Powering Maritime: Challenges and Prospects in Ship Electrification

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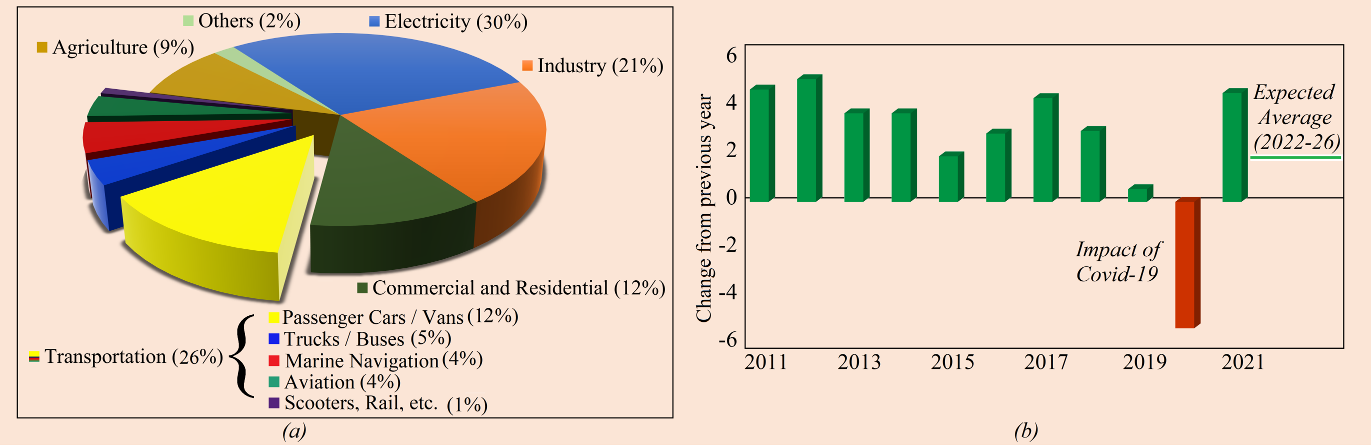
The exponential increase in global greenhouse gas (GHG) emissions and the rapid depletion of fossil fuels over the past few decades have swayed the transportation sector towards becoming more electric. In the last decade, with continuous improvements in battery technology and the interfacing power electronics, there has been immense progress in the electrification of land-based transport. As their electrification gains pace, the focus is shifting towards greening other forms of transport, such as maritime and aviation sectors since they contribute substantially to the total carbon footprint. The marine sector has witnessed huge growth in recent years owing to the development of international trade, wherein it plays an essential role in the transportation of goods across the globe. The variation in ship sizes, types and routes along with their grid-distant nature and water-borne operation distinguishes them from terrestrial EVs. This gives rise to a multitude of unique challenges on board as well as at the ports that they operate around. Power electronics is one of the key enabling technologies in tackling these challenges and thereby creating safe, reliable and emission-free maritime transport.

Background

Marine transport is the backbone of the international trading community. Globally, ships are responsible for the movement of 80% of goods by volume. Compared to other forms of transport like airborne and overland, ships are the most economical and environment-friendly means for transporting goods over large distances. However, with the rapid growth of Asian markets, the volume of shipped goods is increasing at a tremendous rate and there is a rising concern over ship emissions, especially around the ports. When at berth, ships are known to emit various pollutants like SO_X, NO_X, particulates and GHGs which are hazardous to the environment and the population living in the port cities. According to the International Maritime Organization (IMO), CO_2 emissions from international shipping could increase by 250% by 2050. At present, the transportation sector contributes to about 26% of total GHG emissions while maritime systems account for 4% of the total share (Figure 1). Nearly 940 million tonnes of CO_2 are emitted annually by ships and with these numbers projected to go only upward, the maritime industry must navigate towards greener shipping and electrification plays a primary role in achieving that.



(a) *(b)*

Fig. 1. *(a)* Breakdown of the contribution by various sectors towards global GHG emissions; based on data from US Environmental Protection Agency *(b)* Annual change in the international maritime trade since 2011 and its anticipated growth for 2022-2026; based on data from the United Nations Conference on Trade and Development - Annual Review of Maritime Transport

Spectrum of Electrification

Identification of target sectors for vessel electrification involves a study of their sizes, frequency/duration of shore stoppages, suitability of battery-based power in their normal operations and availability of adequate grid power at ports. Mechanical dynamics which can be influenced by re-distribution of weight and even the positioning of this weight becomes an important parameter for a ship designer in the potential electrification of a vessel. A summary of power electronics applications across the spectrum of maritime transport is presented in Figure 2. The use ranges from complete onboard generation in vessels like small solar boats (which do not require onshore charging), to marginal use in ocean-going vessels such as tankers. Still, power electronics is only slowly being pushed to the larger ship market. The Norwegian fully electric and autonomous cargo ship Yara Birkeland which powers from a 7 MWh battery is set to be the first ship of its kind to start operating in 2022 across the Scandinavian fjords. Though the ship leads to zero emissions, its estimated production cost is three times that of a normal ship of its size, indicating the need for optimization at several levels before large-ship owners see this as a feasible alternative. Even for ships that have extreme power-to-tonnage ratios such as tugboats, there has been considerable progress. In August 2022, Damen Shipyards launched the world's first full-sized electric tug — the Damen RSD-E 2513, Sparky (Figure 3). The tug has 80 battery racks employing a total of 2240 batteries, resulting in a 2.78 MWh storage. Even though the initial costs are high, the operating costs are less than one-third of a similar diesel-operated tug.

As of 2022, there are about 600 battery-powered ships of which about 25% are fully electric, nearly 25% are plugin hybrid and the rest do not require shore charging. The average rating of the onboard batteries

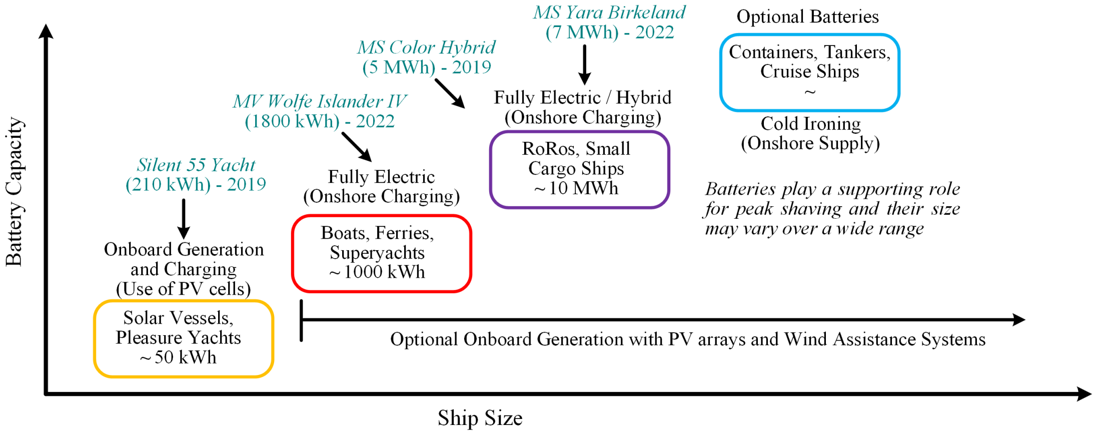
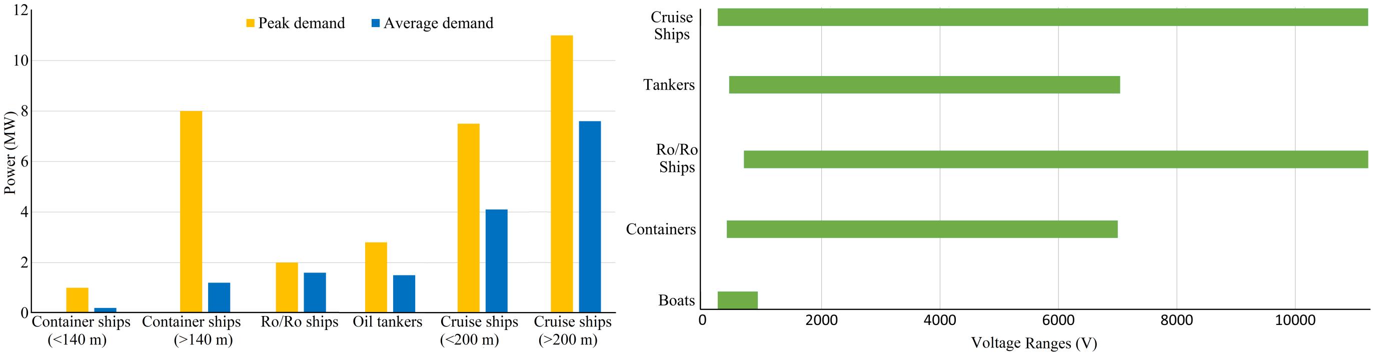


Fig. 2. Spectrum of electrification for marine transport with some recently-built electric ships; the applicability range varies from solar boats which do not require a grid charging infrastructure to large cruise ships where batteries will play only a marginal role for the near future.

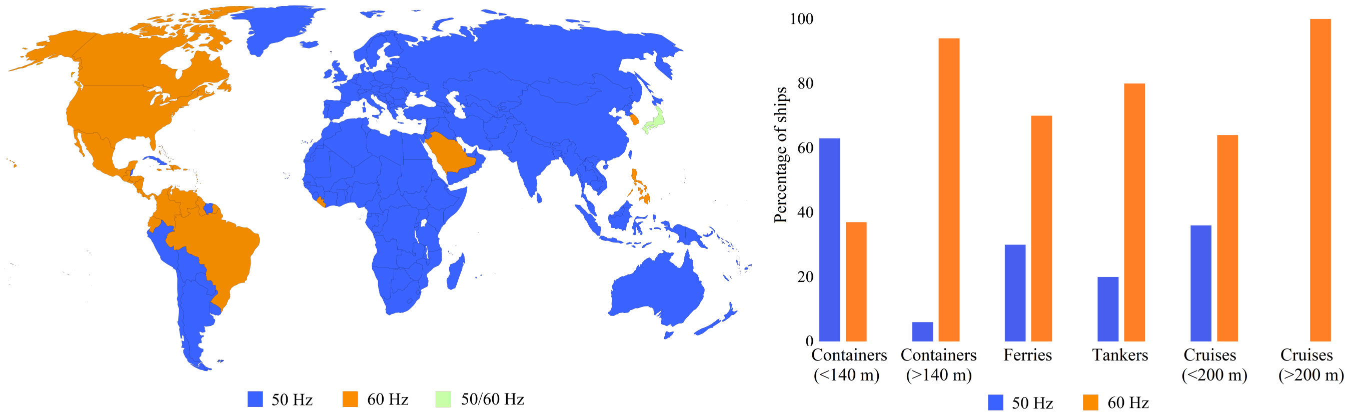
(a) *(b)*

Fig. 3. (a) Damen RSD-E 2513; the electric tug powers from a 2.78 MWh battery which is fully charged in 2 hours (b) Damen ferry 2306 E3; the city ferry uses a 184 kWh battery which is fully charged in 7 minutes through two 5kA CCS2 connectors (Images: Damen Shipyards Group, used with permission)



(a) *(b)*

Fig. 4. *(a)* Variation of average and peak power demand with ship type and size during cold ironing (a shore-to-ship connection when the ship is at the harbour and the onboard generator is turned off to reduce emissions); *(b)* Range of voltages used on board different ship types.



(a) *(b)*

Fig. 5. *(a)* Frequency of mains electricity by countries across the world; *(b)* Frequency of onboard power systems for various types of ships. This disparity between mains and ship power frequency necessitates creating high-voltage shore supply systems at all major ports to facilitate the cold ironing of large ships.

is 1.2 MWh and the required charging power can go up to a few MWs. Electrification has been primarily prioritized in the ferry market. In October 2022, ABB and Incat Tasmania announced the development of 148-meter hybrid ferries which would operate around the Tasmanian region of Australia. Initially, the ferries are expected to function in diesel-hybrid mode and once the shore charging stations are created, battery capacities as high as 30 MWh have been envisaged.

Electric Ships - Onboard Architecture

The evolution of efficient solid-state power devices in recent decades has favoured the possibility of large-scale transportation sectors becoming more electric. In 1988, the *Queen Elizabeth 2* became the first of its kind — a ship with electric propulsion. Since then, optimization of such drive systems to achieve better fuel efficiency, superior drive performance, reduction in emissions and electromagnetic compatibility with other equipment on board has been increasingly explored.

Nowadays with the size of vessels going up to hundreds of meters, the power requirements on board have risen to tens of megawatts (Figure 4, 5). Therefore, modern ships are essentially isolated power systems with all the aspects of generation, protection, distribution, the capability of energy storage, power conversion, etc. For reliability, there is often redundancy in the power system architecture in the form of multiple symmetrical units for generation/distribution. Traditionally, the primary electric distribution of these vessels has been based on an ac system. This is because it allows for simpler protection which is inherent to all ac systems owing to the presence of an instantaneous zero current in every half cycle of operation. However, recently the change to dc-based and hybrid architectures is gaining more popularity because of the following factors:

- For ships with multiple speed drives, a dc distribution eliminates redundant ac/dc stages and enables easy integration of dc power sources such as batteries, fuel cells, etc.
- With only voltage magnitude to cater for, control of a dc-based system is simple while in ac, aspects of grid/ship frequencies, reactive power and synchronization make the control more complex.
- A dc grid system enables the operation of an onboard gen-set at optimum specific oil consumption irrespective of the load by varying engine speed. This is not possible in ac distribution as the variation in speed would change the synchronous machine and system frequency thereby affecting the operation of onboard loads. This additional degree of freedom in dc based systems allows the gen-set to operate at a higher efficiency by consuming lower fuel-mass per unit of energy and reduces emissions. Moreover, the need for an auxiliary generator for harbour use is not necessary as the dc-grid can allow variable speed operation of the gen-set at lighter loading.
- Due to the time-invariant nature of dc quantities in steady-state, there are no problems associated with time-varying magnetic fields such as skin and proximity effects. This leads to conductors having a larger skin depth which saves volume and increases the power density onboard. In a space and weight-constrained environment like a ship, this advantage of a reduced conductor volume is significant.

With improvements being made in solid-state circuit breaker technology, fast protection circuits have become more affordable for ship owners, making hybrid and dc-based systems more popular, especially for smaller vessels. Figure 6 shows the electrical architecture of the *MV Wolfe Islander IV*, a zero-emission ferry to be brought into service in 2022. The onboard system is primarily powered by a 930 V dc bus which facilitates driving the main propulsion system. A smaller ac bus is also present to feed the ac consumers on board. The different interfacing power converters enable energy transfer within the various systems onboard. The symmetrical and redundant structure ensures reliability and allows isolating a part of the system in case of a fault. The diesel generators serve as backups in case of battery failure.

More recently, the use of bipolar dc-grids has been proposed for ships which offer more flexibility in

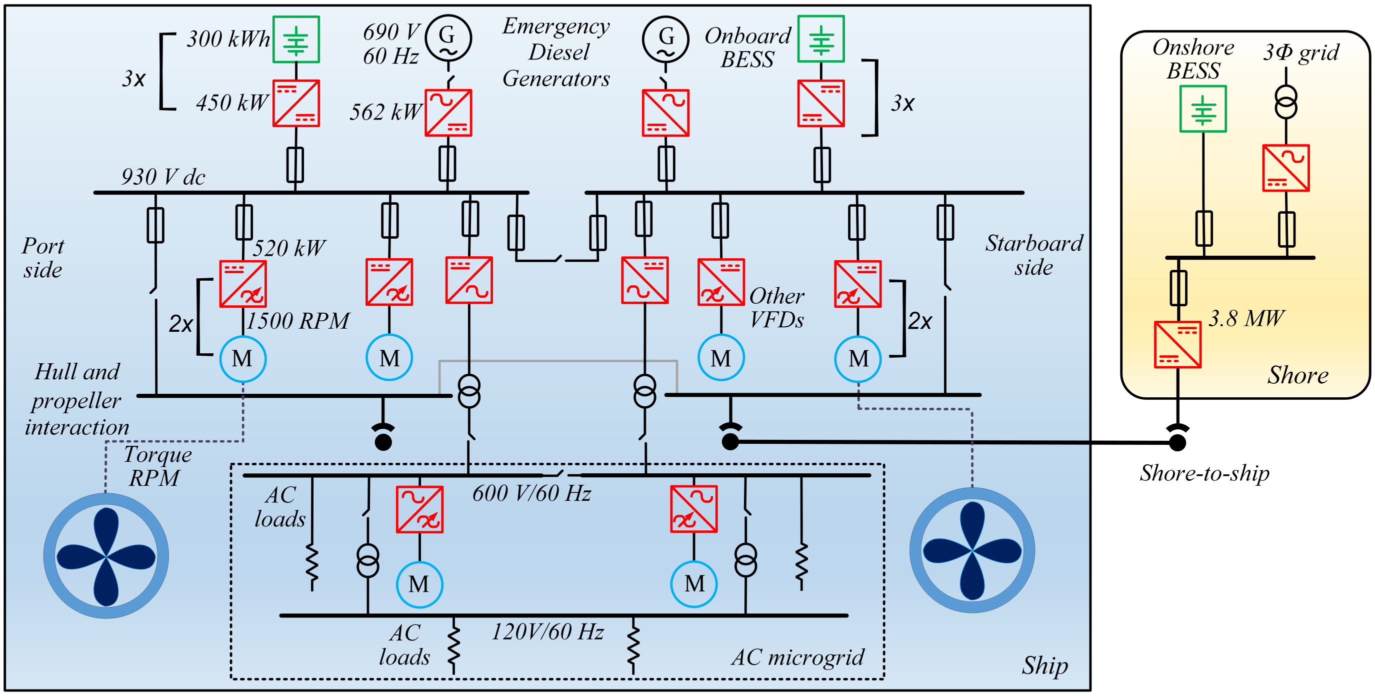


Fig. 6. Single line diagram of an electric ferry, *MV Wolfe Islander IV*, showing several stages of power conversion. The ferry can be connected to the shore from both the starboard and port sides and will serve between Kingston, Ontario and Wolfe Island in Canada.

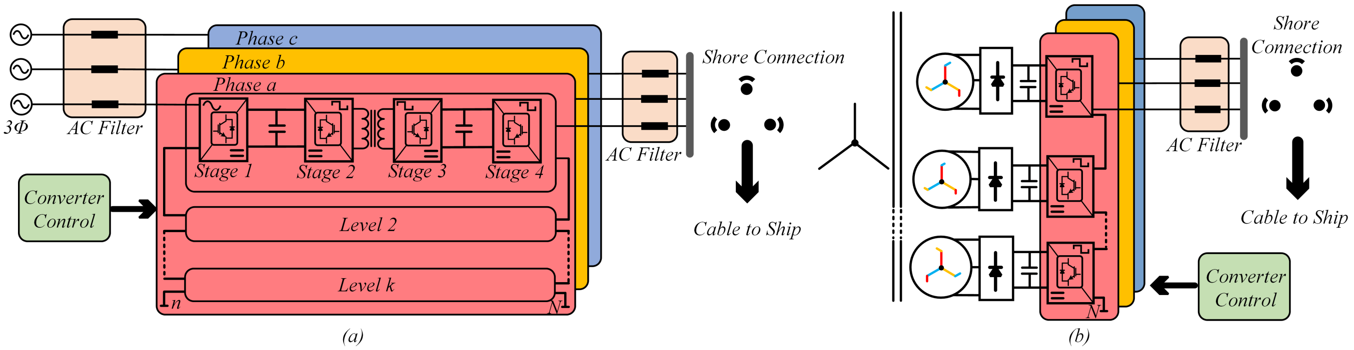


Fig. 7. Modular grid-connected shore converters: (a) Medium frequency isolation-based shore power converters: in the simplest topology (for LV applications), a dual-active bridge is sandwiched between a pair of two-level voltage source converters. For higher voltages, a multi-level structure is more suitable. Furthermore, for shore converters aimed to power ships with a dc distribution, stage 4 conversion is eliminated (b) In high power applications, it is more common to use multi-pulse transformers (zigzag or extended delta) on the grid side with line-frequency isolation and phase shifted secondaries. Other multi-level converters such as modular multi-level and variants of neutral point clamped converter can be used on the ship side for a low-distortion voltage.

distribution and a higher power density. However, power balancing, voltage stability, protection and lack of standards in bipolar dc-grids are some key challenges that has so far limited their implementation.

Shore-to-ship interface

Besides the vessel itself, in recent years, there has also been considerable interest in the design of smart harbour area grids. For the ships that are not battery operated, design aspects of cold ironing are being actively explored. This may be an ac/dc or ac/ac interface with isolation and/or frequency/voltage conversion depending upon the shore supply and the vessel's power system. Most vessels that employ an ac distribution grid have a 60 Hz main bus while a majority of the countries make use of a 50 Hz grid (Figure 5). This necessitates the need for frequency conversion in addition to the voltage scaling that could otherwise be done by conventional transformers. The voltages on board can range from 400 V in small boats to 11 kV in large cruise vessels. Rotating converters employing a synchronous machine pair have been used for shore-to-ship frequency conversion wherein the two machines are coupled mechanically and the difference in pole pairs enables frequency conversion. However, with the advent of power electronics capable of handling large voltages and currents, noise-free static shore converters have become more popular. These converters can feature high-frequency isolation (as in Marpower SPC-II for 25 to 740 kVA) in the form of a dual active bridge connected to voltage source inverters or multilevel converters on either sides to match the respective frequencies of the shore and the ship (Figure 7). In recent years, manufacturers such as ABB, Marpower, and Asea Power Systems have been supplying shore converters to various ports across the globe allowing ship owners to reduce the emissions arising in harbour areas. For LV systems, IGBT-based frequency converters are common (such as ABB PCS-100 for up to 4 MVA) while IGCTs are used for MV systems (such as ABB PCS-6000 for 3 to 6 MVA, ABB ACS-6000 for 5 to 24 MVA). With ship electrification becoming a necessity for the future, the shore infrastructure needed to feed all the vessels should be set up strategically at the ports. The use of high-frequency magnetics has a long-term advantage over rotating converters and bulky transformers because of its low volume in potentially space-constrained port environments. However, cost and reliability considerations create a design compromise that needs to be catered for and accordingly a suitable technology can be implemented specifically to a location and the requirements thereof.

For battery-operated ships and ferries that need to follow a preplanned schedule, the charging process is constrained within a critical time, that can be down to a few minutes for short-distance ferries. Therefore, disturbances and faults in a weak grid that hinder/slow down the process of charging can result in inconvenience for passengers and loss of revenue for ship owners. Battery container swapping has been

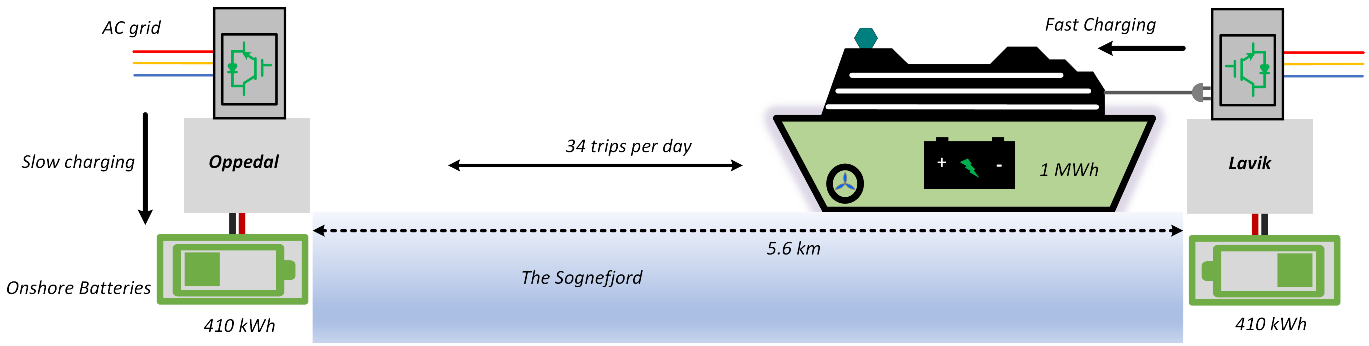
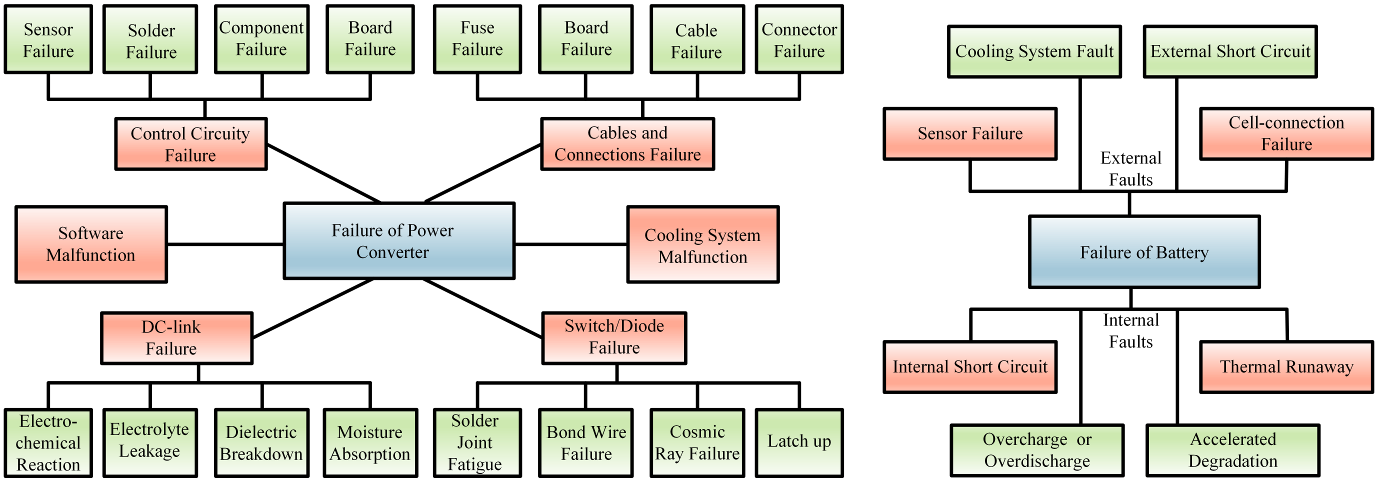


Fig. 8. Operation of motor ferry Ampere sailing between Lavik and Oppedal in the Norwegian inlet, Sognefjord: shore batteries are used to alleviate the power burden on the ac grid when the ferry stops for recharging the onboard batteries at one of the stations.

suggested as one solution to deal with this problem. The method involves charging surplus batteries during base-load hours through renewable energy sources at the harbour. These batteries are then swapped with the exhausted ones from the incoming vessel during peak-load hours. However, several logistics need to be addressed in the replacement of battery packs at the harbour, and the process may be more labour-intensive and costly than making charging cable connections due to equipment, crane operations for transport of batteries, etc. In addition, the lack of fixed standards or types of batteries in ships makes it difficult to have replacements ready for all varieties. Therefore, ensuring sufficient renewable power and energy storage devices at the shore to aid charging during peak-load duration is possibly a better long-term solution. In charging the onboard battery, cable connections with an onboard/offboard charger or wireless methods may be employed. As ship charging power levels can go up to tens of MWs, having connections executed by crew members may not be practical in the future as cable sizes increase with improvements in charging technology. The resulting time lost in the connecting the heavy cables can in turn lead to reduction in the charging energy delivered to the vessel. Inductive power transfer methods have been suggested for wireless charging of ships at the port. However, challenges of tracking receiver coils in tidal/wave movements and of placement of transmitter coils at the shore to optimize power transfer and efficiency are being faced in such systems. Another method is to deploy autonomous robots for plugging in the heavy cables for conventional wired charging and cold ironing. Redundancy-based designs such as interleaved and modular converters are used to enhance the dependability of charging infrastructure. This method is very likely to be the primary charging scheme in the future considering its efficiency, reliability and safety except for smaller boats where the manual plug-in is cheaper and safe. For both wired and wireless charging of batteries, reducing the power demand on the local grid during the charging process is often carried out by employing shore-side batteries which can be charged slowly in the absence of the vessel. In turn, they facilitate fast charging of the ship once it arrives at the station. Figure 8 shows the operation of motor ferry *Ampere* where such a system is employed to reduce the peak power demand on the local grids.

Reliability and Safety

Electrification of vessels involves the introduction of several previously non-existent components in the ship as well as on the shore. It is important to ensure these interfacing parts are always functioning to deliver power to the ship so that they can maintain their planned schedule and that any loss of revenue to the ship owners is prevented. The power delivery system can be compromised in several ways; there may be a malfunction in the ac supply (a line to ground fault, outage, severe unbalance, etc.), a fault in the onshore batteries (short circuit, overheating, degradation, etc.), failure of power electronics semiconductors or a problem in other interfacing components such as inductors, capacitors, transformers, cables, etc. Each of these can result in hampering the charging process and cause inconvenience to the passengers and the operating crew. In order to tackle this, shore converters often have redundancy and modularity-based designs that improve the margin for safety in case of a malfunction by isolating/disconnecting only the



(a) *(b)*

Fig. 9. *(a)* Common causes of failure in power electronic converters *(b)* Various types of faults in batteries. With energy interfaces becoming more electric, condition monitoring of power converters and the development of battery management systems (BMS) play a crucial role in the transition towards reliable emission-free transportation.

faulty part of the system and allowing continued power delivery, be it at a reduced rating. The power management and control architecture should be able to achieve such a bypassing condition. Therefore, the interfacing connection can operate normally or under derated conditions or else be in a state of complete dysfunction. An assessment of the overall reliability of this interface is thus imperative. Markov chain analysis and Fides estimation have been used in literature to assess the reliability of shore-to-ship charging systems. These methods aid in creating indices for derated charging, loss of charging mechanism and the mean time to first failure. IGBTs and battery packs have been identified as the dominant components responsible for system failure. Figure 9 shows the several underlying causes that can lead to a failure within these components. An effective reliability assessment should insure the ship owners against possible economic lapses. However, a safer design may not always be the most efficient and most economical one. Therefore, using these guidelines, carrying out a reliability analysis specific to each case can help narrow down a design compromise where the component placement, system ratings with safety margins, redundancy in the design and historical failure data are all taken into account.

With vessels becoming more electric, their safety and protection mechanisms also need to be altered accordingly. Dangerous touch voltages that occur during line-to-ground faults, residual charges on the cables connecting the ship to the grid and stray currents flowing through undesirable parts can all create safety issues and lead to corrosion or withering of the ship hull. Therefore, appropriate protection mechanisms for over-current and over-voltage are employed to safeguard against any possible accidents. Moreover, passive cathodic protection (for boats or small ships) and impressed current cathodic protection (for larger vessels) are used to protect against corrosion.

Maritime batteries and onboard storage

The advent of energy storage technologies has enabled the transportation sector to become more electric and batteries are at the forefront of this evolution. Other than being the primary energy sources on electric ships, onboard batteries can have several other functions depending upon the vessel requirements:

- They provide an ever-present spinning reserve which means fewer generators are required to remain online in case of large ships.
- They facilitate in making the generators operate at an optimum power point by functioning as energy consumers or producers depending on the existing demand.

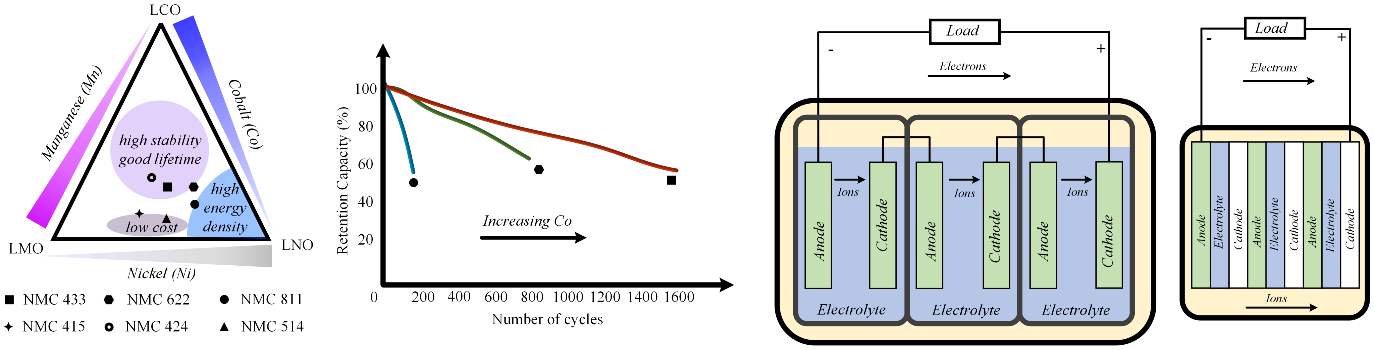
- They provide dynamic support and enhance system stability when sources with low dynamic capabilities are operated under severely varying loading conditions.
- They are able to store the harvested energy from cranes, drilling equipment, etc., thereby increasing overall system efficiency.

As different ship types have varying power requirements and cycles of operation, a variety of energy storage systems have been considered for their use. Several non-conventional storage systems like flywheels, super-capacitors and superconducting magnetic energy storage have been proposed for additional support to onboard batteries because of their high power density. Integration of these sources can be carried out based on the load demand nuances such as the potential presence of pulsed loads, switching dynamics, etc. Moreover, the choice of battery chemistry itself is affected by several factors. Depending on its operational requirements, a vessel can have its time divided between just loitering, navigating, in combat, docking at the port, etc. This leads to a vast difference in the objectives set out for the onboard energy-supplying system in terms of target lifespans, power and energy densities, reasonable cost investments, etc. Based on these factors, several battery technologies have been explored for use in the maritime sector (Table I).

TABLE I
COMMONLY USED BATTERY TYPES IN THE MARITIME INDUSTRY AND THEIR FEATURES. FOR COMPARISON, ENERGY DENSITIES REPRESENT THE BATTERY CELLS; IN MODULES, THE VALUES ARE EXPECTED TO DECREASE (BASED ON DATA FROM EUROPEAN MARITIME SAFETY AGENCY)

Chemistry used	Specific Energy Energy Density	Advantages	Disadvantages	Applicability in maritime sector
Lithium Nickel Manganese Cobalt Oxide (NMC)	150-220 Wh/kg 550-610 Wh/L	Adjustable Wh/kg, Wh/L, cost and safety	High cost of Cobalt	Widely used at present
Lithium Iron Phosphate (LFP)	90-120 Wh/kg 310-350 Wh/L	Higher safety than NMC High-temperature resilience Cathode doping possible for higher power applications	Relatively low Wh/kg Lower voltage and power capabilities	Mildly used in marine applications because of its good safety features
Lithium Nickel Cobalt Aluminium (NCA)	200-260 Wh/kg 580-620 Wh/L	High Wh/kg and Wh/L Long calendar life	Lower safety Higher cost	Suitable for some applications because of its long calendar life
Lithium Titanate Oxide (LTO)	50-80 Wh/kg 160-200 Wh/L	Higher safety characteristics Very high cycle life High power capability	Relatively low SE High initial cost	Suitable for applications requiring fast charging, high power or very large amounts of cycling
Lithium-Sulphur	420-480 Wh/kg 510-590 Wh/L	Higher theoretical Wh/kg and Wh/L	High cost of lithium Susceptible to volume expansion Electrical conductivity quite low Shuttle effects	Commercial availability on a large scale is a challenge
Solid-state	200-400 Wh/kg 700-800 Wh/L (projected)	Non-flammable electrolyte No dendrite formation Potential for high Wh/kg and Wh/L	Low conductivity Small lifetime High production cost	Promising technology for increasing safety, specific energy, energy density in marine applications

Owing to their versatility, Lithium-NMC batteries have emerged as the most widely used technology in the maritime sector. Changing the relative proportions of Nickel (Ni), Manganese (Mn) and Cobalt (Co) enables altering the properties of the battery considerably (Figure 10(a)). These are often denoted by NMC xyz where x, y and z specify relative proportions of Ni, Mn and Co, respectively. NMC 433 (indicating a composition of 40% Ni, 30% Mn and 30% Co) is a commonly used battery chemistry. A higher proportion of Ni improves the energy density of the battery while more Co is good for the thermal management of the battery and ensures a longer lifespan (Figure 10(b)). More recently, solid-state batteries



(a) *(b)* *(c)*

Fig. 10. *(a)* Composition of NMC batteries, *(b)* Effect of Cobalt content on the lifespan of an NMC battery, *(c)* Comparison of the structure of a liquid-electrolyte-based battery and a solid-state battery illustrating the compactness of the latter.

are being explored because their projected high energy density make them a good candidate for use in the transportation sector. The absence of a liquid electrolyte leads to an inherently compact and dense structure giving rise to higher volumetric and gravimetric energy densities (Figure 10(c)).

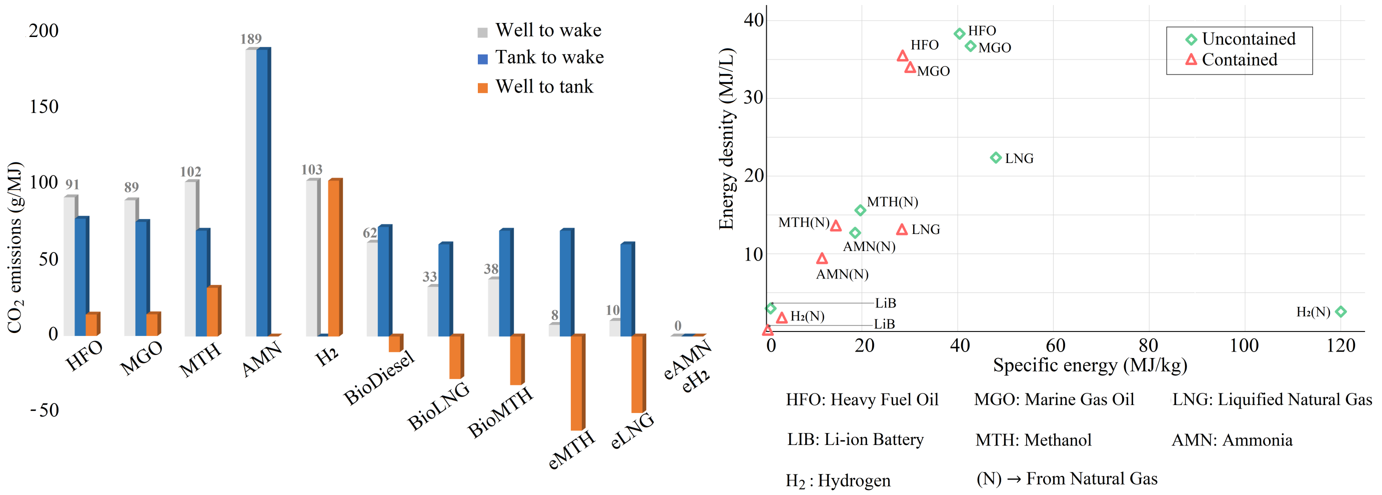
Cleaner fuels

With fossil fuels depleting at a rate faster than ever before, a paradigm shift is necessary to make the maritime sector sustainable and clean. For the sector to completely operate emission-free, the conventionally used onboard power generation units require a complete overhaul. This change can be achieved by the use of alternate (carbon-neutral) fuels and rechargeable battery packs as the primary sources of electrical energy on board. Currently, the world of ships is still heavily dominated by fuels originating from fossils. While most seagoing ships employ heavy fuel oil or marine gas oil, the smaller vessels commonly use diesel-based engines. In recent years, significant research has been conducted on finding cleaner fuels as possible replacements. Besides batteries, hydrogen and biofuels have emerged as some promising alternatives for greener shipping. In particular, proton-exchange membrane fuel cells and solid-oxide fuel cells using ammonia, liquid-hydrogen and methane are getting most of the attention. Although these alternatives are presently more expensive, with competitive and large-scale production, the prices are expected to drop and be even lower than conventional fuels by 2050. Safety issues with their use are a challenge because ammonia and methanol are toxic and hydrogen is highly combustible. Real-time sensors capable of detecting any leakage in the tanks, cells or feed systems are therefore required for preventing any accident. Moreover, though some of them are emission-free in operation, their production can still lead to substantial emissions (Figure 11). Therefore, cleaner methods to synthesize them on a large scale still need to be implemented.

The applicability of these fuels to different ship types based on power and energy density, manufacturing cost, operational efficiency, long-term reliability, etc., is being intensively explored. With restrictions on emissions only becoming stricter, alternate energy sources have recently undergone rapid development. However, due to the long lifespan of ships, the transition to alternative fuels is expected to be relatively slow because of the large costs of retrofitting the old vessels. Moreover, the mandatory regulations of the energy efficiency design index (EEDI) that were introduced by the IMO for restricting ship emissions only apply to newly built vessels leaving ship owners unincentivized to switch to newer technologies.

Distributed architecture and multi-functional storage

Fuel cells have the potential to change the landscape of maritime, aviation and terrestrial transportation systems. Their use can enable a complete transition of the energy framework within a vessel and a substantial decrease in GHG emissions. Since they are static and similar to batteries as opposed to



(a) *(b)*

Fig. 11. *(a)* CO_2 emissions from the existing and prospective marine fuels showing the performance of carbon-capture based e-fuels relative to conventional fuels *(b)* Energy density and specific energy of the various fuels with volume and mass of the tank system included and excluded (based on data from the Maritime Research Institute of Netherlands)

traditional fuel engines, it is possible to distribute them in smaller fragments over a larger space inside a ship rather than in a confined space where all power generation takes place. This is advantageous in a ship because it enables multi-functionality and a battery pack can independently supply energy to meet a particular part of the load on board while also being part of the larger system as a whole. It essentially means the entirety of the energy demand need not be met from the main distribution and small micro-grids onboard may safely function as isolated systems. Unlike with traditional engines, this is practically possible with batteries as there are no moving parts, sounds or localized emissions that necessitate them to be operated separately in a confined space. As modern ships can be hundreds of meters long, the distribution network with all its ancillary and protection equipment can occupy a large amount of space on board. Therefore, a multi-functional setup can save a substantial amount of volume inside the vessel as a distributed architecture can eliminate redundant parts of distribution and protection that take up space. For instance, in case of a fault, the protection system generally isolates a part of the distribution and makes use of alternate cables from the engine room to power vital loads. With distributed battery energy storage systems onboard, the need of such redundant networks may be eliminated in some cases if the batteries can power the vital loads (communication, navigation systems, etc.) for a suitable period of time. In particular, such structures are attractive for naval vessels wherein for better survivability, a zonal electrical distribution is advantageous in case of damage to certain parts of the vessel. Figure 12 shows such a zonal distribution for dc system onboard.

Operational Issues, Management and Control

1) Enhancing Shore Grids: Modern vessels require up to tens of MWs even when docked to feed non-propulsion loads on board. This comprises the climate control system, refrigeration, lighting, communications, entertainment, water treatment and other utilities. Therefore, electrification of ships must simultaneously come with enhancement of distribution grids at the port. Legislative and regulatory measures such as pricing policies play a crucial role in incentivising that. Renewable energy integration at the port sites to support weak grids will indirectly help in accelerating the rate of electrification. Building solar or wind farms near large ports will enable the port grids to withstand the imminent increase in the energy demand. Furthermore, in the case of small ports in remote locations, it is not an economical solution to enhance a weak grid to a level such that it is capable of delivering MWs of power for a few minutes to charge a ferry and then not be using any of the available reserves for the rest of the day. Employing shore

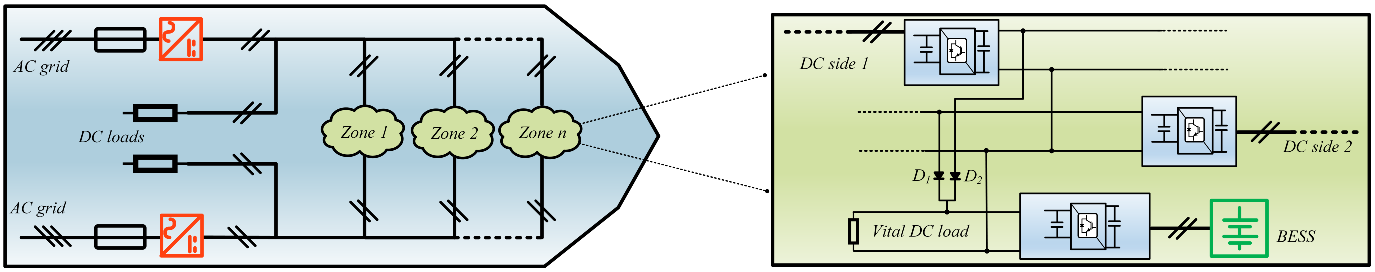


Fig. 12. (a) Zonal electrical distribution in a ship with dc grid (b) Expanded form of a particular zone; dc-dc converters allow fault clearance, power flow management, dc voltage regulation, etc.; in the event that both incoming zones are faulty, the battery pack is used to deliver energy to vital loads and the diodes prevent conduction to the other parts

storage for supporting the grid becomes essential in such cases where the onshore storage can be charged all day and subsequently be used to shave the shore power demand peak on the arrival of a ferry. Since EVs have been in the main markets for a considerable period, there is a growing number of batteries with second-life options. A potential second-life application for them would be in grid support at the ports where a significant load increase is imminent with large-scale ship electrification being on the horizon. In October 2022, the hyper powered vessel battery charging system project (HypoBatt) was announced with the aim of developing a multi-MW charger for the ferries operating in the northwest European regions and coming up with solutions for logistic and technical challenges faced in developing such a system. The project has identified several performance indices such as footprint of shore converter and transformer, connection/disconnection times, charging efficiency, operation and maintenance costs, power availability, etc.

2) Electromagnetic compatibility considerations: Rapidly changing environments within and around the ships, wherein the electrical system is dominated by fast-switching devices, require a closer inspection of the electromagnetic compatibility of the different system components. Various international standards have been defined to serve as guidelines for a shore-to-ship interface such as IEC/ISO/IEEE 80005-1 (for high voltage shore connections - over 1 kV), IEC/ISO/IEEE 80005-2 (for the communication protocol and data interface) and IEC/ISO/IEEE 80005-3 (for low voltage shore connection - under 1 kV), IEEE-519-2014 (for grid power quality) that collectively cover aspects related to the voltage and frequency tolerances, cable management systems, plug-socket pairs, electrical grounding, shore connection switchboards, monitoring and alarms, total or single harmonic distortions of the voltages fed to the ships and the currents drawn from the grid. Since these currents can go up to a few kilo-amperes, minimizing harmonics is essential for reducing distribution system losses and making overall power delivery more efficient. Within the ship itself IEC/PAS 60092-510-2009 (for electrical installations in ships), IEEE C6314, IEC 61000-4-3, IEC 610004-6, IEC 60092-101, for electromagnetic compatibility within the integrated ship power systems are defined to restrict electromagnetic interaction between the various networks on board. As far as ship charging is concerned, there is a considerable lack of standards compared to cold-ironing, especially in dc-based charging. Table II lists the relevant standards for different aspects of the shore-ship interface.

3) Energy Routing and Communication: The electrical framework in ports is experiencing a transition. The vessels are changing from being virtually non-existent on the grid previously to being large consumers and bulk storage providers and this certainly requires an inspection of the energy management plan. Traditionally, an increased load demand in a power system would be met by increased generation on the source side which was available as part of the spinning reserve. Automatic load frequency control, automatic voltage regulators and on-load tap changers constitute the primary control mechanism of this system characterized by unidirectional energy flow and a centralized generation. With the introduction of renewable energy and the evolution of storage technologies, the generation system is becoming more distributed and a number of users can serve as both producers and consumers of energy based on the renewable power, storage capacity and load demand. Modern ports also need to function in such a dual role where an energy exchange is carried out between the grid and users based on the demand at specific

TABLE II
ELECTRICAL STANDARDS IN VARIOUS SHORE-TO-SHIP INTER-CONNECTIONS (BASED ON DATA FROM EUROPEAN MARITIME SAFETY AGENCY)

		Connection	Interoperability	Communication	Directive/ Regulation
CI (Cold Ironing)	HVSC	IEC 62613-1:2016 (General) IEC 62613-2:2016 (Connectors)	IEC/IEEE 80005-1	IEC/IEEE 80005-2	IMO-CI Guidelines EU AFID
	LVSC	IEC 60309-5	IEC/IEEE 80005-3 (under review)	IEC/IEEE 80005-2	IMO-CI Guidelines
	LVSC (inland waterways)	EN 15869-2:2019 (<125A) EN 16840: 2017 (>250A)		Possible application of IEC/IEEE 80005-2	CCNR CESNI – ES-TRIN2019
	Recreational vessels	IEC 60309-2	No standardization	No standardization	Not applicable
Onshore Battery Charging	ac charging	IEC 60309-5 IEC 62613-2	IEC/IEEE 80005-1 IEC/IEEE 80005-3	No standardization (possible application of IEC/IEEE 80005-2 or ISO15118)	Not applicable
	dc charging	No standardization	No standardization		

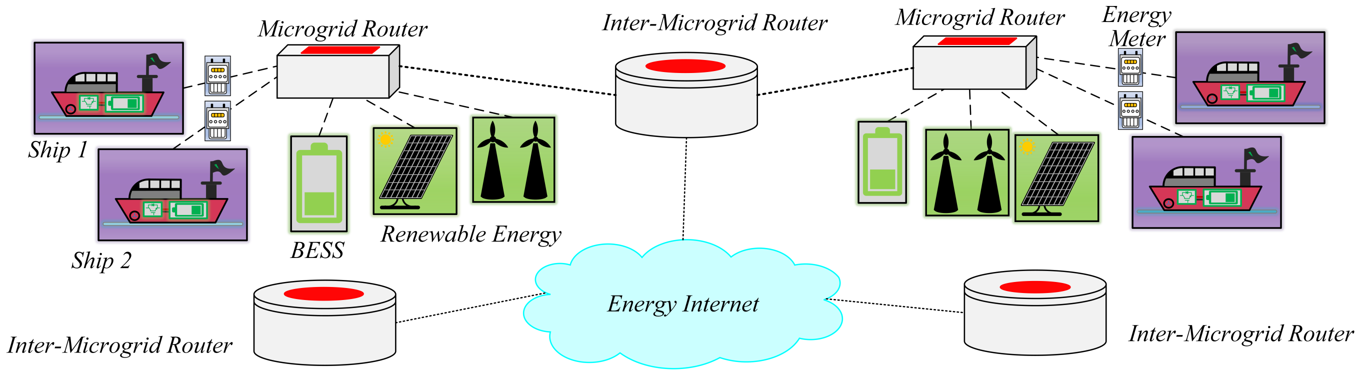


Fig. 13. Energy routing in a port environment: By employing power electronics, communication networks and feeding systems, the use of available energy resources at the port can be maximized

times (Figure 13). This system of energy exchange in a smart grid, also called the energy internet due to similarities with information exchange on the web, could be key in the energy distribution around the ports. Since these large ports can house hundreds of vessels each day among which a large number of the fleet are docked for most of the time, the battery-based vessels can play an important role in power system stability by serving as banks of spinning reserve connected to the grid. For such a bidirectional energy flow-based architecture to function properly, real-time communication between vessels and dynamic management of the energy flow through power converters is paramount. Information about tracking and forecasting the available renewable power, the movement of vessels in real-time with positioning equipment (GPS) and accurate measurements of the energy available in shore storage systems need to be transmitted using a reliable communication system with low transmission latency and high information security is required for the effective operation of the energy router.

4) Energy Metering: The measurement of power exchange between various vessels and the grid through power converters presents challenges of its own. Electromagnetic interference is known to cause faulty readings in static-energy meters where consumers may be billed inaccurately. Though this imprecision may not be significant for small-scale household or car charging infrastructures, it becomes a larger issue where large vessels are consuming power at MW level on a daily basis and a small error may thus cumulatively become quite significant economically over a period of time. Therefore, it becomes imperative to develop, calibrate and test the metering and sensing equipment so that it operates precisely when dealing with large currents and voltages with harmonic content.

Conclusion

Electrification of ships poses several challenges which call for regulatory actions along with technological developments. The use of alternative fuels on board is necessitated in certain marine sectors where state-of-the-art battery-based technologies are not viable for effective operation. The electrification and hybridization of ships will also be earmarked by a trend toward dc-based distribution systems because of their inherent advantages over ac-based systems and advancements in solid-state breaker technology. These new architectures would also enable the existence of distributed energy systems and multi-functionality of the onboard power system where localized microgrids could co-exist independent of the larger power system on board. The vast range of ship types and sizes along with their respective power systems makes the design of shore-to-ship converters a multi-faceted problem. The converters on shore may need to be designed in different ways for charging onboard batteries and enabling cold ironing. This can be done by forecasting the ship routes and berthing-data around the port.

The energy transfer to the ship can be done through container swapping, wirelessly or with conventional cables. Each of these options comes with its advantages and disadvantages and one may be more favourable in certain situations than the other. Attributes such as charging time, cost, movement of the ship while at berth, energy efficiency, system complexity, etc. need to be factored in for choosing the suitable method. The development of energy storage systems plays a vital role in the mass electrification of marine transport. Improvement in energy densities and BMS technology has enabled full-electrification to be pushed to the larger ship market. With the emergence of newer chemistries and solid-state batteries, the battery-based ship market will only experience an upward trend in the foreseeable future. However, with the increased dependence on batteries and power electronics, ensuring reliable and safe long-term operation of these vessels becomes a more complex problem. Reliability analysis and appropriate component-replacement strategy should be adopted to address that and thereby minimize the probability of system malfunction without incurring overwhelming financial losses.

The ship electrification itself comprises several levels wherein the vessel may require charging from the onshore grid or have onboard energy harvesting, or may have a marginal dependence on electrical energy resources. The size of the vessel, its load profile, and the duration of the time spent at the port and in the water collectively decide where exactly it lies on the spectrum of electrification. Besides the vessel itself, there is also a need of enhancing the shore power capabilities which may necessitate intelligent energy routing for more effective utilization of the electrical energy resources available at the ports. Furthermore, with the increased use of solid-state devices and owing to a general trend of power electronics to shift towards a higher switching frequency, the electromagnetic emissions within the vessels need more rigorous attention to avoid undesirable interference problems. Finally, since ships differ vastly from each other on the bases of size, operating voltage and power, there is certainly a need for the establishment of standards, especially for the newer dc-charging based shore connections. With a collective effort from the maritime industries and policymakers, the shipping sector can accelerate the process of reducing its emissions and become a sustainable means of transport for the future.

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