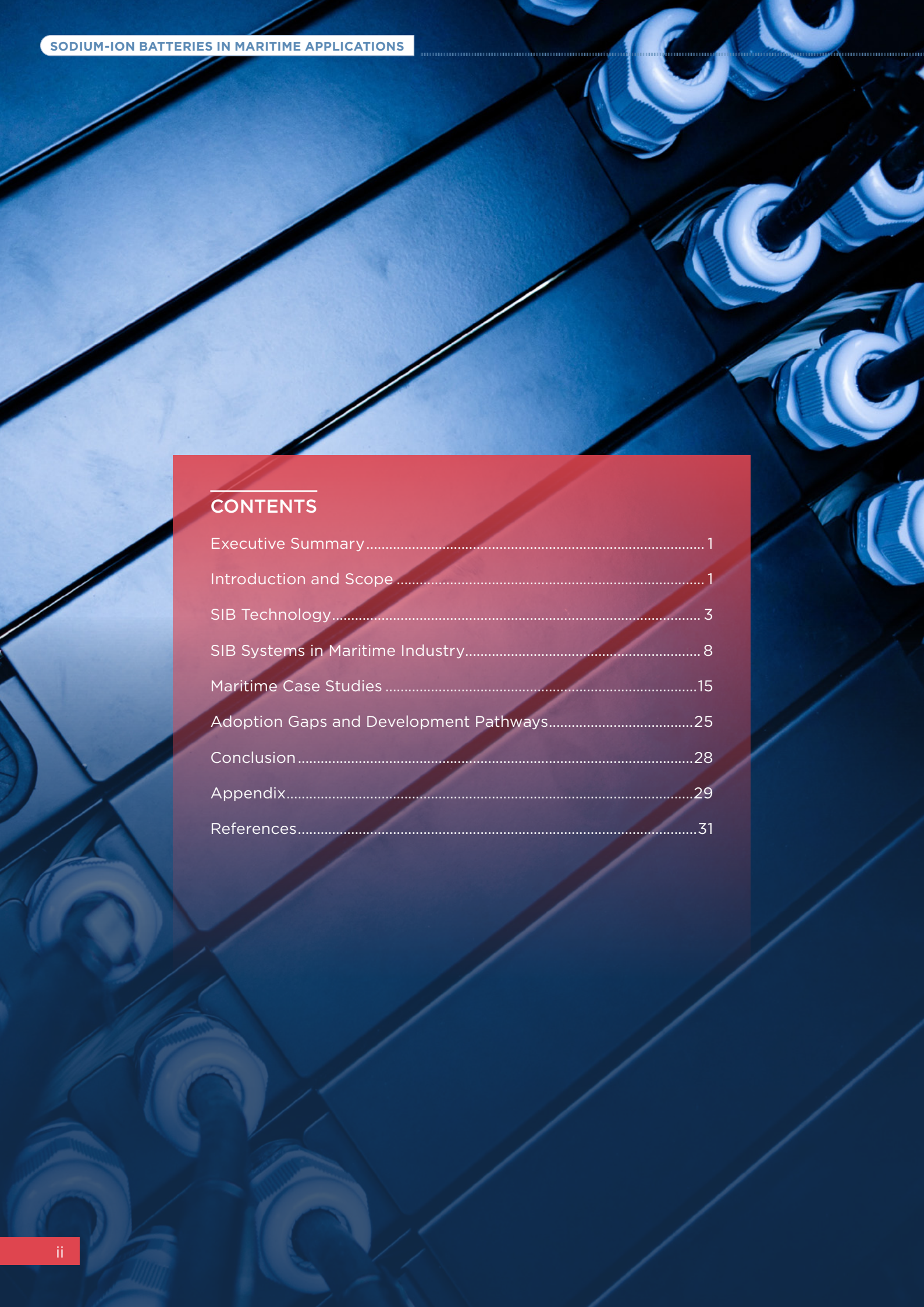
SODIUM-ION BATTERIES
IN MARITIME APPLICATIONS





CONTENTS

Executive Summary 1
Introduction and Scope 1
SIB Technology 3
SIB Systems in Maritime Industry 8
Maritime Case Studies 15
Adoption Gaps and Development Pathways 25
Conclusion 28
Appendix 29
References 31

EXECUTIVE SUMMARY

Maritime decarbonization is increasing demand for electrification and, with it, the need for battery systems suited to diverse operating profiles. While lithium-ion (Li-ion) batteries (LIBs) remain the leading technology due to their maturity and market adoption, their limitations in safety, supply-chain concentration, and performance trade-offs continue to motivate evaluations of alternative chemistries.

This whitepaper examines sodium-ion (Na-ion) batteries (SIBs) as a potential complement to LIBs for maritime applications. SIBs offer several promising attributes, including high power capability, broad temperature tolerance, and potential supply-chain advantages. At the same time, their lower energy density, resulting in larger footprints, and limited commercial maturity remain important constraints for marine use.

The assessment indicates that SIBs are not a universal replacement for LIBs, but they may be technically attractive for selected applications, particularly those with high power demand and moderate energy requirements. Potential use cases include peak shaving, transient power support, short-range operations, and certain hybrid system roles. They are less suitable for energy-intensive applications where space and weight are critical.

The paper also identifies key gaps that must be addressed for wider maritime adoption, including safety validation, system integration, product maturity, life cycle support, and alignment of approval and regulatory frameworks. These factors will be critical in determining whether SIB systems can progress from promising alternatives to practical marine solutions.

Overall, SIBs warrant continued evaluation as part of the maritime electrification pathway. Their future role is likely to be application-specific, with the strongest near-term potential in use cases where power performance and cold-environment tolerance are prioritized over maximum energy density.

INTRODUCTION AND SCOPE

DRIVERS FOR MARITIME ELECTRIFICATION

The maritime industry faces sustainability pressure from international and regional regulations. The International Maritime Organization (IMO) continues to promote greenhouse gas (GHG) emission reductions through commitments such as its 2030 strategy [1]. The European Union (EU) has similarly made climate neutrality by 2050 legally binding [2]. These developments increase pressure on the maritime industry to decarbonize.

Under what maritime duty profiles do sodium-ion battery systems become technically, economically or operationally preferable to incumbent lithium-ion battery systems?

Electrification is considered one of the key decarbonization pathways [3]. With electricity increasingly generated from renewable sources, carbon emissions could be significantly reduced. For vessels with hybrid power systems, the electrical system supports carbon emission reduction by lowering fuel consumption while improving fuel efficiency [4]. In addition, modern control technologies, like robotics and artificial intelligence (AI), rely on electricity to function, making electrification a cornerstone of modern marine vessels and offshore assets.

CURRENT POSITION OF LITHIUM-ION BATTERIES

Among the challenges facing electrical systems, storing electricity is a key issue. Unlike fuels, electricity is a transient energy carrier and requires dedicated storage systems. Within the range of available storage technologies, batteries have proved to be one of the more sensible choices, providing a good combination of capacity, efficiency, and power delivery.

Among the battery technologies, Lithium-ion (Li-ion) batteries (LIBs) have become the centerpiece for electrical energy storage [5], owing to their many strengths. LIBs have reached a remarkably high level of maturity, with a stable supply base and logistics network guaranteeing availability. LIBs have demonstrated their suitability in diverse use cases, ranging from small appliances to road vehicles and large-scale energy storage. Their costs have also declined recently, further establishing their dominance in the energy storage market.

Nevertheless, LIBs still face several challenges that limit their application scope:

- LIBs can enter thermal runaway (TR) and catch fire [6] under abusive conditions, requiring extensive protective features.
- The LIB supply chain is highly concentrated [7] with exposure to critical minerals such as cobalt, nickel, and lithium, posing a potential geopolitical concern.
- LIB systems must operate within the rated power limits of their selected cells. The battery system is to be oversized to meet high power demand without exceeding power limits; otherwise, the system may face increased risk of TR [8].

Given the constraints, energy storage technology continues to evolve as developers seek safer and more cost-effective alternatives that can supplement LIBs where LIBs face limitations.

SODIUM-ION BATTERIES AS AN ALTERNATIVE

Sodium-ion batteries (SIBs) have attracted considerable attention recently and are widely viewed as a viable replacement for LIBs, especially the lithium iron phosphate (LFP) chemistry [9]; some potential advantages under discussion are shown in Figure 1. Applications for SIBs have also emerged: starter batteries to replace legacy lead-acid batteries [10], stationary battery energy storage systems (BESS) [11] and emerging automotive applications [12], demonstrating their promise as LIB alternatives.



Figure 1: Potential advantages of SIBs.

However, for SIBs to be considered seriously for maritime applications, claims and metrics need to be examined, verified and validated within the maritime context. With this whitepaper, ABS intends to provide readers with an overview of SIB systems, evaluate their relevance, highlight potential challenges and propose a practical framework for the industry that may pave the way for wider SIB adoption for maritime use.

Available information, which is a mixture of academic reports and commercial claims, describes SIBs as a higher-power, potentially safer, cost-efficient alternative to LIBs. This paper first reviews these claims at the material level in the "SIB Technology" section to provide a fundamental understanding of SIB technology.

The maritime industry places demanding requirements on energy storage solutions, including harsh-environment tolerance, high durability and reliability, and mission-specific energy and power demands. The "SIB systems in Maritime Industry" section provides a qualitative technical assessment of SIB systems, while the "Maritime Case Studies" section evaluates them quantitatively through case studies.

SCOPE AND LIMITATIONS

Given the current state of SIB development, this whitepaper has several limitations:

- Performance metrics are obtained from publicly available commercial data and inferred from academic reports when commercial data is unavailable. They represent near-term market parameters that are likely to change over time.
- Currently available SIB systems are used in environments quite different from the maritime environment. System parameters are inferred based on available information and comparison with LIB system metrics.
- Given the limitations above, discussions presented here are scenario-based: the SIB systems are evaluated under specifically defined scenario cases with forward-looking estimations and should not be read as indicating general trends in SIB technology.

SIB TECHNOLOGY

ELECTROCHEMISTRY PRINCIPLES

SIBs share many similarities with LIBs but differ in a few key aspects, accounting for their observed performance differences. SIBs similarly use ions to shuttle charges within the cell, and electrons flow in external circuits to complete the electrochemical reactions. Instead of Li_+, SIBs use Na_+ ions; this seemingly simple substitution leads to significant differences in performance.

- Na_+ ions are about 30 percent larger and three times heavier than Li_+ ions, so they require more space to store and transport. This leads to lower capacity in both gravimetric and volumetric terms.
- On the other hand, the larger Na_+ ion radius leads to weaker electrostatic attraction between Na_+ ions and the surrounding electrolyte. As a result, Na_+ ion transport is more favorable inside the cell. This translates into higher current capability and therefore higher power density.
- Sodium has a less negative standard electrode potential, which results in narrower cell voltage ranges than lithium. Combined with lower capacity, SIBs tend to have lower energy density than similar LIB chemistries.
- Sodium chemistry allows alternative material classes to be used as electrodes, offering wider cell choices catering to different use cases.

CELL CHEMISTRIES

LIBs are typically classified by their cathode chemistries, such as LFP or lithium nickel manganese cobalt oxide (NMC), with lithium titanate (LTO), classified by its anode, being the main exception. Similarly, cathode chemistry largely defines key performance attributes including capacity, voltage, and power; therefore, cathode chemistry serves as a primary basis for SIB classification. However, nomenclature within the SIB sector remains less consistent, reflecting the technology's early development stage.

In the sections below, the most popular cathode categories are introduced. As a cautionary note, because SIB technology continues to evolve, some of the materials introduced below may fade out while new chemistries may emerge.

LAYERED OXIDE CATHODES

Layered oxides, like NMC, consist of metal and oxygen ions arranged in a layered structure [13], storing Na_+ ions between the layers. One widely adopted example is $NaNi_{1/3}Fe_{1/3}Mn_{1/3}O_2$, abbreviated as NFMO.

Layered oxide cathodes offer the highest voltage and energy density among SIB cathodes. Disadvantages include material instability and voltage fading over cycling [14]. From a safety perspective, they are susceptible to instability issues: high charge states can trigger oxygen release, gas evolution, and electrolyte reactions, especially for Ni-rich or high-voltage compositions.

At cell level, layered oxide cathodes can achieve higher energy density but raise concerns for cycle life and safety, which need to be addressed at the cell and system level.

PRUSSIAN BLUE ANALOG (PBAS) CATHODES

Unique to SIB chemistry, PBA cathodes make use of $M(CN)_6$ anions to form 3-D networks with open channels for Na_+ ion transport [15], offering good rate capabilities. One example is $Na_xFe\ [Fe(CN)_6]$ (x = 0~1).

Advantages of PBA cathodes include low cost, good rate capability, and long cycle life [16]. Disadvantages include relatively low capacity and quality-control issues such as contamination. In terms of safety, while the framework is oxygen-free, crystal water and defects can contribute to thermal risks; potential release of HCN could be a concern under certain abuse conditions [17].

PBA-based SIB cells typically have high power ratings but suffer from low energy density; cycle life is moderate. One particular concern is quality control because PBAs are sensitive to moisture; this could be a challenge for early-stage production.

POLYANIONIC/NASICON CATHODES

Polyanionic materials consist of large anions that form a network and create open pathways for Na_+ ion movement while retaining structural stability [18]. This class of materials mirrors LFPs and is also called NASICONs (sodium (Na) super ionic conductors). One example is $Na_3V_2(PO_4)_3$ [19], commonly abbreviated as NVP.

Thanks to their robust structure, polyanion cathodes are more stable than other variants, with excellent life cycle and voltage stability [20]; limitations include low capacity and moderate power capability. Polyanionic materials are generally considered the safer option for SIBs but may still suffer from decomposition reactions [21] and TR when abused.

SIB cells with polyanionic cathodes tend to excel in terms of safety and cycle life, while being modest in terms of energy density and power density.

These three major types of cathodes are compared in Table 1 below.

Chemistry	Voltage (vs. Na/Na_+)	Capacity in Milliampere-hours per Gram (mAh/g)	Strengths	Weaknesses
Layered Oxides [13]	2.8–4.2	100~180	High Energy Density	Low Cycle Life
PBAs [15]	3.2–3.8	120~170	High Power	Low Voltage, Low Capacity, Susceptible to Quality Issues
Polyanions [18]	3.0–4.3	90~130	Good Safety, High Cycle Life	Modest Energy and Power

Table 1: SIB cathode material comparison.

HARD CARBON ANODES

SIB anodes fall into two major types: carbon-based and alloy-based, which are briefly discussed below.

Hard carbon is non-graphitizable carbon, composed of disordered domains containing defects, pores and expanded layers that allow Na_+ ion storage via adsorption, intercalation and porefilling mechanisms [22]. By contrast, graphite, the most popular anode choice for LIBs, cannot effectively intercalate the larger Na_+ ion. As an anode, hard carbon typically delivers 250-350 mAh/g and operates at 0-1 V vs. Na/Na_+.

Hard carbon offers several advantages as an anode [23]: high capacity, low cost, low potential (and therefore higher cell voltage) compared with other SIB anode options. Disadvantages are low first-cycle efficiency (some Na_+ ions are irreversibly consumed by solid electrolyte interphase (SEI) formation and structural defects during the first charge), material variability that may affect cell consistency and limited charging rates [24].

Hard carbon is often treated as comparatively safe, but because of factors such as unstable SEI formation, or sodium plating under aggressive conditions [21], TR remains a possibility and safety challenge [25].

Hard carbon is currently the dominant SIB anode choice. Besides its advantages discussed earlier, its production can draw on the mature LIB industry, with shared infrastructure and transferable processing knowledge [26] that give it a cost advantage over other anodes.

ALLOY-BASED ANODES

Alloy-type anodes store sodium by forming alloys, much like silicon (Si) anodes for LIBs. The main types are tin (Sn), antimony (Sb) and phosphorus (P)-based materials [27].

Alloy-type anodes can typically deliver very high capacity: 847 mAh/g for Sn, 660 mAh/g for Sb, and 2596 mAh/g for P, which represents their primary advantage over hard carbon. However, alloy cycling causes significant volume changes, which raises serious durability challenges [28]. Safety issues center around parasitic reactions and rapid degradation; the failure modes also differ from those of hard carbon [29] and remain to be explored in more detail.

Because of both technical and commercial challenges, alloy-type anodes, such as tin (Sn) anodes, remain exploratory [30]. Other development-stage materials worth mentioning include manganese oxide (MnOx) cathodes, organic electrode materials, and titanate-based anodes. While not as prevalent as those mentioned above, they may eventually reach maturity and establish themselves in the SIB market.

CELL SAFETY

There is emerging evidence that SIBs are better understood as a distinct thermal-safety class with both advantages and residual risks [31] in comparison with incumbent LIB systems. Because safety is critical, it is discussed in more detail below.

FAILURE MODES AND CONSEQUENCES

Under thermal stress, SIBs have a similar tendency to LIBs to enter TR. A recent review of practical SIB safety identified that the main risk drivers for TR are flammable organic electrolytes, SEI instability, anode side reactions, and cathode structural degradation [32], which are comparable with LIB systems.

A typical SIB failure pathway involves [25] initial heating, early decomposition, gas generation and release, internal short circuit, and escalation to fire. Representative temperatures for key events are consolidated from literature reports and presented in Table 2 below.

Event Temperatures (° C)	SIB (metal oxide)	LIB (LFP)	LIB (NMC)
Self-heating Onset	94	124.1	97.4
Safety Vent Opening	149.2	151.5	167.7
Separator Collapse	271.1	279.7	231.7
Maximum Temperature	511.7	421	748.6

Table 2: Temperature parameters for SIB-related safety events. Note these values are chemistry- and test-specific.

TR off-gas generation includes species such as CO, CH_4, C_2H_4, CO_2, H_2, and organic volatiles. Exact compositions depend heavily on SIB chemistries and electrolyte formulations, but details are not well established yet [33]. Certain species such as CO and HCN (potentially released by PBA SIB, as discussed earlier) are highly toxic and constitute a major hazard for crew exposure. The ignition and explosive potential of off gas should be further supported with detailed study and simulations.

Compared to LIB TR behaviors, assessments [34] generally place SIB fire hazard between LFP and NMC chemistries [35], though the actual hazard profile depends on the specific SIB chemistry, electrolyte formulation and cell design. Therefore, safety systems including monitoring, detection, and suppression are still required and are designed specifically for SIB systems.

SAFETY KNOWLEDGE GAPS AND RESEARCH NEEDS

Despite the evidence presented above, uncertainties remain in SIB failure behaviors. These include detailed behaviors under electrical and mechanical stress, and how failure behaviors are affected by cell conditions. In addition, whether SIB has the capacity for reignition should be examined in detail, with critical safety system design implications.

Dedicated test standards for SIB cells are not yet internationally available. While OEMs may use LIB standards as interim guidance, given their distinct failure behaviors, standards explicitly addressing SIB risks should be a priority. This issue will be explored further in regulatory gap discussions.

CELL-LEVEL PERFORMANCE BENCHMARKING

Example SIB cell specifications are consolidated in Table 3 below to show cell-level benchmark values. At the material level, layered oxide cathodes can provide higher voltage and larger capacity than PBAs, but this advantage is no longer visible at the cell level from these selected examples, because layered oxide systems are typically limited in voltage range to avoid safety and degradation issues [36], whereas PBAs do not face such constraints [37].



Common Name	PBA SIB	Layered Oxide SIB	Polyanion SIB	Layered Oxide SIB	LFP LIB	NMC LIB	LTO LIB
Cathode	PBA	Layered Oxide [b]	NVPF [c]	$NaCrO_2$, NCO	LFP	NMC	NMC [d]
Anode	HC [a]	HC	HC	HC	Graphite	Graphite	LTO
Nominal Voltage (V)	3.0	3.1	3.7 [e]	3.2	3.2	3.7	2.3
GED (Wh/kg)	160	145	105	125	150	250	89
VED (Wh/L)	300	248	215	270	300	700	176
Maximum Discharge (C-rate)	Up to 10C	5C	15C	10C	1-2C	2C	Up to 25C
Fast Charging Capabilities [f]	0 to 80% SoC within 15 minutes (3.2C equiv.)	0 to 100% in ~10-15 minutes (4-6C equiv.)	10C class charging	15 minutes full charge (4C equiv.)	0.33 - 1C	1C	0 to 80% SoC within 6 minutes (8C equiv.)
Cycle Life (80% Retention)	10,000 to 15,000	>8,000	3,200 (2C charge/5C discharge)	>10,000	5,000 – 10,000	2,500	20,000
Operation Temperature Window	-40 to 70 °C	-40 to 55 °C	-30 to 60 °C	-40 to 60 °C	-30 to 60 °C	-30 to 55 °C	-30 to 50 °C
Data Sources	[38]	[39]	[40]	[10]	[41]	[42]	[43]

Table 3: Indicative cell-level metrics for different chemistries.

Note:

a. HC: hard carbon.
b. Layered oxide from HiNa composition is not publicly disclosed.
c. NVPF = $Na_3V_2(PO_4)_2F_3$, a fluorinated variant of polyanion family.
d. NVPF has higher nominal voltage. Typical polyanion SIB cell nominal voltage is 3.3V [44].
e. Cathode composition is not publicly disclosed by Toshiba. Cathode identity confirmed by independent teardown study [45]
f. Fast charging capabilities are stated as by the suppliers as cell-level demonstrations. C-rate equivalents are calculated based on given SoC (state-of-charge) range and duration only.

Importantly, cell performance is not determined by chemistry alone; Table 3 includes two cells that are based on the same layered oxide cathode chemistry but have different parameters, highlighting that manufacturing technology is equally important for cell performances. It is also worth noting that commercial claims may not fully align with actual cell metrics, tested under real-life conditions; independent validation is often needed to fully understand the cell's performance.

Comparison of SIB cells with LIBs is shown in Figure 2. SIBs can operate at much lower temperatures and deliver high pulse power. However, they are not better than LIBs on every aspect, especially energy density where SIBs are at best comparable with LFP cells. Safety is chemistry-dependent and often involves trade-offs with performance, and commercial maturity remains at a relatively low level.

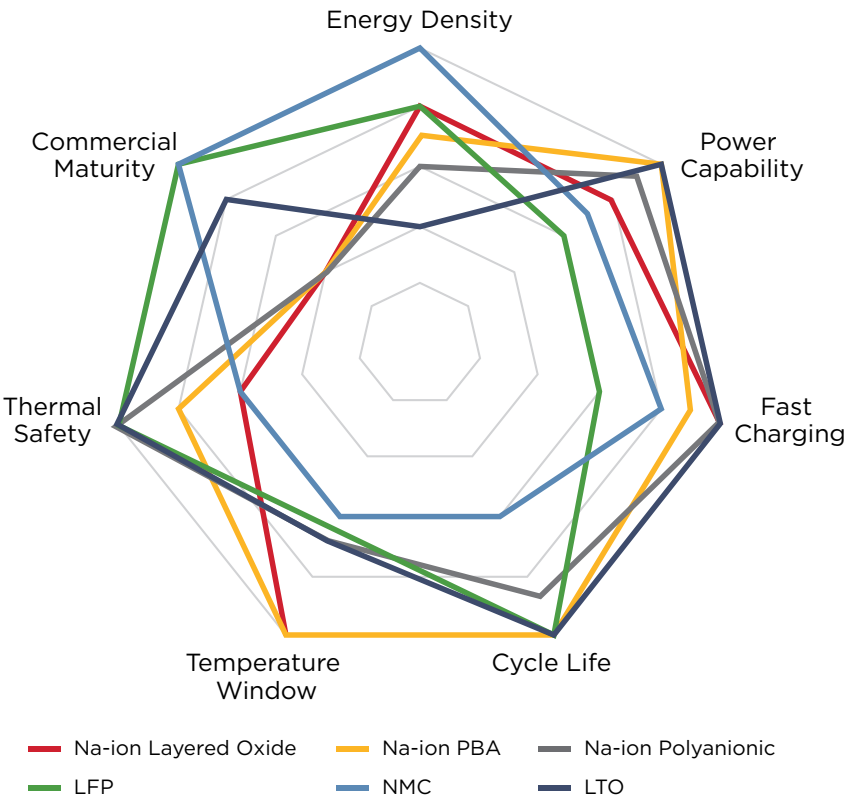


Figure 2: Radar chart of different cell chemistries (SIB and LIB). Please note safety characteristics remain chemistry-specific and will continue to evolve. Na-ion layered oxide parameters are averages of the two cases in Table 3.

Overall, SIB cells possess distinctive characteristics that could enable them to supplement or replace LIBs in selected applications. However, whether these advantages persist at the system level remains to be determined, as enclosure structures, cooling systems, electrical protection systems and fire-protection measures all influence overall performance. This will be discussed further in the next section, where SIB systems in maritime industry settings are examined more closely.

SIB SYSTEMS IN MARITIME INDUSTRY

While SIBs have not yet entered the maritime industry at scale, they may hold relevance to this industry, where a combination of factors such as operational, safety and integration requirements may favor SIB systems.

This section explores the requirements of maritime duty profiles in relation to SIB systems, evaluate potential SIB fits and identify practical constraints for further considerations.

MARITIME CHALLENGES AND CONSIDERATIONS

MARITIME REQUIREMENTS

Compared to land-based usage, maritime use cases can be demanding for energy storage systems. This covers multiple aspects:

- **Installation constraints:** Marine assets typically do not have the luxury of space; installed systems are preferably to be small and lightweight to maximize profit-generating useful loads. Battery systems are required to be size- and weight-optimized, and energy densities become the primary parameter of consideration.
- **Safety criticality:** Maritime systems can be complex and consist of potentially high-risk systems under space constraints. Isolated at sea, vessels rely on the limited safety systems they must deal with any emergencies that may emerge on board. Battery systems therefore must be designed to high safety standards.
- **Reliability under harsh conditions:** Vessel systems, especially propulsion systems, are expected to operate continuously under harsh weather conditions, along with corrosive salt fog posing a threat to protective features. The robustness of the battery system is therefore an important design concern.

- **Scale and lifespan:** EV batteries are typically in the range of tens of kilowatt hours (kWh) with a typical lifespan of 10 years, whereas maritime battery systems are often at megawatt hours (MWh) scale for each individual vessel, and are expected to operate for long durations around 15 to 20 years. Battery system manufacturers are thus faced with huge demand spikes with long quiet periods between orders; this fluctuation forms an important entry barrier, especially nascent SIB systems.

In addition, the mismatch between battery lifespan and vessel life means batteries must be replaced at some point during the vessel's life cycle, adding extra costs for the battery system. This financial impact will be discussed here briefly and analyzed in more detail in the next section.

BATTERY SYSTEM CONSIDERATIONS

Given the multitude of challenges maritime BESS must face, several important indicators are illustrated in Figure 3.

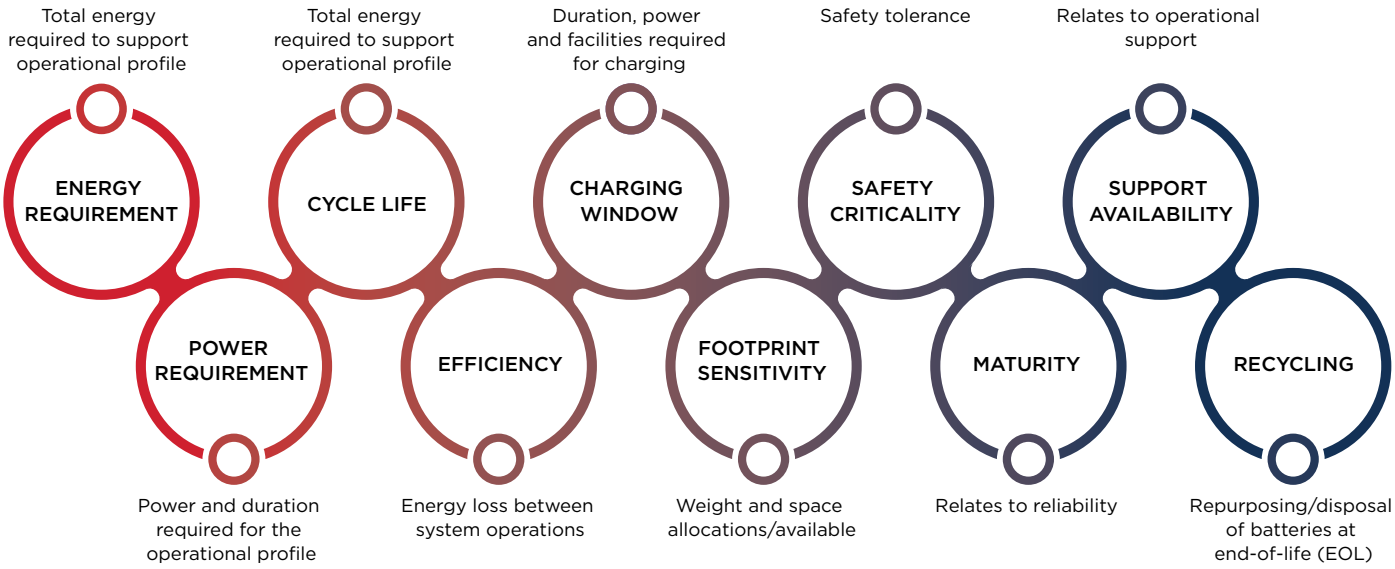


Figure 3: Considerations for BESS Selection.

From the information in Figure 3, performance factors including energy and power requirements are the most prominent as they determine the installation size. Constrained by footprint sensitivity, these three factors collectively determine the feasibility of the battery system. A suitable battery system needs to balance between these factors and is typically customized to the operation profiles of the vessel.

Here are some examples to illustrate the wide variety of battery installations. For ferries, *MF Ampere*, a short-range electric ferry operating within Norway (~5 kilometers (km)), requires 1,090 kWh battery [46]. *Ellen*, operating between Als and Aero (Ærø; 40 km) requires 4.3 MWh battery [47] and uses 1.6 MWh per trip. For tugboats, *Qinggang Tuo 1* is installed with 2.76 MWh LFP battery pack [48], whereas *Crowley* e-tug has a 4.5 MWh ESS onboard [49]. These examples highlight that, for the same vessel type operating under different duty profiles, battery systems can be very different from vessel to vessel and incur very different design considerations.

Deploying SIB technology at the system level presents several challenges. Firstly, safety features are critical to mitigate SIB hazards discussed earlier to an acceptable level. Secondly, auxiliary systems such as electrical protection and environment conditioning are needed for reliable functioning. Lastly, maritime systems require approval for onboard use, and the pathway needs to be established along the system if not already present.

In addition, installing a battery system is a business decision on top of all technical considerations. The technology must reach an appropriate level of maturity before it can be deployed commercially. The profitability of a battery system in turn depends on factors such as efficiency, charging windows, and EOL considerations.

These three areas — operational suitability, system compatibility and financial viability — are examined in greater detail in the following sections.

PERFORMANCE SUITABILITY

MARITIME USE CASES

There are many possible ways to categorize maritime BESS use cases, such as by size, by vessel type, or by function. Here, the power and energy demand profiles are used to better reflect the performance demands placed on BESS. The use cases are divided into these segments:

- High power, moderate energy, examples:
  - Transient power support, e.g., tugboat operations
  - Hybrid power support, e.g., peak shaving
- Moderate power and energy, such as:
  - Short range propulsion, e.g., short-range ferry
  - Auxiliary load, e.g., hotel loads
- Low power, high energy, for example:
  - Long range propulsion power, e.g., deep-sea vessels
- Other cases: onshore support

Onshore support is included as one use case since BESS is typically considered an integral part of the charging system, which is critical for maritime electrification. It has high energy and power demands, but being onshore means it faces fewer footprint constraints.

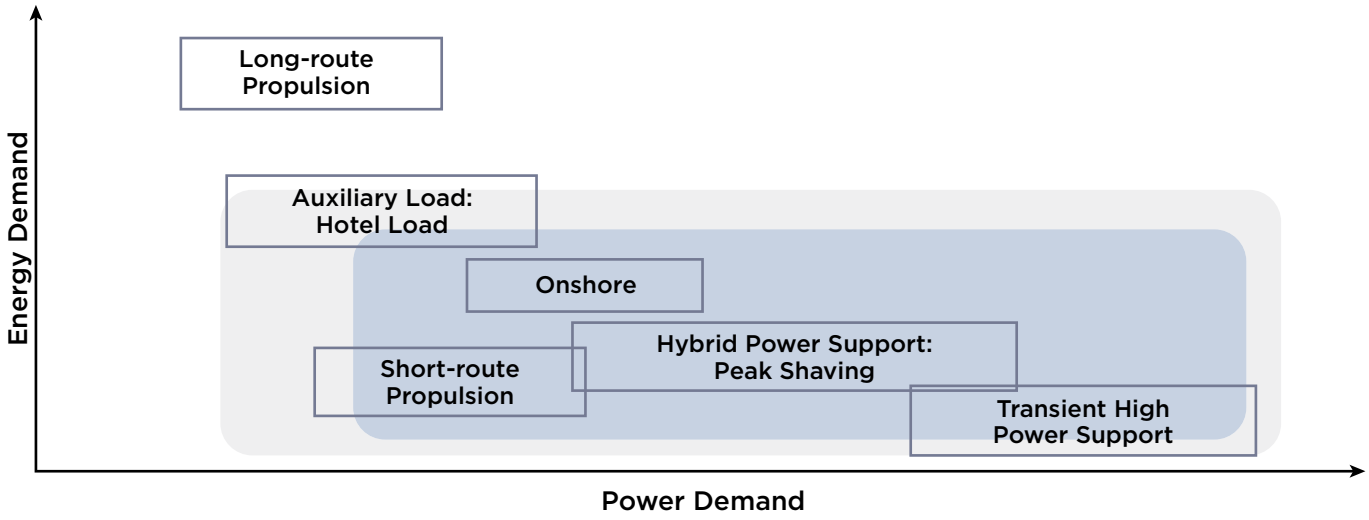


Figure 4: SIB suitability regarding energy and power demand, with current and potential SIB fits highlighted. Blue: current SIB. Gray: future SIB. See: "Maritime Case Studies" section.

SIB SUITABILITY BY USE CASE

As shown earlier, SIB systems typically have lower energy density, but higher power density compared to mainstream LIB systems. SIB technology is thus less favorable when energy capacity is the main criterion but may be acceptable or even preferable to LIBs when power delivery is the primary requirement.

Good Fit: Peak Shaving, Transient High-Power
SIB's high discharge power capabilities mean they are well suited to applications where high-power demand is the primary requirement. This feature allows SIB to avoid the over-sizing issue where LIBs necessitate the use of a much larger battery to keep output within acceptable range.

Medium Fit: Short-Range Propulsion, Hotel-Load, Onshore Support
As an energy storage option, SIB such as polyanion or layered-oxide variants can also perform tasks where energy demand is moderate. This includes short-range propulsion, moderate hotel load, or when charging is adequately provided so batteries can be replenished regularly. Onshore support is a natural extension, given that SIB has already found use cases in grid energy storage [11].

Poor Fit: Long-Range Propulsion
When high energy demand becomes the top priority, it is recognized that battery alone is insufficient for both LIBs and SIBs alike. Battery systems may still find some use as secondary power sources, providing added benefits such as peak shaving.

Figure 4 summarizes these findings, showing SIB suitability for various applications in a power vs. energy demand matrix. It shows that SIBs are technically fit for a range of applications, but technical suitability alone is insufficient for decision-making. Overall business benefits under practical constraints will be the final decision-making criterion. This is discussed in more detail next.

SYSTEM INTEGRATION

When incorporating a battery system onboard, there are additional concerns that may affect both the battery system design and vessel design. These concerns typically cover electrical, environment, and safety aspects, which may require optimization to cater to SIB system features.

SAFETY CRITICALITY

Given the "similar in scope, but different in detail" nature of SIB risks, the safety system design considerations for SIBs should follow LIB safety system requirements to cover critical areas and adjust to fit specific SIB hazards. These safety-critical areas include mechanical protection (vibration, shock, slamming loads), temperature and off-gas detection, ventilation, passive or active suppression, and fixed extinguishers, with factors such as off-gas volume and compositions, TR temperature ranges and fire characteristics considered specifically for SIBs.

As an example, off-gas behaviors and protections are important considerations for LIB system designs [65], but different off-gas behaviors from SIB systems will require different protection considerations covering alternative vent path design, ventilation rate adjustment, and off-gas detector combinations. As such, developing a comprehensive and in-depth understanding of SIB system risks is therefore one of the most critical issues, which are not yet fully understood at the system level. In addition, the impact of calendar aging on SIB safety remains largely uninvestigated and requires dedicated study.

The firefighting philosophy for SIBs requires special attention. Water-based cooling is generally considered more appropriate [66] than gas-based flame suppression [67], similar to the LIB case. One distinct hazard, however, is the potential for sodium-water reactions: sodium deposits, formed during conditions including fast charging, high state-of-charge (SoC) and aging, may react with water to release heat and hydrogen gas. Sodium-water reactions are more vigorous than lithium-water reactions. While such events are considered rare, it should still be recognized as a potential hazardous factor [68] during firefighting.

In addition, sustained post-event cooling is still important; one report [69] showed that SIB can undergo TR at 30 percent of SoC. Further, SIBs can still retain considerable energy even at zero percent of SoC, highlighting stranded energy — energy remaining inside a battery after an accident, that cannot be discharged safely — as another hazard factor [94]. The studies cited above are mostly cell-level studies but provide insights much needed for further system-level safety considerations.

ELECTRICAL PROTECTION

For connection into the vessel power grid, the voltage profile of the battery system, which changes based on SoC levels, needs to be accounted for. As shown in Figure 5 with LFP and three different SIB cells (polyanion, layered oxide and PBA), the SoC-voltage profiles are quite different: LFP is famous for its flat SoC-voltage relationship over a wide SoC range; layered-oxide SIBs cover a large voltage range; PBA SIB voltage profile is narrow but linear; polyanion SIBs could have very complicated profiles with both linear and sloped regions.

While SIB's generally steeper SoC-voltage relationship could support a more accurate SoC estimation based on voltage changes, it is also complicated by other factors, such as stronger temperature dependence of resistance, and hysteresis between charge and discharge [60]. At the system level, state (SoC and state of health (SoH)) estimation inaccuracies create challenges for battery management, such as imbalance control difficulties [61]. The battery management system (BMS) design for SIBs therefore needs to take these factors into account and is to be fully validated before deployment.

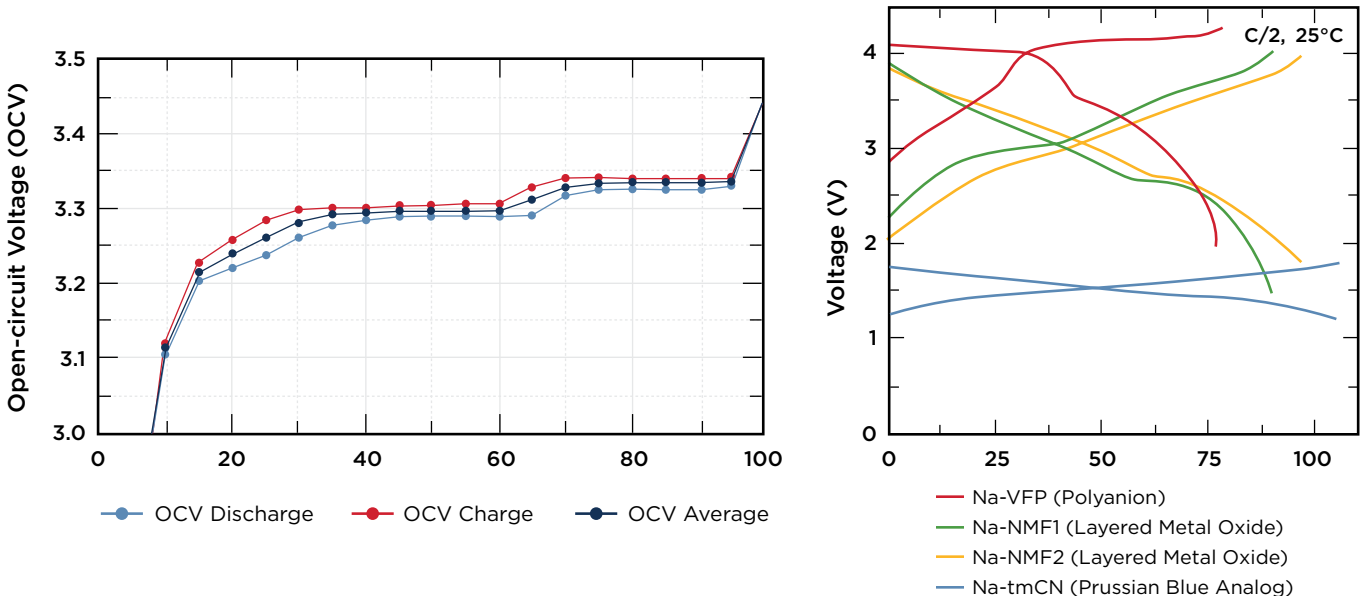


Figure 5: SoC-voltage characteristics for LFP and SIBs: charge/discharge curves for an LFP LIB cell (left) [62] and polyanion, layered oxide and PBA SIB cells (right) [63]. Adapted from Electronics 2021, 10(6), 705, Figure 1 [62], and Energies 2025, 18(3), 661, Figure 1(A) [63], under CC BY 4.0. Original figures were cropped and relabeled.

General electrical safety precautions are important for SIB systems as well, which cover multiple layers of protection and isolation to maintain grid stability, and electrical faults are to be properly handled without escalating to other parts. For example, a robust power management system (PMS) is critical for managing loads of various power sources. Similarly, BMS is an integral part of any battery system and manages its performance and safety. These systems are critical for SIB systems just as they do for LIB systems.

While many design principles can be adapted from LIB practices such as converters and distribution, SIB systems may still require chemistry-specific adjustments. For example, different current limits, usable SoC windows, and cell-to-cell variations need to be considered and validated in the battery system design.

For example, consider fault-current protection — protections taken against current generated by an abnormal electrical fault in the system, such as a short circuit and ground fault. While it has been addressed extensively for LIB systems [64], high-power SIBs with their lower internal resistance to support high C-rates, may produce higher peak short-circuit currents than LIBs, resulting in more intense energy release during the fault event. Protection coordination, such as fuse ratings and response timing, is to be assessed based on detailed understanding of SIB characteristics, which requires further system-level exploration and validation.

ENVIRONMENT CONDITIONING

Battery systems are often protected by features such as IP-rated enclosures to protect against water and sea fog corrosion, and temperature control to maintain optimal operation conditions.

These are required by SIB systems as well, and similar design logic can be borrowed from LIB practice, again adapted to SIB characteristics. For example, SIBs can tolerate -40 °C to 60 °C (Table 3) environment temperature range, which could reduce environmental-control system costs. At the same time, high-power operations for SIBs imply that ohmic heating could become more severe, and must be accounted for, in both battery thermal management system design and overall electrical system integration.

For certain small-scale applications such as starter batteries, passive cooling may be considered sufficient given the short duration of usage and battery performance boundaries. This argument, however, may not apply to larger battery systems with different use profiles. The thermal profiles should be evaluated and simulated to determine the appropriate cooling system requirements.

SYSTEM APPROVAL PATHWAYS

While approval criteria for LIBs can be used as a practical guideline, the differences between SIB and LIB need to be recognized, which means these LIB-specific criteria may not fully address SIB hazard characteristics, and

may need to be revisited when SIB-specific evidence becomes available. This is further discussed in the "Approval Pathways" section.

The discussions above suggest that SIB technology is still on its way to approaching system-level readiness: many aspects of system design remain unclear and calls for in-depth system-level studies to address these issues.

FINANCIAL IMPLICATIONS

The selection of energy storage technology is based on financial impact as well as technical suitability. Multiple factors may affect the outcome, and lifecycle costs — the overall cost of battery system for the vessel throughout its lifetime — is more useful for business case comparisons. These considerations are briefly discussed here.

TECHNOLOGY READINESS

Commercialization Landscape

While manufacturers around the world are entering the SIB market, commercial development stages for them are very uneven, and interest in maritime applications is still emerging as reflected in Table 4.

This lack of established supply chains for maritime applications could potentially constrain the availability of SIB and diminish adoption of interests. It also puts pressure on technology readiness, where availability of long-term technical support remains to be established — typical for technologies at this stage of commercialization. This could lead to potential risks in warranty, software support, maintenance, repair and replacement, and complicated end-of-life (EOL) disposal issues.

Region	Commercial Stage	Maritime interest
China [50, 52, 54, 57]	Ranging from pilot to commercial mass production phase	Actively exploring [51, 53]
UK/India [55]	Pilot/early commercial licensing and deployment stage	No indication
US [56]	Pilot moving into commercial production	No indication
France [40]	Pilot/early commercial production	No indication
Sweden [58]	Pilot stage	Actively exploring [59]

Table 4: Regional landscape of SIB manufacturing

Supply Chain Considerations

Supply chain resilience is one of the often-cited advantages of SIBs, which do not rely on costly lithium and other costly materials, making the SIB system attractive where supply chain security is a concern.

However, while the raw material itself for SIB is not costly, large-scale battery-grade production remains a key challenge that requires significant expertise and manufacturing knowledge, which are rapidly becoming carefully guarded trade secrets.

Also worth noting is that many SIBs do still make use of precious materials like nickel (Ni) and cobalt (Co) and hence may be subjected to the same geopolitical constraints as LIBs do. In short, while SIBs may help diversify the supply chain, immunity against external fluctuations can remain a long-term challenge.

SYSTEM COST

Upfront cost is often the biggest burden for maritime battery applications, which must be paid at an early stage, and can constitute a significant portion of total capex cost [70]. Therefore, battery cost advantage can be a decisive factor in the selection considerations.

SIBs are often perceived as having a cost advantage over LFP, the LIB cost benchmark; however, current SIB cell costs are in fact on par with, or even higher than LFP benchmarks [71], driven by the low raw material costs for LFP production [72]. Some studies [73] suggest this disadvantage reflects the fact that SIB production remains at pilot scale, unable to achieve cost reduction via economies of scale, at least in the near term. Notwithstanding these current constraints, this analysis points to a market development challenge rather than fundamental technology handicap, which may change as production scale increases, and the market grows.

OPERATIONAL CONSIDERATIONS

For battery installation, additional costs over its project life cycle include:

- Electricity cost including wastage
- Maintenance for normal operation cycle
- Replacement when part of the battery system is faulty
- Replacement when battery system reaches end-of-life
- Downtime and service include time and labor costs
- Contingency costs when battery becomes unavailable and are to be replaced with alternatives
- EOL cost including recycling and disposal

These costs should be evaluated as a complete package, as strengths in some fields can be masked by shortcomings in other fields. For example, smaller installation footprints may have lower initial costs but require multiple system replacements, resulting in higher total costs overall. In addition, these factors can change over time, for example maintenance costs can be higher for SIB systems now but are expected to decrease as systems mature, while electricity and end-of-life costs stay level or even increase due to changing demands.

Another cost factor is that the "early-stage" status of SIB production may also introduce higher cell-to-cell variations as manufacturing technology matures, which eventually manifests as degradation heterogeneity [74], increasing maintenance and replacement costs.

SYSTEM COST PROJECTIONS

Future SIB system costs are subject to the fluctuations of market development, and manufacturing costs may decrease if market development progresses. The competitiveness of SIBs not only depends on the cost reductions and market maturity of SIBs but are also subject to the potential fluctuations of LIB systems, especially those of LFP batteries.

For illustration purposes, representative cost figures for stationary BESS systems with LFP and SIBs are listed in Table 5. They do not fully reflect price trends for maritime systems but can provide some useful indications on future price trends between LFP and SIB. Overall, the prospects for SIB in maritime applications remain positive but are significant uncertainties affected by a diverse array of factors.

Metric	LFP stationary BESS [75]	SIB stationary BESS [76]
Cell Cost Today	~$40–80/kWh depending on market/ source; Chinese domestic stationary LFP cells around $40/kWh were cited in late 2025	~$59–87/kWh average estimates today; some broader ranges in older briefs run ~$80–105/kWh
Pack Cost Today	~$70–104/kWh depending on chemistry and source	~$90–125/kWh commonly cited in briefs/ reports
Utility Scale System Cost Today	~$125/kWh in highly competitive markets for large $4h_+$ projects; often higher in United States (U.S.)/EU	Not well established publicly; near LFP but often still higher today based on available cost commentary
Long Term Cost Outlook	Still falling, but already highly optimized and under intense competition	Potentially faster cost decline than LFP if production scales

Table 5: System cost metrics for stationary BESS projects. Maritime ESS may be more costly than stationary BESS applications because of additional safety requirements.

So far, the financial discussions have remained qualitative and directional, which presents a mixed outcome for SIBs: it may be cost saving on some aspects but could be more costly on others. A better understanding could be achieved by adding a quantitative element in the form of case studies, combined with selected sensitivity analysis cases, which are carried out in the next section.

MARITIME CASE STUDIES

As discussed previously, there are many factors affecting the financial aspects of SIB applications, and their trade-offs could be complicated. In this section, a quantitative element is introduced to evaluate SIB's suitability in a maritime context, illustrated with two example vessels. They are representative of current LIB system use cases and form a concrete baseline for SIB evaluations.

CASE STUDY METHODOLOGY

CASE SELECTIONS

Given SIB's high-power capacity and cold environment tolerance, novel applications such as icebreakers could be interesting but too niche for broader maritime application evaluations. Therefore, cases where LIB systems have already demonstrated their merit were considered. This would permit better appreciation of the potential and pitfalls of SIB systems. Further, the cases selected are to cover very different demand profiles, from high-power use cases to high-energy ones.



Figure 6: Example vessel illustration. AI-generated image.

Based on the selection criteria, two study cases are selected: electric harbor tugboat, and containerized battery (CBS) powered containerships.

Case A: Electric Harbor Tugboat
Already gaining interest in its potential to reduce port operation carbon emissions, electric tugboats constitute a valuable platform to study battery systems in maritime, including SIB systems. It typically has a short operation range within the port area, short duty duration but requires high power when performing operations, making it the "high-power-demand" study case of choice.

There already exist several LIB-powered electric tugboats in operation, such as *Eon*, a 29 meter (m) long, 50-ton bollard pull equipped with 2 MWh LIB battery pack [77], that operates in Singapore ports. The first case is thus built based on this example vessel.

Case B: CBS-Powered Container Ship
Designed for near-sea operations, container ships equipped with swappable CBSs are gaining popularity, especially in China. Operating longer routes, these containerships require more energy for operation range, while the standardized CBS supports swapping, capable of completing the recharge process in under half an hour. These features make this case interesting on two fronts: how parameters change with a SIB-equipped CBS, and how this system performs in energy-dominated applications.

The selected reference example is *Ningyuan Diankun*, currently (as of July 2026), the largest pure electric sea-going container vessel [78], 127.8 m in length with 10 CBS systems onboard, offering a cargo capacity of 740 twenty-foot equivalent unit (TEU). This second case is used to evaluate SIB performance under similar circumstances, where the balance of energy density and cost is most important.

CASE STUDY METHODOLOGY

Key Calculations

Calculations for total lifecycle costs are separated into three components: battery sizing, system costs and operational costs. These three aspects are expected to be sufficient to answer questions surrounding maritime installations, such as installation footprint demands, initial cost hurdles, and overall lifecycle costs, for financial considerations.

Since the study focuses on battery technologies comparisons, a calculation combining installed assets and operations is sufficient to produce cost differences for current analysis; details of absolute values such as impacts of financial instruments are not included.

Cell Chemistry and Sizing Calculations

With the key usage parameters given, the battery system size is calculated based on both power and energy demands, and the higher value is selected. SoC/SoH limitations are also factored in, to ensure the demand can still be met throughout battery system lifespan.

Battery parameters for sizing calculations are listed in Table 6. They are estimated based on available commercial systems with a conservative margin. For SIB systems, commercial information is often insufficient or absent; in such cases, representative cost figures are extrapolated from cell-level information, based on observed LIB cell-to-system cost change trends.

Cell manufacturers typically optimize one or two performance attributes, among energy density, power density or cycle life, at the expense of the third. Given the selected case studies that are power-focused and energy-focused respectively, high-energy and high-power variant parameters are populated for NMC, LFP, and SIB separately, based on representative maritime systems instead of niche high-power cells which are not widely used in this field.

Generally, for SIB systems, polyanion or metal oxide types are considered as the “high-energy” type, and PBAs as the “high-power” type. Note that the “high-energy” SIB still falls behind LFP batteries in terms of capacity, but “high-power” SIB can exceed that of high-power NMC batteries.

Cycle life values are based on usable duty-window values relevant to maritime cycling assumptions; such values are estimated for SIB systems based on similar parameter extrapolation methods.

Chemistry (Subtype)	GED (Wh/kg)	VED (Wh/L)	GPD (W/kg)	VPD (W/L)	Cycle Life	Cell Cost ($/kWh)
NMC (Energy) [79]	170	210	120	150	4,000	**130**
NMC (Power) [80]	110	140	350	500	4,000	**130**
LFP (Energy) [81]	130	210	80	120	7,000	**100**
LFP (Power) [82]	115	140	150	220	6,000	**100**
SIB (Energy) [39]	115	170	180	260	6,000	**130**
SIB (Power) [40]	70	100	450	650	7,000	**150**

Table 6: Chemistry characteristic assumption values, at the system level. Cell-level costs are used for baseline calculations.

System Cost Estimations

Based on installation sizes, the installation cost is calculated based on cell costs, accompanied by add-ons accounting for a range of factors in system integration.

Available cell-level costs from commercial sources are used as baseline, instead of system-level averaged costs, to ensure these values remain comparable across different chemistries and platforms. It does put SIB at a disadvantage, as pilot-stage productions typically inflate the cell prices. This, however, will be discussed further in sensitivity analysis and future deployment scenarios.

For system factors, three key portions are considered: 1) cooling system, 2) safety features, and 3) risk contingency (See Appendix), which are assumed to be related to cell costs. SIBs are assumed to have higher system integration costs, lower cooling system costs, and comparable protection system costs against the LFP benchmark. An additional risk contingency factor is added, representing overruns because of technology uncertainties.

Total Lifecycle Cost

The total lifecycle cost combines 1) asset cost (capex), combining installation cost and replacement cost, 2) operations cost (opex), including electricity cost, maintenance cost, and 3) EOL costs containing disposal cost and residual value (See Appendix).

Replacement is calculated based on total required electricity throughput versus lifetime throughput of the battery system; it is assumed that an entirely new system is replaced each time, at the same cost. Operation and maintenance costs are calculated on a yearly basis and treated as fraction of installation system cost. Electricity consumption and electricity loss due to roundtrip efficiency are both considered. Finally, EOL costs add up disposal cost and residual values.

NMC has a negative EOL value (net gain), as its critical material content makes its recycling revenue-generating. This is opposite for LFP and SIB, which contain minimal amounts of valuable minerals, and disposal process with net loss for EOL costs.

STUDY LIMITATIONS

The biggest limitation comes from uncertainties surrounding SIB systems. For SIB systems, the technology is developing, the supply chain is maturing, and the relevant costs are affected by acceleration or deceleration of the development paces. This may have a significant impact on the business case and is further explored with sensitivity analysis in later sections.

As discussed in the previous sections, system design for SIB may not follow the same principles as LIBs, which may add further uncertainty to the cost estimations and would require further studies for clarification. ABS can support collaboration among stakeholders involved in SIB development and deployment, further elaborated in the next section.

Given the complexity of the case studies, system costs are not broken down into component-level details, such as potential changes in safety protection features requirements and accompanying cost savings.

CASE STUDY A: ELECTRIC HARBOR TUGBOAT

CASE PARAMETERS

With reference to the example vessel, the following parameters are constructed in Table 7.

Parameter	Value
Duty Duration/h	2
Usable Energy Required (kWh)	2,000
Continuous Power Required (kW)	750
Peak Power Required (kW)	3,000
Peak Power Duration (minimum)	10
Daily Cycles (cycles/day)	4
Days per Year (days/year)	330
Project Life (years)	15
Degradation Reserve	1.15

Table 7: Electric harbor tugboat requirements.

The defining feature is the high peak power demand, at 3 MW, although only for a short duration. While charging protocol is another critical factor, it also depends on port infrastructure and fleet management, so it is not discussed as part of this case study. Given the high-power demand, NMC, LFP and SIB power-type battery systems are specifically included.

RESULTS AND COMPARISON

Battery Sizing and Footprint

The results shown in Table 8 clearly indicate that energy-type batteries are penalized for their low power density and need to be oversized, except for the energy-type SIB, which already provides sufficient power capacity. The power-type SIB requires oversizing to meet energy demands because of its low energy density.

System Configuration	NMC (Energy)	NMC (Power)	LFP (Energy)	LFP (Power)	SIB (Energy)	SIB (Power)
Installed Energy (kWh)	4,887.5	3,538.5	5,606.3	2,875.0	2,555.6	2,555.6
Installation Mass (kg)	28,750	32,168	43,125	25,000	22,222	36,508
Installation Volume (m^3)	23.3	25.3	26.7	20.5	15.0	25.6

Table 8: Expected system configurations.

It should be emphasized that SIB system parameters are extrapolated from current LIB systems, which could change as dedicated SIB systems are developed.

Total Lifecycle Cost

Total lifecycle cost is presented in Table 9. NMC are heavily penalized for the short cycle-life (4,000 cycles) assumptions, resulting in multiple replacements required for the entire life cycle.

Value (Million $)	NMC (Energy)	NMC (Power)	LFP (Energy)	LFP (Power)	SIB (Energy)	SIB (Power)
Capex	3.65	3.25	1.57	1.21	1.55	1.71
Opex	4.72	4.55	4.62	4.40	4.62	4.65
EOL Cost	(0.20)	(0.18)	0.11	0.08	0.08	0.08
Total Cost	8.17	7.63	6.30	5.70	6.25	6.43

Table 9: Cost calculations and breakdowns. Initial cost refers to first battery system cost (same definition below).

For this case study scenario, the LFP high-power type system is clearly favorable. Despite the favorable installation footprints, SIB total cost currently exceeds the LFP benchmark, driven primarily by the higher cost inputs used at this early production stage.

SENSITIVITY STUDIES

For the sensitivity studies, three key parameters are selected: cell cost basis, cycle life, and roundtrip efficiency. Values for SIB are varied, total lifecycle costs are compared to the LFP baseline, and the differences in costs ("Δ total lifecycle cost") are calculated and shown in Figure 7. The results show a clear sensitivity to cell costs and roundtrip efficiency. When cell cost is around 100 $/kWh on parity with LFP cells, it starts to achieve a net cost reduction compared to LFP baselines. On the other hand, variations in cycle life do not result in a cost advantage over LFP, though cost reductions are achievable. These two simple cases highlighted two main factors for further improvements: battery cell cost reduction and roundtrip efficiency improvements.

While current SIB cell cost premium is the key factor, it does not reflect inherent material costs but rather are consequences of nascent production scale and fundamentally a market-maturity challenge rather than a technology limitation.

Roundtrip efficiency is another factor worth considering given the magnitude of electricity consumption; small improvement in roundtrip efficiencies can be highly favorable when total costs are considered. Overall, these findings support the earlier analysis that the main hurdles would come from manufacturing scaling up and system integration.

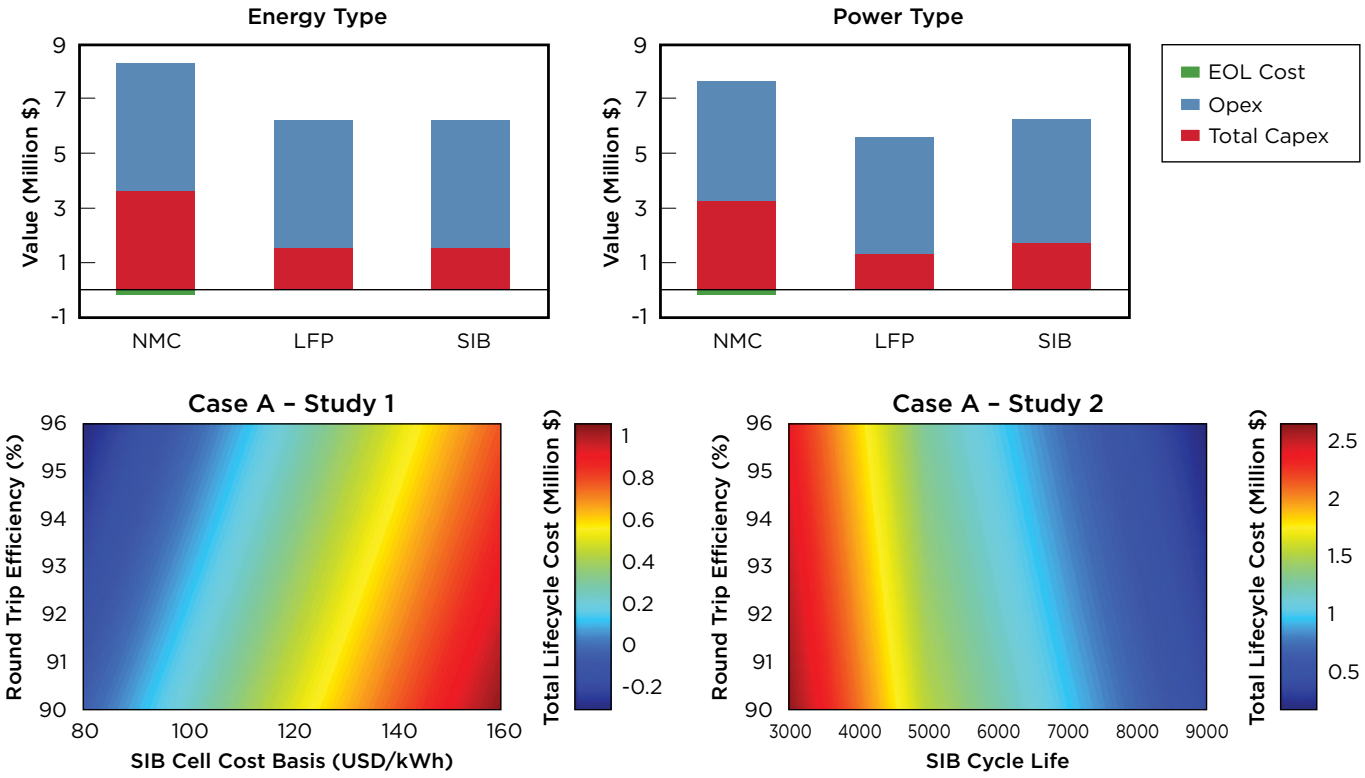


Figure 7: (Top left) cost breakdown for energy-type cases; (top right) cost breakdown for power-type cases; (bottom left) sensitivity study of cell cost, round trip efficiency vs. total cost changes against LFP baseline; (bottom right) sensitivity study of cycle life, round trip efficiency vs. total cost change, also against LFP baseline.

CASE STUDY B: 800 TEU CONTAINERSHIP

CASE DEFINITION

With reference to the example vessel, the following parameters are listed in Table 10.

Parameter	Value
Baseline Container Counts	24
CBS Energy Limit (kWh)	2,000
Baseline Energy Required (kWh)	30,000
System Cost Factor	2
Container Fixed Cost ($)	200,000
Daily Cycles (Cycles/Day)	2
Days per Year (Days/Year)	330
Project Life (Years)	15
Degradation Reserve	1.15
20-ft Container Total Volume (m^3)	33.2
Battery Space Fill Proportion (%)	50%

Table 10: Containership usage parameter assumptions.

CBSs, compared to normal battery system installations, are more integrated and standardized. To reflect this characteristic, a standard "system cost factor" is incorporated to calculate system cost based on cell costs. On top of that, a flat container cost is added as the containers are built to meet international standards. Cell choices considered are LFP and SIB, both energy-type. NMC is not considered because currently available CBS products offered mainly use LFP.

The maximum allowable energy per CBS is evaluated using two cases. In the first case, SIB CBSs are set to have the same capacity as the LFP ones, which helps keep other parameters constant. In the second case, this limit is removed; the uncapped per-container capacity is calculated based on space fill proportion by batteries, estimated to be 50 percent accounting for internal equipment and arrangement. These two cases ("capped" and "uncapped") are discussed separately, as energy density may change the comparison.

RESULTS

Capped Container Case

Calculation outcomes are presented in Table 11. Since the container capacity is limited, installation base is identical for all cases.

System Configuration	LFP	SIB
Installation Footprints		
Total Installed Capacity (kWh)	48,000	48,000
Container Count	24	24
Total Battery Mass (kg)	369,231	417,391
Total Installed Mass (kg)	424,431	472,591
Total Installed Volume (m^3)	796.8	796.8
Cost Breakdown (in million $)		
Initial Cost	14.40	17.28
Capex	28.80	34.56
Opex	39.47	42.65
EOL Cost	0.48	0.48
Total Cost	68.75	77.69

Table 11: Capped container capacity case results.

In this energy-dominated scenario, SIB systems show higher costs and somewhat larger mass footprints at current parameters, which is expected given the lower energy densities and higher costs compared to LFP systems.

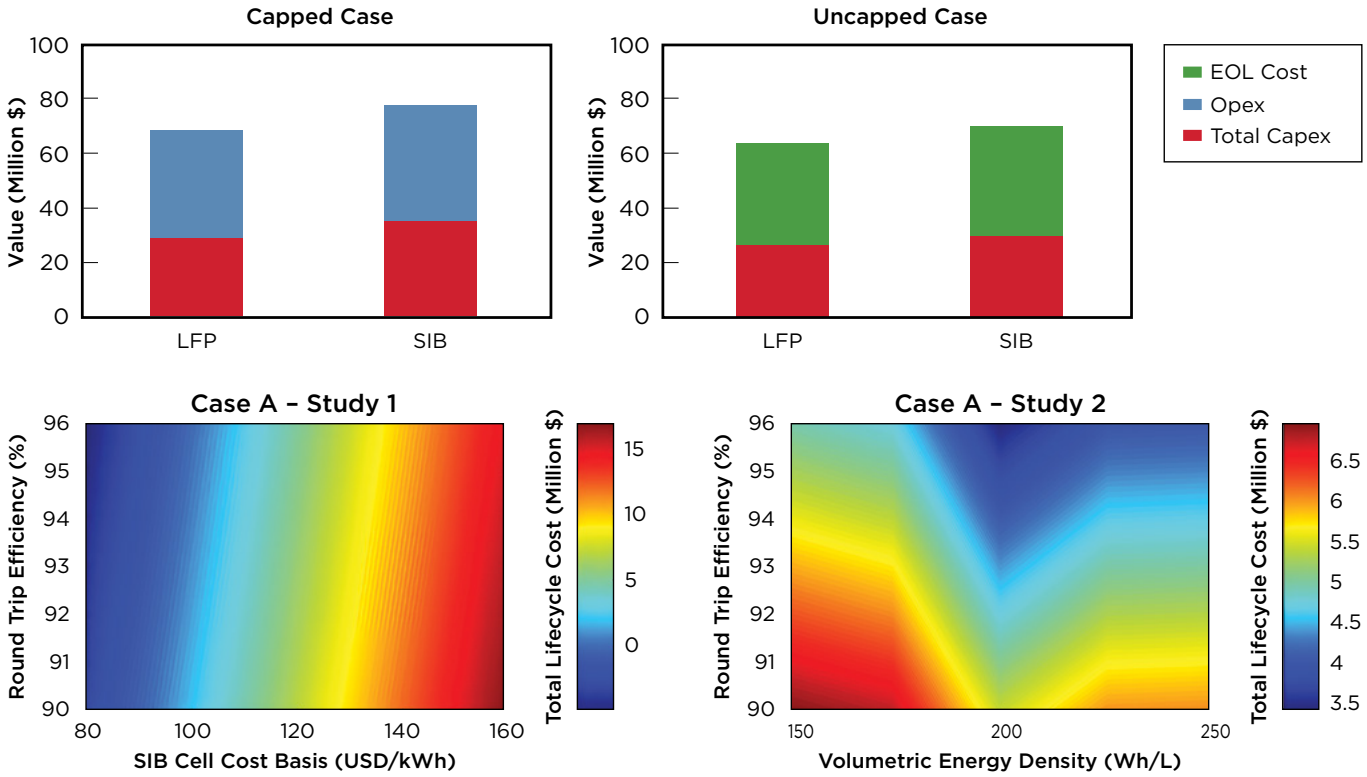


Figure 8: (Top left) cost comparison for capped capacity case; (top right) cost comparison for uncapped capacity case; (bottom left) sensitivity study of cell cost basis, round trip efficiency vs. cost reductions; (bottom right) sensitivity study of VED and round trip efficiency vs. cost reductions.

Uncapped Container Case

When the capacity cap is removed, the results as shown in Table 12 change slightly but are still in agreement with earlier capped capacity cases. SIB systems at current level are not yet at cost parity with LFP systems when energy demand becomes the dominating factor.

System Configuration	LFP	SIB
Installation Footprints		
Container capacity (kWh)	3,486	2,822
Container Count	14	15
Installed Energy (kWh)	48,804	42,330
Installed Battery Mass (kg)	375,415	368,087
Total Installed Mass (kg)	407,345	402,587
Installed Volume (m^3)	464.8	498.0
Cost Breakdown (Values in Million $)		
Initial Cost	12.56	14.01
Total Capex	25.12	28.01
Opex	38.42	40.69
EOL	0.49	0.59
Total Cost	64.03	69.28

Table 12: Uncapped container size case.

SENSITIVITY STUDIES

For case B, sensitivity studies are conducted on both scenarios, respectively.

For the "capped" case, cell cost and roundtrip efficiency, similar to case A, are found to be most impactful for cost reductions. However, in this case a more aggressive cell cost reduction down to about 90 $/kWh is needed to reach cost parity with LFP systems. The reason is that for energy-intensive use cases, the biggest advantage of SIB systems — power density — is not fully utilized.

For the "uncapped" case, VED, which impacts the energy content of individual containers, is another impactful factor besides cell costs. However, the observed trend is non-linear, with VED at 200 Wh/L showing a local minimum. Two factors are in force here: lower VED values result in higher container counts, and system oversizing due to containers installed in whole units, rather than simply catering to the system's demand closely.

FUTURE DEPLOYMENT SCENARIOS

Given the rapid advances of SIB development, three selected future scenarios are considered to explore how the situation might change in 5-10 years' time, based on 1) a conservative 5-10 percent change from baseline, 2) a moderate scenario of 20-30 percent change, and 3) an optimistic change of 30 to 50 percent, as exploratory scenarios intended to reflect technically plausible development pathways. Cell cost and cycle life values used larger change margins, while roundtrip efficiency and energy density used smaller change margins. Detailed input values for future projections are shown in Table 13.

Parameters for Case A	Baseline	Case 1	Case 2	Case 3
Cell cost ($/kWh)	150	135	112.5	97.5
Roundtrip Efficiency (%)	92	93	94	95
GED (Wh/kg)	70	77	84	91
Cycle Life	7,000	7,700	8,750	10,500
Parameters for Case B	**Baseline**	**Case 1**	**Case 2**	**Case 3**
Cell Cost ($/kWh)	130	117	97.5	84.5
Roundtrip Efficiency (%)	92	93	94	95
VED (Wh/L)	170	187	204	221
Cycle Life	6,000	6,000	7,500	9,000

Table 13: Future scenarios parameter inputs.

Earlier, cell cost was identified as one of the main cost reduction factors. For future scenarios, cases two and three have cell cost levels comparable with current LFP benchmarks. This is one of the most frequently cited advantages of SIB systems [73].

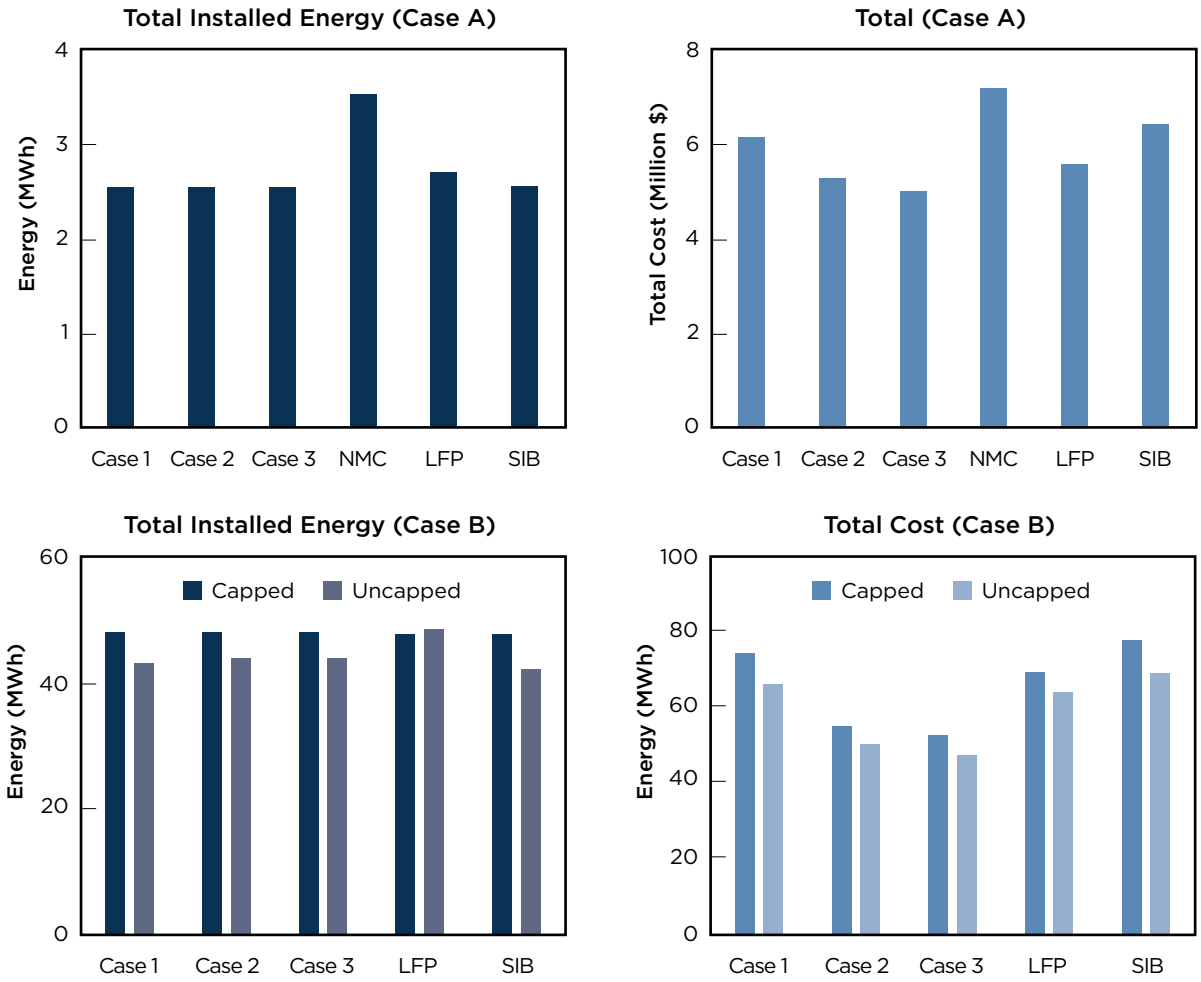


Figure 9: Future SIB scenario studies for case A: (top left) total installed energy, and (top right) total cost for future scenarios. Also shown are case B: (bottom left) total installed energy and (bottom right) total cost for future scenarios of case B. Please refer to Table 13 for SIB case definitions (cases 1, 2 and 3).

For case A, at moderate to optimistic future scenarios a smaller installation base and lower total costs are achieved for SIB systems in comparison with LFP benchmark, showing a favorable outlook for future SIB applications.

For case B when container capacity is capped, future cases can deliver a favorable total cost with moderate projections (Figure 9, case 2). When container capacity is not capped, SIB systems can appear favorable in terms of installed energy, while costs are slightly higher than LFP baseline, at conservative projections (Figure 9). However, the actual contributing factor is that LFP is oversized because of the use of full containers. This points to a potential advantage of SIB systems; smaller per container capacity may provide greater flexibility in system configuration.

Overall, the conclusion from the case studies suggests moderate improvements of SIB system parameters: cell-level costs, cycle life, energy density, and roundtrip efficiency, could position SIB at competitive level with incumbent LFP systems. These improvements are individually modest, and many are already under active development, such as cell cost, energy density and cycle life. Achieving SIB competitiveness does not require breakthrough innovations; rather, it depends on incremental improvements along established development pathways.

CASE STUDY FINDINGS

The case studies and future SIB projections deliver a coherent message: SIB can find relevance in maritime applications particularly in applications where power demand is the primary design driver. It is also clear that continued development in SIB is needed to improve its business attractiveness.

From a technical suitability aspect, current SIB systems are already comparable with LIB systems for high power applications and can deliver a footprint advantage where cell characteristics match the duty profile. One factor that could further improve its appeal is roundtrip efficiency. Maritime installations are large-size installations; even small improvements in roundtrip efficiency could deliver impactful cost reductions in wastage.

More challenges could come from the financial aspect, where both sensitivity studies and future projection scenarios point to cell costs (currently above LFP) being the key hurdle for SIBs to become favorable in a business case. Nevertheless, the current cost gap reflects a production challenge; closing it will require coordinated efforts across the value chain: cell manufacturers scaling production, upstream suppliers establishing pipelines, and downstream system integrators building maritime-specific experience. On this aspect, ABS seeks to support closer collaboration with the SIB ecosystem so the potential can be fully realized.

ADOPTION GAPS AND DEVELOPMENT PATHWAYS

Besides technical limitations and business challenges, the path of SIB systems towards applications is not straightforward. The maritime context demands high reliability, safety and conformity, which are achieved through a structured framework of international standards, statutory regulations and class requirements. For SIB systems to successfully enter maritime applications, a similar framework must be constructed. Unfortunately, just as SIB is still at its early stage of commercialization, the regulatory network is also at its infancy, with many gaps waiting to be filled.

This section will identify these gaps and explore mitigation pathways, organized around deployment and regulatory considerations. Greater collaboration between the maritime industry and battery manufacturers could help address these challenges.



Figure 10: Illustration of SIB application gaps.

GAPS TO MARITIME ADOPTION

For SIB systems, many of these gaps stem from a lack of available system-level information. These gaps are categorized into four types: performance and validation, hazard and safety protection, commercial and support, and regulatory framework.

GAPS IN PERFORMANCE AND VALIDATION

Despite numerous claims and reports regarding SIB performance, system-level performance metrics that are verified and validated are scarce, which hinders a reliable assessment of the performance metrics, especially for large-scale, mission-critical installations.

This scarcity reflects limited installation cases for SIB systems, which are expected to supply the industry and public alike with first-hand, reliable usage data. Without such pilot projects, data collection remains challenging, which further hinders technology adoption.

GAPS IN HAZARDS AND SAFETY PROTECTION

Safety is always a top priority for the maritime industry. For SIB systems, understanding of its safety in maritime context is limited. While laboratory testing has provided valuable cell-level insights, those may not reveal the whole risk profile when used at large scale, under a challenging maritime environment.

The risk mechanisms associated with SIBs are broadly similar to those of LIB systems but are sufficiently different in detail that directly transferring safety design principles for LIB systems to SIB systems is not the best option.

For example, given a lower TR temperature of SIB cells [25], temperature detection threshold is to be lowered; ventilation rate and arrangement are to be designed specifically for the off-gas composition[33]; and potential for reignition requires further exploration and testing. Directly adopting LIB safety system designs without validating against SIB-specific hazards may risk creating a false sense of security.

GAPS IN COMMERCIAL AND SUPPORT

Maritime energy storage projects are characterized by long cycle life and large variations in demand over time. For a typical vessel, battery systems are expected to be delivered at the MWh scale within a short timeframe, supported for 10 years or longer and ultimately decommissioned or disposed of at the end of the project life cycle.

These features create huge demand for spikes and long-time service obligations for cell manufacturers and system integrators, which can be particularly challenging for emerging technologies like SIBs. When such obligations cannot be reasonably guaranteed, clients would move away from SIB systems altogether.

REGULATORY GAPS

Since its increase in popularity in the 2020s, various organizations and government bodies have started developing regulations for SIBs. A brief overview is presented below.

Regulatory Body	Area	Key Developments
UN	Transport	UN Model Regulations Rev. 23 [84], UN 38.3 [85]
IMO	Transport	IMDG code updated based on UN regulations [86]
SAC (GB)	Application, Reginal	GB/T 44265-2024 is active for SIB ESS; other standard projects are underway
UL	Application, Reginal	Several standards (UL 1973, 9540A) referred to SIBs under generic battery umbrella

Table 14: Current SIB regulations overview.

n the case of LIB, the regulatory framework is constructed over many layers: a) production layer, for example IEC 62619; b) transportation layer, mainly through UN and IMO regulations; c) application layer; for the maritime case, it is supported by international standards and classification society requirements, for example ABS Requirements for Use of Li-ion Batteries in the Marine and Offshore Industries [65].

Examining the existing regulations surrounding SIBs, it is very clear that the coverage for the different layers is highly uneven. The transportation layer is comparatively well established through international regulations. UN model regulations in its 2025 updates included new entries: UN 3551: SIBs with organic electrolytes, UN 3552: SIBs contained in equipment, UN 3558: vehicles containing SIBs, and UN 3564: SIBs installed in cargo transport units. The IMO IMDG code subsequently included those entries in the 42-24 amendment for maritime transportation requirements.

On the other hand, production and application layers remain incomplete. Internationally recognized standards are yet to be established. At national level, SAC (China) has requirements limited to stationary ESS applications, while UL (US) covers SIBs using existing LIB requirements as a reasonable stop-gap solution, but may not fully match SIB hazards. At international level, IEC technical committee TC 21 [87] states several "secondary sodium-ion cells" standards are in pipeline, such as IEC 63591, 63711, and 62281. Publication, however, will still take time.

In the maritime industry, classification societies have not yet developed dedicated requirements for SIB systems because deployment remains limited. Without an established regulatory framework, SIB adoption in the maritime industry will likely remain fragmented, limited in scale and could potentially put both manufacturers and end users at risk.

MEASURES TO ADDRESS ADOPTION GAPS

For SIB technology to achieve market success, these gaps are to be overcome first. While they cover many distinct aspects, the root cause is insufficient information visibility at the system level. Therefore, several measures are proposed to improve information flow and reduce barriers to adoption.

- Information sharing at the system level through a network that collects, validates and shares system-level information on SIBs, including battery performance, risk profiles and long-term degradation trends. This information is critical to support design and evaluation.
- Pilot studies of SIB systems at sizes relevant to large-scale applications. It is encouraging that SIB has already seen applications in stationary ESS installations, covering the large-scale installation spectrum. Experience gained from these projects can provide valuable input to the information network.
- Project collaboration to create a shared ecosystem. Entry barriers for SIB to enter maritime industry exist on both ends: vessel owners face huge initial capital demands, while battery manufacturers must provide long-term service obligations. A consortium comprising stakeholders across the ecosystem, supported by credible organizations including ABS, may provide assurance and help reduce these barriers

ABS' ROLE IN TECHNOLOGY DEVELOPMENT

ABS' ROLE IN THE SIB ADOPTION PATHWAY

As a classification society that prioritizes safety and innovation, ABS believes SIB technology has potential for maritime applications and aims to support clients on their path to technology adoption. With respect to the bridging routes mentioned earlier, ABS can support several aspects of the adoption pathway through evidence validation, knowledge development and framework construction.

ABS can assume the role as third party assessor and perform pilot project verification and information validation, so this information is accessible and credible for the maritime and battery industry.

ABS also actively engages clients from the maritime ecosystem including regulators, ship owners, shipyards and system integrators; as such, ABS can facilitate collaboration among regulators, shipowners, shipyards and system integrators to pave the way for SIB maritime market readiness.

A PRACTICAL ABS-CLIENT COLLABORATION STRATEGY

Further elaborating on the support from ABS for the SIB adoption pathway, a six-step strategy is proposed here based on practical development routes.

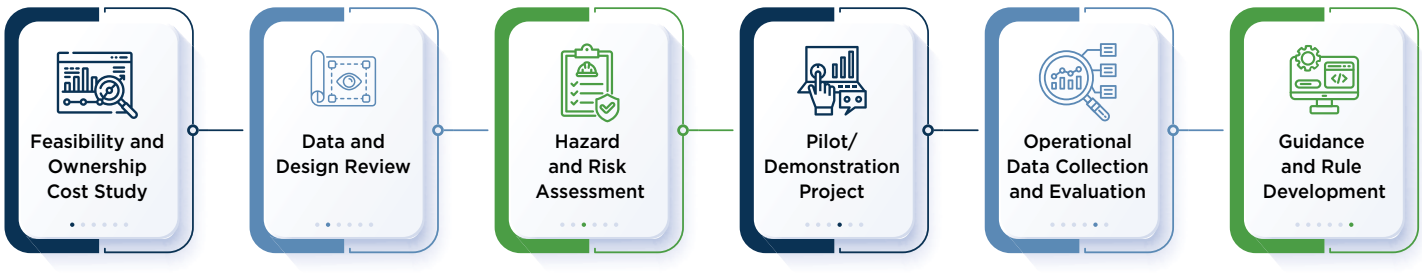


Figure 11: Six-step pathway for ABS-client joint SIB technology applications.

Stage 1: Feasibility Study
ABS supports the client to make well-informed decisions on project designs by conducting feasibility studies on technical and financial aspects of the intended project. This will provide forecast reference points and highlight potential challenges so they can be resolved on time.

Stage 2: Data and Design Review
After the project starts, ABS, with its team of highly experienced maritime engineers and technology experts, is well positioned to support clients on design reviews, ensuring the assets are seaworthy.

Stage 3: Hazard and Risk Assessment
To further support operational safety, ABS supports risk assessment by reviewing and validating the hazard assessment produced. This will support project credibility when foreseeable risks are accounted for and appropriately addressed.

Stage 4: Pilot or Demonstration Project
Transitioning from design to construction and demonstration is often challenging; ABS can provide support in the form of technical assessment, ensuring the components conform to standards and perform as intended.

Stage 5: Operational Data Collection and Evaluation
For pilot projects, data collection constitutes a core component. ABS can support this with software tools and established methodologies to collect and analyze data, and is capable of real-time data support, which will be valuable for the project execution phase.

Stage 6: Guidance and Rule Development
With successful project conclusion and client consent, ABS shares lessons learned and project experience through structured reports. The lessons learned, like some of ABS' earlier published reports, can provide the industry with valuable insights into SIB technology.

The six-step collaboration strategy presented above aligns with the ABS New Technology Qualification (NTQ) process outlined in ABS *Marine Vessel Rules* Part 1D [88], which provides a formal, stage-gated framework to qualify novel technologies. The ABS NTQ process provides a structured pathway for evaluating and qualifying SIB technology for maritime applications

CONCLUSIONS

The discussions above indicate that SIB technology is likely to find suitable roles in the maritime industry where its strengths can be effectively applied, particularly in high-power use cases and possibly some niche areas where temperature tolerance is critical.

Practical challenges also exist for maritime entry, particularly around cost competitiveness and system-level validation. Nevertheless, these reflect the current level of market maturity more than fundamental technology limitations. Before SIBs can be applied in maritime settings, several gaps must be addressed, including limited information availability and incomplete regulatory development.

As a classification society, ABS has identified several roles it can fulfill and a practical collaboration strategy for SIB maritime applications. ABS can support collaboration across the SIB ecosystem and help build the foundations for its development.

APPENDIX

CASE STUDY INPUT DETAILS

Assumptions for financial calculations:

Chemistry	Cell Cost ($/kWh)	Integration Factor	Cooling System Factor	Risk Contingency Factor	Operation and Maintenance Factor	EOL Baseline ($/kWh)	Residual Value ($/kWh)
NMC (Energy)	**130**	1.15	0.25	0	0.04	45	55
NMC (Power)	**130**	1.15	0.23	0	0.04	45	55
LFP (Energy)	**100**	1.15	0.22	0	0.038	25	15
LFP (Power)	**100**	1.15	0.22	0	0.038	25	15
SIB (Energy)	**130**	1.2	0.2	0.1	0.04	25	15
SIB (Power)	**150**	1.18	0.18	0.08	0.04	25	15

DESCRIPTION OF LIFECYCLE COST CALCULATIONS

For Case A, sizing is calculated separately for energy-basis and power-basis; the largest is selected for further finance-related calculations.

DEFINITIONS

E_U	Usable Energy
SOC	Usable SoC Range
GED	Gravimetric Energy Density
GPD	Gravimetric Power Density
VED	Volumetric Energy Density
VPD	Volumetric Power Density
P_P	Peak Power
F_{OM}	O&M Factor
F_{RT}	Roundtrip Efficiency
$C_{EOL,base}$	End-of-life Base Cost
$C_{electricity,base}$	Electricity Unit Cost
n_{day}	Number of Daily Cycles
n_{year}	Number of Days Per Year
n_{life}	Project Life in Years
n_{cycle}	Battery Cycle Life
F_{cool}	Cooling System Cost Factor
F_{risk}	Risk Contingency Cost Factor
F_I	Integration Factor
$C_{R,base}$	Base Residual Cost
F_D	Degradation Factor
C_{Cell}	Cell Cost

EQUATIONS

1. Required Energy, $E_R = \frac{E_U}{SOC} * F_D$
2. Energy-based Mass, $m_E = \frac{E_R}{GED}$
3. Power-based Mass, $m_P = \frac{P_P}{GPD} * F_D$
4. Installed Mass, $m = \max(m_E, m_p)$
5. Installed Energy, $E = m * GED$
6. System Factor, $F_S = F_I * (1 + F_{cooling} + F_{risk})$
7. Initial Cost, $C_{initial} = E * C_{cell} + F_S$
8. Annual Throughput, $Q_{annual} = E_U * n_{day} * n_{year}$
9. Lifetime Throughput, $Q_{lifetime} = Q_{annual} * n_{life}$
10. Battery Cycle Life Throughput, $Q_{cycle} = E * SOC * n_{cycle}$
11. Replacement, $n_R = int\left(\frac{Q_{lifetime}}{Q_{cycle}}\right)$
12. Replacement Cost, $C_{replacement} = n_R * C_{initial}$
13. Total Capex, $C_{Capex} = C_{initial} + C_{replacement}$
14. O&M Cost, $C_{OM} = C_{initial} * F_{OM} * n_{life}$
15. Electricity Cost, $C_{electricity} = Q_{annual} * \left(\frac{1}{F_{RT}}\right) * C_{electricity,base} * n_{life}$
16. Total Opex, $C_{Opex} = C_{OM} + C_{electricity}$
17. TOTAL EOL Cost, $C_{EOL} = E * \left(C_{EOL,base} - C_R\right)$
18. Total Lifecycle Cost, $C_{LCC} = C_{Capex} + C_{Opex} + C_{EOL}$

For Case B, the calculation is similar with one small difference. Instead of calculating the battery size directly, the container capacity is calculated first (in an uncapped capacity case), and number of containers are calculated. Taking note “fractional container” is not used.

DEFINITIONS

F_F	Volume Fill Factor
$V_{container}$	Container Volume

EQUATIONS

1. Container Capacity, $C_{container} = V_{container} * F_F * VED$
2. Number of Containers used, $n_{container} = int\left(\frac{E_R}{C_{container}}\right) + 1$

   Total installed capacity results are verified to reduce oversizing, if the difference between required energy and installed capacity is too large.
3. Installed Capacity, $C_{installed} = C_{container} * n_{cont}$
4. The rest of the calculation is the same as case A workflow.

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ACRONYMS AND DEFINITIONS

ABS	American Bureau of Shipping
BESS	Battery Energy Storage Systems
BMS	Battery Management System
capex	Capital Expenditures
CBS	Containerized Battery System
CCS	China Classification Society
EOL	End of Life
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicles
GED	Gravimetric Energy Density
GHG	Greenhouse Gas
GPD	Gravimetric Power Density
IACS	International Association of Classification Societies
IMDG	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
LFP	Lithium Iron Phosphate (LIB cathode material)
LIB	Lithium-ion (Li-ion) Battery
LTO	Lithium Titanate (LIB anode material)
NASICON	Sodium Super-ionic Conductors (SIB cathode material)
NMC	Nickel-Manganese-Cobalt (LIB cathode material)
NTQ	New Technology Qualification
OCV	Open-circuit Voltage
OEM	Original Equipment Manufacturers
opex	Operational Expenditures
PBA	Prussian Blue Analogs (SIB cathode material)
PMS	Power Management System
SEI	Solid Electrolyte Interphase (LIB internal structure)
SIB	Sodium-ion (Na-ion) Battery
SOC	State of Charge
SOH	State of Health
TCO	Total Cost of Ownership
TEU	Twenty-foot Equivalent Unit
TR	Thermal Runaway
UN	United Nations
VED	Volumetric Energy Density
VPD	Volumetric Power Density

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