UL 1973
Sodium-Ion	**Anode:** Carbon-based (e.g., Graphite) **Cathode:** e.g., Sodium vanadium phosphate (NVP), sodium lithium manganese oxide (NLMO) Electrolyte: Sodium salt (e.g., sodium hexafluorophosphate (NFP), and organic carbonates solvent (e.g., EMC, DMC).	• Similar to Li-ion batteries. • An unstable passivation layer forms on the anode side.	While Na-ion batteries are still in the early stages of their marine application, they show significant potential. Their wide range of advantages, including cost-effectiveness, strong safety features, excellent temperature performance and environmental sustainability, makes them a compelling choice for marine battery use.	Pilot scale production (TRL: 6-7)	IEC 62619 IEC 62620 UL 1973
Redox Flow	*Example Vanadium* RFB **Anode** (Anolyte): e.g., V^{2+}/V^{3+}. **Cathode** (Catholyte): e.g., VO^{2+}/VO^{2+}. **Solvent:** e.g., Hydrochloric (HCl) and sulfuric (H2SO4)-based acidic solutions.	Typically, a redox flow battery includes storage tanks and pumps. For instance, vanadium in different oxidation states is dissolved into an acidic solvent to form a cathode (catholyte) and anode (anolyte) (liquid-based electrodes instead of solid). The catholytes/anolytes are stored in tanks and pumped externally to a membrane, where the electrochemical reaction occurs.	Due to their low energy density, redox flow batteries require careful consideration of space and weight to determine their suitability for hybrid and dynamic applications in maritime environments. However, they can be excellent candidates for energy-harvesting applications where space and weight	Commercialized (TRL: 8-9)	IEC 62932 UL 1973

Table 5: Comparison of working mechanisms and technological maturity of different battery types.
(Continued from previous page)

NEXT GENERATION BATTERIES FROM A SAFETY PERSPECTIVE

Like Li-ion batteries, next-generation batteries face many safety challenges, including TR and gas generation. Table 6 summarizes the safety concerns for seven next-generation batteries.

For instance, silicon anode batteries are prone to instability due to silicon's volumetric changes during cycling, producing toxic and corrosive SiF_4 gas along with other TR gases.

Lithium-sulfur batteries generate H_2S and volatile ether-based vapors, heightening safety risks. Lithium-metal batteries face dendrite formation, a key TR trigger.

Sodium-ion batteries, though safer with lower heat generation due to their reduced energy density, have an unstable SEI that can trigger TR.

Solid-state batteries, which use non-flammable solid electrolytes, may reduce TR risk, with trigger temperatures ranging from 200–400° C. However, some research indicates that once triggered, solid-state batteries can release much higher thermal energy [24]. Their electrical and mechanical stability remains insufficiently explored and understood.

Vanadium redox flow batteries, despite their low energy density, are immune to TR under abuse conditions. However, comprehensive research on gas generation characteristics is still needed to fully assess their safety.

Battery Type	Thermal Runaway	Gas Generation
Silicon Anode	• Silicon/graphite composite anode is widely studied due to commercial availability over pure silicon anode batteries. • Pure silicon anode cells have a TR behavior similar to Li-ion batteries. • TR heat generation decreases with increasing silicon content in composite anodes.	• Silicon anode expansion during cycling causes unstable SEI and gas formation. • Thermal runaway may generate SiF_4 gas alongside typical Li-ion battery gases.
Li-S	• Thermal runaway behavior shows similar behavior to Li-ion batteries. • Sulfur melting at 100° C leads to endothermicity during TR.	• Thermal runaway may generate hydrogen (H_2), CO_2, and ethylene (C_2H_4) along with H_2S, specifically from sulfur cathode during TR. • Vapors from ether-based solvents are generated due to their low boiling points.
Lithium Metal	• Lithium dendrite formation is a major safety concern leading to TR. • The onset TR temperature can be significantly lower compared to Li-ion batteries, resulting in substantial heat generation.	• Generates Li-ion battery gases such CO, CO_2, HF, and hydrocarbons during TR.
High Temperature Sodium	• Considered safer due to less reactive cathode materials and, in some cases, less flammable electrolytes. • However, the high operating temperature of sodium-sulfur batteries makes them susceptible to TR. This can be triggered by internal short circuits, overcharging or mechanical damage. The molten state of sodium and sulfur has a risk of exothermic reactions.	• During TR, Na-ion batteries release various gases, including CO_2, H_2, and CO. Hydrogen is the primary flammable gas, but it can also release hazardous gases such as sulfur dioxide (SO_2) and H_2S, which are toxic and flammable.
Na-ion	• Less prone to TR due to the solid electrolyte. • Further studies are needed to assess the heat generated during TR. • Temperature characteristics of the TR profile are similar to Li-ion batteries.	• Gas generation depends on the composition of the electrolyte. • For polymer solid electrolytes, similar gases to those produced by Li-ion batteries are generated, but in different quantities and with different lower explosion limit compositions. • The quantity of gas generated is 40% lower than Li-ion batteries.
Solid-State	• Less prone to TR due to the solid electrolyte. • Further studies are needed to assess the heat generated during TR. • Temperature characteristics of the TR profile are similar to Li-ion batteries.	• Gas generation depends on the composition of the electrolyte. • For polymer solid electrolytes, similar gases to those produced by Li-ion batteries are generated, but in different quantities and with different lower explosion limit compositions. • The quantity of gas generated is 40% lower than Li-ion batteries.
Redox Flow	• No TR observed in any abuse scenarios.	• No flammable gases are produced due to the use of aqueous electrolyte.

Table 6: Safety concerns related to next generation batteries.

Next-generation batteries show promising potential but are facing challenges for direct implementation in offshore and marine applications. These challenges are primarily due to the limited understanding of TR behavior, insufficient research on gas generation and explosion hazards, and the lack of a robust safety management strategy for large-scale applications. Additionally, delayed explosions following the initial suppression of a battery fire remain poorly understood. To address these challenges, detailed research and large-scale field tests are crucial to enabling safe operation and facilitating wider adoption of these technologies. Moreover, the limited onboard space in offshore and marine environments necessitates the careful selection of the most effective fire suppressant or combination of fire suppression systems to maximize safety and effectiveness.

Battery technologies continue to evolve, and this study may not encompass all novel technologies or designs. This highlights the need for ongoing updates and reviews to keep pace with advancements. ABS conducts design reviews for new battery technologies following the guidelines outlined in the ABS *Rules for Alternative Arrangements, Novel Concepts and New Technologies*, which emphasize a goal-based approach. Any new battery technology should comply with the requirements for qualifying innovative technologies as outlined in these Rules. The goal-based standards help ensure that the design meets specific safety, reliability and performance criteria, rather than adhering strictly to prescriptive requirements. By focusing on the intended outcomes and objectives, ABS can foster innovation while maintaining high safety and efficiency standards. This method involves rigorous risk assessments, thorough testing and continuous monitoring to help ensure that the new battery technology is both viable and compliant with ABS standards.

	Battery Technology[5]									
	Current Commercial Technologies [15]				Emerging Technologies					
Safety Requirements	Lead Acid	Nickel[6]	Lithium-ion	High Temperature Sodium	Sulfur	Silicon Anode	Lithium Metal	Solid-State	Sodium-Ion	Flow
Internal Protection Devices		X	X	X	X	X	X	X	X	X
BMS			X	X	X	X	X	X	X	X
Thermal Runaway[7]/ Explosion Control	X	X	X	X	X	X	X[8]	X[6]	X	X
Ventilation	X	X[9]	X	X	X	X	X	X	X	X
Thermal Management or Environmental Control System	X	X	X	X	X	X	X	X	X	X
Spill (Electrolyte Leakage) Control/ Neutralization	X	X								X
Arrangement and Separation[10]	X	X	X	X	X	X	X	X	X	X

Table 7: Battery technology-specific requirements.

CONCLUSIONS

Exploration of next-generation batteries for marine applications reveals a promising future characterized by technological advancements, improved performance and enhanced safety. This study begins with an understanding of current technologies, particularly Li-ion batteries, which have dominated the market due to their high energy density and efficiency. Despite their advantages, Li-ion batteries face challenges such as safety risks, limited range and high initial costs, all driving the development of alternative solutions.

Emerging battery technologies offer great potential. Silicon anode batteries promise higher capacity and longer life cycles, while lithium-sulfur and lithium metal batteries present opportunities for increased energy density and reduced costs. These innovations are crucial for meeting the growing energy demands of marine vessels and reducing environmental impact.

Beyond Li-ion, solid-state batteries represent a significant leap forward. Polymer and ceramic solid-state batteries offer improved safety and stability, addressing the TR issues associated with conventional Li-ion batteries. The outlook for solid-state batteries is optimistic, with ongoing research focused on enhancing their performance and scalability.

Sodium batteries, including high-temperature sodium, Na-ion and aqueous sodium variants, provide a cost-effective and abundant alternative to lithium-based systems. Their potential for large-scale energy storage and reduced environmental impact makes them a viable option for marine applications.

Flow batteries, with their ability to store energy in liquid electrolytes, offer flexibility and scalability, making them suitable for marine applications. Their long cycle life and low maintenance requirements further enhance their appeal.

From a safety perspective, next-generation batteries must address the inherent risks associated with energy storage systems. Advanced monitoring and control systems, along with rigorous testing and compliance with international standards, are essential to enable the safe operation of these batteries in marine environments.

Ultimately, the future of marine battery technology lies in the continuous innovation and development of next-generation systems. By overcoming the limitations of current technologies and embracing emerging solutions, the marine industry can achieve greater efficiency, sustainability and safety, paving the way for a cleaner and more reliable energy future.

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[5] Battery systems prone to TR should be installed with extrinsic safety and suppression measures to tackle and prevent the TR propagation at the module or pack scale. Water mist-based fire suppressant systems are the most widely used and highly effective in cooling down the battery fires.

[6] Nickel battery technologies covered in this column include NiCd, NiMH and nickel zinc.

[7] Thermal runaway protection is permitted in a BMS battery management system that has been evaluated with the battery.

[8] The protection in this column is not required if documentation acceptable to the class society, including a hazard mitigation analysis.

[9] Exhaust ventilation is not required for NiMH batteries.

[10] Required to be in a dedicated space.

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LIST OF ACRONYMS AND ABBREVIATIONS

BMS Battery Management Systems

GHG Greenhouse Gas

IEC International Electrotechnical Commission

LCO Lithium Cobalt Oxide

LFP Lithium Iron Phosphate

NCA Nickel Cobalt Aluminum

NMC Nickel Manganese Cobalt

NiCd Nickel-Cadmium

NiMH Nickel-metal Hydride

RFB Redox Flow Battery

SEI Solid Electrolyte Interphase

SoC State of Charge

SPE Solid Polymer Electrolyte

TR Thermal Runaway

TRL Technology Readiness Level

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