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Batteries for Maritime Applications



Drivers, benefits, and functional role of batteries in vessels.

HEAVY-LIFT VESSEL LES ALIZÉS, JAN DE NUL

THE MARITIME INDUSTRY IS TRANSITIONING from traditional fossil fuel-based power and energy systems to cleaner and more efficient energy practices. Battery adoption is driven by three main factors: regulations, technoeconomic development, and improved infrastructure for onshore charging with new methods of charging batteries for maritime applications. While regulations have driven the maritime industry toward sustainable energy practices, advancements in technology and large-scale battery adoption have made a variety of battery chemistries more accessible, affordable, and longer lasting. This has resulted in the adoption of batteries not just as a means to meet regulations but also as an alternative technology in combination with traditional fossil fuels. This means that having batteries on board offers several advantages, such as reducing emissions and the operational hours of other onboard power sources, among many others. The benefits of batteries on board are categorized into environmental and operational performance, covering a total of 11 distinct advantages. The wide variety of ship types and operations means these benefits are realized in diverse ways, with batteries used differently across various vessel types. A total of 15 distinct maritime battery functions are identified, each with its benefits and applications within the maritime

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industry. These functions range from using batteries in a battery electric mode, where batteries serve as the sole power source on board, to acting as a spinning reserve during dynamic positioning applications. A hypothetical tugboat system is used to demonstrate various battery functions. This article discusses maritime batteries' drivers, benefits, and functions, highlighting their role in the maritime industry.

Drivers for Maritime Battery Adoption

Battery adoption is driven by three main factors: regulations, technoeconomic development, and improved infrastructure for onshore charging.

Regulation

The adoption of batteries on board vessels has several drivers. The primary driver is the stricter emission regulations put in place by the International Maritime Organization (IMO). Two indicative checkpoints have been set. The first is to reduce by 2030 the total annual global greenhouse gas (GHG) emissions from international shipping by a minimum of 20%, with an aspirational target of 30%, relative to 2008 levels. Second, by 2040, the objective is to achieve a reduction in total annual GHG emissions from international shipping by at least 70%, aiming as high as 80%, compared to 2008 levels. The European Union (EU) has broadened the EU Emission Trading System (ETS) to include carbon dioxide (CO_2) emissions for all large ships (5,000 gross tons and above) entering EU ports, irrespective of their flag. Under the ETS, 50% of emissions from voyages beginning or ending outside the EU are covered. The ETS also covers 100% of emissions on voyages between two EU ports and emissions within EU ports. To ease the transition, shipping companies are required to surrender allowances for a portion of their emissions during an initial phase-in period, as follows:

- *2025*: 40% of emissions reported in 2024
- *2026*: 70% of emissions reported in 2025
- *2027 onward*: 100% of reported emissions.

Starting on 1 January 2030, under the FuelEU Maritime Regulation, container and passenger ships berthed at ports within the jurisdiction of an EU member state will be required to connect to an onshore power supply for all their energy needs while at berth. The scope of these regulations from the IMO and EU are comprehensive, covering operations between continents, within continents, and individual ports. While onboard batteries primarily act as energy storage devices, substantial progress toward regulatory compliance and decarbonization is being driven by alternative fuels, such as hydrogen for fuel cells, and by lower-carbon options, including liquefied natural gas, ammonia, and, potentially, nuclear energy through small modular reactors.

Technoeconomic Developments

Technologically, the rapid decline in the cost of batteries, emerging chemistries, and shore charging capabilities have enabled batteries to be seen as alternative sources of power on board, rather than solely as a means of improving environmental image. Battery costs have significantly decreased over the past decade and are projected to decline further due to rising demand across industries. An International Renewable Energy Agency study highlights anticipated technological advancements, projecting not only lower installation costs but also longer battery life spans, strengthening batteries' viability for onboard applications.

As of April 2023, Corvus Energy had supplied over 60% of the battery systems installed on board vessels in Europe, totaling 750 systems, from 2018 to 2023. These systems use nickel manganese cobalt oxide (NMC) batteries, which are currently the most cost-effective option due to their widespread adoption in the automotive industry and high charge rate (C-rate) capabilities. Lithium iron phosphate (LFP) batteries are gaining traction in the maritime industry due to their superior thermal stability and the absence of cobalt, which is both costly and associated with ethically and environmentally contentious supply chains. Fast charging and a long cycle life are crucial for maritime applications like ferries that have brief docking periods. To meet this demand, lithium titanate oxide batteries are gaining popularity due to their rapid charge/discharge rates and significantly longer cycle life, despite offering lower energy density and cost per kilowatt hour than NMC and LFP. In addition to these lithium-ion chemistries, lead–acid batteries have been traditionally used, while redox flow batteries are being explored for future applications due to their deep discharge capabilities and long life span.

Charging Infrastructure and Methods

Advancements in charging infrastructure and strategies have expanded battery use in maritime applications. For example, *Ellen*, the largest battery electric ferry in Denmark, operates on a 4.3-MWh battery, with support from a 4-MW shore charging facility that enables vessels with frequent port stops to electrify. Norway's Fredrikstad River ferry also utilizes emerging wireless charging, delivering 100 kW of power to a 50-passenger electric ferry. Similarly, Wärtsilä's wireless system on the 85-m MF *Folgefonn* has the potential to transfer over 1 MW, indicating its applicability for larger vessels. However, one key drawback of onshore charging is the limited availability of shore power infrastructure. This has been offset in two ways. The first involves containerized battery technology, such as Skoon Energy's mobile battery system at the Port of Amsterdam, which offers flexible energy storage for short-term applications. The second method is through battery swapping technology, demonstrated by Wärtsilä on the Dutch inland ship *Alphenaar*, which enables high-energy-demand

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vessels to operate with quick dock turnarounds. Finally, offshore charging is an emerging concept toward adopting batteries for vessels that venture into the deep sea to service platforms or wind farm installations. This venture has been driven by Maersk's Stillsrom project and Damen's battery electric service operations vessels. The maritime battery landscape is illustrated in Figure 1, depicting various maritime activities, battery applications, and charging methods.

Benefits of Maritime Batteries

Batteries can be integrated into onboard energy and power systems as fully electric or hybrid power systems. These batteries may serve as the vessel's only energy storage source or work alongside other energy storage devices, such as supercapacitors, to create a hybrid energy storage system. Based on the type of vessel and operational requirement, batteries can be integrated on board for various benefits. These benefits can be broadly categorized into two categories, namely, environmental and sustainable benefits and operational and performance advantages. Examples of realized benefits with maritime batteries are highlighted in Table 1.

Environmental and Sustainable Benefits

Enabler of Clean Energy Sources

One of the primary benefits of maritime batteries is their ability to integrate clean energy sources into vessel operations. Batteries can directly support using alternative fuels and technologies, such as fuel cells, which tend to have slower dynamic responses. By providing a buffer to

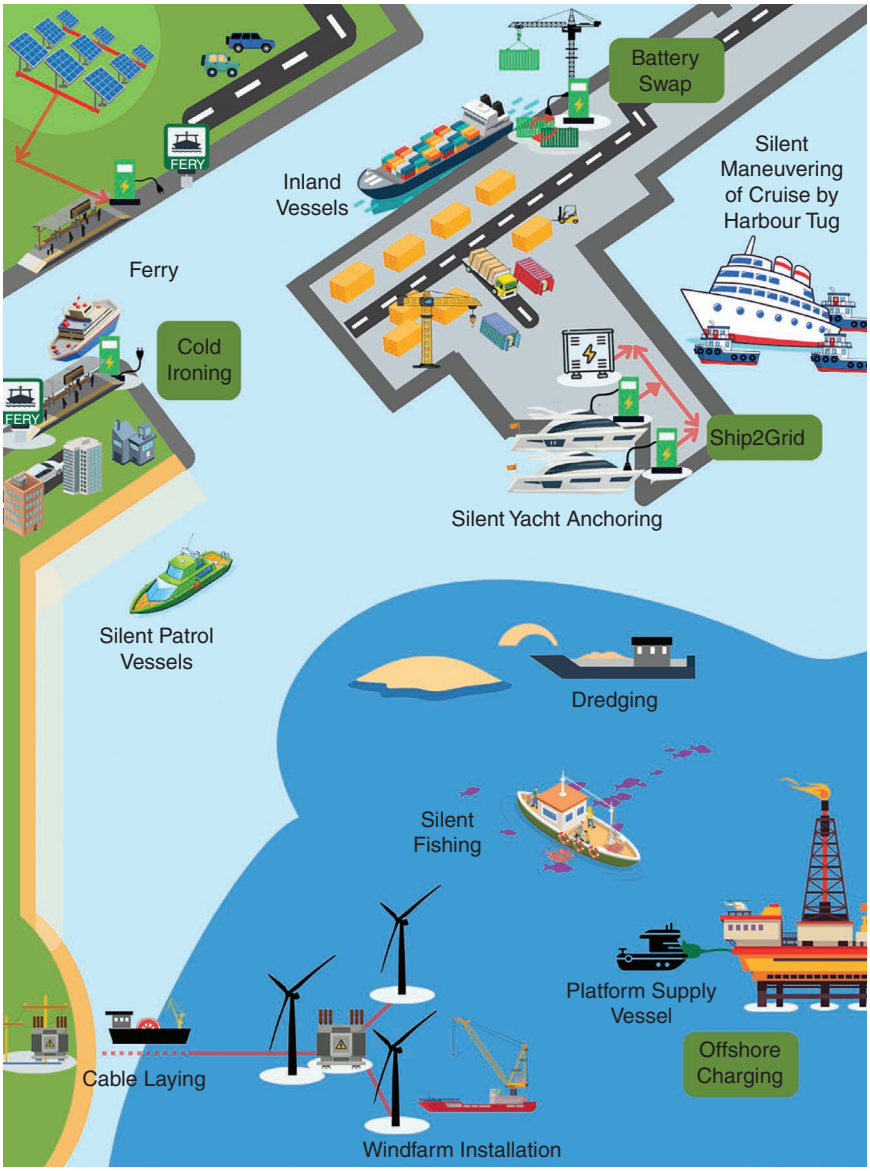

Figure 1. The maritime battery landscape.

TABLE 1. Examples of realized benefits with maritime batteries.

Benefit	Vessel Type	Name	Battery Size (kWh)	Gain	Supplier
Enabling clean energy sources	Cruise and ferry	*Ryfylkeferjen*	4,001	Hydropower charged	Corvus Energy
Lowered emissions	Tugboat	*Sparky*	2,784	465 tons of CO_2 annually	Echandia
Fuel savings	Merchant	*Rainbow Spirit*	610	22% diesel savings	Corvus Energy
Reduced running hours of other onboard sources	Aquaculture	*Fjord Hybrid*	252	87.5% reduction in diesel engine operation	EST-Floattech

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these sources, batteries ensure that energy and power demands are met. Additionally, maritime batteries promote the indirect use of renewable energy through shore-based charging (cold ironing), allowing vessels to draw power from grids with high renewable energy penetration, further reducing reliance on fossil fuels.

Lower Emissions

Reducing emissions is one of the most critical advantages of maritime batteries. They significantly contribute to lowering the carbon footprint of vessels by optimizing the operation of diesel engine generator (DEG) sets. Batteries can enhance fuel efficiency by smoothing the load and maintaining the engine at a higher and more efficient operating point, leading to reduced emissions. Moreover, batteries can facilitate hybrid or fully electric propulsion systems, drastically reducing or even eliminating harmful emissions in certain modes of operation.

Silent Operation

Batteries enable quieter vessel operations, particularly when employed in battery electric propulsion systems or as a means to reduce the number of active DEG sets. This decrease in noise and vibration is especially beneficial for certain vessel types, such as fishing vessels, where a quieter environment can lead to greater productivity and comfort for the crew. The reduced noise pollution also aligns with regulatory standards, making battery-powered vessels more suitable for sensitive environments.

Compliance With Regulation

With environmental regulations becoming increasingly stringent, maritime batteries provide a critical solution for compliance. By reducing emissions and noise levels, particularly near ports, batteries allow vessels to meet regulatory requirements while mitigating environmental impact. This positions battery-powered or hybrid vessels as a viable means of transitioning toward regulatory goals.

Operational and Performance Advantages

Fuel Savings

Fuel savings are a direct consequence of optimized power source operation facilitated by batteries. Whether in hybrid or battery electric configurations, batteries allow other sources on board to operate at/around their most fuel-efficient point. For example, DEGs tend to be most efficient when operating around 70%–90% of their rated power, while fuel cells achieve optimal efficiency between 20% and 40% of their rated power. By leveraging batteries to store excess energy and release it during high demand, fuel consumption can be minimized across various operational scenarios.

By reducing emissions and noise levels, particularly near ports, batteries allow vessels to meet regulatory requirements while mitigating environmental impact.

Regenerative Energy

Another significant benefit of batteries is their ability to capture and store regenerative energy. For instance, ship cranes and other heavy equipment can generate excess energy during lowering or braking operations. Batteries can capture this energy and store it for later use, reducing reliance on the vessel's main DEG set. This regenerative energy improves fuel efficiency, reduces emissions, and lowers operational costs.

Higher Redundancy and Reliability

Batteries improve the redundancy and reliability of onboard power systems by serving as an additional backup power source, acting as a spinning reserve. This is particularly crucial for dynamic positioning vessels, where maintaining precise control over the vessel's position is essential. In such scenarios, batteries ensure continuous operation even if the online source fails, thereby improving the overall reliability of the vessel's operations. Such a requirement falls under the "Battery (Power)" notation of DNV's class requirements.

Reduced Running Hours of Other Onboard Sources

During periods of low load demand, batteries allow for a reduction in the number of active power sources, which translates into fewer running hours for secondary power sources. This not only prolongs the operational life of these power sources but also increases their efficiency by raising their load percentages. In situations where a spinning reserve is required, batteries can act as virtual generators, maintaining system reliability without the need to run additional generators.

Reduced Frequent Start-Up and Shutdown of Other Onboard Sources

Frequent start-ups and shutdowns of power sources can reduce the equipment's operational life span and efficiency. Batteries mitigate this issue by temporarily absorbing excess power or providing supplemental power during low-demand periods, preventing the need for frequent start-ups/shutdowns of other onboard power sources. This not only enhances the life span of the vessel's power systems but also improves fuel efficiency and operational continuity.

Power Quality

Batteries play a crucial role in enhancing power quality on board vessels. High-demand equipment, such as

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propulsion motors, pumps, and thrusters, can cause significant fluctuations in power demand. When these demand spikes exceed the capacity of the onboard generation systems, it can result in voltage and frequency instability. Integrating batteries helps stabilize these fluctuations and also contributes to active and reactive power compensation.

Compact Systems

Compared to traditional fuel-based systems, batteries offer a more compact solution for energy storage. They occupy significantly less space while storing considerable amounts of energy. This space saving advantage is particularly valuable in vessels, where available space is limited. By integrating batteries into propulsion systems, vessels can free up space for additional equipment or cargo.

Maritime Battery Functions

Maritime battery functions refer to the role of the battery within the energy and power system on board. These functions can be categorized based on their characteristics, including whether they are energy or power intensive, the nature of the charging or discharging process, the control logic employed, and the battery load profile. A total of 15 functions are identified and grouped as energy intensive or power intensive and further categorized by charging, discharging, or both. An example tugboat with two DEGs and one battery is considered, as described in Figure 2. Three cases are considered to depict the different possible onboard functions. To explain the cases and functions, the following notations are used: P_D for power demand and P_{DEG} and P_{bat} for DEG and battery power, respectively. The minimum continuous and rated power of the DEG are denoted by, $P_{r\text{-}min}$ and $P_{r\text{-}max}$. Furthermore, DEGs have limited ramping capabilities, and the maximum change in power between two consecutive time steps is denoted by ΔP_r. In the first case, two DEGs are equally sized to provide half of the maximum power each, while the battery supports the system. In case 2, the two DEGs are sized to provide one-third of the maximum onboard power each, and the battery provides one-third of the remaining power. In the third case, the system is sized similarly to case 1. The power split defining the functions for these cases is shown in Figures 3–5. The figures illustrate conceptual operating scenarios to show that the battery's functionality is defined not only by its contribution to the power split but also by how it depends on the operating state of the other onboard sources.

Energy-Intensive Functions

Battery Electric

Much like fully electric vehicles, batteries are used on board vessels for battery electric operation. During such a battery electric operation, the battery system is the sole provider of energy and power to the power and propulsion system. In this function, it is essential to ensure that sufficient energy and power are available on board through batteries for the required period. For such vessels with no other power source on board, charging is typically performed via shore charging/offshore charging or, in some

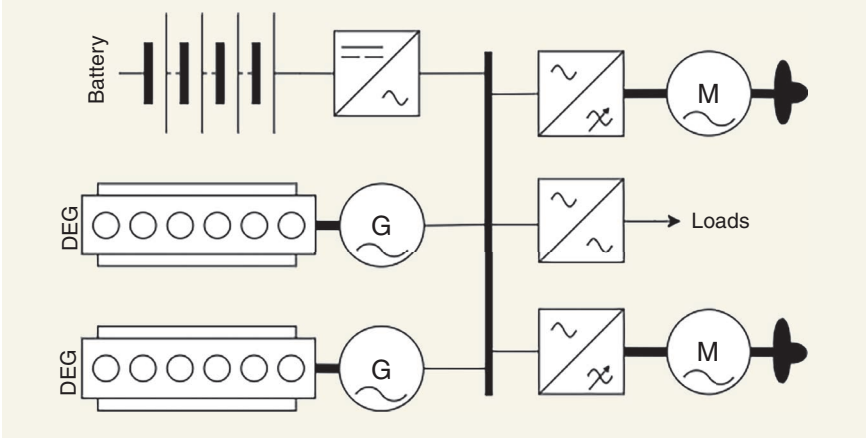

Figure 2. The considered system.

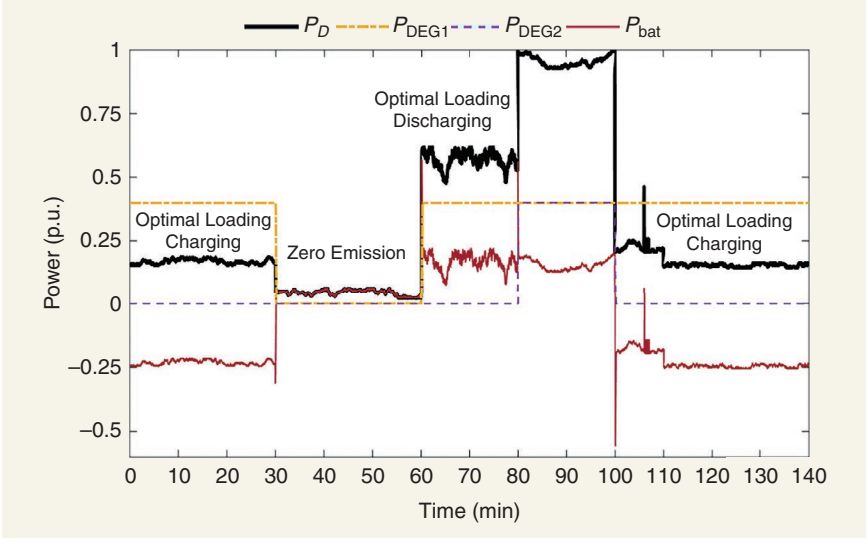

Figure 3. Case 1: zero emissions and optimal loading. DEG1 is optimally loaded when the power demand is not low. DEG2 is optimally loaded during high power demand. When the power demand is low, DEG1 is turned off. DEG1 and DEG2 have a maximum power of 0.5 per unit (pu).

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cases, battery swap technologies. Depending on the ship type and application, battery functions can be either energy intensive or power intensive, requiring different charging strategies. These strategies are categorized as out of operation, top up, and mixed charging. Out-of-operation charging involves charging the battery when the vessel is not in use, such as overnight. This method overcomes shore charging power limitations and reduces the need for fast-charging batteries, enabling the use of batteries with higher energy capacities. In contrast, top-up charging is used between operational cycles, allowing for smaller battery capacities but requiring higher C-rates during charging. Mixed charging combines these two approaches: the bulk of the energy is charged when the vessel is out of operation, with additional top ups between cycles. This method provides a balance between power and energy demands. On board, the battery only discharges. The benefits of battery electric operation include enabling cleaner energy sources, lower emissions, silent operation, and compliance with regulations.

The diverse benefits are useful to various vessel types and operational requirements, making batteries versatile for hybrid and fully electric power systems.

Zero Emission

Zero-emission mode is depicted in Figure 3, between 30 and 60 min. In this function, batteries are the sole provider of power on board, while other power sources remain off. Thus, during this interval, $P_{DEG} = 0$, and the battery supplies the full demand; i.e., $P_{bat} = P_D$. Batteries can be charged on board or through cold ironing, with requirements varying between energy intensive or power intensive based on the charging method. For example, yachts can charge slowly during idle periods for noiseless and emission-free operation. Benefits include reduced emissions, noise, and operational hours for other power sources and potential fuel savings.

Optimal Loading

The battery ensures that primary power sources operate at their optimal load by providing or storing energy as needed. During this function, the battery may charge or discharge, with the energy management system maintaining sufficient energy and power levels automatically. The function is illustrated in Figure 3, where the DEGs are loaded at 80% of their maximum power ($P_{DEG1} = 0.8{*}P_{R\text{-}max}$). The system switches other power sources on or off as the battery reaches full charge or discharge, eliminating the need for manual intervention. This energy-intensive function reduces fuel consumption and emissions while optimizing loading points and extending the mean time before overhaul (maintenance).

Peak Shaving

In this function, the battery supplements the power and energy needs of the propulsion system when the primary onboard source operates at maximum capacity ($P_{DEG1} = P_{r\text{-}max}$). The energy management system ensures that the battery has sufficient energy to support this function for a defined duration. Specific to hybrid vessels, the battery can be charged on the shore or on board. For instance, as shown in Figure 4, the battery works with the primary DEG at its maximum power between 60 and 80 min. Such a strategy avoids starting a second DEG (between 60 and 80 min in Figure 4; $P_{DEG2} = 0$). Key benefits include reducing frequent start-ups of additional power sources, thereby lowering their operational hours.

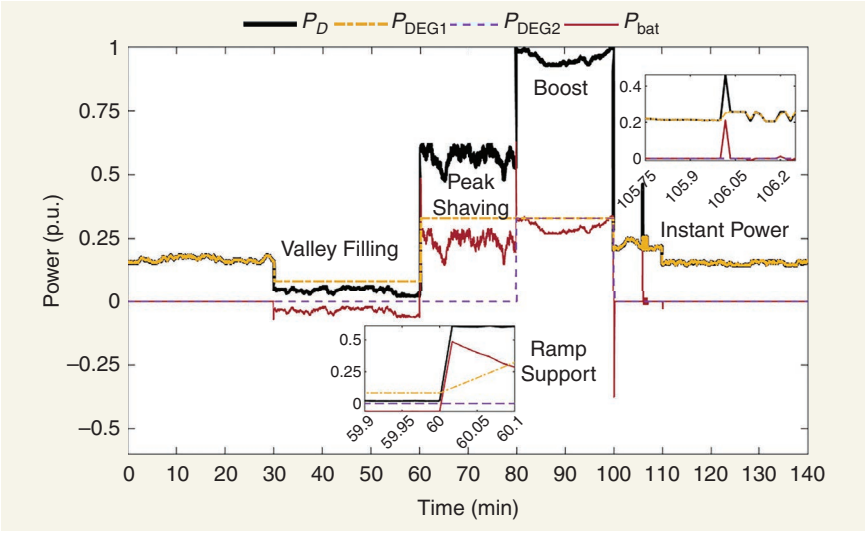

Figure 4. Case 2: peak shaving, boost, ramp support, immediate power, and valley filling. DEG1 is on through the operational profile, whereas DEG2 is on only during peak power demands. DEG1 and DEG2 have a maximum power of 1/3 pu.

Boost

The boost function is similar to peak shaving but involves the battery providing power and energy when all other onboard sources operate at their maximum capacity ($P_{DEG1} = P_{DEG2} = P_{r\text{-}max}$). This function appears in Figure 4 between 80 and 100 min. Unlike peak shaving, the energy management system does not guarantee sufficient battery energy, requiring operators to

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manage charging actively. Operations may be disrupted if the battery lacks charge. Batteries can be recharged via cold ironing or on board. Key advantages include enabling smaller DEGs, with batteries meeting additional demand.

Valley Filling

During periods of low power demand, the battery supplies charging reserve ($P_{bat} \leq 0$) to the system, ensuring that the online source remains operational without shutting down. This is depicted in Figure 4 between 30 and 60 min. The energy management system maintains an adequate battery charge to support this function, minimizing the need for proactive discharge. If low demand persists, the operation can become energy intensive. The required charging power is determined by the difference between the minimum power demand and the minimum operational power of the primary source. This approach enhances the loading efficiency of primary power sources, such as DEGs, improving fuel efficiency and reducing the frequency of switching power sources on and off.

Load Leveling

The battery ensures load leveling by providing and storing power to balance the load on other onboard sources over a defined period. The energy management system maintains sufficient energy and power availability for this function, which involves both charging ($P_{bat} \leq 0$) and discharging ($P_{bat} \geq 0$) the battery. This function is present in Figure 5 between 0 and 60 min and 100 and 140 min. This approach is particularly useful when cold ironing is unavailable, allowing the battery to be charged on board. Key benefits include onboard battery charging, reducing reliance on shore charging, and avoiding low-load DEG operation, potentially extending maintenance intervals. Additionally, for vessels using fuel cells, the battery prevents inefficient loading, reducing degradation and improving efficiency.

Ship2Grid

The battery contributes to the power produced by the vessel power system to provide power to the loads on board and also supply power to the grid. This can be done by both battery electric ships or hybrid vessels. Such a function can be utilized to provide power to weak coastal grids or perform energy arbitrage. Batteries on vessels are generally much larger than those of electric vehicles, providing substantial power and aiding in the decongestion of coastal networks.

Energy Harvesting

The battery supports renewable energy sources by storing excess energy during periods of overproduction and discharging when needed. The energy management system ensures sufficient capacity to capture and utilize renewable energy effectively during peak production periods.

Backup

The battery functions as a backup power source for critical onboard systems in case of failure. This is for a localized system of critical loads. The vessel management system ensures that the battery maintains sufficient energy and power to fulfill this role when needed.

Power-Intensive Functions

Instant or Immediate Power

The battery provides instant power to the propulsion system when the primary source cannot ramp up/down quickly (i.e., $|\Delta P_D| \geq |\Delta P_r|$). This high-power function typically occurs for a limited duration, shorter than the time required for the DEG to ramp up to its maximum power. Such a function may include charging or discharging. This function is evident in Figure 4 between 105.9 and 106.1 min. The energy management system ensures that the battery maintains sufficient power to perform effectively. Unlike peak shaving, boost functions, or valley filling, this function addresses situations where the primary power source cannot reach its maximum or minimum limits. Key benefits include improved power quality and enhanced system performance during maneuvering operations or for vessels with pulsed loads.

Load Smoothing

The battery supplies power when the primary power source cannot meet fluctuating power demands (i.e., $|\Delta P_D|$

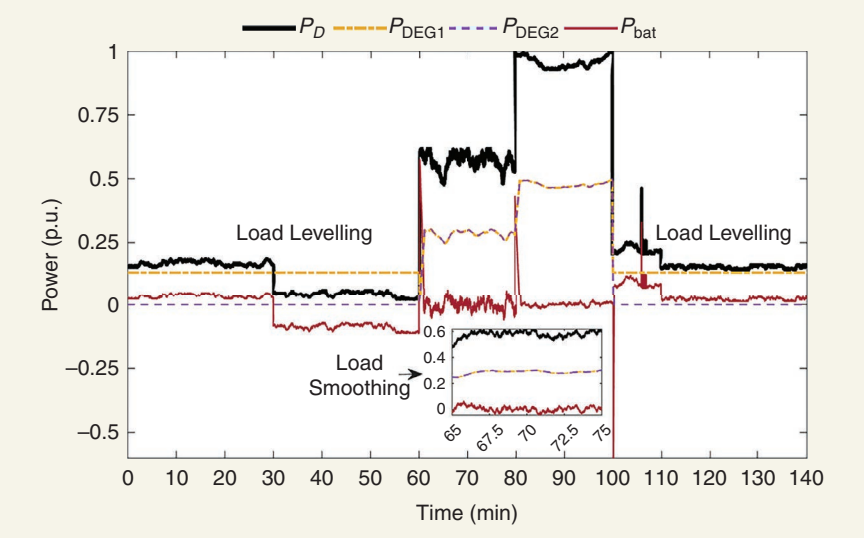

Figure 5. Case 3: load leveling and load smoothing. The load is leveled out by DEG1 during low power demands. During high power, both DEG1 and DEG2 are on, and the battery helps smoothen the load experienced by the DEGs. DEG1 and DEG2 have a maximum power of 0.5 pu.

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≥ $|\Delta P_r|$) or when it is not optimal to do so. The energy management system guarantees that there will always be sufficient power to cover this function. The vessel operator does not need to proactively ensure that there is sufficient discharge or charge capacity in the battery. Such a function involves both charging ($P_{bat} \leq 0$) and discharging ($P_{bat} \geq 0$) the battery. This occurs in Figure 5 between 60 and 75 min. Such a function is neither energy intensive nor power intensive compared to the installed capacity on board. The primary benefit of this function is improved power quality and smoother loading of the primary power source.

In the long term, technological advancements and renewable energy will enable batteries to complement fuel cells and other energy sources in onboard systems.

Regenerative Operation

The battery provides energy and power to loads capable of recovering energy during their operation. The energy management guarantees that there will always be sufficient charge and discharge power to cover the function. Such a function is power intensive. The battery is typically recharged during its operational cycle. Such a function improves the energy efficiency of vessels. This function is commonly implemented on vessels equipped with cranes.

Ramp Support

The battery supports the system during the ramping up or down of other sources on board, supplying the necessary power to maintain power balance. This power-intensive function prevents sudden power loads on primary sources, reducing wear and tear and extending the life span of DEGs. Such support is also beneficial when batteries are combined with fuel cells. This function is shown in Figure 4 between 59.9 and 60.1 min.

Reserve and Spinning Reserve

The battery serves as a reserve during critical operations, providing dynamic support to the power system to maintain power balance. It requires sufficient energy and power capacity to handle primary power source failures. The energy management system ensures enough reserve energy to turn on alternative power sources if the online sources fail. Per DNV (2015) class regulations, energy storage systems used as spinning reserves must support 30 min of operation. Incorporating a battery allows one DEG to be turned off, significantly improving the loading of the online DEG. Additionally, the battery provides dynamic support if the DEG cannot follow the load. The spinning reserve function without a battery and with a battery is described in Figure 6. This function reduces reserve DEGs' operational hours, increases fuel savings, and is particularly beneficial for dynamic positioning vessels.

Battery Functionality Overview and Integration Challenges

While batteries offer several benefits, they also present operational and integration challenges. Each battery function demands specific power and energy levels while interacting with the vessel's energy and power management systems. These functions require varying degrees of operator attention. Table 2 defines relative energy and power intensity on a scale of one to four: one indicates that energy and power are readily available, while four means they are critical and must be managed carefully. A parallel one-to-four scale reflects the operator's required attention, from none (one) to continuous monitoring or an automated energy management system (four). Table 3 provides a comparative view of battery functions across energy and power criticality and the level of operator involvement they require, with vessel examples for context. The subsequent discussion examines the integration and operational implications.

Battery electric functionality is most commonly found in ferries. Battery adoption is straightforward because fixed routes and schedules make sizing and operations predictable despite demanding energy and power requirements. For vessels without predictable routes, defining battery requirements is more uncertain. The same logic applies to zero-emission operation:

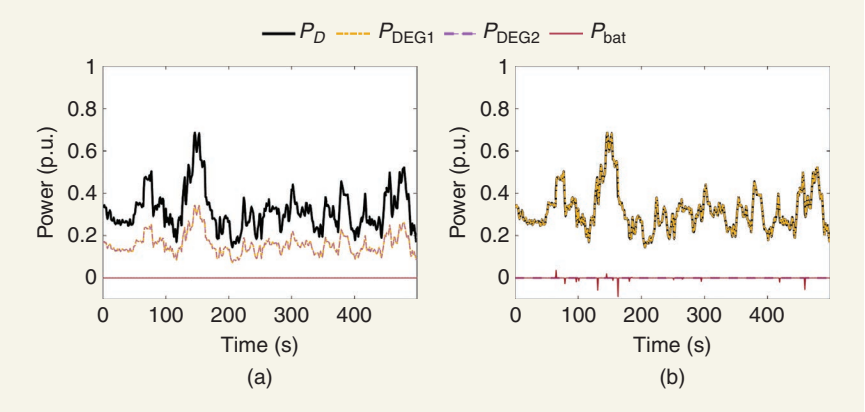

Figure 6. The power split during spinning reserve: (a) without battery support and (b) with battery support.

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although batteries power the vessel, adoption of this function is driven by the redundancy provided by other onboard power sources, which lowers operational risk.

Functions such as optimal loading, peak shaving, load leveling, and valley filling demand considerable energy and operator oversight. Here, batteries enhance efficiency rather than determine whether a vessel can operate, and they are widely adopted despite their energy demands. In contrast, boost functionality is operationally essential on some vessels because batteries must ensure that peak power demand is delivered. Power requirements are relatively easy to define, but the corresponding energy capacity must be engineered carefully and managed during operations.

Ship-to-grid power exchange is not an alien concept. Large power–ship projects have demonstrated feasibility (MV *Karadeniz Powership Kaya Bey*), but integration is still constrained by grid connection hardware and contractual arrangements between vessel owners and utilities. Vehicle-to-grid systems for cars are further along, and their development offers practical models for maritime applications.

Energy harvesting is drawing more interest in shipping, as seen with solar installations on MV *Vertom Tula* and the planned setup on BRF *Froan*. These systems will not cover full energy needs, but reducing carbon-derived energy is still a tangible gain. The main obstacles are limited deck space for panels and the challenge of persuading owners to take on additional capital costs when batteries already represent a major capital commitment.

Instant power, load smoothing, regenerative operation, and ramp support are essentially passive uses of

TABLE 2. The classification scale for battery energy intensity, power intensity, and required operator attention.

Scale	Energy Intensity	Power Intensity	Operator Attention
1	Minimal use relative to capacity	Very low power requirement	No operator attention.
2	Energy balances passively	Occasional higher power but not sustained	Operator is aware battery is being utilized
3	Sustained demand	Operation needs sustained or near rated power	Requires deliberate operator action
4	Critical energy loss compromises core function	Near maximum power; this capability becomes state of charge dependent	Continuous monitoring/automated energy management needed

TABLE 3. Criticality ratings for battery functions.

Function	Energy Criticality	Power Criticality	Operator Attention	Example Vessel
Battery electric	4	4	2	*Ellen* (car ferry)
Zero emission	3	2	2	*WN21* (tugboat)
Optimal loading	3	2	2–3	*Les Alizés* (heavy-lift vessel)
Peak shaving	3	2–3	2–3	FPS *Maas* (container vessel)
Boost	4	2–3	4	MV *Sea Change* (ferry)
Valley filling	3	2	2–3	*Three Gorges Hydrogen Boat 1* (passenger catamaran)
Load leveling	2–3	2	2–3	*North Sea Giant* (offshore support vessel)
Ship2Grid	2	2	2	BlueGrid vessel-to-grid system
Energy harvesting	2–3	2	2	MV *Vertom Tula* (cargo) BRF *Froan* (bulk carrier)
Backup	4	2–3	1	Almost all ships
Instant power	1	2	2	*Boka Da Vinci* (dive support vessel)
Load smoothing	1–2	2	1–2	Passive function on most hybrid vessels
Regenerative operation	2	3	2	*Les Alizés* (heavy-lift vessel)
Ramp support	1–2	3	2	Passive function on most hybrid vessels
Reserve and spinning reserve	4	4	4	*North Sea Giant* (offshore support vessel)

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batteries since they draw little energy relative to the total capacity and operate in short bursts. The real barrier to adopting batteries solely for these functions is justifying the investment when the direct return is limited. Still, these functions can play a strategic role by making it easier to integrate cleaner onboard power sources, such as fuel cells.

Finally, backup power and the spinning reserve are critical from the perspective that batteries must be fully charged to deliver such a functionality, and the operator must ensure this in the case of spinning reserve. However, defining such requirements while engineering is straightforward, and the benefits are tangible (reducing operational expenditure) and proven.

Together, these varied functions show that batteries adopt distinct operational roles whose value depends on careful integration, realistic performance expectations, and a clear understanding of where they genuinely improve a vessel's power architecture.

Conclusions

Driven by strict international and regional regulations, advancements in battery technology, and improved charging infrastructure, the adoption of maritime batteries has become both a regulatory necessity and a viable alternative to fossil fuel-based systems. Maritime batteries play a crucial role in transitioning to cleaner and more sustainable energy practices. In the short term, they can work with DEGs to reduce emissions and save fuel costs. In the long term, technological advancements and renewable energy will enable batteries to complement fuel cells and other energy sources in onboard systems. Batteries will remain essential to achieving both environmental and operational advantages, including reducing emissions, noise pollution, and fuel consumption while enhancing system reliability and overall performance. The diverse benefits are useful to various vessel types and operational requirements, making batteries versatile for hybrid and fully electric power systems. This article identified 15 distinct functions of maritime batteries, each addressing specific operational challenges. These functions cover energy-intensive and power-intensive applications, which showcase the benefits of utilizing one battery for different functions, realizing various benefits. Continued advancements in battery chemistries, cost reductions, and charging technologies will further solidify the role of batteries as an essential component of sustainable power and energy systems on board.

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