PRACTICAL CONSIDERATIONS FOR
HYBRID ELECTRIC POWER SYSTEMS
ONBOARD VESSELS

APRIL 2022

ABS

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1 OVERVIEW

1.1 OBJECTIVE

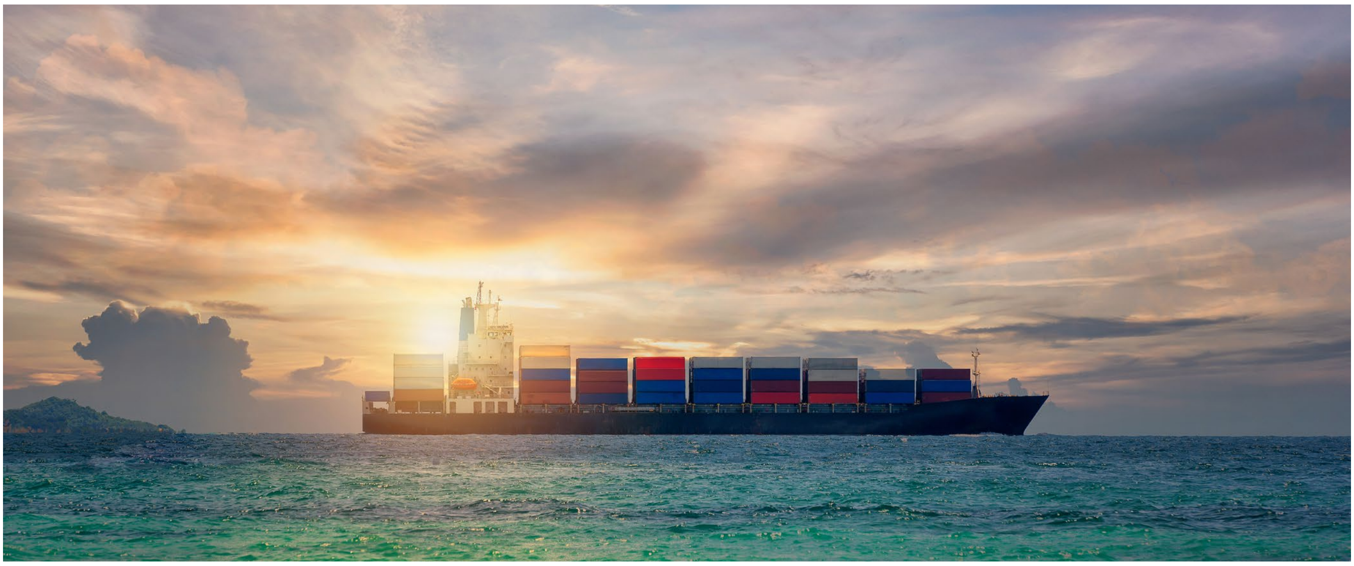
The International Maritime Organization's (IMO) greenhouse gas (GHG) strategy, adopted in 2018, sets ambitious targets to reduce total annual GHG emissions by at least 50 percent by 2050 compared to 2008. It also seeks to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40 percent by 2030, and a 70 percent reduction by 2050 compared to 2008 [1], [2].

Many technologies are being considered to reduce carbon emissions from shipping. Hybrid Electric Power Systems (HEPS) is one of the technologies that can help meet the IMO GHG reduction target for 2050. The ABS *Guide for Hybrid Electric Power Systems for Marine and Offshore Applications* [3] provides requirements for the design, construction, testing and survey of vessels utilizing Hybrid Electric Power Systems.

ABS provides additional information to highlight the Hybrid Electric Power Systems that can assist the marine industry to meet the IMO GHG goals. This publication focuses primarily on the practical considerations for Hybrid Electric Power Systems for marine power application from the following perspectives:

- Power propulsion architecture
- Using renewable energy sources
- Using energy storage systems
- Integration of Battery Management System (BMS), Power Management System (PMS) and Energy Management System (EMS)
- Application of Computer-based Modeling and Simulation
- Impact of Port Infrastructure
- Regulatory Compliance

For the working principles, advantages and disadvantages of different renewable energy sources (such as fuel cell, solar photovoltaic, wind-assisted ship propulsion) and energy storage systems (such as Lithium-ion batteries, Flywheels, supercapacitors), and respective Class requirements and advisories, please refer to the appendix "Related ABS Documents".



1.2 INTRODUCTION

Hybrid Electric Power Systems (HEPS) combine internal combustion engine-driven generators and/or shaft generator/motors driven by a main engine with an energy storage system (ESS) consisting of batteries and supercapacitors, and/or other non-traditional sources of power (such as fuel cells, etc.) technologies to form the power generation and propulsion system of the vessel. The architecture of a hybrid system can be designed specifically for the requirements of each vessel and thus optimize the use of each component for maximum efficiency. The combination of two or more new technologies when conventional generation is not installed on board also constitutes a Hybrid Electric Power System [3].

2 CONSIDERATIONS ON POWER AND PROPULSION ARCHITECTURES

While the pressure to reduce fuel consumption and emissions has increased, the operating profile of ships has become increasingly diverse. For example, offshore vessels perform numerous tasks such as transit and critical dynamic positioning (DP) operations, while naval ships perform traditional patrol operations in the open sea and are also deployed in littoral operations. These and other diverse operational profiles have led to a growing variety of power and propulsion architectures [4]. When applying Hybrid Electric Power Systems to marine vessels, the vessel-specific operational profiles require analysis to find the power and propulsion architecture that matches the need. Various Hybrid Electric Power Systems power and propulsion architectures and arrangements are introduced in the following sections.

2.1 ELECTRICAL PROPULSION

In a typical electrical propulsion architecture, multiple diesel generator sets feed a fixed frequency electrical bus. This bus feeds the electrical propulsion motor drives and hotel loads, in most cases through transformers. The electrical propulsion motor drives also include power electronic converters used to control shaft line speed and thus ship speed [4].

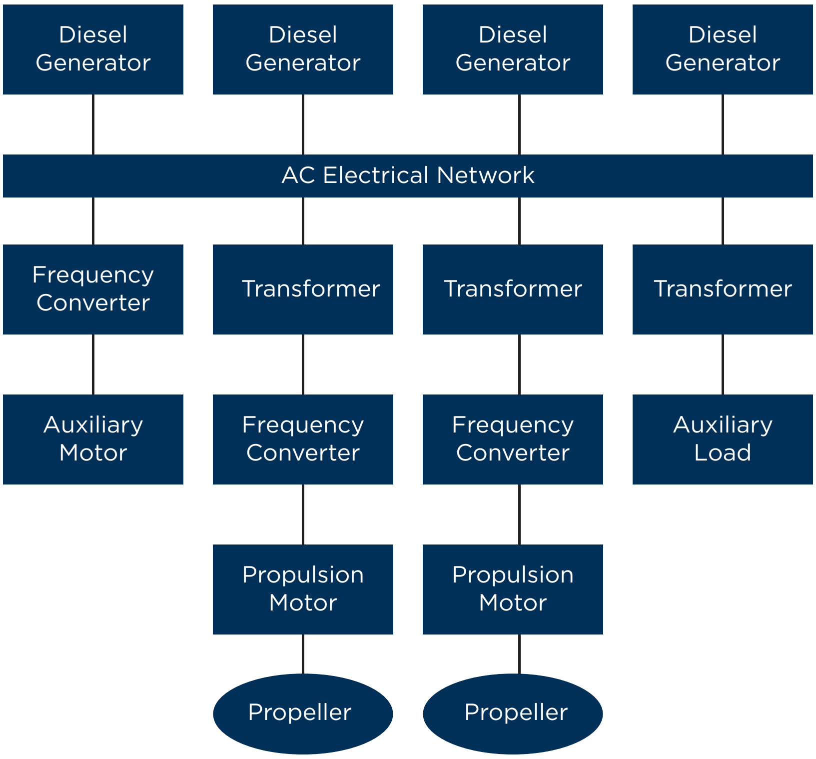


Figure 1: Typical electrical propulsion system layout.

2.2 HYBRID PROPULSION

In hybrid propulsion, a direct mechanical drive provides propulsion for high speeds with high efficiency. Additionally, an electric motor powered by generators can be coupled to the same shaft through a gearbox or directly to the shaft driving the propeller. This can provide propulsion for low speeds, thus avoiding the need to run the main engine inefficiently at partial load. The motor could also be used as a generator to supply power for electrical loads on the vessels' electrical network. Therefore, vessels that frequently operate at low speed can benefit from a hybrid propulsion system [4].

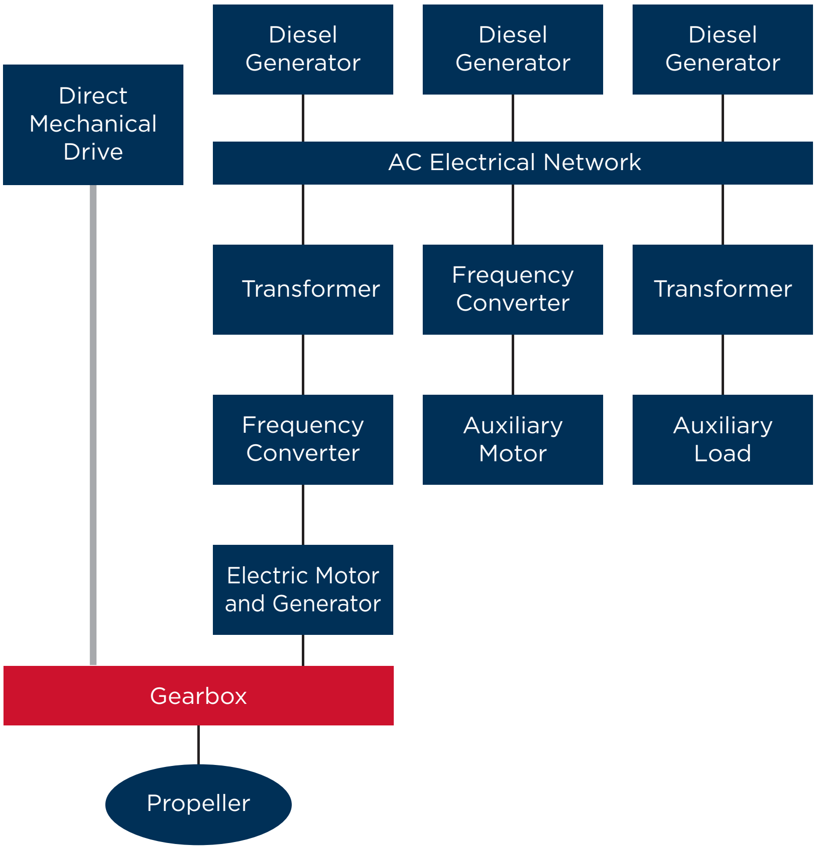


Figure 2: Typical hybrid propulsion system layout.

2.3 ELECTRICAL/HYBRID PROPULSION WITH HYBRID POWER SUPPLY

In this architecture, a combination of two or more types of power sources are used to provide electrical power. The power supply can be from combustion diesel engines, gas turbines or steam turbines, or electrochemical power supply from fuel cells, solar photovoltaic, wind-assisted ship propulsion (WASP), or stored power supply from energy storage systems such as batteries, flywheels or supercapacitors [4].

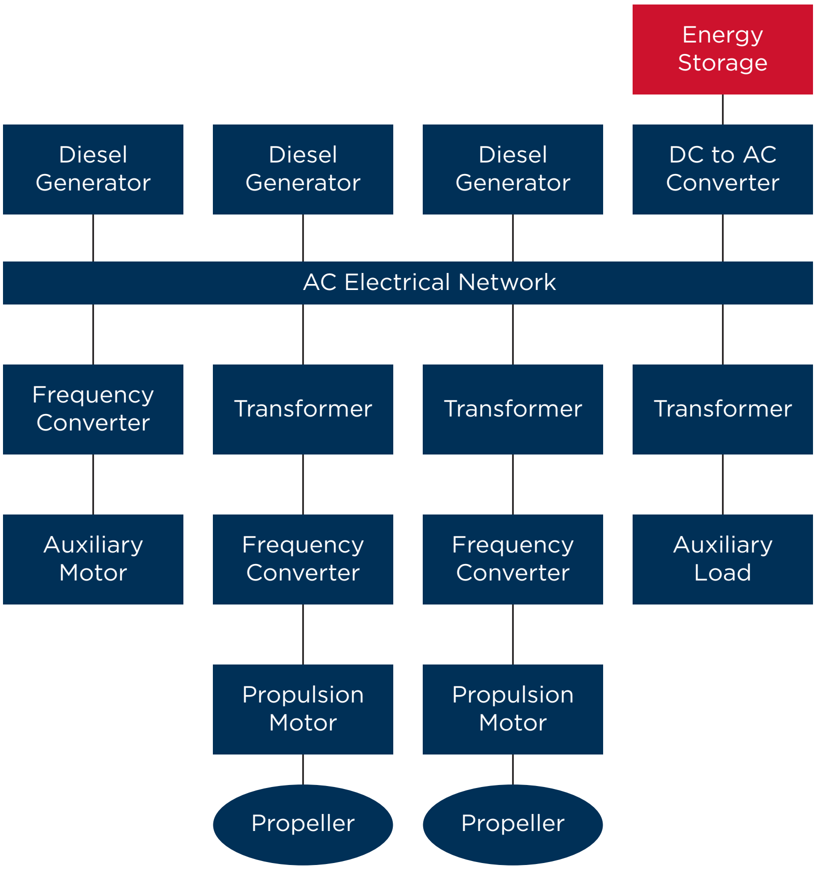


Figure 3: Typical electrical propulsion system with hybrid power supply.

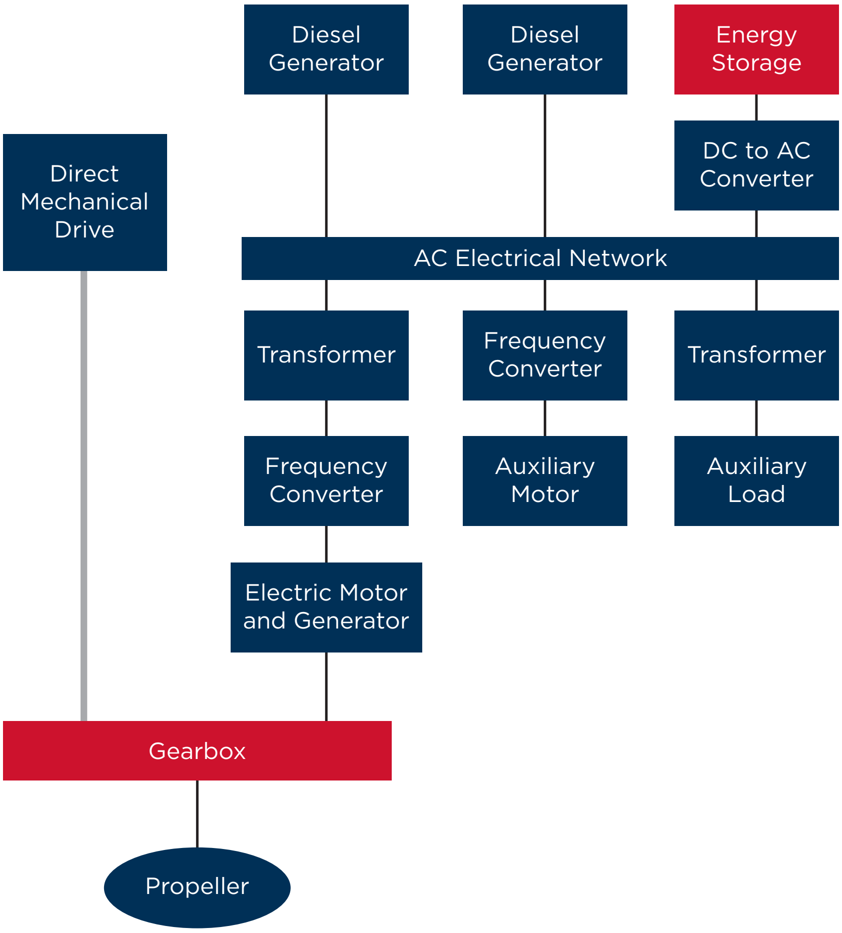


Figure 4: Typical hybrid propulsion system with hybrid power supply.

3 CONSIDERATIONS ON THE USE OF RENEWABLE ENERGY SOURCES

Fuel cells, solar photovoltaic and wind-assisted ship propulsion are several main renewable energy sources being used in the marine industry. This section provides information on considerations for their application in marine ships.

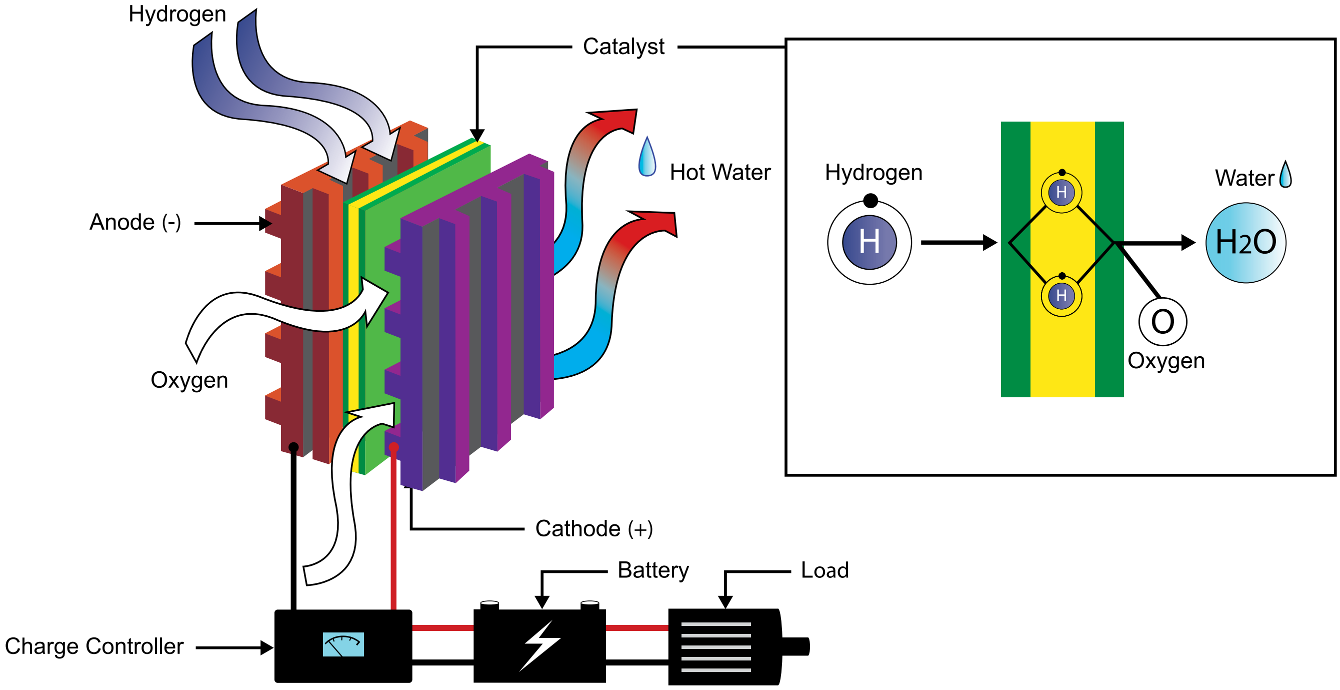


Figure 5: Sample hydrogen fuel cell.

3.1 FUEL CELLS MARINE POWER SYSTEM APPLICATION CONSIDERATIONS

Fuel cells as clean power sources are very attractive for the maritime sector. Proton exchange membrane (PEM), molten carbonate and solid oxide fuel cells are considered to be several promising options for maritime applications [5]. Power capacity, safety, space arrangement, reliability, durability, and risk assessment are important factors that demand attention when applying fuel cells as marine power systems [5], [6].

(I) POWER CAPACITY

The power demands for marine power systems range from a few kilowatts (KW) to tens of megawatts (MW). The maximum power output of fuel cells is normally only several MW, which limits the use of fuel cells in auxiliary power units (APUs), as well as propulsion power plants for inland and short-sea shipping. Creating hybrid systems by coupling with turbomachinery, high-temperature fuel cells, such as Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) offer the potential to provide propulsion power for larger maritime vessels rather than just for auxiliary power [5].

(II) SAFETY

The safety of fuel cell power systems depends primarily on the choice of fuel, with key considerations related to fuel density, flashpoint, auto-ignition temperature, flammability limits and toxicity. Redundant monitoring for leakage, emergency shutdown systems and rapid venting of leaking fuels into the atmosphere are indispensable risk-mitigating measures for gaseous or low flashpoint fuels, such as hydrogen, ammonia, methane and methanol. This applies especially to ammonia and methanol, which can be toxic and dangerous to humans [5].

The ABS *Guide for Fuel Cell Power Systems for Marine and Offshore Applications* provides detailed requirements on fuel cell safety, such as structural fire protection, firefighting systems for methyl/ethyl alcohol-based fuels, personnel safety equipment for the use of ammonia as a fuel, fire detection and alarm systems arrangements.

(III) SPACE ARRANGEMENT

The compartment in which a fuel cell is located is to be considered as a Category A machinery space according to SOLAS Chapter II-2, and IGF Code (International Code of Safety for Ships using Gas or Other Low Flashpoint Fuels) for fire protection purposes. To minimize the probability of a gas explosion, the fuel cell space is to be designed to mitigate hazards to lower hazardous levels under all operating conditions. Due to the nature of hydrogen leaks within the fuel cell stacks, the fuel cell space is to be classified as a hazardous area Zone 1. Therefore, equipment or components installed in this space are to be of a certified safe type (suitable for the hazardous area location) [6]. In some specific cases, the area classification of such space will be subjected to local or flag Administration requirements.

The ABS *Guide for Fuel Cell Power Systems for Marine and Offshore Applications* provides detailed requirements for fuel cell arrangement and installation requirements. The document also provides guidelines on addressing alternative designs, which may be subject to additional engineering review activities, tests, trials, and surveys during construction as applicable by ABS to verify design effectiveness and safety.

(IV) RELIABILITY

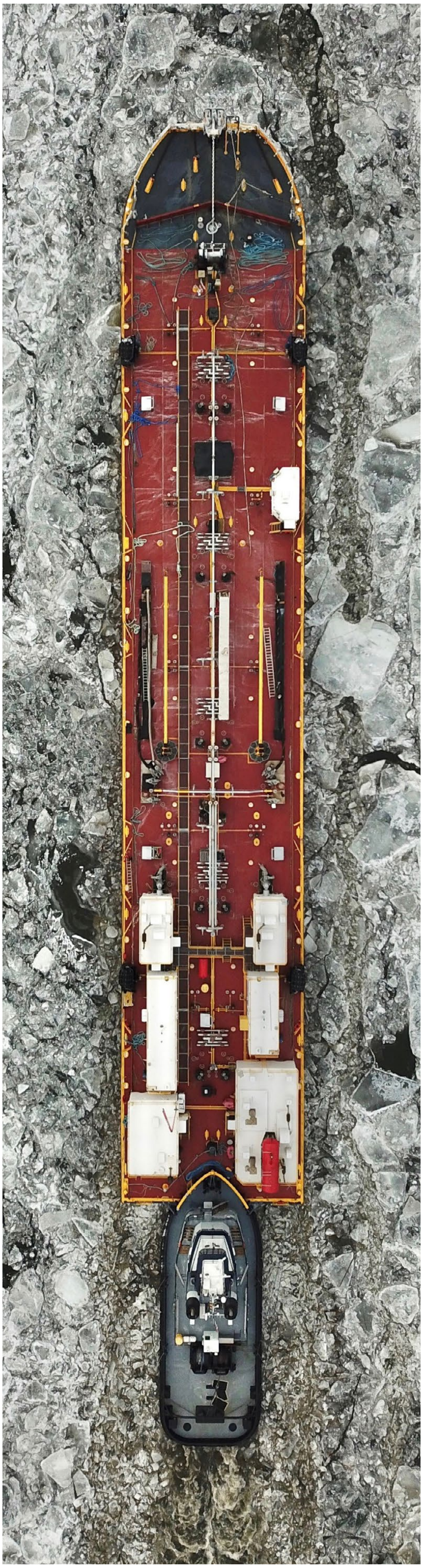
For MCFC and SOFC power systems, high operating temperatures and cycling effects due to load changes make the fuel cell stack vulnerable to failure, with the probability of failure further increased when introducing integrated fuel reforming units and water heat recovery units. The design of redundant systems and components could be employed to avoid a complete loss of power due to single-point failures. Battery banks are viable options for fuel cells to buffer the load fluctuations to avoid negative cycling effects [5].

(V) DURABILITY

The lifetimes of PEMFCs for distributed power systems and transportation applications are estimated to be 80,000 and 8000 hours, respectively, by the U.S. Department of Energy [7]. Some MCFC and SOFC plants have achieved a lifetime of more than 40,000 hours [8]. Maintaining steady-state operation is important to obtain prolonged durability and can only be achieved through appropriate system design and an optimized control strategy encompassing all elements of the power system [5].

(VI) RISK ASSESSMENT

Risk assessments are to be conducted to identify risks arising from the use of fuels (methyl/ethyl alcohol, hydrogen, etc.) which may affect the structural strength or the integrity of the ship, safety of crew on board, and preservation of the environment. Consideration is to be given to the hazards associated with physical layout, operation, and maintenance following any reasonably foreseeable failure. The risks are to be analyzed using acceptable and recognized risk analysis techniques. Loss of function, component damage, fire, explosion, and electric shock are to be considered as a minimum. The analysis should identify risks that can be eliminated wherever possible. Identification of risks, and the means by which they are mitigated, are to be documented to the satisfaction of ABS and to the flag administration if required [6].



3.2 SOLAR PHOTOVOLTAIC MARINE POWER SYSTEM APPLICATION CONSIDERATIONS

Developments in solar photovoltaic technologies are spurring the integration of solar energy into many applications that were previously considered uneconomical. The maritime industry has been mainly focused on deploying this technology on smaller vessels and car carriers, but the use of photovoltaic solar technology in larger ships is slowly gaining acceptance and is seen as one of the viable pathways to reducing GHG from shipping [9].

The installation of photovoltaic (PV) arrays and its integration into the power system can help to reduce greenhouse gas emissions, improve energy efficiency, and contribute to the stability of the ship's power system. However, installing a PV system requires significant attention.

i. Solar irradiance is the amount of solar resources at a particular position and time. The solar resource depends strongly on latitude and climatic conditions. PV modules receive continuously varying solar radiation, especially when used on ships with dynamic and different sailing routes. The irradiation weather routing data plays a major role on determining the system installation on board ships [10].
ii. PV systems generate the most electricity in direct sunlight. Dust, clouds, and other particulates decrease output. Another important issue is the energy production in the hours corresponding to main sunlight insolation, which may not match the peaks in energy demand. This makes an electricity storage system necessary to be part of the installation.
iii. Due to the relatively high area requirements for power generation, PV arrangements on ships in some cases may be better suited to passively charge onboard energy storage systems which assist peak load shaving and transient load buffering. Therefore, power conversion equipment and battery charging arrangements are critical when considering PV on board.
iv. PV panels installed in marine applications must be resistant to harsh sea conditions like high humidity, salt, and corrosion. Short circuits and deterioration to the mechanical parts of the converters are caused by humidity and salt [11].
v. The PV systems installed in ships have tight area constraints as compared to land PV systems. They should be fitted in a manageable location to allow ease of access [11].
vi. Different maximum power point tracking (MPPT) control methodologies are currently available for tracking maximum power from PV panels. The application of these methodologies in ship PV systems becomes complex as the marine environment frequently varies. The performance of typical MPPT methods decrease especially when a large-scale PV system is installed in marine vessels [11]. Therefore, more reliable, and robust MPPT control methodologies for large ocean-going ships need to be developed.

Due to the required area on ships, PV arrays may be suitable for vessels with large open areas or unobstructed surfaces. Solar panels have been installed on car carriers, ferries, yachts, and more recently on bulk carriers, containerships, tankers, and cruise ships to supplement onboard power. With enough surface area, solar panels may contribute to a fraction of the ship's power load requirements, but due to intermittent insolation, they may be better suited as auxiliary power sources.

3.3 WIND-ASSISTED SHIP PROPULSION MARINE POWER SYSTEM APPLICATION CONSIDERATIONS

Interest in wind power has increased as the maritime industry seeks to reduce the impacts of fossil fuels. The existing scientific literature has identified wind-assisted ship propulsion (WASP) technology as a promising option to increase the energy efficiency profile of the maritime transport industry and decrease the CO_2 emissions produced by its operations [12], [13].

The WASP technologies break down into seven main categories [14], [15], [16]:

- Rotors: Rotating cylinders installed on deck that generate thrust from the Magnus Effect.
- Towing kites: Kites provide thrust to ships with the lift generated by higher altitude winds.
- Suction wings: Wings creating an upward-lifting force similar to the wings on airplanes.
- Rigid sails/wing sails: Foils that could be adjusted to produce aerodynamic thrust forces.
- Soft sails: Traditional sails with modern features.
- Wind turbines: Turbines installed on the deck of the ship that generate thrust or electricity.
- Hull sails: Sails that use relative wind with symmetrical hull foils to generate aerodynamic lift.

When applying wind-assisted ship propulsion to marine vessels, key factors that influence the operational performance of the technology are to be considered. [12] Identified key factors in environmental, onboard, and commercial categories:

i. Environmental factors such as wave speed, wave height, and seasonal patterns may affect the wind energy available to be utilized by the technology.

ii. On-board factors such as route optimization, master's decision making, and crew training may affect how effectively the technology is operated.

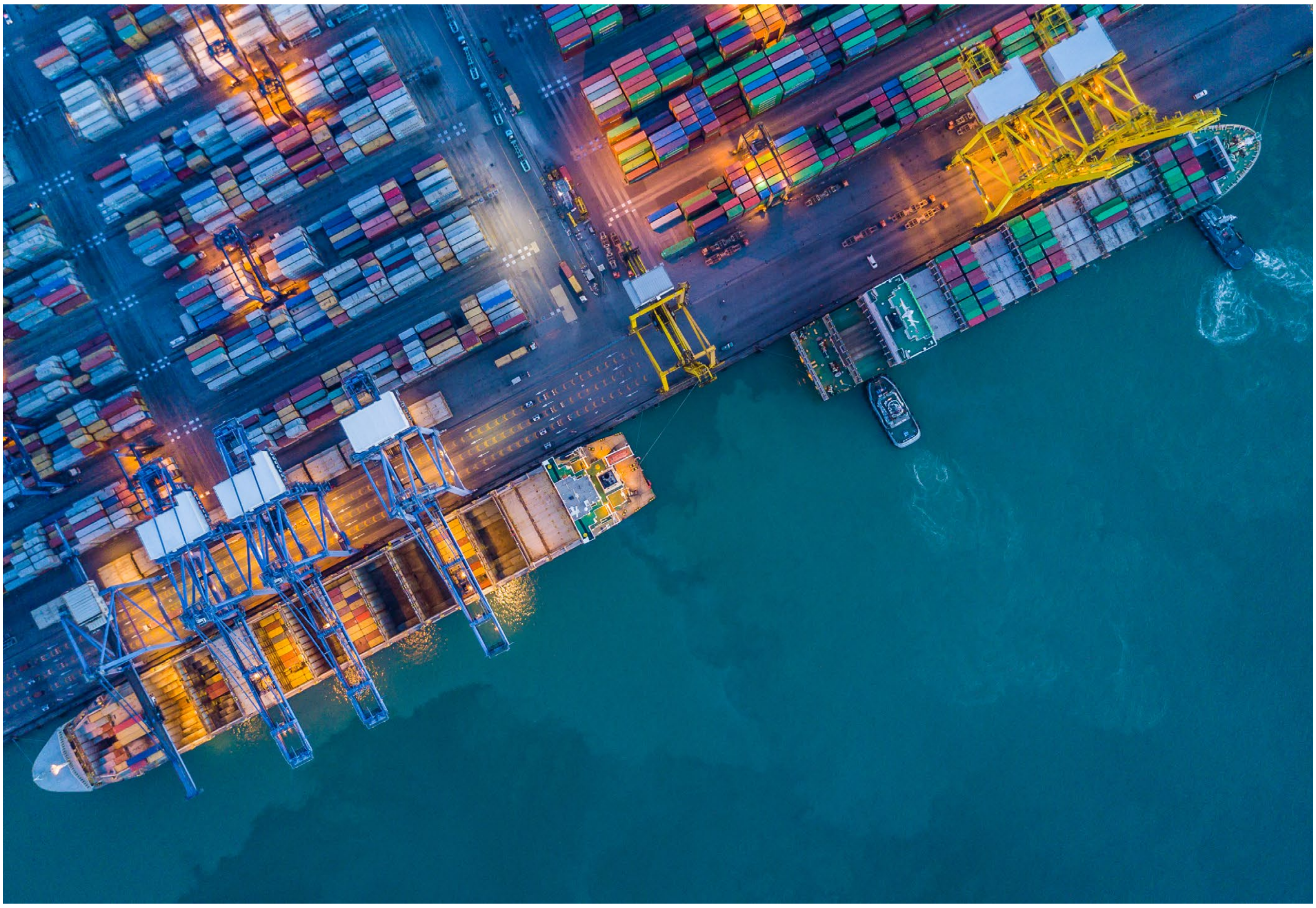
iii. Commercial factors such as trade pattern, trip duration, trip irregularity and port calls may affect the compatibility of the technology with the ship's commercial commitments.

iv. To achieve optimal economic benefits from the adoption of wind-assisted ship propulsion technology, it is important to take a systematic approach rather than treating each factor independently.

Despite the promising trend of technological diffusion and the appealing character of wind propulsion technologies, the current adoptions represent only a small percentage of the total fleet.

4 CONSIDERATIONS ON THE USE OF ENERGY STORAGE SYSTEMS

Lithium-ion batteries, flywheels, and supercapacitors are some of the promising energy storage technologies for use in the marine industry. This section provides information on the considerations of their application in marine ships.



4.1 LITHIUM-ION BATTERIES MARINE POWER SYSTEM APPLICATION CONSIDERATIONS

The Lithium-ion battery is commonly preferred for marine vessel applications due to the high cell voltage, high energy density, long service lifecycle, low self-discharge, and low maintenance requirements [17] [18].

When applying Lithium-ion batteries to marine vessels, key factors influencing the operational performance, lifetime and safety of the batteries are to be considered.

(I) BATTERY DIMENSIONING

Two main parameters are important when battery systems are dimensioned: the energy storage capacity and the power rate at which energy can be transferred in and out of the battery. The battery dimensioning depends on the applications of the battery system. For example, thruster operation requires large amounts of power, but for backup supply purposes, only for short durations. In this case, a high-power, low-capacity battery system can satisfy the requirements [19].

(II) LIFETIME

The degradation of a lithium-ion battery is governed primarily by two factors: temperature and the nature of the cyclic loading of the battery.

- The optimal cell temperature range is 59° to 86 °F [20]. Temperature also influences the degradation due to the battery being cycled. If the battery is charged at too low temperatures, lithium plating can occur in the battery, resulting in a reduced lifetime [19].
- The charging and discharging rate and frequency have a considerable effect on the lifetime of a lithium-ion battery. The smaller the percentage of the total capacity that is charged and discharged in one cycle, and the less frequently the battery is charged and discharged, the longer its service life [19].

(III) COOLING AND THERMAL MANAGEMENT SYSTEM (TMS)

Cooling of the battery pack during normal operations is important, especially during charging and discharging. The TMS must ensure an equal temperature distribution throughout the system to ensure homogeneous aging of the cells, and thereby prevent variations in self-discharge rates and capacities between the individual cells [19].

(IV) THERMAL RUNAWAY

A thermal runaway is an exothermal reaction of the battery cell materials, occurring due to internal failures, where the temperature of a battery cell increases rapidly as the energy in the cell is rapidly released. This may lead to evaporation of gasses which may, depending on the composition of the cell, be flammable, and this requires gas channels that can safely ventilate such gasses. The battery management system (BMS) must be able to detect a faulty cell at the risk of overheating and isolate the whole pack or the string with the module containing the faulty cell [19]. The application of lithium-ion batteries on vessels requires proper fire protection, fire-fighting systems, fire/thermal detectors, and gas detectors depending on the chemistry of the battery cells. The fire suppression medium should follow the material datasheet of the original equipment manufacturer of the battery cells.

(V) BATTERY SPACE

The battery space is to be considered an Auxiliary Machinery Space or a Machinery Space and is subject to additional structural fire protection requirements. The ABS *Guide for Use of Lithium-ion Batteries in the Marine and Offshore Industries* provides detailed guidance on the battery installation and space.

4.2 FLYWHEEL MARINE POWER SYSTEM APPLICATION CONSIDERATIONS

Interest in flywheel energy storage increased in the 1960s and 1970s due to NASA-sponsored programs proposing flywheels as possible sources of power for space missions [21]. Over the years, flywheels have been used as a viable energy storage (in the form of rotational kinetic energy) option technically suited for reliable and cost-effective use in various applications, such as rail transport, road transport, space industries, utility grids, and onboard aircraft carriers [22].

When applying Flywheel Energy (rotational) Storage Systems to the marine industry, the following key factors should be considered:

- The capital cost of the system can be very high due to the need for special materials at high speed, i.e., light mass, and the expensive magnetic bearing in the heavy mass [22].
- In general, the Flywheel Energy Storage System must be balanced to ensure sufficient mechanical performance.
- Operational safety of Flywheel Energy Storage Systems is to be considered during installation and operation due to the dynamic environment and the high rotational speeds.
- Flywheel Energy Storage Systems have a higher power output, measured in Watts , but cannot store as much energy, Watt-Hours, for a long period of time [22].
- Flywheels excel in short-duration and high daily cycles applications [23].
- Flywheel Energy Storage Systems can be used in conjunction with batteries to prolong the battery storage life by using the energy stored in the Flywheel Energy Storage System first, so the batteries' workload should be drastically reduced, thereby improving the battery lifespan [24], [25].
- Flywheel Energy Storage System can compete with supercapacitors in short-term storage applications in the seconds to minutes range [24].
- In most cases, the Motor/Generator is connected directly to the flywheel rotor and operates in a vacuum, which makes rotor cooling a challenge [23].
- Standby losses are often cited as a major disadvantage for flywheels, although in terms of loss as a percentage of rated power, losses are similar to Lithium-ion batteries [23].

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4.3 SUPERCAPACITORS MARINE POWER SYSTEM APPLICATION CONSIDERATIONS

The supercapacitor is an emerging technology in large-scale energy storage segment for infrastructure backup power, peak power shaving, heavy transportation, automotive, marine vessel, utility grid and microgrid services applications [26], [21], [27], [28].

When applying supercapacitors in the marine industry, the following key factors are to be considered [28]:

(I) LIFETIME

The basic end-of-life failure mode for a supercapacitor is an increase in equivalent series resistance and/or a decrease in capacitance. Prolonged exposure to elevated temperatures, high applied voltage and excessive current will lead to increased equivalent series resistance and decreased capacitance [28].

(II) VOLTAGE

Supercapacitor modules are rated with a nominal recommended working or applied voltage. If the applied voltage exceeds this recommended voltage, the result will be reduced lifetime. If the voltage is excessive for a prolonged period, gas generation will occur inside the supercapacitor cells and may result in leakage within the module [28].

(III) DISCHARGE CHARACTERISTICS

When determining required capacitance and resulting equivalent series resistance for an application, it is important to consider both the resistive and capacitive discharge components. In high current, rapid pulse applications, the resistive component from module equivalent series resistance is the most critical. In low current, longer duration applications, the capacitive discharge component is the most critical [28].

(IV) AMBIENT TEMPERATURE

Temperature in combination with voltage can affect the lifetime of a supercapacitor. In general, an increase of ambient temperature by 10 °C will decrease the lifetime of a supercapacitor by a factor of two. As a result, it is recommended to use the supercapacitor at the lowest temperature possible to decrease internal degradation and equivalent series resistance increase over time [28].

(V) VOLTAGE IMBALANCE

Voltage imbalance between modules can occur during all operation states if there are large differences in capacitance value, so it is recommended that strings of individual modules contain the same module family of similar capacitance [28].

5 CONSIDERATIONS FOR INTEGRATION OF BATTERY, POWER AND ENERGY MANAGEMENT SYSTEMS

Battery Management Systems (BMS), Power Management Systems (PMS) and Energy Management Systems (EMS) are the main monitoring and controls systems used to maintain the Energy Storage System (ESS) functions safely, properly, and efficiently. The functions of the BMS, PMS and EMS and their integration considerations will be introduced in this section.

5.1 BATTERY MANAGEMENT SYSTEM

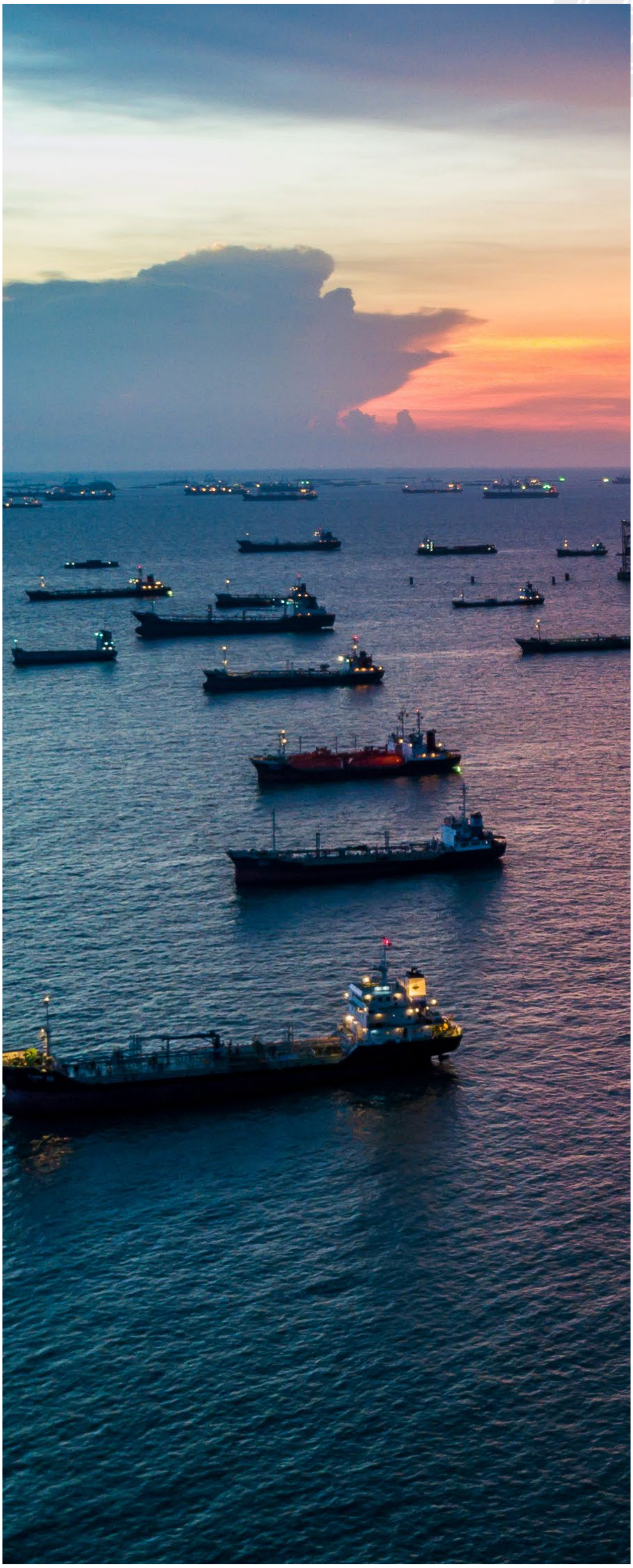
A BMS is the electronic control system that monitors and manages a battery's performance and keeps the battery from operating outside of its safety margins. The main functions of the BMS are as follows [19], [29], [30]:

- Calculating the power limits for charging and discharging the battery independent of the state of charge and temperature
- Determining the state of charge and state of health
- Monitoring the voltage of the cell in order to protect the cell from under- and over-voltage conditions and rebalancing the cell(s) if necessary
- Monitoring the cell temperature, detecting a faulty cell at the risk of overheating, isolating the battery pack, or if this is insufficient, the entire string containing the faulty cell

5.2 POWER MANAGEMENT SYSTEM

A PMS is employed for the generation and distribution of electrical energy and ensures power supply to the marine ships in accordance with the various operational readiness conditions. The equipment within PMS includes the engines, generators, switchboards, and energy consumers [31], [32]. Some of the main functions of the PMS are [32]:

- Load dependent start and connections of diesel generators
- Load dependent stop and disconnections of diesel generators
- Synchronization and load shearing
- Load shedding
- Load calculation and monitoring
- Load control of dynamic consumers
- Blackout prevention and restoration
- Power and voltage control



5.3 ENERGY MANAGEMENT SYSTEM

The EMS is the system-level control and monitoring system in the marine power system. The EMS is responsible for overall system power flow control and management [29]. Some of the main functions of the EMS are as follows [3], [33]:

- Calculates energy demands/usages of vessels in specific operation modes and guarantee that energy demands from all the systems is efficiently met
- Optimizes the battery charging/discharging, and maintains the state of charge and state of health of the batteries within safe service limits
- Optimizes load sharing between batteries and other power sources
- Monitors environmental and system loads and adjusts operations in order to optimize energy usage
- Ensures adequate transient dynamics during load changes and guarantees system stability
- Ensures the safety of the crew and the ship in the event of an emergency

The following are some of the typical algorithms and control strategies in the EMS [33]:

- Algorithms for system-level energy usage calculation in different system operation modes
- Algorithms for splitting the load between the parallel power sources
- Equivalent Consumption Minimization Strategies for fuel consumption optimization
- Model-based predictive control for optimizing energy consumption

5.4 COMPLIANCE WITH CLASS RULES CONSIDERATIONS

Depending on the application and the associated operating profiles, the specific marine vessels may have a variety of power and propulsion architectures. As a result, the ESS system (including BMS, PMS, EMS) onboard ship can be a system of systems with various topologies and hierarchies. Following applicable guides and rules from classification societies will help to address the complexity when integrating BMS, PMS and EMS into an ESS and help the marine vessels with integrated ESS to comply with Class Rules.

ABS publishes several different Rules and Guides to help the maritime industry to solve the above challenges. For example, the ABS *Guide for Hybrid Electric Power Systems for Marine and Offshore Applications* [3] introduces some of the functions of the BMS, PMS, EMS, and applicable management technologies, and provides steps for integrating these systems per ABS Rules and Guides. The Guide also provides a reference list of ABS Guides for the integration of lithium-ion battery systems, supercapacitor systems, and fuel cell power systems into the Hybrid Electric Power Systems.

6 APPLICATION OF COMPUTER-BASED MODELING AND SIMULATION FOR HYBRID ELECTRIC POWER SYSTEMS SIMULATION AND TESTING

6.1 MODELING AND SIMULATION DEFINITION

Computer-based modeling and simulation is the process of developing a mathematical and/or logical model of a system and then using it to obtain data for decision making. The developed mathematical model emulates a physical system in a virtual form which provides flexibility for analysis, evaluation, optimization and testing in a safe and cost-effective way. The key parameters of a physical system, assumptions, and design approaches used for a mathematical model must be accurate and clear to ensure that the outcomes of computer-based simulation are adaptable to real-world applications.

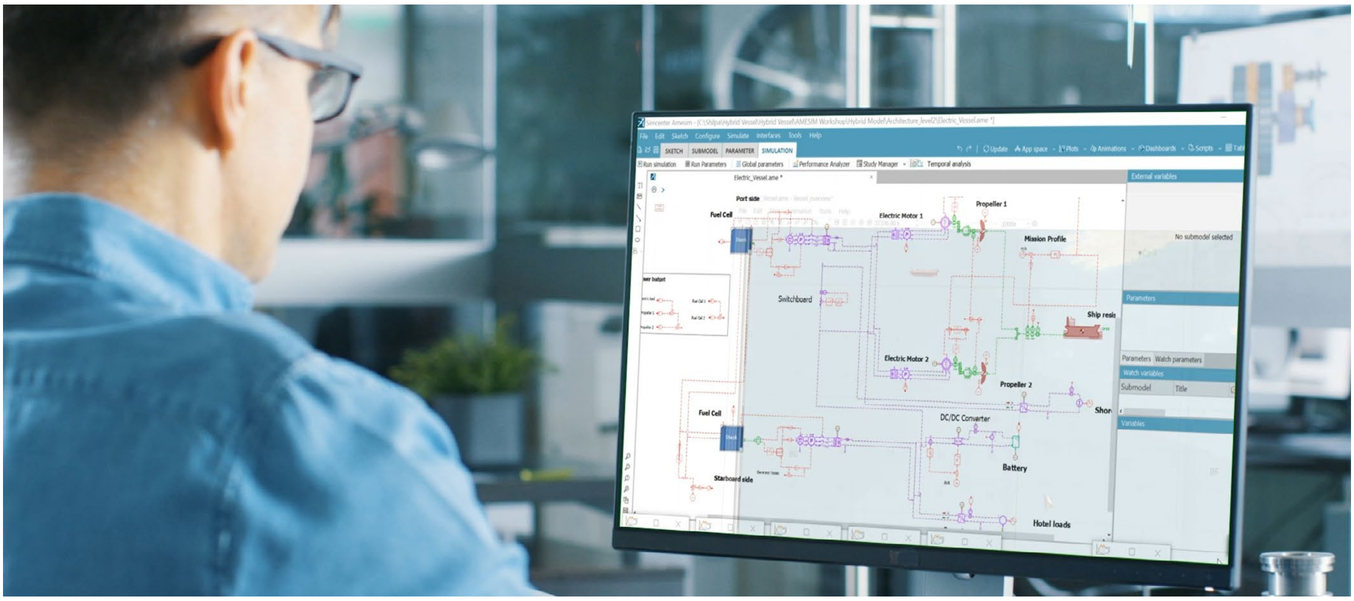
6.2 MODELING AND SIMULATION APPROACHES

Three different approaches are used to model, simulate, and evaluate physical systems: physics-based, data-based and hybrid approaches.

i. A physics-based approach represents a physical system using mathematical models. This approach requires various specifications, design parameters and other key parameters of each component of a physical system. A physics-based approach requires a longer time for model building but provides high granularity for each component e.g., a digital twin of an engine.

ii. A data-based modeling approach approximates the behavior of a physical system using measured data from the same or similar system. This approach is usually adopted for low granularity black box models e.g., fuel consumption calculation of an engine model based on a look-up table from an engine manufacturer.

iii. A hybrid approach combines both physics-based and data-based modeling principles to approximate a physical system in a much faster way when compared with a complete physics-based modeling. A good example is the mathematical model of a propulsion motor simulated using measured shaft power of the same motor or similar motor with the same capacity. In general, the selection of an appropriate modeling and simulation approach is based on the level of granularity, available time, and purpose of the model.



6.3 BENEFITS OF APPLYING MODELING AND SIMULATION FOR HYBRID ELECTRIC POWER SYSTEMS

The conventional document-based computation performs evaluations such as power flow, fuel consumption, efficiency, etc. of a vessel under steady-state operating conditions. However, vessels with existing or retrofitted energy-efficient technologies and power sources such as fuel cells, solar photovoltaic , wind-assisted ship propulsion, batteries, flywheels, or supercapacitors possess high dynamic behavior. The addition of different energy sources into a vessel's electric power system also brings complexity in control and power management.

In such cases, modeling and simulation tools are more suitable to evaluate and understand the time-varying performance characteristics of a vessel and to improve and optimize the overall system performance by strategizing the operation of additional energy-efficient technologies and power sources in a regulated manner for various operating scenarios.

From the perspective of the maritime industry, some of the advantages of using computer-based modeling and simulations are listed below.

- Multi-domain digital model (a model with components belonging to different engineering domains) of a complex system such as a marine vessel can be developed and used for performance and reliability studies.
- Studies on fuel consumption and Greenhouse Gas reduction by integrating various green energy technologies in a virtual environment rather than in a physical system.
- Optimal sea route selection by considering vessel performance under weather and sea conditions, fuel consumption, voyage time, etc., in advance, before a vessel starts to sail.
- Comparison and benchmarking of various design concepts in different operational scenarios in a cost-effective manner.
- Develop, evaluate, and test controller algorithms using Model-in-the-Loop (MIL), Software-in-the-Loop (SIL) and Hardware-in-the-loop (HIL) in a safe and cost-effective manner.

6.3.1 SOME GENERIC CASES WHEN APPLYING MODELING AND SIMULATION TO HYBRID ELECTRIC POWER SYSTEMS

Some of the generic cases in which modeling, and simulation can be used to understand and improve the overall performance of hybrid electric power systems are listed below.

- The characteristics of alternative power sources are dependent on various factors. For example, output power from solar panels and propulsion thrust provided by a WASP system are influenced by weather conditions, geographical area, vessel sailing direction, etc. The modeling and simulation of hybrid electric power systems can provide insights about the characteristics and performance of the overall system due to additional intermittent energy sources. Based on the simulation study results, recommendations and suggestions can be provided to the owner with regard to the most appropriate energy combination or mix for a particular design to optimize the vessel's electric power generation system and maximize the return on investment.
- For a hybrid propulsion system possessing engines, generators and shaft generators, when operating in Power Take Off (PTO) mode, shaft generators can replace some of the generators onboard and provide power to the consumers. By reducing the number of generators for a particular ship operating profile (e.g., seagoing), the utilization factor of each on-line generator and the overall vessel's fuel efficiency can be improved. Therefore, modeling and simulation can be used to analyze and select optimal numbers and combinations of generators and shaft generators in a hybrid propulsion system to achieve optimal fuel efficiency.
- During intermittent loading conditions of a vessel, additional generators may be utilized to meet the load demand. However, by starting a new generator, the overall utilization factor of on-line generators may decrease. This can lead to an inefficient operating condition.
- Under such scenarios, onboard batteries could be charged by generators; thus, increasing the utilization of the on-line generators. Simulation studies can provide insights into the battery system's conditions, charging states, and battery capacities that must be selected to improve the overall efficiency of the generators.
- For a vessel driven and powered by engines and generators, a minimum number of generators must be connected on-line to meet the vessel's load demand. Simulation studies can provide insights to ship designers to enable them to optimize the loading conditions and efficiency of the vessel's generators. Ship designers can also use this tool to trial the implementation of various energy efficiency or energy storage technologies. By optimizing the generators' loading conditions, the system's fuel consumption can be reduced.

6.3.2 ABS CASE APPLYING MODELING AND SIMULATION TO HYBRID ELECTRIC POWER SYSTEMS

ABS is working with Hudong-Zhonghua Shipbuilding and The Technology Group Wärtsilä in a joint development project (JDP) to develop a future multi-fuel electric Liquefied Natural Gas Carrier (LNGC) vessel.

Using advanced multi-physics modeling and simulation, the project applied various decarbonization technologies and solutions such as energy storage systems,air lubrication systems and a new hybrid electric propulsion platform to investigate its performance against the IMO's Carbon Intensity Indicator up to at least 2050.

The model of a new electrical propulsion, generation and distribution system was created. Using real operational data from existing LNG Carriers, simulations were carried out to obtain the estimated fuel consumption, and to predict the Carbon Intensity Indicator (CII) performance of this new design concept.

7 IMPACT TO PORT INFRASTRUCTURE – SHORE POWER CHARGING CONNECTION

Shore power connection technologies have been in use for many years as solutions to supply vessels and to reduce emissions from ships when in port or docked. Near-shore power supplies contribute to support cargo operations (including ballast and liquid cargo pumps onboard and crane operations), maintenance or provisions transfer, and other hotel loads while in port. Shore power connection, however, is not necessarily designed to supply large-scale onboard energy storage systems. Practical design considerations for shore power charging stations, such as flexible power cables, supporting davits, or modern automated connection systems can be adopted from onshore power supply installations.

The development of shore charging facilities has also grown from low voltage systems derived from land-based charging such as those for electric vehicles. Marine charging stations, with the need to supply more power for energy storage systems onboard, typically are designed to provide power at medium AC voltage levels or low to medium DC voltage levels. The required power and arrangements for charging drives the design of the station, source of power, and energy storage on shore.

During charging operations from the shore, the load demand requirements of an energy storage system could be in the order of MWh; In some instances, the coastline grids (which are designed to provide power for routine tasks) may not have the infrastructure to deliver higher power requirements in a short time span; Hence, either grid reinforcement or the setting up of a specialized grid station that can be utilized for charging purposes is required [34].

A shore power station may be located at an existing berth space, near-shore anchorage or mooring areas, on a purpose-built platform, or by a power supply barge for harbor use. However, depending on a vessel's voyage and operations in port, charging stations may not be always available. Examples of those operation activities are cargo transfer, loading and unload operations, passenger or car loading and unloading, stand-by at anchor or mooring, and other fueling or maintenance activities. The operational profile in port can indicate where charging can be best accomplished based on other activities.

Consideration is to be taken into account regarding a typical grid shore power station cost [35] with payback periods that are based on the utilization of the resources. In the case of low traffic, the grid station might be underutilized to obtain financial benefits from the capital spending.

Renewable energies, such as solar PV energy and wind energy, could be used for charging. But because these energies are dependent on intermittent weather conditions, high-capacity battery banks at the port area could be used to store the renewable energy. Investment would be required to set up renewable energy resources and battery banks [34].

A charging station may be specifically designed for a certain type of vessel or operation but may not be suited for others. For the best use of a charging station, consideration should be given in the design to:

- The rate of routine vessels or stops
- The number of vessels designed to use the station
- The ability to supply variable power loads to different vessel energy storage requirements (AC vs. DC, low voltage vs. high voltage, slow charging vs. fast charging, etc.)
- Land-based power supply availability for the designed power supply grid-connected versus off-grid power supply

Safety is another factor that needs to be considered. When the ship's batteries are charged, there is a possibility of arcing when connecting and disconnecting that might be dangerous and may damage the equipment. Suitable insulation is required between these charging systems and the ESS. Appropriate firefighting systems would also be needed to handle emergencies [34].

The ABS *Guide for High Voltage Shore Connection* provides detailed guidance and requirements for the design, installation, and survey of high voltage shore connection installations.

8 REGULATORY COMPLIANCE CONSIDERATIONS

The growing availability of alternative energy storage and generation technologies provides more options and benefits to designers of vessels and offshore installations. These options can be combined in different and imaginative ways, and this has led to the advent of more complex electrical systems. When a preliminary decision is made on a design, it can then be reviewed for practical aspects such as layout, Failure Modes and Effects Analysis, response in a blackout, operation and maintenance aspects. It can also be reviewed for compliance with Class Rules, other regulatory aspects and owner requirements [21].

8.1 ABS SERVICES

The existing classification requirements and international regulations may not take into account the advances created by rapidly evolving energy storage and generation technologies. To address the above challenge, ABS offers new technologies qualifications (NTQ), and novel concepts review and approval services to the marine and offshore industries.

8.1.1 NEW TECHNOLOGIES QUALIFICATIONS

During the new technologies qualification process, a systems engineering approach is used to allow for systematic and consistent evaluation of new technologies as it matures from a concept through confirmation of operational integrity in its intended application. The approach is divided into a five-stage process that is aligned with the typical product development phases of a new technology:

- Feasibility Stage
- Concept Verification Stage
- Prototype Validation Stage
- System Integration Stage
- Operational Stage

The qualification activities within each stage employ risk assessments and engineering evaluations that build upon each other in order to determine if the new technology provides acceptable levels of safety in line with current offshore and marine industry practices. The qualification efforts by all stakeholders including the vendor, system integrator and end-user at each stage are recognized and captured within a new technology qualification plan. Completion of qualification activities as identified within each stage of the new technologies qualification process results in a Statement of Maturity being issued by ABS attesting to the maturity level of the new technology.

ABS *Guidance Notes on Qualifying New technologies* [36] provides a general procedure for vendors/system integrators/end-users to guide them through the process of obtaining Statements of Maturity attesting to the maturity level of new technologies. The process can be applied to technologies seeking qualification independent of class approval or installation on ABS classed assets.

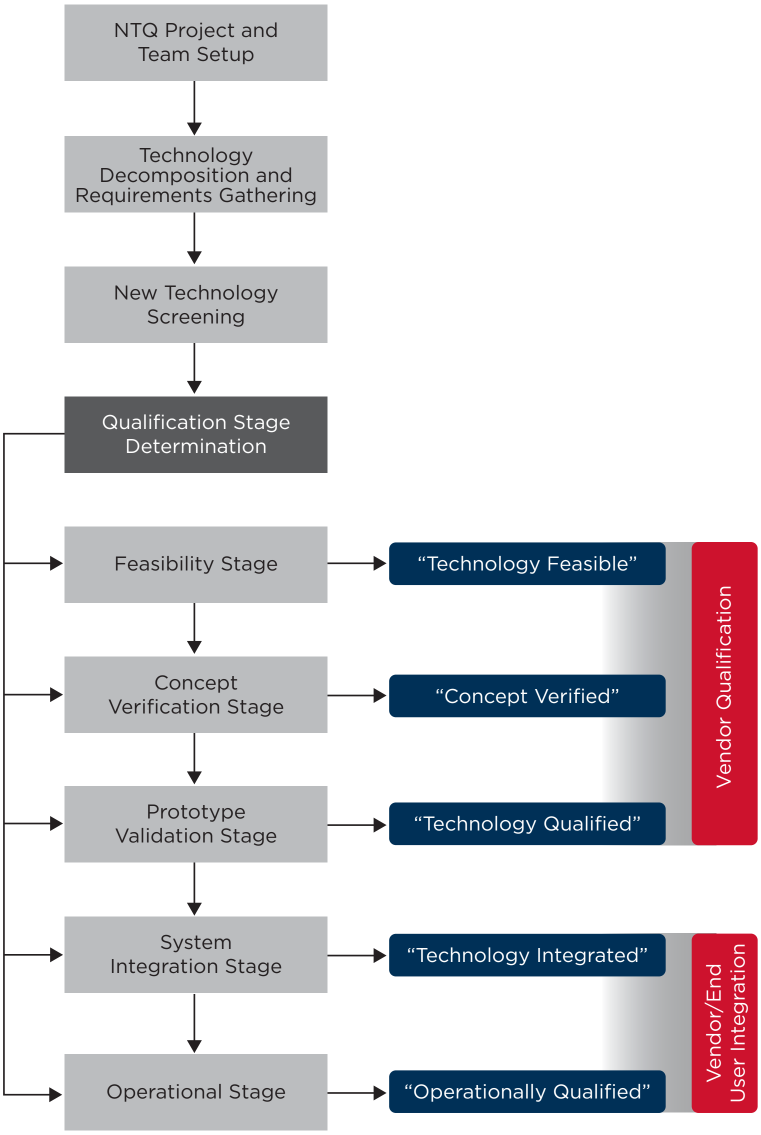


Figure 6: New Technology Qualification Process

8.1.2 NOVEL CONCEPTS REVIEW AND APPROVAL

While individual new technologies can be qualified by following the ABS new technology qualification (NTQ) process, the classification of a novel concept that includes these new technologies may have additional requirements to address the integration/interfacing with existing conventional technologies as well as the asset itself that may not be satisfied through the NTQ process on its own.

The novel concepts review and approval service offers ABS clients a methodology for requesting Classification of a novel concept. During the novel concepts review and approval process, ABS reviews the proposed novel concepts from the project concept phase through maintenance of classification while in operations. The approval is on the basis that special consideration through appropriate engineering evaluations and risk assessments have been given to the novel features to determine if the concept provides acceptable levels of safety in line with current offshore and marine industry practices.

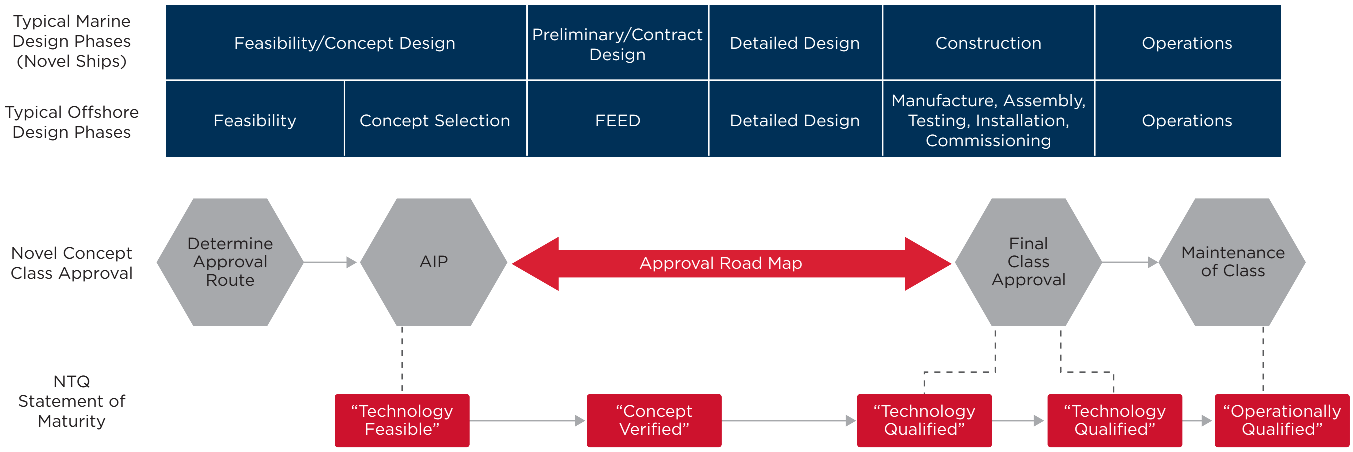


Figure 7: Novel Concept Class Approval Process

Typical clients that the Novel Concept Class Approval process is most applicable for include the end-users or system integrators (e.g., owner/operators, shipyards, etc.) who integrate new technologies qualified by the NTQ process with conventional technologies and/or the asset. The detailed description of the process and responsibilities of ABS is provided in the ABS *Guidance Notes on Review and Approval of Novel Concepts* [37].

9 CONCLUSION

Hybrid Electric Power Systems (HEPS) can help the marine industry to meet the IMO GHG goals.

This publication provides information for practical considerations for Hybrid Electric Power Systems for marine power application from the following perspectives:

- Power propulsion architecture
- Use of renewable energy sources
- Use of energy storage systems
- Integration of Battery Management System, Power Management System and Energy Management System
- Application of computer-based modeling and simulation
- Impact of port infrastructure
- Regulatory compliance

When a preliminary decision is made on a design of a Hybrid Electric Power System, it needs to be reviewed for compliance with Class rules and other regulatory aspects.

ABS provides the new technologies qualifications service that can be used to qualify new technologies (such as alternative energy storage and generation technologies) by confirming their ability to perform intended functions in accordance with defined performance requirements, and the novel concept review and approval service that can help to obtain class approval for an asset that incorporates new technologies.

The integration of the new technology qualification service and novel concept review and approval service provides end-users of the qualified technologies with the added benefit that the transition from new technology qualification to Class Approval will be seamless. It provides regulatory agencies with the confidence that hazards associated with the introduction of the new technology have been systematically identified and mitigated.

10 LIST OF ABBREVIATIONS

ABS	American Bureau of Shipping
APUs	Auxiliary Power Units
BMS	Battery Management System
DP	Dynamic Positioning
EMS	Energy Management System
ESS	Energy Storage System
FC	Fuel Cells
FMEA	Failure Modes and Effects Analysis
GHG	Greenhouse Gas
HEPS	Hybrid Electric Power Systems
HIL	Hardware-in-the-Loop
IGF Code	International Code of Safety for Ships using Gas or Other Low Flashpoint Fuels
IMO	International Maritime Organization
MCFC	Molten Carbonate Fuel Cell
MIL	Model-in-the-Loop
MPPT	Maximum Power Point Tracking
NTQ	New Technologies Qualifications
PEMFC	Proton Exchange Membrane Fuel Cell
PMS	Power Management System
PV	Photovoltaic
SIL	Software-in-the-Loop
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
SOH	State of Health
TMS	Thermal Management System
WASP	Wind-assisted Ship Propulsion

11 RELATED ABS DOCUMENTS

ABS *Advisory on Autonomous Functionality*

ABS *Guide for Hybrid Electric Power Systems for Marine and Offshore Applications*

ABS *Advisory on Hybrid Electric Power Systems*

ABS *Guide for the Use of Supercapacitors in the Marine and Offshore Industries*

ABS *Advisory on Decarbonization Applications for Power Generation and Propulsion Systems*

ABS *Guide for Fuel Cell Power Systems for Marine and Offshore Applications*

ABS *Guide for Use of Lithium-ion Batteries in the Marine and Offshore Industries*

ABS *Guide for High Voltage Shore Connection*

ABS *Guidance Notes on Qualifying New technologies*

ABS *Guidance Notes on Review and Approval of Novel Concepts*

ABS *Guide for Wind Assisted Propulsion System Installation*

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