ABS ADVISORY ON DECARBONIZATION APPLICATIONS FOR POWER GENERATION AND PROPULSION SYSTEMS

OUR MISSION

The mission of ABS is to serve the public interest as well as the needs of our members and clients by promoting the security of life and property and preserving the natural environment.

HEALTH, SAFETY, QUALITY & ENVIRONMENTAL POLICY

We will respond to the needs of our members and clients and the public by delivering quality service in support of our Mission that provides for the safety of life and property and the preservation of the marine environment.

We are committed to continually improving the effectiveness of our HSQE performance and management system with the goal of preventing injury, ill health and pollution.

We will comply with all applicable legal requirements as well as any additional requirements ABS subscribes to which relate to HSQE aspects, objectives and targets.

TABLE OF CONTENTS

1 INTRODUCTION

Climate change is an overarching global issue. The United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement in 2015, pledging to take on increasingly ambitious targets aimed at stabilizing and then sharply reducing Green House Gas (GHG) emissions to keep the average global temperature rise below 2° C and preferably limit it to a safer 1.5° C above pre-industrial levels.

The International Maritime Organization (IMO) recently set ambitious targets for decarbonization of the global fleet, to reduce CO_2 emissions per transport work by at least 40% by 2030 and 70% by 2050, and to reduce GHG emissions from shipping by at least 50% by 2050, compared to 2008. This strategy was set in April 2018 by Resolution MEPC.304(72). In addition, a roadmap (2017–2023) was approved for developing a “comprehensive IMO strategy on reduction of GHG emissions from ships.” The revised strategy is due for adoption in 2023.

The timeline and roadmap for the strategy includes short-term, mid-term, and long-term measures ranging from 2018–2023, 2023–2030 and beyond 2030, respectively. This initiative for the first time brought the shipping industry broadly in line with the goals of the United Nation's (UN) Paris Agreement to combat climate change.

Recognizing the overall challenge of the 2050 IMO targets, ABS has developed a series of documents to reference available carbon reduction strategies, identify gaps for meeting the 2050 goals, and inform the shipping industry as it enters the uncharted waters of the 2030/2050 emissions challenge.

This advisory focuses on shipboard technologies for power generation and propulsion utilizing alternative or renewable fuels with lower carbon content than conventional fuels for the reduction of GHG emissions, taking into consideration the technological complexity, current application, available fuel options, current regulatory requirements and safety concerns. The GHG impact is a complicated issue that encompasses the total emissions accounted from the Well-to-Wake lifecycle. However, this advisory addresses only the impact from Tank-to-Wake that is directly linked to the vessels' power generation and propulsion.

The state of the art technology for power generation and propulsion such as internal combustion engines, gas turbines, and steam turbines can potentially reduce GHG emissions by using low carbon content fuels such as liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol, and ethane, and the industry is developing technologies to use these fuels more efficiently. Ammonia and hydrogen have zero carbon content and if feasible can help to achieve zero carbon emissions. The challenges of power generation technology onboard ships adopting these fuels is the key aspect to be addressed.

Reducing fuel consumption is another way to reduce GHG emissions from shipboard power systems. A hybrid system utilizing batteries, supercapacitors, or renewable energy sources such as wind and solar can either facilitate the propulsion or reduce fuel consumption onboard., thus reducing or partially eliminating GHG emissions.

Carbon capture technology is a potential supplemental solution for reducing a vessel's overall carbon footprint. Although an aftertreatment solution, a post-combustion carbon capture system onboard can also reduce net carbon emissions.

Different marine power generation systems have different levels of technology maturity and readiness. The fuel efficiencies of well-established systems such as internal combustion engines, steam turbines and gas turbines have been shown continually in the marine industry. Other technologies such as wind, solar, and fuel cells are still under development for marine applications, and are mostly used to supplement, or in some cases replace, traditional gensets during varying operational scenarios, such as those at sea, during maneuvering and while docking. Table 1 below shows the energy conversion efficiency for the respective power generation systems.

Table 1: Energy Efficiency Comparison for Different Conversion Types

Power Generation Device	Conversion Type	Energy Efficiency
Diesel engines	Chemical to mechanical	Slightly over 50% (medium speed)
Steam turbine	Chemical to thermal	Up to 50% (primary)
Gas turbine	Chemical to electrical	Up to 40% (primary)
Gas turbine + steam turbine (combined cycle)	Chemical/thermal to electrical	Up to 60% (combined)
Wind turbine	Kinetic to electrical	Up to 60% (primary, theoretical limit)
Solar cell	Radiative to electrical	6-40% (primary, technology-dependent, 15-20% most often, 85-90% theoretical limit)
Fuel cell	Chemical to electrical	40-60% (primary), up to 85% combined heat and power (CHP)

Table 2 below illustrates the major power generation systems, the current status of their compatibility with different type of alternative fuels, and key considerations for the application of different fuels. The supply readiness includes factors such as infrastructure and security of supply. Energy density is an important factor that has significant implications on the fuel storage space required onboard the vessel.

Table 2: Examples of Power Generation Systems and Fuel Types

Fuel Type	Internal Combustion Engines	Gas Turbines	Steam Turbines	Fuel Cells	Energy Density (MJ/lt)	Global Bunkering Availability
Marine gas oil (MGO)	🟢	🟢	🟢	◐ *	39.8	Bunkering available globally
Heavy fuel oil (HFO)	🟢	🟢	🟢	◐ *	38.4	Bunkering available globally
LNG	🟢 **	🟢	🟢	🟠 *	21.6	Bunkering available regionally
LPG	🟢 **	🟢	🟢	🟠 *	24.9	Bunkering available regionally
Methanol	🟢 **	🟠	🟠	🟠 *	15.7	Developing bunkering capacity
Ammonia	◐	🟠	🟠	🟠 *	15.7	Developing bunkering capacity
Hydrogen	◐	◐	◐	🟢	9.2	Developing bunkering capacity
Biofuels – Biodiesel	🟢	🟢	🟢	◐ *	38.0	Developing bunkering capacity

**Depending on the types of the fuel cells, fuel reforming may be needed to utilize the fuel*
*** Please refer to Section 2 Internal Combustion Engines for further discussion on the applications for alternative fuels*

Legend:

- 🟢 Compatible, readily applicable
- 🟠 Compatible, readily applicable, under research
- ◐ Compatible in principle but currently under research and development

Some fuels are well matched with power generation systems, while others are better for reducing GHG emissions. Many of the newer fuel types also possess poor energy density. Yet there is no obvious choice of fuel or power generation system that could dominate in the future. The feasibility of the power generation system and fuel option combination are discussed in the following sections.

2 INTERNAL COMBUSTION ENGINES

Reciprocating engines have been used for the propulsion and power generation of vessels since the early 19th century and have been proven to be one of the most robust and dependable marine technologies. Throughout the 20th and early 21st century, engines have undergone significant improvements driven by technological development, fuel availability, economics and now, environmental factors. In a similar fashion, the current IMO regulations for GHG reduction from shipping are driving technological advancements in engines aimed at improving their efficiency and enabling the use of low- and zero-carbon fuels. This section provides an overview of the existing and emerging internal combustion engine technologies, the fuels considered for medium- and long-term use, as well as associated technologies for fuel storage, delivery, and emissions control.

2.1 CURRENT APPLICATIONS

2.1.1 STATE-OF-THE-ART

Of the two primary combustion cycles, the Diesel cycle and the Otto cycle, the vast majority of modern vessels use diesel internal combustion engines as their prime movers due to their operating simplicity, robustness, and high efficiency compared to the other combustion type.

Dual-fuel engines entered the marine propulsion sector in 2005 in the form of medium-speed engines used in diesel electric configurations for propulsion and power generation on LNG carriers, and following the pilot projects for gas-only engines on ferries that started around 2000. Since then, the types and applications of dual-fuel and gas-only engines have expanded to cover market demand and to satisfy regulations imposed through the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) and The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). The use of slow-speed, 2-stroke, dual-fuel engines for main propulsion on LNG carriers has now emerged as the propulsion system of choice, with major manufacturers offering a different engine combustion philosophy for gas mode operation. The large, 2-stroke dual-fuel engines currently in production use natural gas (methane) in combination with HFO/MGO pilot injection fuel in a dual-fuel combustion process. Two main injection methods have been used, the low-pressure gas injection used by WinGD in the X-DF series of engines utilizing the Otto combustion concept in gas mode; and the high-pressure gas injection used by MAN ES in the ME-GI engines, utilizing the diesel diffusion combustion concept in oil and gas modes (Figure 1). The key difference between the two is that the low-pressure system injects gas into the cylinder early in the compression stroke at pressures of up to 16 bar, while the high-pressure system injects gas into the cylinder late in the compression stroke at pressures up to 300 bar for LNG and pressures up to 400 bar for ethane gas.

The low-pressure gas injection concept uses the Otto combustion cycle wherein the gas is injected through the cylinder liner and mixed with air prior to compression. After compression, the gas-air mixture is ignited by pilot oil and combustion occurs with propagation of a flame front throughout the combustion chamber. Gas-air mixtures outside the flammable range cannot be ignited, which results in fuel slip/methane slip. The outcome is a relatively low peak combustion temperature that generates comparatively low NOx emissions and can achieve IMO Tier III compliance without the need for aftertreatment. This combustion process is, however, sensitive to variations in load, scavenge air temperature and gas composition. Such variables can reduce efficiency and increase the methane slip. Dual-fuel Otto cycle engines are not as efficient as Diesel cycles engines because the compression ratio is limited due to the risk of knocking and misfires.

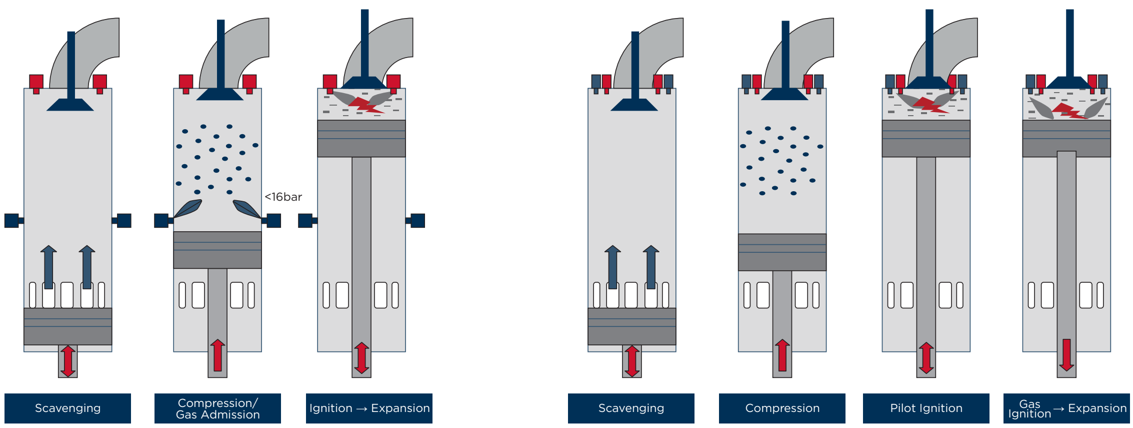


Figure 1: Comparison of Low-pressure vs. High-pressure Gas Injection Engines

High-pressure gas injection creates a turbulent flow that results in an ideal mixture of air and gas when delivered to the pilot flame. This combustion process leads to higher cylinder temperatures, higher fuel efficiency and a somewhat higher formation of NOx that requires aftertreatment to achieve IMO Tier III compliance. However, ignition through pilot fuel is fully robust, leading to a stable combustion process that is insensitive to variations in gas composition, scavenge air temperature and load. As a result, both carbon and hydrocarbon emissions are low, indicating that the fuel efficiency is very close to optimal.

From a regulatory safety perspective, the IGF Code defines a high-pressure system as anything that supplies gas at 10 bar or higher, so both systems carry that designation which mainly applies to piping, pressure vessel design, and certification.

The introduction of alternative fuels such as LPG, methanol, ethane and ammonia has spurred further development of internal combustion engine technologies, for example the MAN ES slow-speed, 2-stroke, high pressure (HP) engines that can use a dual-fuel combustion mode. The modifications required to accommodate alternative fuels focus on the fuel storage and delivery systems, since the different fuel properties require different methods for fuel containment and injection into the cylinder. This has driven the development of the MAN ES ME-GI HP combustion concept for application with fuels that can be maintained in a liquid phase up to injection, and the ME-LGI engine, used for methanol, LPG and ammonia. In this concept the high pressure is generated in the fuel injectors (similar to conventional diesel internal combustion engines) and the fuel supply systems are therefore low pressure. For more information see the ABS *Advisory on Gas and Other Low Flashpoint Fuels.*

Aside from the use of dual-fuel, 2-stroke engines, a range of 4-stroke, dual-fuel engines have been used for applications of marine and stationary power generation. These engines were first introduced in diesel-electric gas carriers with outputs in the 6-18 MW range, such as the Wärtsilä 50DF and MAN ES 51/60DF engines. As the size and type of ships using gas as fuel increased, so has the number of available marine-gas and dual-fuel engine types. The established marine engine manufacturers have expanded their ranges and other manufacturers have entered the market.

In dual-fuel configuration, the engines use low-pressure gas injected into the intake port, which creates a nearly homogeneous gas-air mixture in the cylinder, ignited by a diesel injection late in the compression stroke. However, in the gas-only configuration, the engines use a pre-chamber spark gas (SG) ignition system, which includes a gas injector in the intake port and a second gas injector directly into the pre-chamber.

Combustion initiates in the pre-chamber using a spark discharge. After the pressure rises in the pre-chamber, gas forms high-speed jets in the main chamber, which creates distributed ignition sites in the cylinder. This process results in rapid combustion of the fuel-air mixture and enables the use of a high compression ratio for higher thermal efficiency. It also offers high combustion efficiency which reduces methane slip. The second fuel injector placed directly into the pre-chamber enables the engine to operate at very lean mixtures by injecting additional gas into the pre-chamber and promoting lean ignition. This process was used by other manufacturers such as Rolls Royce Bergen and Mitsubishi with early marine gas as fuel applications.

2.1.2 RESEARCH AND DEVELOPMENT

The advent of NOx and SOx regulations from the IMO has motivated research and development efforts for 2-stroke and 4-stroke marine engines. Current efforts can be categorized into two main areas: 1) understanding combustion processes for improving efficiency and emissions with conventional and alternative fuels; and 2) design aspects of engine systems and component development.

In the first area, manufacturers are collaborating with academic and research organizations to investigate the combustion processes of marine engines so that they can maximize combustion and thermal efficiency while minimizing emissions. These processes include fuel injection in the cylinder and mixture preparation, ignition by pilot injection and heat release, and post-oxidation of soot particles and unburned hydrocarbons. Recently commenced research projects have also indicated the investigation of low temperature combustion processes for application in marine engines.

In the second area, manufacturers and suppliers are focusing on improving engine design and auxiliary components, such as the fuel gas supply system and their components, simplifying component design for reducing complexity and cost, reducing engine friction, and developing advanced boosting systems (e.g. two stage turbocharging). Manufacturers are also utilizing flexible valvetrain systems for improved control of gas exchange and methane slip, in-cylinder emissions control systems such as internal or external Exhaust Gas Recirculation (EGR), and direct or indirect water injection for NOx control. These subsystems are integrated into the engine system to enable accurate control of the combustion process to improve efficiency and emissions formation while maximizing the operating load.

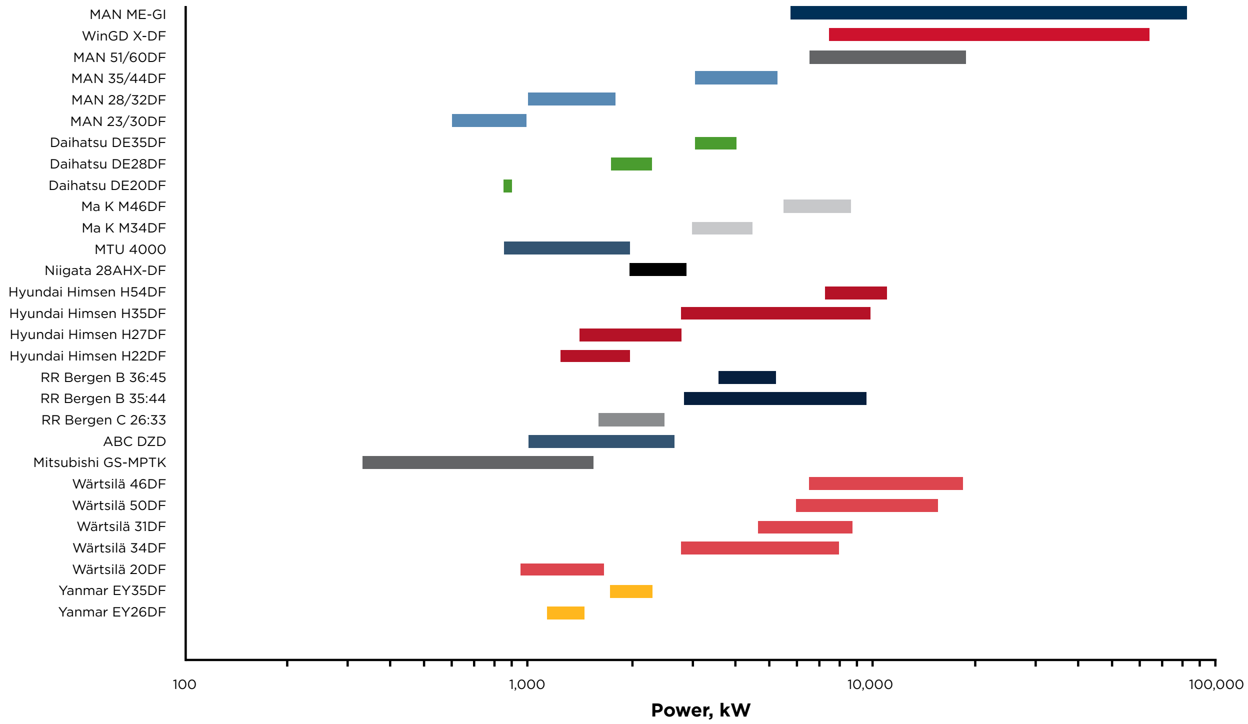
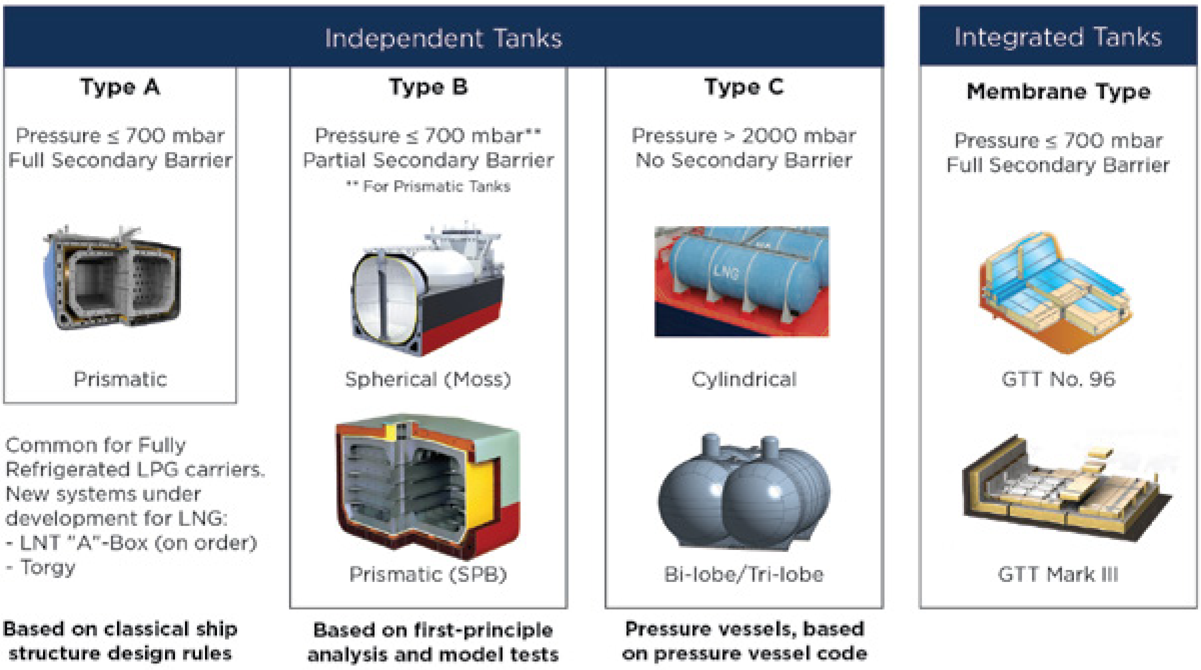


Figure 2: Range of Marine Dual-fuel and Gas Engines

2.2 SUPPORT EQUIPMENT AND SYSTEMS

2.2.1 CONTAINMENT AND STORAGE

The design and operational requirements for different LNG fuel containment systems are described in the IGC and IGF Code, namely independent tank types A, B and C and dependent membrane tanks (Figure 3). Types A, B and membrane are low pressure, nominally "atmospheric" tanks, and Type C tanks are designed using pressure vessel codes. The predominant technologies used for LNG carrier fuel containment in the past 20 years are the membrane and Type B Moss systems. Type A, B and membrane tanks require a secondary barrier to contain leaks from the primary barrier. Type A and membrane systems require a full secondary barrier. Type B requires a partial secondary barrier, since they are designed using advanced fatigue analysis tools and a "leak-before-failure" concept, for which small leaks can be managed with partial cryogenic barrier protection and inert gas management of the inter-barrier space. Type C tanks are designed using pressure vessel code criteria and conservative stress limits and thus do not require a secondary barrier.



© LNT Marine, GTT, JMU, Moss Maritime, TGE Marine Gas Engineering, Kawasaki Heavy Industries, Ltd., Marine Chemist Association

Figure 3: Tank Options for LNG Storage Onboard

The easiest way to keep LNG cooled at ambient pressure is to allow part of the cargo to evaporate or boil off. LNG is stored and transported as a boiling liquid and therefore requires an effective boil-off gas (BOG) management strategy. Historically, cargo containment systems were designed with maximum boil-off rates (BOR) of 0.15% volume per day, which matched well with the fuel requirements of the relatively low-efficiency steam turbine plants. The transition to diesel-electric and slow-speed DF engines that started in 2005 and 2014, respectively, has driven designs with improved LNG tank insulation and BOR as low as 0.08% to better match the available BOG to the higher efficiency of the internal combustion engines.

For gas-fueled ships, the amount of BOG available may not be enough to sustain the power demands of propulsion, so the fuel gas supply systems need to force vaporization of the LNG into conditions suitable for the engines. The ship still needs to manage the BOG and LNG tank pressures at all times, which can lead to many potential combinations for fuel supply and BOG management equipment.

The revised IGC Code allows gases other than natural gas to be used as fuel. If acceptable to the administration, other cargo gases may be used as fuel, providing that the same level of safety as natural gas in the code is ensured. However, the use of cargo identified as toxic in Chapter 19 would need to be specifically agreed upon by the flag Administration.

The IGF Code contains functional requirements for all appliances and arrangements for the usage of low-flashpoint fuels. Part 1 of the IGF Code covers only natural gas, but other fuels can be used as well, provided that they meet the intent of the goals and functional requirements and provide an equivalent level of safety by application of the Alternative Design process. The latter has to be demonstrated as specified in The International Convention for the Safety of Life at Sea (SOLAS) regulation II-1/55, which refers to the IMO Guidelines MSC.1/Circ.1212; refer also to MSC.1/Circ.1455, "Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments," for guidance on alternative design approval. This approach is addressed in the ABS *Marine Vessel Rules* (MVR) under 5C-13-2/3.

2.2.2 EMISSIONS CONTROL

For compliance with the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI Regulation 13 NOx limits, there are a number of routes that apply. Where possible, engine designers try to comply with emissions regulations without exhaust aftertreatment systems. This is because of the increased complexity, cost, and additional consumables of the aftertreatment system. There are a number of engine designs that can meet the IMO Tier III limits without aftertreatment. These engines may be referred to as advanced diesel engines since they may incorporate 2-stage turbocharging, variable valve timing, variable geometry turbocharging, common rail fuel systems, Miller timing and likely Exhaust Gas Recirculation (EGR). The use of Selective Catalytic Reduction (SCR) aftertreatment systems is another route to Tier III compliance, as well as the low-pressure Otto process dual-fuel and gas engine option. These engines can meet Tier III without aftertreatment, but gas availability should be considered at all times.

EGR is accomplished by redirecting exhaust gas back into the cylinder to create a mixture of fresh air, fuel and burned gas at the beginning of the cycle. This is an established technique and can be accomplished either by trapping exhaust gas into the cylinder during the exhaust stroke (internal EGR), or by using an external loop from the exhaust pipe back into the intake (external EGR). These two techniques have roughly the same effects in suppressing NOx formation during combustion. The amount of NOx formed during combustion has an exponential dependence on the cylinder temperature. Adding exhaust gas into the fresh mixture increases its heat capacity and thus limits the temperature rise and NOx formation.

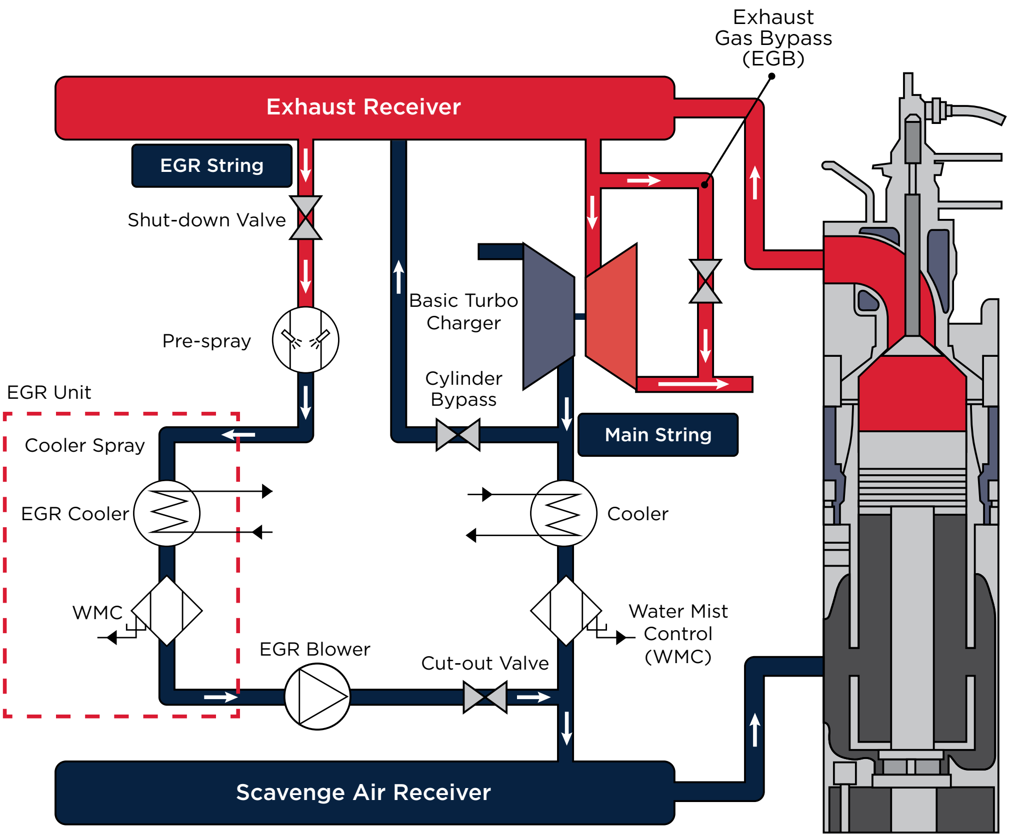
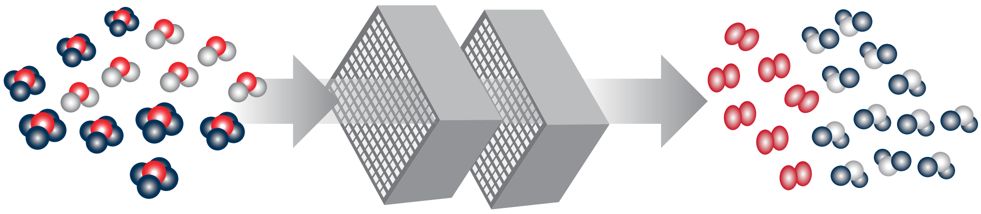


Figure 4: Sample of Exhaust Gas Recirculation System

EGR can be accomplished using a high-pressure or low-pressure loop depending on the bleeding point of exhaust gas in relation to the turbocharger. However, the recirculated exhaust gas must be cleaned and cooled before it can be mixed with the intake air. Fresh water can be used to clean and cool the recirculated exhaust gas. Condensation from the combustion process accumulated in the EGR unit needs to be removed and treated. The water discharged overboard is referred to as bleed-off water and is subject to the IMO Guideline MEPC 307(73), 2018 Guidelines for Discharge of Exhaust Gas Recirculation (EGR) Bleed-Off Water. The relatively high sulfur content of marine fuels necessitates a scrubber and water treatment system for EGR unless operating on Ultra-Low-Sulfur Diesel (ULSD). This scrubber is similar but smaller to those used on SOx scrubbers because of the lower mass flow rates of EGR.

EGR is an effective method for controlling NOx formation, but it may not be sufficient to reduce NOx to the desired levels for compliance in certain engines or in the future with the advent of more stringent regulations. In these cases, SCR can be used as a means of exhaust gas aftertreatment. SCR systems have been extensively used in stationary and automotive applications and they have high NOx reduction efficiency at over 90%. SCR relies on the use of ammonia as a reductant of NOx to nitrogen and water vapor. Since ammonia is toxic to humans, it is stored and used in a urea solution, commonly known as Diesel Exhaust Fluid (marketed as "AdBlue" in automotive applications), which is injected into the exhaust stream prior to the catalytic converter.



$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$$

Urea + Water > Ammonia + Carbon Dioxide

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

Nitric Oxide + Nitrogen Dioxide +Ammonia > Nitrogen + Water

Figure 5: Principle of Selective Catalytic Reduction

NOx reduction reactions require high temperature and therefore the placement of the catalyst is important. For 4-stroke medium and high-speed engines the SCR catalysts can be installed downstream of the turbocharger. For 2-stroke slow-speed engines the SCR catalyst is typically fitted before the turbocharger, known as high pressure SCR, since the high thermal efficiency gives low exhaust temperatures. Low pressure SCR systems can also be applied to 2-stroke engines and located in the downstream exhaust but typically utilize a burner or heating system to raise exhaust temperatures. The combination of the reductant and the catalyst technology is critical to performance. Catalysts are continuously being developed to improve conversion efficiencies at lower temperatures. Catalysts are manufactured from ceramic materials and incorporate active catalytic components of base or precious metals such as vanadium, platinum, copper, and iron. For marine applications, where the sulfur content in the fuel is relatively high, vanadium catalysts are the norm. The maximum catalyst temperature also has to be controlled to avoid formation of sulphates, thermal damage or vanadium emissions. This need emphasizes the role of SCR as a critical part of the overall engine emissions control strategy. The interaction between the engine and SCR control systems is key to continued emissions compliance and maintaining exhaust temperature within the upper and lower limits for the particular catalyst and fuel specification. There are also concerns related to urea slip, the cost and availability of urea, transient response of the SCR system due to thermal inertia, and the additional soot blowing equipment required for marine fuels. For more information on NOx compliance and technologies, see the ABS *Advisory on NOx Tier III Compliance*.

2.3 FUEL OPTIONS

The majority of internal combustion engines use HFO, MGO, or marine diesel oil (MDO) for power generation and most of the dual-fuel engines in production use LNG to accompany HFO or MGO for pilot injection fuel in the dual-fuel combustion process. Other fuels used in dual-fuel engines include ethane, methanol, and LPG, with many operators already using biodiesel-infused fuels. Several ammonia and hydrogen projects are under development.

LNG is a relatively mature low-carbon content fuel, comprised primarily of methane. Its C/H ratio offers a potential reduction of carbon dioxide (CO_2) emissions from internal combustion engines. However, methane slip is particularly an issue in two-stroke or four-stroke engines that operate in the Otto cycle and must be minimized as it contributes to the onboard emissions and overall GHG footprint of the vessel. There are a number of published studies focused on the Global Warming Potential (GWP) impacts of LNG as a fuel considering the Well-to-Wake lifecycle and they show a wide range of the potential CO_2 reduction when using LNG as a marine fuel. The Life Cycle GHG Emission Study [1] developed by Thinkstep reported methane as a marine fuel as having CO_2 reductions in the range of 7%-21%, depending on combustion technology, on a 100-year GWP basis. The ICCT study Climate Implications of Using LNG as a Marine Fuel [2] reported CO_2 emissions in a range of 16% increase to 15% reduction, depending on combustion technology, on a 100-year GWP basis. The technology for using LNG as a marine fuel is an active research topic. The industry is currently developing in-cylinder emissions control strategies, which could be combined with aftertreatment systems. Other measures can be combined with either combustion concept, such as EGR, methane oxidation catalysts and other aftertreatment systems used to treat the exhaust gas to further reduce the methane emissions of using LNG.

Other alternative fuels such as ethane, methanol, and LPG have been explored by the industry, and some engines using these fuels are in production for commercial use. The lower energy content (compared to fuel oil) of all the alternative fuels considered (including LNG) limits the amount of energy that can be stored on board; therefore, future designs must accommodate the different fuel characteristics and balance the required fuel volumes, loss of cargo space, and/or more frequent bunkering. Methanol- and LPG-burning marine engines are in operation on pilot installations and on dedicated gas/chemical carriers and are therefore currently considered mature fuels by engine manufacturers, which have produced engine platforms able to use them. Many of the alternative fuels can be produced renewably and can be used to meet the carbon-reduction goals of 2030 and have the potential to be carbon-neutral fuels in the future. In 2015, a Wärtsilä Z40 engine was converted to use methanol on the ro-pax vessel *Stena Germanica*, which is still in operation today.

Table 3: Sample Dual-fuel Engines Developed for Other Alternative Fuel Types

Dual Fuel Engines	Conventional Fuels			Alternative Fuels			
	HFO	Marine Diesel	MGO	LPG	Methanol	Ethane	Ammonia
MAN ES ME-LGI	●	●	●				◐
MAN ES ME-LGIM	●	●	●		●		
MAN ES ME-LGIP	●	●	●	●			
MAN ES ME-GIE	●	●	●			●	
Wärtsilä DF	●	●	●		●	●	◐

Legend:

- ● Compatible, ready for commercial installation
- ◐ Compatible in principle but under research and development

Biofuels are produced from biomass, including plants, waste oils and agricultural waste. Catalytic processing and upgrading of biomass can yield liquid fuels with physical and chemical properties comparable to diesel oil; this is desirable from a design standpoint because they can be used as drop-in fuels with minimal or no changes to marine engines and their fuel delivery systems.

Currently, the most widely used component is fatty acid methyl ester (FAME) or biodiesel, which is described in the latest ISO (8217/2017) specifications for marine fuel blends and is being offered by major oil companies. The standard allows for 7% biodiesel in the fuel blend, but some shipowners are testing richer blends, from 20 to 100%. FAME is a first-generation biofuel and faces challenges associated with its poor oxidative stability and its potential to degrade over time. Hydro-treated vegetable oil (HVO) is an advanced biofuel, which is often referred to as renewable diesel. HVO is produced using modern hydro-treating processes, which yield high-quality fuels with better stability than FAME biodiesel.

HVO has similar physical and chemical properties to MGO, making it fully compatible with existing engines and fuel-delivery systems. Renewable diesel can also be produced from biomass gasification, using the Fischer-Tropsch (FT) process. It is often referred to as a gas-to-liquid or biomass-to-liquid fuel. Renewable diesel fuel is thought to be a promising medium- to long-term solution for shipowners because it can offer a significant reduction in carbon output with minimal capital expenditures. However, its carbon reduction potential is on the Well-to-Tank side of the fuel lifecycle.

Ammonia and hydrogen offer possible Tank-to-Wake zero carbon solutions towards decarbonization. Hydrogen offers high energy content per mass, high diffusivity, and high flame speed. Hydrogen as a fuel has been demonstrated in internal combustion engines, gas turbines, and fuel cells. However, it requires cryogenic storage (-253° C or lower) and dedicated fuel supply systems for containment. Significant technical advances are needed before hydrogen can be considered a viable, large scale, commercial fuel option; particularly for marine applications where energy content on a volumetric basis is low for hydrogen (9.2 GJ/m^3) and application would therefore significantly impact deep sea ship design. Energy loss during storage and boil-off gas (BOG) generation are also challenges for hydrogen application.

Compared to hydrogen, ammonia storage is relatively more practical due to its energy density (15.7 GJ/m^3) and liquefaction temperature (-33.6° C). The drawback of ammonia is its toxicity. However, it has been handled as cargo and reductant in Selective Catalytic Reduction (SCR) for many years. Therefore, on board handling of ammonia is feasible. Ammonia as fuel for internal combustion engines is under development. The challenges inherent to its combustion is that it usually requires a large percentage of pilot fuel to achieve ignition.

Further elaboration on ammonia and hydrogen as marine fuel are available in ABS publications Setting the Course to Low Carbon Shipping Outlook I and Outlook II.

2.4 SHIP DESIGN AND MODIFICATIONS

2.4.1 GENERAL ARRANGEMENT

Internal combustion engine installation is a mature technology and has well established general arrangement requirements. Depending on the type of fuel used, appropriate fuel containment systems can be designed accordingly.

2.5 REGULATORY REQUIREMENTS

There are many International Association of Classification Societies (IACS) machinery Unified Requirements (UR) applicable to internal combustion engines. UR M35 specifies the requirements for alarms, remote indications and safeguards for main reciprocating internal combustion engines installed in unattended machinery spaces. UR M78 addresses the requirements for trunk piston internal combustion engines supplied with low pressure natural gas as fuel. IACS Recommendation Rec.147 specified the Type Approval Certificate of Internal Combustion Engine and UR Z18 addresses survey requirements for machinery.

Other Unified Requirements M44, M51, M71 and M72 are the main URs detailing the design approval, type test, conformity of production, certification of components and factory acceptance test (FAT) requirements for internal combustion engines.

Where low-flashpoint gaseous fuels, such as LNG, are used for internal combustion engines, additional IGC Code requirements or IGF Code requirements are to be complied respectively for installation on LNG and non-LNG carriers. ABS incorporates the IGC Code and IGF Code under Parts 5C-8 and 5C-13 of the ABS *Marine Vessel Rules* respectively.

2.6 CREW TRAINING

Internal combustion engine is a mature technology, thus training schemes for conventional propulsion vessels are to be followed in conjunction with any additional flag and coastal state training requirements that may apply.

For ships with internal combustion engine installations subject to the IGF Code, i.e. are powered by LNG or other low-flashpoint gas and fuels, their crews are to be trained and qualified in accordance with the requirements in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) in conjunction with any additional flag and coastal state training requirements that may apply.

Some important aspects of training and education for gas-fueled ship operation include fuel safety, awareness and risk management apply.

2.7 SAFETY

Particular attention is to be paid to internal combustion engines powered by unconventional fuel sources such as low-flashpoint fuels.

The design and installation for LNG (or other low-flashpoint fuels) powered systems are to follow applicable statutory and class requirements. Major safety issues are associated with fire, explosion, and toxic hazards due to the nature of the low-flashpoint fuels. Crew onboard ships with such installations are to be trained on the awareness of the hazard, appropriate handling of such fuel, as well as mitigation and safety measures to be taken and qualified in accordance with recognized standard.

3 STEAM TURBINES

Steam turbines are one of the most versatile and oldest prime mover technologies. They are still in use for driving electric generators, propulsion shafting, and other mechanical machinery such as large centrifugal pumps. About 80% of the world's electricity is generated by steam turbines.

Figure 6: Children's Toy Windmill. A Simple Turbine

A steam turbine, as suggested by its name, is powered by hot pressurized steam. Similar to a windmill, it has blades that spin when steam blows past them, but unlike the windmill where the whole blade assembly is exposed to environment, the blades of a steam turbine are fitted inside a sealed casing. Steam injected into the casing is constrained and forced through the blades, making the blade and shaft assembly rotate.

This section provides an overview of the current and emerging applications of steam turbines for marine propulsion, fuel considerations and other related topics.

3.1 CURRENT APPLICATIONS

With its improved power-to-weight ratio, steam turbines rendered steam engines obsolete for propulsion, first in naval ships and later in commercial vessels in the first half of the 20th century. Marine steam turbines as propulsion engines may be classed into two groups, i.e., propulsion steam turbines to drive a propeller via reduction gear, or steam turbines to drive electric generators that then supply power for electrical propulsion.

The advantage of steam turbines as mentioned previously make it a practical option for some types of ships where high power demand cannot be met by diesel engines, and where space for passengers, cargo or ammunition/jet fuel, or a low level of vibration and noise is the top priority of consideration. Table 4 lists some of the ships with steam turbine installation.

Table 4: Ships with Steam Turbine Installation

Example of Ships with Steam Turbine Installation				
Name	Type	Size (LxDxd in m)	Power (kW)	Year Built
Gerald R. Ford	War Ship	337 x 78 x 12	260,000 (Nuclear)	2017
Simaisma	LNG Carrier	285.4 x 43.4 x 9.9	28,000 (S/Turbine)	2006
Energy Frontier	LNG Carrier	277 x 49 x 11.6	29,400 (S/Turbine)	2003
Inigo Tapias	LNG Carrier	284 x 43 x 11.4	28,000 (S/Turbine)	2003
Disha	LNG Carrier	277 x 45 x 9.1	26,500 (S/Turbine)	2004
Excalibur	LNG Carrier	277 x 43 x 11.9	26,500 (S/Turbine)	2002
Excel	LNG Carrier	277 x 43 x 11.9	26,500 (S/Turbine)	2003
Radiance of the Seas	Cruise	293 x 32 x 8.5	57,600 (COGES*)	2001
Brilliance of the Seas	Cruise	293 x 32 x 8.5	59,000 (COGES*)	2002

** Combined Gas turbine Electric and Steam System (COGES)*

3.1.1 CHARACTERISTICS

Based on the design and arrangement of blades, modern steam turbines can be divided into impulse and reaction turbines.

- In impulse turbines, steam jets are directed at the turbine's bucket-shaped rotor blades. The pressure exerted by the jets causes the rotor to rotate and the velocity of the steam to reduce, as it imparts its kinetic energy to the blades.
- In reaction type steam turbines, the steam passes from fixed blades of the stator through the shaped rotor blade nozzles causing a reaction and rotating the turbine shaft.

To optimize the use of the energy contained in the steam, turbine blades may be arranged in multiple stages in series in the turbine casing. As steam moves through the series of blades (with smaller blades at the higher-pressure end and bigger/longer blades along the steam path), it expands and cools giving up the maximum energy it originally contained. The high-pressure and immediate stages are typically impulse turbines and the low-pressure stage is usually reaction type turbines.

With high pressure and high temperature steam, a steam turbine can turn at incredibly high speeds, e.g., 10,000 to 12,000 rpm. The output of a steam turbine could be up to 1,000 MW [3]. The upper limit of inlet steam temperature and pressure depending on the material and design of the steam turbine varies from 2 MPa/320~350° C to 31 MPa/700~725° C [4].

The thermal efficiency of a steam turbine depends on turbine size, load condition, gap losses and friction losses. Larger multiple stage turbines may reach an efficiency level up to about 50% while smaller ones have lower efficiency.

Unlike reciprocating engines, the flow of steam through the blades of a steam turbine make it rotate continuously without the need for a piston and crankshaft arrangement.

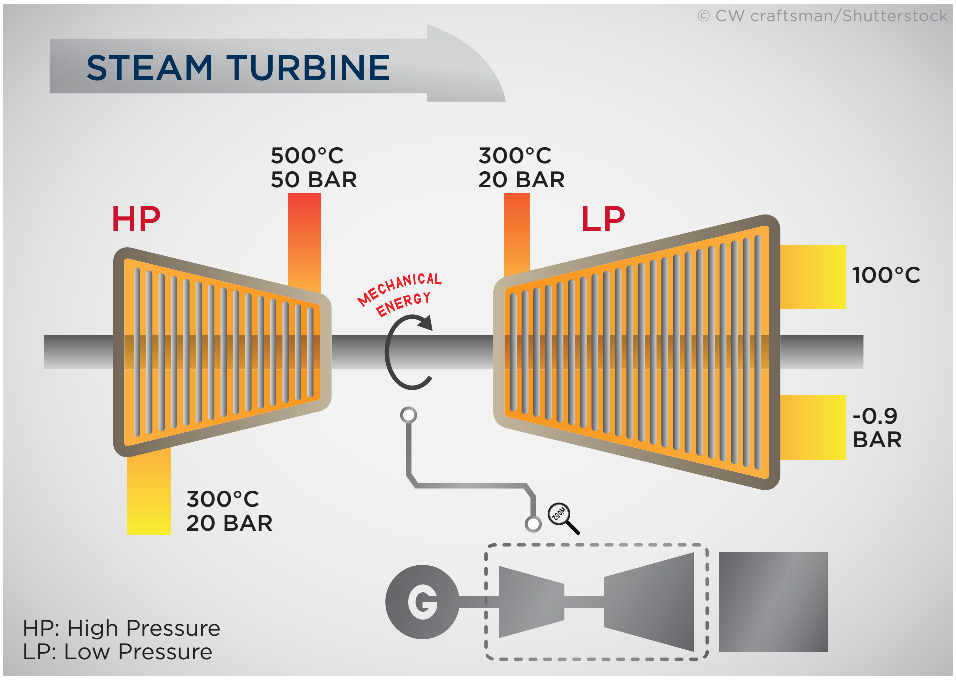


Figure 7: Multiple Stage Steam Turbine

Steam turbines offer various advantages compared to other types of engines:

- High rotational speed
- Compact in size (high power/weight ratio)
- Smooth operation with negligible vibration
- No internal lubrication needed
- Oil-free exhaust steam
- High reliability due to few moving parts
- Ability to utilize high pressure and high temperature steam

3.1.2 STATE-OF-THE-ART

Combined Gas turbine Electric and Steam System (COGES)

In some high-power demand ships, gas turbines are used due to their dual-fuel burning capability, high reliability, high power/weight ratio and excellent emission performance. However, the thermal efficiency of gas turbines is relatively low as indicated in Table 1 of this Advisory. Steam turbines may be used in combination with gas turbines to improve overall thermal efficiency. Such a combination is named a Combined Gas Turbine Electric & Steam System (COGES). The energy efficiency of a Gas Turbine combined with a Steam Turbine can be up to 60% [5].

In COGES propulsion, the gas turbine drives the generator, which feeds into the main switchboard and in turn and provides the electric power and propulsion demand. The propeller is driven by a frequency-controlled electric motor. The exhaust gases from the gas turbine are used to generate steam in a heat recovery steam generator (HRSG). This steam drives the steam turbine generator in turn, which also feeds into the main switchboard.

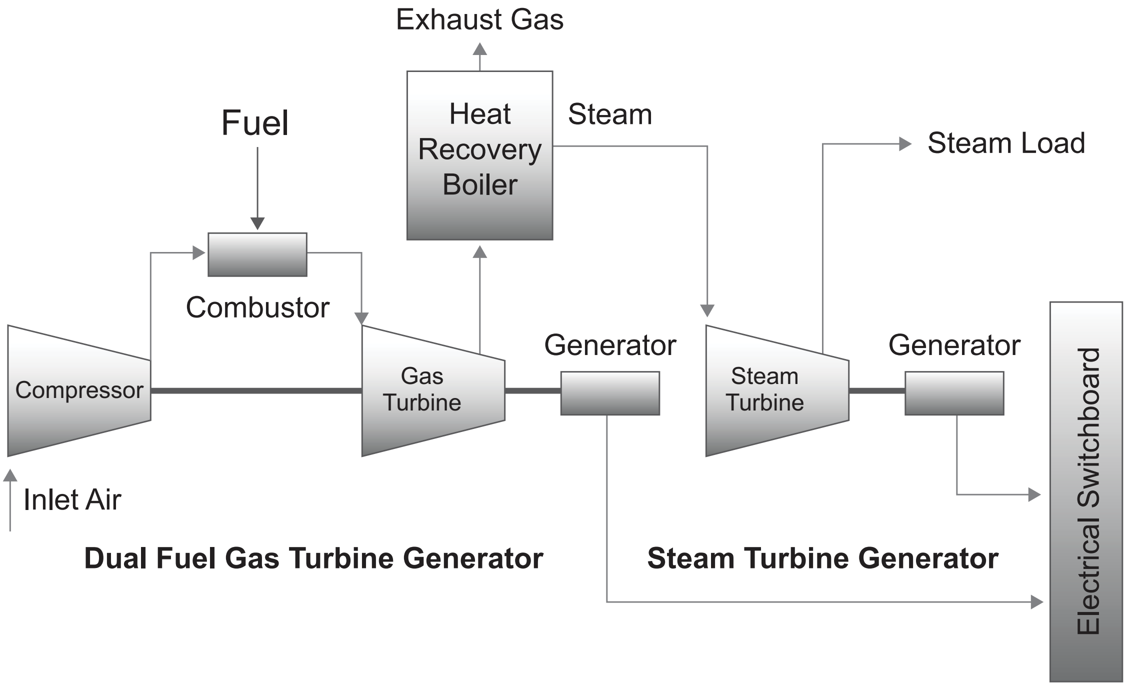


Figure 8: Typical COGES Arrangement

As indicated in Table 4, besides naval and cruise vessels, steam turbines have been a practical option for LNG carriers over the last several decades based on economic considerations, environmental regulation, and safety issues. One of the economic considerations is the use of the BOG on LNG carriers. Historically, cargo-containment systems were designed with a maximum BOR of 0.15% volume per day, which matched well with the fuel requirements of the relatively low-efficiency steam turbine plants.

Nowadays, the four-stroke, dual-fuel engine developed in 2004 and two-stroke dual-fuel engines after 2010 have been adopted, offering efficiency advantages over steam turbine propulsion. However, steam boiler-turbines are still used on board ships. One of their applications is to utilize them in Steam Turbine and Gas Engine propulsion systems, particularly on LNG carriers.

Steam Turbine and Gas Engine Propulsion (STaGE propulsion) – hybrid propulsion system

STaGE is derived from the Steam Turbine and Gas Engine. STaGE propulsion is a hybrid propulsion system that comprises an ultra-steam turbine plant and a combination of a dual-fuel engine and a propulsion electric motor (DFE-PEM plant). The steam turbine is based on a high-efficiency reheating steam cycle. The boiler and the dual-fuel engine can work on both gas and liquid fuel. Reportedly, the STaGE plant on the below-mentioned LNG carrier emits about 20% less CO_2 than conventional turbine plants for the similar size LNG carrier [6].

The electricity generated by the dual-fuel engines drives the propulsion electric motor. The waste heat of exhaust and jacket from the dual-fuel engines is recovered by heat recovery system to preheat the feed water supplying to the boiler. The waste heat is also recycled to generate auxiliary steam as well as the drive steam for the main turbine. This combination helps to improve fuel efficiency.

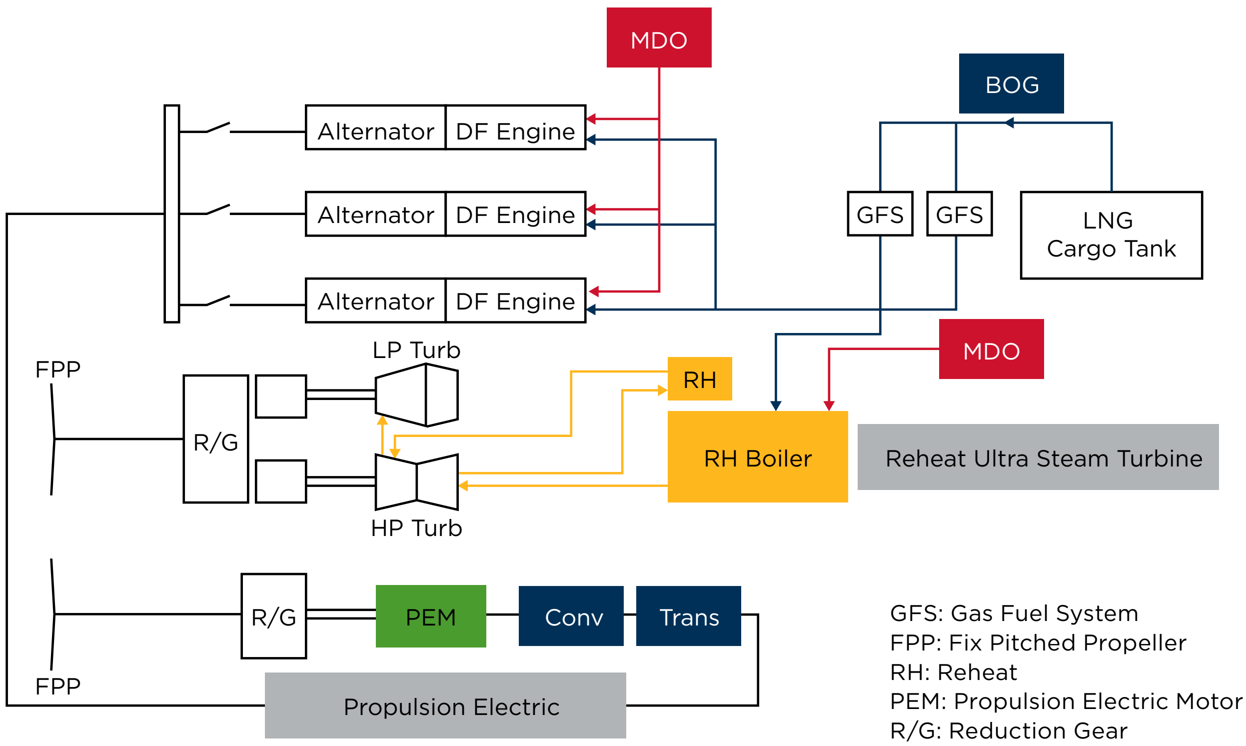


Figure 9: Steam Engine and Gas Engine Propulsion

Improvement of fuel efficiency is also due to the possibility of optimum load sharing of the dual-fuel engine. The STaGE system makes it possible to run the dual-fuel engines at optimized loading while the steam turbine takes part of the propulsion load to avoid increased numbers of dual-fuel engines in operation but running at low load at a certain required level of propulsion power.

The other benefits of using a STaGE plant compared to the same size LNG carrier using conventional turbine plants includes:

- Reduced maintenance work
- Reduced CO_2 emissions
- High reliability/redundancy

An example of such application are LNG carriers constructed at the Nagasaki Shipyard by Mitsubishi Heavy Industry. The latest one of the series vessels is *Diamond Gas Sakura*, which was delivered on May 15, 2019. The other two are *Diamond Gas Orchid* and *Diamond Gas Rose*.

3.1.3 FUTURE RESEARCH AND CHALLENGES FOR APPLICATIONS

Besides the above mentioned COGES and STaGE, there are other combinations for the application of steam turbines, such as the following [7]:

- Diesel as main engine and steam turbine for power as part of the recovery system
- Combined Diesel Engine and Steam Turbine (CODES) – both for electric power generation
- Combined steam and gas turbine (COSAG) – steam turbine is main engine and when high power is required, gas turbines are put into use

Steam turbines are used mainly on a special type of vessels such as naval vessels, cruise ships, LNG carriers, onboard floating, production, storage, and offloading (FPSO) vessels and icebreakers, which require higher power, lower specific engine weight, better comfort levels (less noise and vibration) and lower emissions (NOx and SOx).

Advancements in material technology and thermodynamics will help to reduce turbine losses. The United States Department of Energy funds collaborative research and development toward the development of improved ultra-supercritical steam turbines capable of efficiencies of 55-60% that are based on boiler tube materials that can withstand pressures of up to 5,000 psi and temperatures of 760° C. To achieve these goals, work is ongoing in materials, internal design and construction, steam valve development, and the design of high-pressure casings. A prototype is targeted for commercial testing by 2025 [8]. Such technology may be marinized for application on ships.

A combination of steam turbine with other application could be an effective and viable measure for waste heat recovery that could improve overall energy efficiency. Steam turbines will continue to play a role in marine applications.

3.2 SUPPORT EQUIPMENT AND SYSTEMS

3.2.1 STEAM GENERATOR/BOILER

A steam turbine is an energy converter rather than a primary energy source. Equipment required for the operation of a steam turbine is steam-generating equipment, commonly referred to as boiler although a steam generator and boiler are not exactly the same. Energy is transferred from the boilers to the steam turbine through an intermediate medium - the high pressure, high temperature steam.

Steam-generating equipment that turns water into steam by boiling at sub-critical pressure is called a steam boiler. Equipment turning water into steam without boiling at super-critical pressure is called a steam generator. The critical point for water is at about 374° C and a pressure a little over 22 MPa.

Depending on the heat source, the steam generator can be nuclear powered, oil (fuel) fired boiler or waste heat boiler (economizer).

Nuclear-powered steam generators use the heat generated in a nuclear reactor to heat the feed water to generate steam, either in a primary cooling loop or a secondary cooling loop, depending on the reactor design. The steam is supplied to steam turbines that in turn drive a propulsion shaft via reduction gear or provide electric power onboard a ship for propulsion and for other use. As mentioned previously, nuclear-powered systems are mainly used on military vessels and limited commercial vessels. The application is detailed in the Nuclear Section of this Advisory.

Oil (fuel) fired boilers are commonly used on commercial vessels. Depending on the construction, such boilers can be categorized as fire-tubed boilers and water-tubed boilers. As the name suggests, fire-tube boilers have tubes through which the hot gases, or "fire," generated from the burners pass through. The tubes are surrounded by a sealed tank of water, which is heated as the "fire" passes through the tubes. The water is heated to a boil and converts into steam. Water-tube boilers use the opposite configuration. The water travels through tubes that are surrounded by the hot gas. This allows heat to be transferred to the water and results in the water boiling into steam.

Exhaust gas boilers, also called economizers, recover the heat of exhaust gas from engines or gas turbines to generate steam.

Saturated steam and superheated steam are two typical states of steam. Saturated steam is generated by heating water to the boiling point for its pressure. Such steam may contain water droplets. Superheated steam on the other hand is steam at a temperature higher than its vaporization point at the absolute pressure where the temperature is measured. Superheated steam has the capacity to give out a certain amount of internal energy while still in its gaseous state. Such characteristics make it more suitable for steam turbines than saturated steam, which reverts to the liquid state following heat loss and could cause damage to the equipment and components.

3.2.2 SUPPORTING SYSTEMS

In commercial applications for power generation or propulsion, oil (fuel) fired boilers are typically used for steam generation, or as part of a composite boiler (economizer plus fired section). The main supporting systems for such boilers and steam turbines include:

- Lubricating oil systems for steam turbines and reduction gears, where applicable
  - Lubricating oil pumps and piping
  - Lubricating oil cooler, filters/strainers, purifiers, lubricating oil tanks
- Cooling water systems for steam turbines and reduction gears, where applicable
  - Condenser cooling piping and lubricating oil cooling piping
- Feed water systems for boilers
  - Feed water piping including feed water tank, feed water pumps, feed water heaters
  - Feed water analyzers and chemical systems
- Steam systems
  - Power steam and auxiliary steam piping including strainers, steam cutoff valves
  - Exhaust steam piping to condensers including blow-off valves
  - Steam escape piping including pressure relief valves
- Condensate water systems for boiler
  - Condensate water piping including condensers, distillate tanks, cascade tanks (hot wells), condensate pumps and condenser vacuum pumps
- Soot blowing systems for boiler
- Exhaust gas systems for boiler
  - Feed fans, air heaters
- Fuel system for boilers
  - Fuel oil service piping and fuel gas piping, as applicable

3.3 FUEL OPTIONS

Fired boilers may operate on a great variety of fuels, such as wood, coal, municipal solid waste and sludge, liquid fuel, and natural gas. For marine applications, HFO came into more general use and began to replace coal as the fuel of choice in the early 20th century. Its advantages were convenience, reduced manpower by removing the need for trimmers and stokers, and reduced space requirements for fuel bunkers.

Stricter environmental regulations, particularly the IMO regulation in MARPOL Annex VI for sulfur limit in marine fuels used onboard ships, limits the fuel options for boilers. For meeting the sulfur limit requirements, the practical options currently being adopted are:

- VLSFO - Very low sulfur fuel, typically blended heavy fuel oil with sulfur content not more than 0.50% for global use
- ULSFO - Ultra-low sulfur fuel, typically distillate fuel with sulfur content not more than 0.10% for use in ECAs
- LNG - Natural gas in liquid form with zero sulfur content

IMO NOx emission requirements are not applicable to boilers due to the nature of the combustion process where negligible fuel-bound NOx is formed.

LNG as a practical option for boiler fuel can reduce CO_2 by up to 21% compared to conventional liquid marine fuels. In addition, LNG is also an economic option to make use of the BOG on LNG carriers. Dual-fuel boilers are a mature technology and has been in marine application for years.

Adoption of alternative and zero-carbon fuels in the marine industry is one of the options to achieve emissions goals, in addition to technology development and optimization of ship operation, as discussed in the internal combustion engine section. Biomass could be a practical option for land boilers but marinizing the application will be limited due to its energy density and the constrained space on a ship.

Other fuel options are technically possible but commercial viability could be a determining factor for marine applications. Currently, application of these fuel to boilers appears to be a low priority.

3.4 SHIP DESIGN AND MODIFICATIONS

3.4.1 GENERAL ARRANGEMENT

The major equipment in a steam turbine installation includes steam turbines and boilers as well as other key auxiliaries such as condensers, condensate pumps, feed water pumps, feed water heaters, boiler fuel pumps and heaters, and boiler exhaust gas draft fans. In propulsion systems directly driven by steam turbines, a reduction gear is necessary to match the effective propeller speed.

Engine rooms are typically located aft on a ship and below the accommodations, and boilers are normally installed in the engine room casing.

A more common application nowadays is to combine steam turbines with other types of propulsion in a hybrid system without two-stroke slow speed engines. This makes the overall arrangement of the engine room more flexible due to the elimination of the largest piece of equipment (the engine).

3.4.2 RETROFIT OPTIONS

Retrofitting of steam turbines may not be a practical option. Instead, some steam ships are being modernized by installing internal combustion engines with dual-fuel capability for better energy efficiency and lower emissions.

However, it is possible to refurbish a boiler to burn cleaner fuel, e.g., distillate fuel. The ABS *Marine Fuel Advisory* provides information on switching from residual marine fuel to distillate fuel.

3.5 REGULATORY REQUIREMENTS

SOLAS Regulation II-1/32, II-1/33 and II-1/53 contain requirements related to boiler and steam piping.

IACS UR M26 Corr.1 specifies the requirements for safety devices for steam turbines. IACS UR Z18 address survey requirements for machinery including steam boilers and propulsion steam turbines.

Where low-flashpoint fuels such as LNG is used for steam turbines, IGC Code requirements or IGF Code requirements are to be complied with respectively for installation on LNG Carriers and on non-LNG Carriers.

3.6 CREW TRAINING

Steam turbines using conventional fuels, such as liquid fuel, are a mature technology. Training schemes for conventional propulsion vessels are to be followed in conjunction with any applicable additional flag and coastal state training requirements.

For ships with steam turbine installations powered by LNG, crews are to be trained and qualified in accordance with the requirements in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW).

3.7 SAFETY

Safety concerns are dependent upon the type of power used for steam turbines. Attention is to be paid to steam turbines powered by unconventional fuel sources such as low-flashpoint fuel or nuclear power. The design and installation for LNG (or other low-flashpoint fuel) powered steam boiler-turbine systems are subject to the IGF Code and are to follow the applicable statutory and class requirements. Major safety concerns are fire, explosion and toxic hazard due to the nature of the low-flashpoint fuel.

For ships with steam turbines powered by nuclear, please refer to safety under the Nuclear section of this Advisory.

4 GAS TURBINES

The applications of marine gas turbines have increased significantly from naval vessels solely to encompass a broad range of commercial vessels. Gas turbines can achieve a greater weight to power ratio than traditional diesel engines and now offer a wide range of power in relatively small sizes and are used in a variety of power generation designs. Combustion in gas turbines is continuous, with average temperatures and pressures that are lower than the peak temperature level of diesel engines. This reduction in temperature can reduce NOx emissions. Historically, the main drawbacks of gas turbine propulsion were high fuel consumption and lower efficiency, which have been improved with design advancements. The modular gas turbine offers a high level of flexibility on new vessel construction and life cycle constraints. The low weight and volume, high reliability, high speed, ease of maintenance and servicing due to its modular parts, low maintenance costs, and low emissions characteristics make gas turbines appealing for marine applications. Moreover, gas turbines can be operated on a wide range of fuels including natural gas. This section provides an overview of the existing and emerging gas turbine technologies, fuel considerations, and other related topics.

4.1 CURRENT APPLICATIONS

Gas turbine operation is approximated using the Brayton cycle where four consecutive processes take place: isentropic compression in the compressor, constant pressure heat addition in the combustor, isentropic expansion in the turbine and constant pressure heat rejection. In gas turbines, specific components are designed to perform each function of the cycle separately. These functions are intake, compression, combustion, expansion, and exhaust.

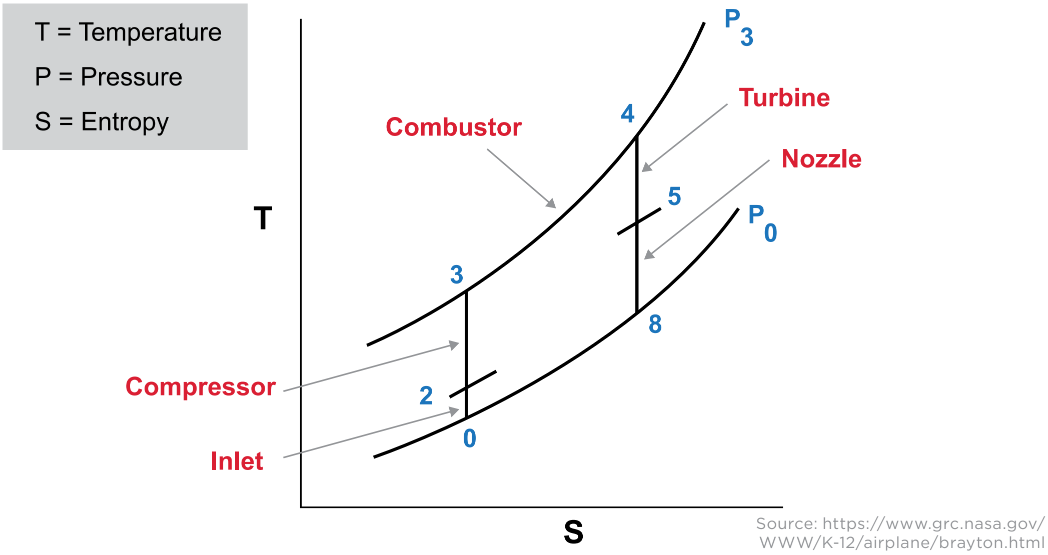


Figure 10: Ideal Brayton Cycle (T-S diagram)

Air is inducted through the air inlet duct by the compressor, which then compresses it to a high pressure. The compressed air is then discharged into the combustion chamber where fuel is injected through nozzle(s). The fuel-air mixture is ignited by an igniter(s) and combustion occurs to produce high pressure, high velocity gas. The hot and rapidly expanding gases are directed through the turbine rotor assembly where the turbine extracts the energy from the high pressure, high velocity gas flowing from the combustion chamber. In the turbine, thermal and kinetic energy are converted into mechanical energy that drives the connected shafting, equipment, compressor, and the auxiliary systems of the gas turbine. The gases are then vented out through the exhaust duct [9].

Generally, in military ships, gas turbines are used in combination with other propulsion units, such as diesel engines, which provide some operational flexibility based on the speed requirements of the ship. CODAG stands for Combined Diesel and Gas Turbine System, wherein the diesel engine is used in low-power operation and the gas turbine kicks in when high power is needed. In CODOG systems every propeller has one diesel and one gas turbine. Gas turbines and diesel engines can only run separately because of the simple gear arrangement. This requires a bigger gas turbine for the same peak power demand than the lower demand of cruising speeds.

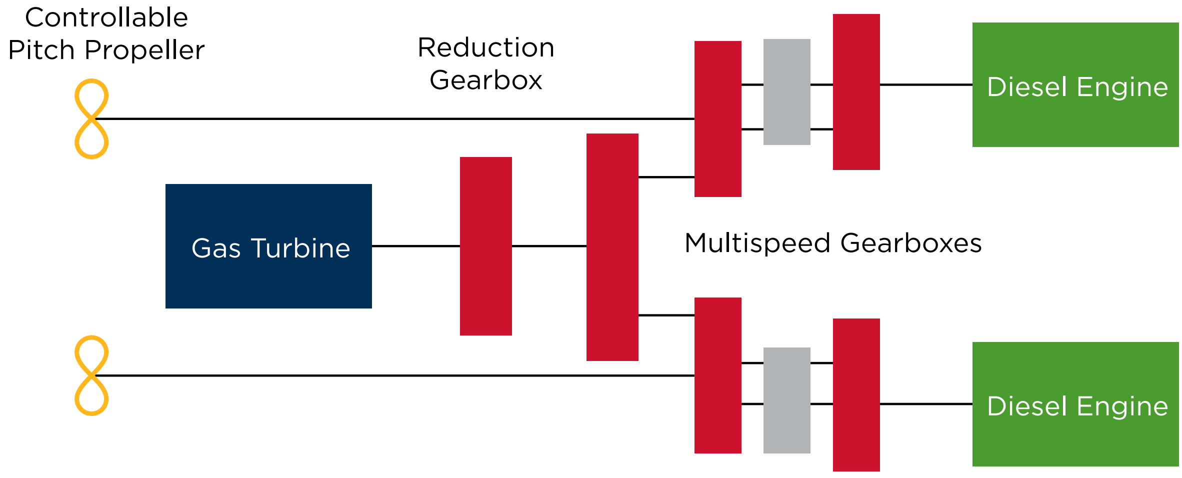


Figure 11: CODAG Arrangement

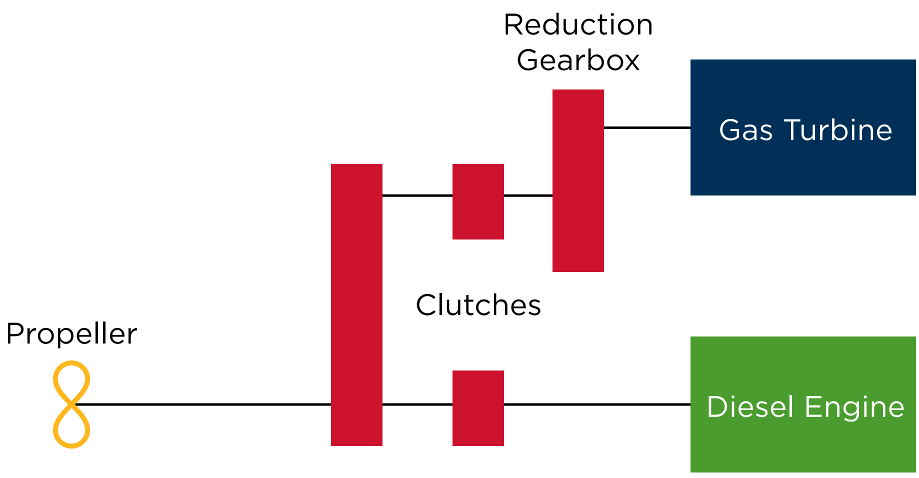


Figure 12: CODOG Arrangement

Similarly, some cruise ships use a Combined Gas and Steam (COGES) system which provides overall advantages through reductions of exhaust emissions, noise, and vibration over traditional diesel engine systems. Also, a gas turbine power plant occupies much less space and needs 50% less ancillary systems than a diesel electric propulsion system.

In the offshore industry, especially onboard FPSOs, lower emissions and decreased weight and footprint of topside modules is often required, thus making gas turbine power plants a unique solution to replace large diesel generator engines [10].

4.1.1 DESIGN PARAMETERS

Gas turbines are designed and produced with specific power output and sizes unlike diesel engines which are generally customized to be vessel specific. The size and power of the gas turbine is determined during the design phase of the vessel. Generally, marine gas turbines are derived from lightweight aircraft engines which have already undergone intensive and expensive research and development efforts.

The turbine drives the compressor which supplies the air for combustion and cooling purposes. In any application, about half of the energy produced by the turbine is consumed by the compressor and electrical demands of the accessories. In shaft-powered or marine gas turbines, the prime mover or the original gas turbine part is called a gasifier or gas generator turbine. Only the gasifier is required to run on the starting cycle, which reduces the starting power requirement. In larger gasifiers, the compressor and turbine are divided into two parts, as low pressure and high pressure units.

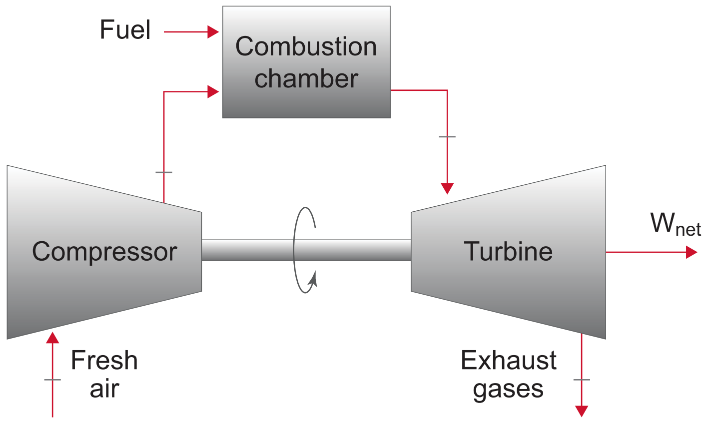


Figure 13: Simple Cycle Gas Turbine

The low-pressure compressor is driven by the low-pressure turbine and the high-pressure compressor is driven by the high-pressure turbine. This is to ensure stability at high pressures, but also because each compressor has different optimum operating points and speeds. Only the HP rotor needs to be turned during starting, and therefore even the largest gas generator can be started using a battery.

4.1.2 EMISSIONS

The emissions of a gas turbine can be reduced by using LNG to achieve a nearly 100% reduction in SOx and particulate emissions, 85-90% reduction in NOx emissions and 15-20% reduction in CO_2 emissions, compared to using diesel. However, the CO_2 emissions of a vessel can be further reduced by using other alternative fuels in gas turbines or through a combination of technologies for power generation and propulsion [8].

4.2 FUEL OPTIONS

Gas turbines have flexibility in the types of fuels they use, which is an important advantage. Almost any flammable gas or light distillate petroleum product such as gasoline (petrol), diesel, kerosene (paraffin) and natural gas may be used as fuel. In general, diesel oil is used for marine applications and natural gas/diesel oil is used for stationary power generation depending on local availability.

NATURAL GAS: The most common forms of natural gas used in marine vessels are either LNG or compressed natural gas (CNG). The interest for LNG-powered vessels is increasing among the many types of vessels other than LNG carriers, but CNG-powered vessels remain in use by CNG carriers. Several studies have shown that LNG can be successfully used to replace diesel fuels in marine gas turbines, as the thermodynamic performance in the gas turbine cycle with LNG can approach that of diesel operation.

AMMONIA: Ammonia has been considered to have potential as a long-term marine fuel. Several gas turbine manufacturers have made advancements in the use of ammonia-fueled turbines with successful trials. It is the second most widely used and commercially available chemical, due to its use in making fertilizer.

BIODIESEL: Biodiesel or FAME is a renewable, biodegradable and oxygenated fuel with similar physical and chemical characteristics to diesel. Biodiesels are ethylic or methyl esters of acids with long chains derived from vegetable oils and animal fats through a thermochemical process involving transesterification. The oxygen content of biodiesel can offer the benefit of reducing unburned hydrocarbon and particulate matter emissions [11].

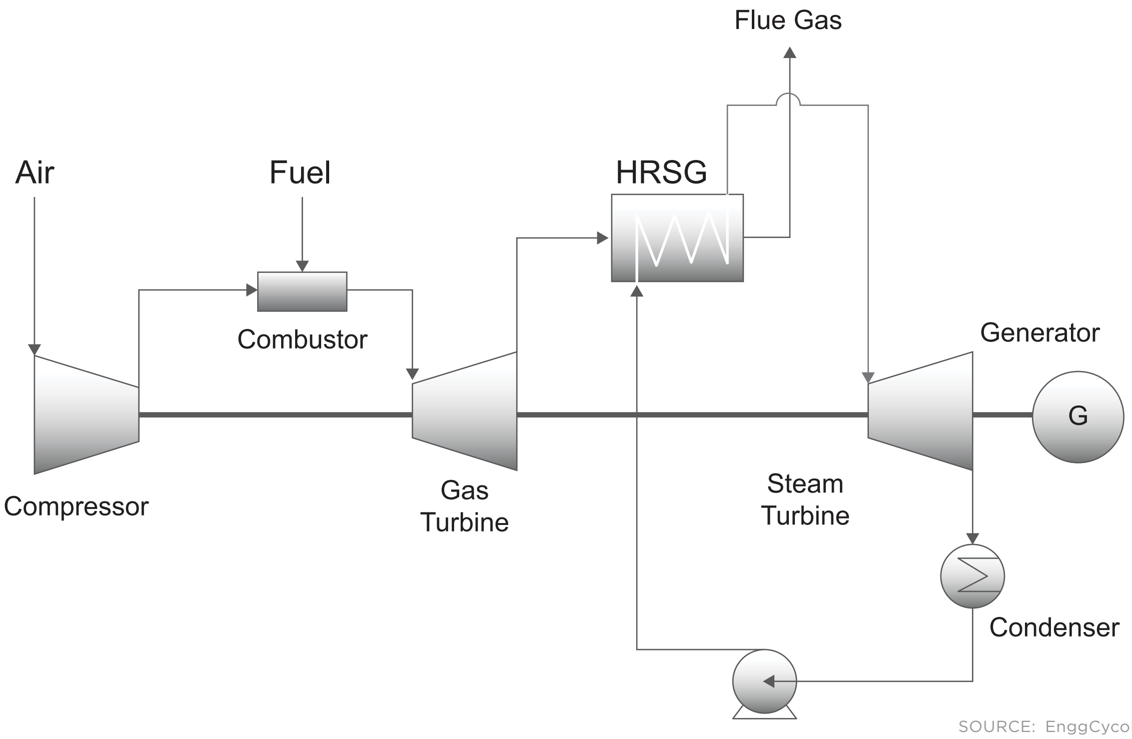
Currently biodiesel is not a popular choice for gas turbines, but it could possibly become a promising alternative fuel for diesel-driven gas turbines. With the ongoing technological advancements of both gas turbines and the development of improved biodiesel fuel, biodiesel may be the future of the most viable solution for a carbon free marine industry.

Gas turbine manufacturers currently tend to design combustors to operate with different fuels such as natural gas, diesel, and heavy oils as a response to the strong demand by customers for fuel diversity. Similarly, ongoing research works are in progress to develop combustors compatible with biodiesel [12].

4.3 SHIP DESIGN AND MODIFICATIONS

The installation of gas turbines onboard vessels for propulsion and power generation can be accomplished through three approaches:

DIRECT PROPULSION: Gas turbines can be used to propel a vessel directly through a gearbox. However, this is not optimal for large cargo vessels due to the attendant massive gear box.



SOURCE: EnggCycolpedia

Figure 14: Combined Cycle Power Generation

POWER GENERATION: Gas turbines can be coupled to generators to produce adequate power for the main propulsion and auxiliary loads of a vessel.

COMBINED CYCLE POWER GENERATION: To boost the efficiency of the total power generation of a vessel, gas turbines can be used in tandem with a steam turbine to form a combined cycle. Exhaust gases of the gas turbine flow through a recuperator or Heat Recovery Steam Generator (HRSG) to recover heat and produce steam to feed the steam turbine. This combined cycle generates additional electric power by combining the gas and steam turbines, which can provide sufficient power output for the entire needs of a vessel.

4.4 REGULATORY REQUIREMENTS

IACS UR M60 specifies the requirements for Control and Safety of Gas Turbines for Marine Propulsion Use. IACS UR Z18 address survey requirements for machinery.

Where low-flashpoint fuels such as LNG are used for gas turbines, IGC Code requirements or IGF Code requirements are to be complied respectively for installation on LNG Carriers and on non-LNG Carriers.

4.5 CREW TRAINING

Appropriate crew training is key for the safe and smooth operation of vessels installed with marine gas turbines; currently the number of crew familiar with and having adequate knowledge of these equipment types and systems is low. Training is needed to improve awareness of the general arrangement and systems, provide an overview of the installed equipment, explain how the system is arranged, and describe how these systems are to be used. All crews are to have an adequate understanding of the operation of the installed equipment and be able to provide maintenance based on the user or maintenance manual as per the instructions provided by the manufacturers, and in conjunction with any flag and coastal state training requirements that may apply.

4.6 SAFETY

Marine gas turbines are typically installed within an enclosure inside the engine room of a ship. Generally, the other equipment associated with the gas turbine (e.g. gear box, power generator etc.) is installed outside the enclosure. The safety requirements of a marine gas turbine using liquid or gaseous fuels is very important and are needed to adequately maintain appropriate electronic control and detection systems. The essential auxiliaries of the gas turbines are also monitored and controlled by electronic systems. It is important to mention that real time monitoring and effective fault diagnosis are crucial during the operation of a marine gas turbine, which increases the safety and reliability of a vessel. Considering the safety aspects, several monitoring and diagnostic techniques have been developed to monitor a gas turbine and its system operation which is to detect and provide necessary solutions immediately to resolve any issues for safe uninterrupted operation. However, it is very important to strictly adhere to the routine and preventative maintenance by crew for all equipment and systems as instructed by the manufacturer.

5 FUEL CELLS

The fuel cell is an energy generation technology that converts fuel and air into electricity and water through an electrochemical reaction. Similar to an electrochemical battery, electrical energy is produced in the form of direct current (DC) power. Unlike a battery, the fuel and the oxidant are stored outside of the cell and are transferred into the cell as the reactants are consumed. The fuel cell converts energy rather than storing it and can provide continuous power as long as fuel is supplied.

Fuel cells have a variety of applications for providing electric power in remote areas as well as for industrial, residential, and commercial buildings. Fuel cells are often seen as a competing technology to internal combustion engines. However, their operational characteristics are quite different in a way that can make them complimentary technologies in a hybrid system.

This section provides an overview of fuel cell technology, fuel options and other related topics.

5.1 CURRENT APPLICATIONS

A fuel cell typically consists of a negative electrode (anode), a positive electrode (cathode), an electrolyte, a fuel and oxygen (air) system, electrical terminals and ancillary devices. When fuel is fed into the anode and air is fed to the cathode, a catalyst at the anode separates molecules into protons and electrons, which take different paths to the cathode. The electrons then flow through an external electric circuit to power a load. The protons transport through the electrolyte to the cathode, where they react with oxygen and electrons to produce heat and water.

The most common fuel used for fuel cells is hydrogen, but some types of hydrocarbons such as natural gas and biogas can also be used for certain types of fuel cells through reforming. Interest is growing in the use of ammonia as a feeder to hydrogen-fed fuel cells; upon reformation of ammonia, hydrogen is provided to the cells to generate electric power. Certain fuel cell types can internally reform the fuel to run on ammonia directly, eliminating the need to separate the hydrogen and nitrogen elements before input.

Fuel cells use an electrochemical process to generate energy instead of combustion, which can make them more efficient than combustion systems. Additionally, the waste heat output can be captured for Combined Heat and Power (CHP), a cogeneration that can reduce energy costs up to 40%. The hydrogen fuel cell together with CHP can potentially bring the system efficiency to 85%.

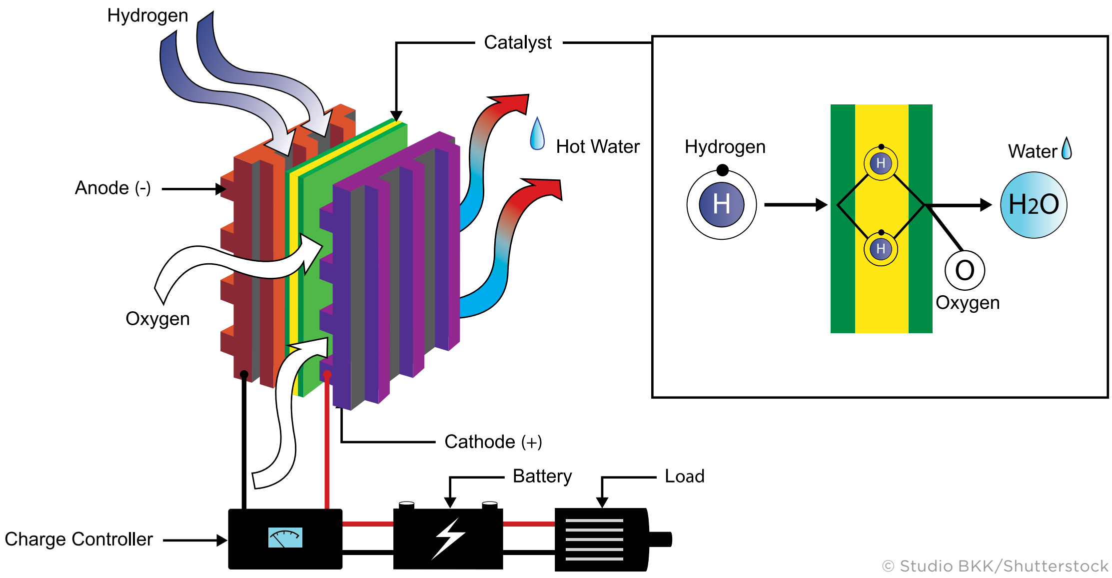


Figure 15: Hydrogen Fuel Cells

5.1.1 CHARACTERISTICS

Fuel cells are classified according to the different types of electrolytes they use.

PROTON EXCHANGE MEMBRANE (PEM) FUEL CELLS: PEMs use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. They need only hydrogen, oxygen from the air, and water to operate. They are typically fueled with pure hydrogen supplied from storage tanks or reformers (a device that extracts pure hydrogen from hydrocarbon or alcohol fuels). PEM fuel cells operate at relatively low temperatures, typically less than 120° C and typically use a noble-metal catalyst such as platinum to separate the hydrogen electrons and protons.

A variation of PEM is Direct Methanol Fuel Cells, which can use pure methanol directly without reforming. The methanol is usually mixed with water and fed directly to the fuel cell anode.

ALKALINE FUEL CELLS (AFC): AFCs use a solution of potassium hydroxide in water as the electrolyte and can use a variety of nonprecious metals as the catalyst at the anode and cathode. AFCs operate at temperatures between 100° C and 250° C. The oxidant supplied must be pure oxygen as carbon dioxide (CO_2) can negatively affect the performance of AFCs.

PHOSPHORIC ACID FUEL CELLS (PAFC): PAFCs use liquid phosphoric acid as an electrolyte which is contained in a Teflon-bonded silicon carbide matrix and porous carbon electrodes containing a platinum catalyst. PAFCs operate at temperatures between 150° C and 220° C. PAFCs are more tolerant of impurities in fossil fuels that have been reformed into hydrogen than other fuel cell types.

MOLTEN CARBONATE FUEL CELLS (MCFC): MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix. Nonprecious metals can be used as catalysts at the anode and cathode. MCFCs operate at 600° C to 700° C. MCFCs do not require an external reformer to convert fuels such as natural gas and biogas to hydrogen. At the high temperatures at which MCFCs operate, methane and other light hydrocarbons in these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming.

SOLID OXIDE FUEL CELLS (SOFC): SOFCs use a hard, non-porous ceramic compound as the electrolyte. SOFCs operate at 650° C to 1000° C. The high temperatures remove the need for a precious-metal catalyst such as platinum. SOFCs reform fuels internally, which enables the use of a variety of fuels such as natural gas, biogas, and gases made from coal.

The current available types of fuel cells classified by the electrolytes used each have their own distinct advantages and challenges.

The performance of fuel cells decays with time as the gas diffusion layers (GDLs) and membrane degrade. Endurance was a significant challenge for the earlier generations of fuel cells. However, the latest generations have demonstrated lifetimes and operating hours that can meet or exceed stringent marine requirements.

5.1.2 STATE-OF-THE-ART

Fuel cell systems in the maritime industry have been primarily installed or considered for installation on military submarines, commercial ferries, offshore support vessels and yachts. They have also been deployed as fuel cell power systems for cruise ships, while other marine applications are in the planning stages. The power electronic converters are readily available to connect the fuel cell to alternating current (AC) or DC electrical networks, and can be programmed to provide voltage, frequency regulation and load sharing. The fuel cell power output ranges from kilowatts to multiple megawatts, and they can be integrated to provide more power.

In 2015, ABS collaborated with industry partners to initiate the San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (*SF-BREEZE*) project which aims to build a high-speed passenger ferry powered by hydrogen fuel PEM fuel cells for operation in the San Francisco Bay. The *SF-BREEZE* received Approval in Principle (AIP) from ABS in 2016.

ABS has also been involved with fuel cell projects including the development of a prototype hydrogen fuel cell unit to power onboard refrigerated containers. This fuel cell unit fits into a standard 20-foot container to replace the diesel generators which power refrigerated containers both in port and while being transported by barge. ABS also issued an AIP for this containerized hydrogen fuel cell generator unit.

Current fuel cell technology can either use pure hydrogen or other fuels that can be used to extract hydrogen. In the latter case, fuel reforming is needed to extract the hydrogen from the fuel, which increases the system complexity and cost. See the ABS *Advisory on Hybrid Electric Power Systems* for more details.

Current fuel cell technology supports small- to medium-sized marine applications. As vessel owners search for emissions-free power solutions for larger vessels such as ro/pax, cruise ships, containerships or tankers, scaling up fuel cell technology will become more critical.

The broad diversity of the fuel cell types and their application with different marine fuels, such as LNG, methanol, ammonia and hydrogen has not yet identified a single superior, preferred arrangement. However, more feasibility studies and safety assessments of their operations are expected to provide a greater understanding of best practices.

Fuel cells are a source of DC power that is compatible with battery, hybrid-electric architectures and can be deployed in parallel configurations to meet the power requirements of hybrid-electric propulsion and auxiliary power systems. They also can be optimized for given power, fuel storage and fuel consumption.

5.1.3 RESEARCH AND FUTURE DEVELOPMENT

In general, the availability of resources, including fuel cell manufacturers and fuel infrastructure storage, transportation, bunkering, etc., is expected to grow as more vessels are equipped with fuel cell power systems to obtain a cleaner fuel solution. As capabilities grow, the inherent limits on voyage length have the potential to expand the number of viable sailing routes for this technology.

- In 2019, ABS collaborated with Daewoo Shipbuilding & Marine Engineering to examine the viability of hybrid SOFC and gas turbine generator technology for future generations of LNG carriers. This theoretical work demonstrated the high efficiency of electricity and heat co-generation.
- The Oslo-listed Havyard Group is working with other Norwegian companies to design, certify and deliver a large-scale hydrogen power solution that can be retrofitted into ro/pax vessels. The project is focusing on developing safe storage solutions for cryogenic hydrogen on board vessels and in other unregulated areas related to hydrogen.
- Another Norwegian firm, NCE Maritime CleanTech, is working on a project that involves retrofitting an offshore support vessel with a 2-MW fuel cell using ammonia. Scheduled for completion in 2023, the project will examine the feasibility of using sustainably sourced ammonia in a SOFC system on a commercial ship.
- In Japan, Tokyo Kisen Co. and e5 Lab Inc. are working with several groups to develop the design and regulatory baseline for a tugboat powered by hydrogen fuel cells. e5 Lab is a joint venture group tasked with designing the electric vessel and sharing the information with all stakeholders in the shipping industry. The targeted launch year for the commercial operation of the tug is 2022.
- Canada's Ballard Power Systems recently presented its modular, 100 kW PEM fuel cell stack that can be used in various combinations in parallel to provide the power and redundancy needed by a vessel, from 100 kW to 1 MW or more. These PEM stacks can be used as the main propulsion system for small vessels, such as ferries and river boats, for auxiliary power on larger vessels, such as cruise ships, or for providing shore power to vessels when they are docked.

5.2 SUPPORT EQUIPMENT AND SYSTEMS

Fuel cells require complex and unique support and control systems that can vary depending on the fuel cell types and applications. Some basic components of fuel cell systems are:

FUEL CELL STACK: An assembly of cells, separators, cooling plates, manifolds and a supporting structure that electrochemically converts (typically) hydrogen rich gas and air reactants to DC power, heat and other reaction products. A **fuel cell module** is made of multiple fuel cell stacks with applicable additional components for integration into a power system.

FUEL CELL REFORMER: An arrangement of all related fuel-reforming equipment for processing gaseous or liquid primary fuels into reformed fuel for use in fuel cells, typically used to convert hydrocarbon conventional fuels to a gaseous mixture of hydrogen and byproducts, called reformates. The reformates are sometimes "purified" to remove CO_2 and other compounds before being sent to the fuel cell stack to remove the impurities in the gas interacting with the fuel cell catalyst.

HUMIDIFIERS: Some fuel cell types such as PEM do not work well when the polymer electrolyte membrane is dry. A humidifier is usually included to control the moisture level for the inlet air. The water produced by the fuel cells may be recycled to increase hydration.

FUEL CONTAINMENT SYSTEM: The arrangement for the storage of fuel including tank connections. It includes, where fitted, a primary and secondary barrier, associated insulation and any intervening spaces, and adjacent structure, if necessary, for the support of these elements. If the secondary barrier is part of the hull structure, it may be a boundary of the fuel storage hold space.

FUEL CELL POWER CONDITIONING SYSTEM: Fuel cells produce electricity in the form of DC. If the fuel cell is used to power equipment that uses AC, then the current must be converted, and the power must be conditioned with current inverters and conditioners. Conversion and conditioning will reduce system efficiency slightly, at around 2-6%.

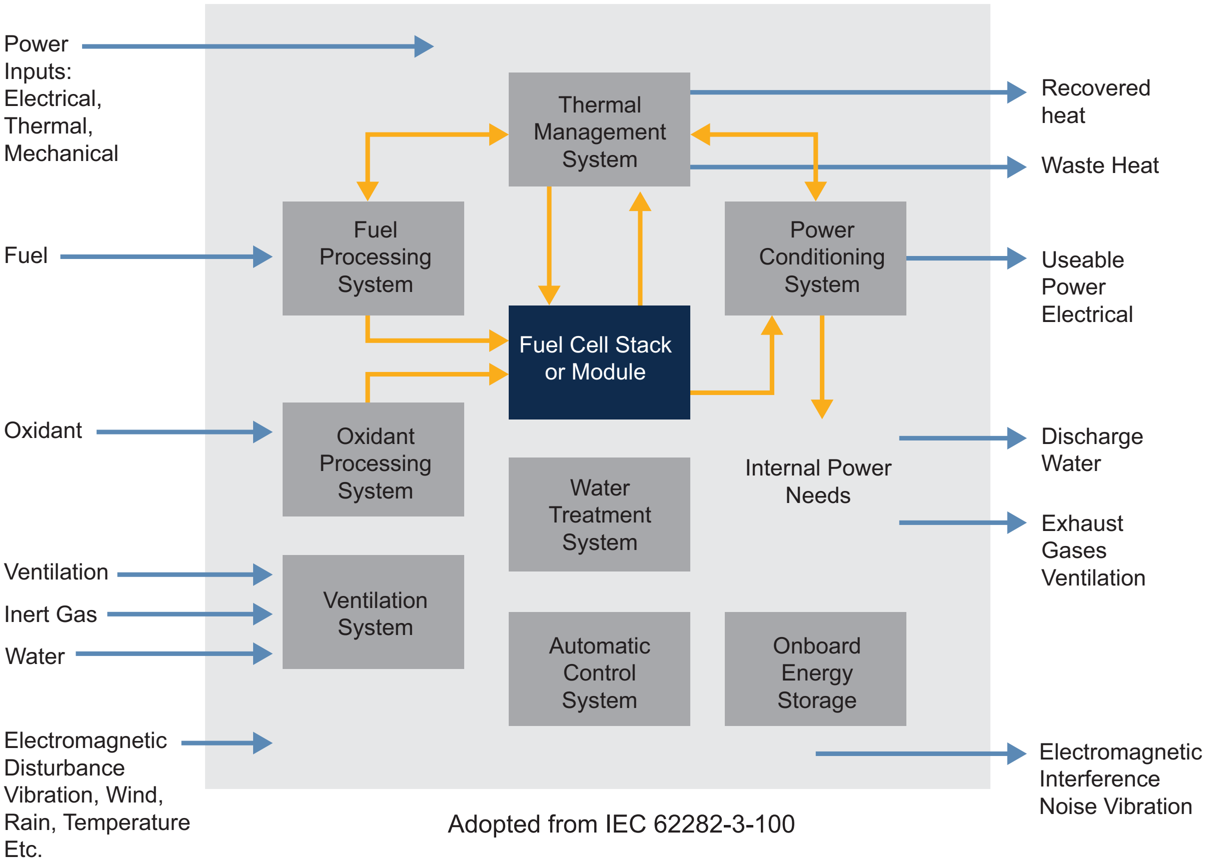


Figure 16: Fuel Cell Power Systems

5.3 FUEL OPTIONS

Hydrogen and oxygen are the basic requirements for fuel cells. Some fuel cells, however, can use other hydrocarbon fuels such as natural gas, biogas and ethanol through a reformer before entering the fuel cell.

Hydrogen is a zero-carbon fuel. Although abundant as an element, hydrogen is almost always found as part of other compounds and must be separated before it can be used. The current demand and application for hydrogen is in chemical manufacturing and refineries.

The use of hydrogen as a marine fuel is covered within the scope of the IGF Code but, at present, there are no specific initiatives at the IMO to develop hydrogen-focused requirements. However, this could favor applying the risk-based approach of the alternative-design process, allowing for greater freedom in design solutions.

Methanol can be directly used by Direct Methanol Fuel Cells and offers much higher energy density than hydrogen. Methanol is already available worldwide and been used in a variety of applications and can be easily transported, stored and used. It is mostly produced from natural gas but can be produced from renewable sources.

The current IGF Code does not cover methanol as a fuel, but as a low-flashpoint fuel, it can be considered under its alternative design provisions (2.3 of the IGF Code) and risk assessments (4.2) at IMO level, proposals have been made to amend the IGF Code and to include methanol as a marine fuel.

Ammonia as a fuel for fuel cells is a novel concept with ever growing interest. Once the technology matures, hydrogen from ammonia reformation can be provided to the cells to generate electric power. Certain fuel cell types can internally reform the fuel to run on ammonia directly, eliminating the need to separate the hydrogen and nitrogen elements before input.

An issue with using ammonia as a fuel is the undissociated ammonia concentration in the product gas. Although present at concentrations less than 50 ppm, this is still enough to damage fuel cells with acid electrolytes, so an acid scrubber is needed to remove the final traces of ammonia gas.

The 2016 IGC Code permits the burning of cargoes other than natural gas when not identified as toxic products, therefore this would exclude the burning of ammonia cargoes on IGC Code ships, unless appropriate regulations were agreed or as an exemption with the vessel Flag Administration.

5.3.1 CONTAINMENT AND STORAGE

Hydrogen has a relatively low energy density and requires more than 4 times the volume for storage than conventional fuel. In gas form, storage requires high-pressure tanks, and hydrogen's low volumetric density makes those units large, heavy and difficult to accommodate. In liquid form, the tanks can be smaller, but they must withstand cryogenic temperatures of -253° C. Storage of liquid hydrogen requires at least 5 times the volume of petroleum-based fuels.

Hydrogen is one of the smallest molecules and containing it is a technical challenge. The transportation of hydrogen poses similar challenges to storage. It exhibits high permeation through container walls, which means any system must anticipate leakage and its design, which also needs to emphasize ventilation. Leakage forms heavy condensation, which creates a fire hazard, and, in liquid form, it makes steel structures brittle. Leakage in enclosed spaces can quickly cause asphyxiation, so storage systems need their design and application to consider the appropriate materials, ventilation and leak detection/alarms.

Methanol has higher energy density compared to hydrogen and requires approximately 2.4 times more storage volume of conventional fuels. Methanol is a colorless and tasteless liquid at ambient temperature that is readily dissolved in water. The liquid form can be stored and supported with similar infrastructure for conventional fuel, with minor modifications.

There already exists a mature network for transporting methanol worldwide for the other applications However, if considered as a marine fuel, infrastructures such as bunkering facilities and fuel supply systems must be developed.

Ammonia has higher energy density than hydrogen and occupies less volume, but still requires about 3 times the volume of conventional fuels. Its advantages need to be weighed against the energy losses and additional equipment required for conversion to hydrogen before it is used in engines or fuel cells. Ammonia maintains a liquid state at low or high temperatures. Industrial scale storage uses low temperatures, which requires energy to maintain a temperature of -33° C, which requires lower capital cost than pressurization.

Ammonia can be transported on land and sea via pipelines, shipping, trucking and rail. Ship transport corresponds to comparatively higher amounts in either liquid or gas states. Road and rail transport use pressurized storage vessels for safety and simplicity, but the weight and therefore capacity are limited. To use ammonia as a fuel, the relevant infrastructures will need to be developed.

5.4 SHIP DESIGN AND MODIFICATIONS

The nature and trade route of each vessel will have a great influence on the fuels and new technologies adopted by each vessel as they pursue a pathway to a zero-carbon future. For a long-term solution, zero-carbon fuels would require the redesign of vessels and optimization of operational factors to avoid compromising travel distance, refueling needs, or cargo volume.

Short-sea vessels can be early adopters of new fuels and technologies that may compromise their range at sea but offer environmental benefits. Short-sea shipping can accommodate the use of fuels with low energy content – such as methanol or ammonia – that require more frequent bunkering. From a commercial perspective, short-sea shipping oftentimes competes with ground transportation, so new technologies will need to satisfy the regulatory landscape to keep the sector environmentally and economically competitive.

Deep-sea vessels will require more holistic approaches to adopting new fuels and technologies and would require a significant redesign, not least because their fuel tanks would require retrofitting to store enough energy for longer deep-sea travel. Deep-sea vessels are used for intercontinental trade and are therefore subject to global regulations. The trend toward more stringent regional regulations, such as those seen in emissions control areas, may increase the complexity of maintaining the compliance of deep-sea vessels that tend to operate in multiple jurisdictions. Also, from a commercial perspective, the large vessels used for deep-sea shipping tend to be designed for a single cargo, which is more subject to market fluctuations and supply chain risks. This uncertainty makes shipowners more cautious about adopting new technologies before they are operationally and economically proven.

5.5 REGULATION REQUIREMENTS

The use of hydrogen as a marine fuel is covered within the scope of the IGF Code, but at present there are no specific initiatives at IMO to develop hydrogen-focused requirements. IMO reference document MSC.420 (97) was developed to support the carriage of liquefied hydrogen, which is applicable to ships subject to the IGC Code. There are pilot projects investigating the use of hydrogen as a marine fuel, the deep-sea transport of liquefied hydrogen, and liquefied hydrogen bunker ship concepts.

IMO has been developing requirements for fuel cells for some time now and plans to release interim guidelines in due course.

Reviews for marine and offshore installations are primarily risk-based studies in combination with IMO regulations, IACS requirements and industrial standards relevant to the specific design and configuration of the system. The IGF Code is currently being revised to address requirements for fuel cell systems.

ABS recently published the *Guide for Fuel Cell Power Systems for Marine and Offshore Applications* to provide guidance for the design, evaluation, and construction of support systems for use of fuel cells on ships and may be applied to all types of vessels. The requirements in the Guide have been developed considering the IMO Draft Interim Guideline to the IGF Code pertaining to fuel cells.

5.6 CREW TRAINING

Training should provide the competence to the crew to operate the fuel cell system safely and provide guidance on fuel cell system safety, emergency situations, and alarm condition. Where necessary onboard training should be considered as follows:

1. A training manual shall be developed based on the specific design of the fuel cell and applicable relevant national code/company rules.
2. A Material Safety Data Sheet (MSDS) for the fuel cell's fuel must be included in the training manual. MSDSs provide safety information on all potentially hazardous or toxic substances.
3. The training shall be undertaken on a regular basis and continuously.
4. The operation, inspection, maintenance and troubleshooting of the fuel cell system shall be carried out only by trained crew, and to be use of appropriate Personal Protective Equipment (PPE).
5. Information required for the safe operation and maintenance of the fuel cell system should be obtained by the fuel cell manufacturer.

5.7 SAFETY

The application of fuel cell systems in the maritime industry is still challenged by many factors. Current practices are usually investigated using risk-based studies. The challenges include fuel management, personnel safety, hazardous areas management, operation and maintenance. The safety requirements for the intake and exhaust, including airflow, ventilation, and allowable backpressure also require serious consideration. Lighter than air fuels (hydrogen, methane, other gases) need special ventilation arrangements to reduce their hazardous risks. Due to the chemical nature of the fuels used in fuel cells, toxic exposure, asphyxiation and explosion are risks for the crew.

The non-hydrogen supply for many fuel cell systems is reformed externally to hydrogen and other byproducts prior to introduction into the fuel cell, so the hydrogen portion of the fuel system (from the reformer to the cell) needs special consideration.

6 NUCLEAR

Nuclear power was first used for propulsion of naval submarines in 1955. Since then, it has been applied to a great number of commercial and naval applications, ranging from submarines and aircraft carriers to icebreakers and floating power plants. Currently there are 140 naval vessels and five marine vessels active and operating with nuclear power, while even more vessels are now under construction. It is clear that the technology could be a viable option to provide the powering needs of any vessel.

With the 2030 and 2050 IMO targets on the horizon, nuclear power appears as an option that merits further research and consideration. When developing designs for vessels with planned service past 2050, there is value in achieving a zero-emissions footprint by operating with nuclear reactors that may not need any refueling for the design life of the vessel.

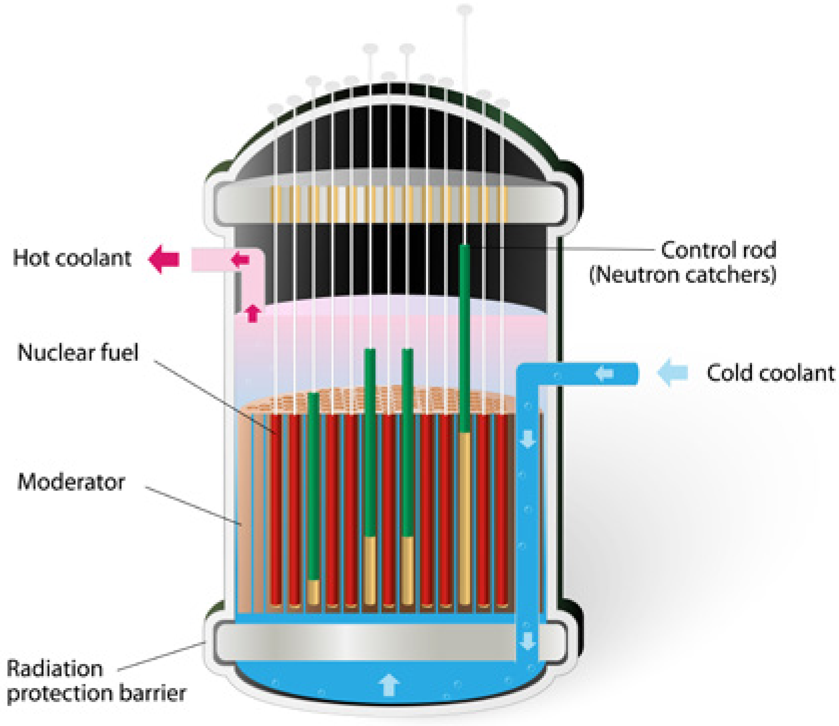


Figure 17: An Example of Nuclear Reactor

The majority of marine nuclear applications use pressurized water reactors, but there are many other reactor types including the following:

- Thermal Reactors (Pressurized Water Reactors, Boiling Water Reactors, Pressurized Heavy Water Reactors, Advanced Gas Cooled Reactors, Light Water Graphite Reactors, Molten Salt Reactors, Thorium Molten Salt Reactors)
- Fast Neutron Reactors (Traveling Wave Reactors, Molten Chloride Fast Reactors, Stable Salt Fast Reactors, Molten Chloride Salt Fast Reactors, Sodium Cooled Fast Reactors)
- Small Modular Reactors
- Fusion Reactors

Table 7: Nuclear Reactor Types

Technology Maturity	Reactor Types
Currently in Operation	• Pressurized Water Reactor (PWRs) • Boiling Water Reactors (BWRs) • Pressurized Heavy Water Reactors (PHWRs) • Advanced Gas Cooled Reactors (AGR) • Light Water Graphite Reactors (RBMK)
Ongoing Research and Development	• Molten Salt Reactors (MSR) - Thorium Molten Salt Reactor (TMSR) - Molten Chloride Fast Reactor (MCFR) - Molten Chloride Salt Fast Reactor (MCSFR) - Stable Salt Fast Reactor (SSFR) - Sodium Cooled Fast Reactor (SFR) • Traveling Wave Reactor (TWR) • Small Modular Reactors (SMR) • Fusion

The main safety concerns of nuclear-powered ships are related to the behavior of the reactor during accidents and in the event of the sinking of the ship. The development of reactor designs has led to passively safe systems especially in Generation III and IV reactors. This minimizes the chance of meltdowns and the release of radioactive material. The safety benefit of these passive systems makes them an option for marine use once they have been marinized for the intended application. Such reactor types include the High-Temperature Gas-Cooled reactor and the Molten Salt reactor, both using the size and surface area of the core for natural heat dissipation, and at high core temperatures are designed to safely contain any fission products.

Although it is a technologically ready option for marine propulsion, nuclear propulsion in commercial shipping is in limited use. Public perception of nuclear power as unsafe and the high cost of constructing such a vessel currently prevents the immediate uptake of nuclear power as an option.

Furthermore, liability insurance also requires a different legislation and framework, which should follow schemes similar to the ones used for land-based reactors.

Trade and vessel access are also challenging as different port states and regions have regulations on nuclear vessels or carriage of radioactive materials. The port will not require additional features for cargo operations, but shipyards and/or other facilities will have to be developed or specialized for refueling and maintenance activities related to the handling of radioactive materials and nuclear reactors. Similarly, onboard personnel will also require training and be constantly updated to maintain competence in the operation of nuclear reactors, while the same applies to superintendents and other relevant onshore personnel. An alternative is that the reactor remains the property of its developer and monitoring and maintenance of the reactor is performed by these specialized crews.

6.1 EXISTING VESSEL APPLICATIONS

6.1.1 GOVERNMENT / MILITARY

The primary user of nuclear power for marine purposes is military vessels. Several nations have equipped their fleets with nuclear-powered vessels. A summary of current published military vessels is below:

US Navy	73 Submarines (55 Attack, 18 Ballistic / Guided Missile) 11 Aircraft Carriers
Russian Navy	21 Submarines (13 Attack, 8 Ballistic / Cruise Missile) 1 Battlecruiser
China	14 Submarines (9 Attack, 5 Ballistic)
British Navy	10 Submarines (6 Attack, 4 Ballistic)
France	9 Submarines (5 Attack, 4 Ballistic) 1 Aircraft Carrier
Indian Navy	1 Submarine

6.1.2 COMMERCIAL

The only commercial vessels currently deploying nuclear power are six active Russian icebreakers. Following the success of nuclear-powered propulsion in icebreakers in the Arctic, a new LK-60 series of Russian icebreakers, Project 22220, was contracted to Baltijsky Zavod Shipbuilding in St. Petersburg. The first vessel of the series, *Arktika*, was laid in November 2013, and was delivered to Atomflot in 2020. Two more LK-60 icebreakers, *Sibir* and *Ural*, have been contracted to be built.

The LK-60 series has a draft of 10.5 m with full ballast tanks, a displacement 33,540 t, and is designed for use in the Western Arctic year-round and in the eastern Arctic in summer and autumn. They have a length of 173 m, beam of 34 m, and can break through 2.8 m thick ice at up to 2 knots. They are powered by two RITM-200 reactors of 175 MWt each, delivering 60 MW at the three propellers via twin turbine-generators and three electric motors.

Another series of icebreakers, LK-120, Project 10510 Lider, will be powered by two RITM-400 reactors of 315 MWt each to deliver 120 MW propulsion through four electric motors and four propellers. It will be designed to break through 4.5 m thick ice, or 2 m thick ice at 14 knots, and is intended for deep-sea use in the eastern Arctic. It will have a length of 205 m, beam of 50 m, draft of 13 m, and deadweight of 55,600 t.

Project 10570 is also under development, for LK-40 series, intended for shallow water and the Arctic shelf. These vessels will have a length of 152 m, beam of 31 m, draft of 8.5 m, displacement of 20,700 t, and they will be powered by a single RITM-200B reactor of 209 MWt delivering 40 MW at the propellers [13].

Figure 18: Russian Nuclear Powered Icebreaker "Yamal"

6.2 TECHNOLOGY APPLICATIONS

6.2.1 CURRENT TECHNOLOGY AND DEVELOPMENT

While limited developments have occurred in the marine world, much nuclear power research and development is ongoing. The general options for reactor design and planned reactor physics revolve around the following reactor types:

6.2.2 REACTOR GENERATIONS

- Generation I – Early prototype reactors in 1950s-1960s. Promoted the launch of civil nuclear power.
- Generation II – Reactors with economic and reliability focus. Started operations in late 1960s and comprise the majority of worldwide nuclear reactors. These reactors require active safety measures.
- Generation III – These are normally of Gen II design with additional improvements in safety systems (requires passive system), construction, and efficiency. Activity in this generation started in 1990s.
- Generation III+ or Generation IV – Additional safety improvements from Gen III. Current nuclear development projects (since 2000s) [14]

6.2.3 THERMAL REACTORS

Thermal reactors use slow or thermal neutrons to maintain fission reaction in the uranium fuel. They require a moderator to slow the neutrons from the fission process.

- **PRESSURIZED WATER REACTORS** (PWRs) – Approximately 60% of nuclear reactors worldwide and almost all marine nuclear applications: PWR reactors are cooled and moderated by light water (i.e., regular water as H_2O). Because this medium is not sufficient for the reaction to use natural uranium, enriched uranium must be used (increasing U235 from 0.7% to about 3.5% to 5%). Pressurized light water (approximately 150-160 bar) does not boil as it passes around the reactor (or through the reactor) in the primary loop. This loop is then fed to a steam generator where it heats the secondary light water at a lower pressure (60 bar). The secondary water boils and the steam is used to drive the turbine generators. Pressurized containment requires large and extensive infrastructure around the plant. Additionally, the light water moderator requires energy to be released. Therefore, it is necessary to provide redundant power to the condenser or other cooling heat exchangers to prevent a dangerous shutdown [15].
- **BOILING WATER REACTORS** (BWRs) – Approximately 20% of nuclear reactors worldwide. BWR reactors allow the pressurized (about 70 bar) light water that passes through the reactor to boil and power the turbine generators. After the turbines, a heat exchanger condenses the water and it is pumped back into the reactor. Similar to the PWR reactors, special precautions for the infrastructure and emergency shutdown procedures must be in place to protect the plant from hazardous meltdowns. Additional precautions are also necessary because the water becomes radioactive when circulated. This means that there must be extra shielding in the non-reactor parts of the power plant (turbine, condenser, etc.)
- **PRESSURIZED HEAVY WATER REACTORS** (PHWRs) – Approximately 10% of nuclear reactors worldwide. Commonly called Canada Deuterium Uranium (CANDU) Reactors, the PHWRs use heavy water (deuterium oxide, 2H2O) for both coolant and moderator. The heavy water has superior performance over light water in terms of neutron absorption and therefore, the reactor can be fueled by unenriched (natural) uranium. The heavy water is pressurized so as not to boil from the reactor heat exchange and a secondary light-water loop powers the steam turbine generators [16].
- **ADVANCED GAS COOLED REACTORS** (AGR) - designed by the British, the AGR design uses CO_2 as the coolant and graphite as the moderator of the nuclear reactor. Gas heat exchange allows for higher efficiency temperatures (up to 650° C) within the reactor, and the heavy metal insulation used in these temperatures also allows the use of low-enriched uranium fuel. Emergency shutdown systems include nitrogen injected into the gas to cool the reactor rapidly [17].
- **LIGHT WATER GRAPHITE REACTORS** - RBMK reactors use light water for coolant and graphite as a moderator. Its unique design uses individual channels to contain slightly-enriched uranium fuel rods, each with light water passing through to cool, and all surrounded by the graphite. The system allows the light water to boil and operate the turbine generators [18].

- **MOLTEN SALT REACTORS** (MSR) - Molten Salt Reactors differentiate from the above reactor types due to its fuel state. The fuel (uranium or plutonium) is dissolved into molten salts (fluoride or chloride). While the operating temperatures of MSRs can be the highest of all reactors (700-800° C), there is little to no pressurization required, which eliminates the risks of pressurized reaction chamber explosive breaches [19, 20]. When MSRs are used for thermal reactions, graphite can be used as the moderator. Alternate salt moderators are currently being researched that do not require graphite. These salt configurations can improve operations of the reactor by reducing need to address frequent graphite problems. Compact versions of MSRs are also in development with promising technology and goals of commercialization over next 7-10 years. If MSRs are utilized as fast-neutron reactors, they do not require graphite moderators. There are many possible configurations of MSRs for both thermal and fast-neutron reactor types.
- **THORIUM MOLTEN SALT REACTOR** (TMSR) – In development by Shanghai Institute of Applied Physics (SINAP), the Thorium Molten Salt Reactor is still in the design phase. Using Thorium dissolved in fluoride coolant as fuel, SINAP expects the MSR method with thorium to produce less waste, decrease fabrication costs, and possess effectively unlimited burn-up, while operating at lower temperatures than pelletized or solid thorium fuel sources. The current phase of development is focused on preparing and testing the thorium fuel sources. Other forms of TMSR reactors being developed only partially utilize thorium as a fuel source (TRISO in pebbles or solid blocks), by using it to supplement degraded uranium. SINAP expects its first plant to open by 2025 and see commercial deployment of the TMSR after 2030.

6.2.4 FAST NEUTRON REACTORS

These allow the transition from uranium fuel to plutonium for additional fissile material. The new isotope can absorb fast neutrons and sustain criticality for the reactor. These reactors are commonly referred to as breeder reactors because depending on design, they can generate more fissile products than they consume [21]. In general, these types of reactors can use existing nuclear waste as fuel, which can reduce the need to dispose of or store the waste products of the operation. Additional work is being conducted in this area.

- **TRAVELING WAVE REACTOR** (TWR) – TWRs can use depleted uranium and operate without the need for fuel reprocessing as the nuclear reaction occurs without the need to remove fuel from the core. Therefore, the TWR produces reliable heat and electricity over an extended, continuous period. Industry projects aim to initiate the prototype operations in the mid-2020s, and expects to see the global commercial deployment of the TWR towards 2030 [22].
- **MOLTEN CHLORIDE FAST REACTOR** (MCFR) – For MCFR reactors, the fuel and coolant are provided by molten chloride salt fuel. Reportedly as a passively safe molten salt design, the MCFR operates at high temperatures to increase reactor efficiency, and also allows for batch refueling, which eliminates the need for enrichment or reprocessing, and further eliminates the risks of weapons augmentation using nuclear waste [22]. MCFR testing is ongoing, but industry research expects a 1,100 MW prototype reactor to be in operation by 2030 [23].
- **STABLE SALT FAST REACTOR** (SSFR) – Unlike pressurized reactors, the SSFR ambient-air cooled tubes contain the fuel salt, and the tank also holds the molten salt coolant. Ambient air heat exchange provides constant passive cooling to the jacket of the reactor. These systems are not reactive with air and water like other fast breeder reactors. Simple refueling requires the individual salt tubes to be removed and replaced, allowing continuous reaction operation. Industry research expects to open the first SSFR before 2030 [24].
- **MOLTEN CHLORIDE SALT FAST REACTOR** (MCSFR) – Similar to MCFR, the MCSFR highlights a passively safe system, including low pressure (near atmospheric) reactor and a salt freeze plug that allows for safe, passive shutdown by draining the reactor if the temperature limits become excessive or if power is lost. The MSCFR reactor is designed to be installed and operate underground for protection from the environment and is capable of burning over 95% of the fuel provided. Testing and optimization of the MSCFR is ongoing in the US, where research projects expect prototype testing around 2025 and commercialization of the technology by 2030 [25] [26].
- **SODIUM COOLED FAST REACTOR** (SFR) – ARC (Advanced Reactor Concepts). Based on modular components for remote site assembly, the ARC-100 SFR is another reported passively safe molten salt reactor that can be fueled by existing nuclear waste. In addition to a passive “walk-away” failsafe, this factory assembly has a 20-year refueling cycle. ARC is proceeding with the development of the ARC-100 SFR reactor after a 30-year Experimental Breeder Reactor-II (EBR-II) project successfully demonstrated the reliability and feasibility of SFR power plants. The development of the SFR continues with the intention to operate the first plant within 8 years [27] [28].

6.2.5 SMALL MODULAR REACTORS (SMR)

Research and development continue in the area of smaller reactors and the options for their use. These simpler designs with lower power outputs are projected to have considerable growth by the International Atomic Energy Agency (IAEA). There are more than fifty concepts globally with a few of these ongoing projects approaching near term deployment [29].

6.2.6 FUSION

Recent activity by research groups has caused an increased awareness of fusion as a possible future power source. A recent (March 2019) patent "Plasma Compression Fusion Device" was filed in the U.S. [30]. Though there is/has been much research in this area, containment and sustainment remain the biggest challenges. Operational temperatures of the gases (hydrogen and helium) are at millions of degrees. This plasma derivative can't touch its containment, so it is normally controlled with magnetic fields. The second challenge is harnessing the heat of fusion requiring the capture of the free neutrons with some media for kinetic heat transfer and subsequent energy transfer.

6.3 SUPPORT EQUIPMENT AND SYSTEMS

6.3.1 REACTOR MACHINERY COMPARTMENT

Nuclear plant sizing varies based on technology deployed and power required. Based on the predominant marine use of pressurized water reactors (PWR), the below examples are provided as a reference (weights and sizing are based on previous applications and may vary based on vessel design and application). The use of alternative nuclear technologies would necessarily change the size and weight requirements of the reactor and its support systems. Decisions on reactor size will be based on available thermal power and subsequent efficiencies to achieve propulsion and electric power. Vessel power requirements will vary based on vessel size and operational envelope. Some example power requirements are in below table for reference:

Table 8: Examples of Propulsion and Electrical Power Requirements

Vessel Type	Size	Propulsion plus Electrical Power Generation
Container Carrier	200 kDWT	30-35 MW
Tanker	300 kDWT	26-30 MW
Bulker	400 kDWT	23-28 MW
LNG Carrier	~170k M^3	22-26 MW

For example, for effective power of approximately 25 MW of propulsion plus electrical generation: with expected thermal efficiencies of the reactor (efficiency for marine pressurized water reactors ranges from 22 – 33%), would require a reactor with a thermal output of at least of 75 – 115 MW.

Considerations for nuclear plant design:

- Excessive vibration and excitations from vessel motion and vessel oscillating machinery
- Reactor design needs to be compact relative to land-based applications
- Reactor weight must be considered for longitudinal strength and stability
- Load following capabilities (how quickly can reactor power follow steam demand)

Components Necessary:

- Reactor Core: The estimates of thermal power and effective power for the reactor can give approximate sizing in both weight and volume.
- Containment Vessel/Reactor Compartment: The containment vessel houses the reactor core, control rod assembly, primary coolant loop, coolant pumps, pressurizer and steam generator. The reactor containment vessel will fit in approximately a 10x10x10m space.
- The reactor compartment with all its components will weigh approximately between 1,100 and 1,800 tons depending on design. The more compact the design, the less water and steel is required, resulting in the weight disparity. Additionally, systems are required for primary coolant maintenance (chemistry, charging, etc.)

- Shielding – The nuclear propulsion plant requires reliable shielding to protect persons on board ship, or within the immediate vicinity of the ship, against the hazardous effects of radiation under normal and accident conditions. Shielding primarily utilizes water, lead, and concrete. Each has different radiation attenuation abilities. As a reference, the shielding on the NS Savannah incorporated the following:
  - Primary Shielding – Water / Lead combination - ~ 200 tons
  - Secondary Shielding – Concrete, Lead, Polyethylene - ~1,800 tons
- Machinery Space Isolation / Safety Enclosure – Depending on vessel and reactor core design and risk assessment, an additional level of isolation may be required. Per the IMO, there are to be multiple levels of barriers for radioactive containment. If the machinery space housing the reactor compartment is part of the barriers, the space is to be gastight and watertight.
- Components that come in contact with primary reactor loop (filters, valves, pumps, etc.) can be potentially contaminated. Controls are to be put into place for storage/disposal of potentially contaminated materials. This also includes the testing for potential contamination to understand storage and disposal requirements.

6.3.2 MACHINERY COMPARTMENT (NON-NUCLEAR)

The following is typical equipment installed on the vessel. This equipment is equivalent to standard steam/condensate/feed systems that support conventional boiler/steam plants as discussed in previous sections.

Steam Plant Configuration:

- Feed/Steam Piping
  - Feed pumps
  - Steam cutoff valves and distribution piping
- Propulsion Turbine (unless electric propulsion option)
  - High-Pressure Turbine
  - Low-Pressure Turbine
  - Reduction Gear
- Generator Turbines
  - 2-4 depending on design and vessel loading and redundancy requirements
  - Additional generators necessary for electric propulsion option
- Condensate System
  - Main condenser
  - Generator condenser
  - Condensate pumps
- Auxiliary Equipment
  - Makeup water (Reverse Osmosis (RO)/Distillation Plant)
  - Chemistry

6.4 FUEL OPTIONS

Nuclear power departs from the traditional marine fuel schema by relying on a fissile product to support sustained nuclear reactions. The primary nuclear fuel used relies on isotopes of Uranium. In most cases, the Uranium requires an enrichment process to increase the percentage of fissile isotopes. Different reactor designs as specified in this section utilize different isotopes and fuel enrichment levels. Procurement, use of and handling of nuclear fuels needs to be considered for vessel construction, fueling, and end of life activities.

6.4.1 REFUELING

Refueling of nuclear reactors in most cases may be required very few times in the lifetime of a vessel, or in some modern reactors, no refueling may be necessary for the lifetime of the vessel. If refueling is required, it should be performed in specialized shipyards by properly trained personnel and following strict procedures, because even a small accident may lead to a release of radioactive materials to the vessel and/or shipyard. Similarly, maintenance activities of nuclear reactors should be handled by shipyards that are specialized in the specific reactor type used [31].

Refueling and certain maintenance by crew trained for nuclear reactor operation may not be possible, as this involves procedures that can be performed only by specialized teams possessing specific qualifications, skills, and tools. The process of refueling requires the unloading of radioactive waste, such as spent nuclear fuel, removing decay heat, performing preparatory works, and then loading the new fuel. This process in some cases may take up to three months and is normally completed in dedicated nuclear management facilities [32].

Consideration should also be given to and provisions developed for the recycling of the spent nuclear fuel, as burying spent nuclear fuel is not a good option economically or environmentally. A study made by Deutch et al. (2003) showed that known uranium reserves are sufficient for the next 70 years, without including the needed reactor power for shipping [33].

6.4.2 END OF LIFE (DISPOSAL)

Decommissioning and disposal of nuclear-powered vessels is a topic that must be considered during the design of the vessel. The practices that are currently followed for naval vessels may be applied in marine vessels as well.

As an example, the United States Navy follows the Ship/Submarine Recycling Program (SRP) for the disposal of decommissioned nuclear vessels. The process requires that firstly any nuclear fuel is removed, usually performed simultaneously with decommissioning. The following stage includes the initiation of the SRP, by cutting the vessel into several parts and those that are free of hazardous and toxic wastes are either returned to production or are sold as scrap materials. This process is considered the best economic approach for complete disposal.

The reactor compartment is removed, sealed and then kept in open dry storage and slated to be eventually buried. The burial trenches have been evaluated to be secure for at least 600 years before the first pinhole penetration of some lead containment areas of the reactor compartment packages occurs, and several thousand years before leakage becomes possible [34].

6.5 SHIP DESIGN AND MODIFICATIONS

6.5.1 VESSEL DESIGN

Predominantly in steam-driven marine vessels, the engine room and boiler are located aft of and below the accommodations with the cargo midship and forward. Due to the weight of the reactor, support structures and equipment, marine reactors are historically placed closer to midships. For example, a slow speed diesel engine weighs approximately 1,000 metric tons while a reactor assembly may exceed 4,000 metric tons. To minimize extensive steam piping, the engine room tends to be co-located with the reactor. Depending on intended vessel design, electric propulsion can be considered to reduce the need for a long shafting system that may reduce cargo capacity. With a midship assembly, the vessel design will require lengthening to accommodate the reactor and its containment vessel. The accommodations block remains near the aft end of the vessel and a portion of the space originally housing the engine room and boilers can be used for the required auxiliary support equipment and the electric propulsion units. A few concept studies have been conducted.

6.6 REGULATORY REQUIREMENTS

Development of marine applications will have to maneuver a complicated regulatory scheme involving both international, regional, and local requirements. Additionally, once operational, there will be requirements for port state compliance for the areas of operation. The primary agencies are:

- IAEA – International Atomic Energy Agency, https://www.iaea.org
- IMO – Resolution A.491 - IMO has requirements for nuclear ships, since 1981, with Resolution A.491 amending SOLAS 1974 to include in Chapter VIII the "Code of Safety for Nuclear Merchant Ships".

6.6.1 NATIONAL LAWS:

In addition to international regulations, local requirements will come into play based on planned operations.

- United States - U.S. NRC – U.S. Nuclear Regulatory Commission
  - https://www.nrc.gov/
- United States - U.S. Code of Federal Regulations, Title 10, Chapter I, Part 20
  - https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/
  - https://gov.ecfr.io/cgi-bin/ECFR?page=browse
- China – National Energy Association
  - http://www.nea.gov.cn/
- France – ASN, Nuclear Safety Authority
  - http://www.french-nuclear-safety.fr/
- Japan – Nuclear Regulatory Authority
  - https://www.nsr.go.jp/english/
- Russia – Federal Reserve for Environmental, Technical and Nuclear Supervision
  - http://www.en.gosnadzor.ru/

Local requirements concerning nuclear-powered vessels are not internationally uniform. Although the technological safety level of vessels powered by nuclear applications is standardized, many nation states have further restrictions on vessels visiting or passing through its waters. Such vessels may be restricted to certain sea lanes and ports [35].

6.7 CREW TRAINING

The operation of reactors is of course very different from the operation of a diesel engine or gas boiler, and the existing training schemes for conventional propulsion vessels are not applicable to nuclear reactor operators. A typical training cycle for a nuclear operator can extend to two years. In addition, since different reactor types require different operations and handling, the training of the crew is dependent on the reactor type utilized and likely must be performed on land-based working reactors of the same type.

The common superintendent practices on dry dockings and daily performance monitoring will have to adapt to nuclear reactors. Therefore, superintendents and other relevant shoreside personnel will require training to remain current on the principles and practices for nuclear propulsion, as well as the installed reactor types. However, depending on the ownership of the reactor, which may be the property of the developing company, the monitoring and inspections of the reactors may be performed by the developing company's engineers, and the reactor is considered as a black box for the shipping company, which may alleviate the need of such training from shipping companies' shoreside personnel.

6.8 SAFETY

Primary safety considerations are driven by lessons learned in previous disasters. Whether referencing Chernobyl (1986) or Fukushima (2011), there exists a need to push risk informed regulation, management system response to severe accidents, assessment of natural hazards, and mitigation of plant blackout.

The main safety concerns of nuclear-powered ships are related with the behavior of the reactor during an accident and in the event of the sinking of the vessel. The development of reactor designs has been to create passively safe systems especially in Generation III and IV reactors. This can minimize the chance of meltdowns and loss of radioactive material. Practices like those used for the fire protection of engine spaces during cargo fires should also be adequate if considering that there are no flammable hydrocarbons present in such arrangements. In addition, for ship groundings without any damage to the engine space, the risks are considered to be the same as with a conventional-powered ship. However, reactor behavior after sinking is a challenge posing additional risks.

A meltdown occurs when the temperature of the nuclear fuel elements becomes so high that damage to the core occurs and fission products are released. Land-based reactors prior to Generation III primarily use active cooling for meltdown prevention. However, this requires constant access to the reactor, as well as constant and ready availability of emergency equipment and emergency power, none of which can be guaranteed in the marine environment. For such reasons, passive cooling and reactors of later generations (III and IV) that reduce meltdown risk makes them options for marine use.

Such reactor types include the High-Temperature Gas-Cooled reactor and the Molten Salt reactor. Both types use the size and surface area of the core for natural heat dissipation. At high core temperatures, they are designed to safely contain fission products.

Scenarios for marine accidents will require an appropriate emergency response capability. Depending on vessel location, this capability will rely on local regions and nation states for assistance. Radiation response programs exist for certain port state organizations. The shipping industry must consider the impact of emergency response and how proper vessel support would be accomplished.

A safety assessment should be conducted prior to fueling. Typically, this includes a description of the ship, the propulsion and reactor system, and a discussion on operation under normal sea, port, emergency and fault conditions. Additionally, it should include a description of reactor control, containment, radiation protection, radioactive waste disposal, refueling, standby and emergency components, inspection and survey procedures, manning, and training requirements. As part of the safety assessment, credible accident scenarios should be evaluated. The intent is to confirm that the nuclear installation does not cause an undue hazard at sea or in port, to the crew, the passengers, the public, or to the waterways or natural environment.

7 WIND

Wind energy was once the dominant propulsion method for ships. Although wind propulsion has been superseded by modern engines in ships, in the interest of reducing GHG emissions, renewable wind energy has re-emerged for both propulsion and as a source of electrical energy.

Wind-assisted propulsion, although similar, differs in that wind is not the primary means used for propulsion but is used to reduce the energy consumption of a vessel. Current wind technology applications cannot provide propulsion forces to the scale of the main propulsion method with the same reliability and therefore wind can only be used for propulsion assistance on modern commercial ships. This is partially due to the restrictions in design that call for a large clear deck, minimal rigging, and resolution of stability issues.

Wind-powered electrical energy onboard is also explored as another method to reduce emissions. Application includes vertical wind turbines installed on deck to generate and recharge batteries to provide additional electric power.

7.1 CURRENT APPLICATIONS

7.1.1 KITE SAIL / RIGID SAIL

The kite sail concept consists of a large kite which is attached to and flies from the bow of a ship. This uses the pull created by the kite to assist in moving the ship through the water.

Kites are the form of wind-assisted propulsion on commercial ships requiring the least amount of retrofit and alteration of the ship. The low cost of retrofitting a system with minimal interference with the ship's existing structure and the associated computer automation to determine the ideal kite angle and position are what makes this design attractive. Additionally, kites allow capturing wind at higher altitudes where wind speed tends to be greater and more consistent.

Several companies have developed kite sail technology. SkySails Group, based in Germany, has developed large automated kite sails for several vessels, most notably commercial ship *MS Beluga Skysails*. The SkySails wind propulsion system consists of three main components: a towing kite with rope, a control system for automatic operation, and a launch and recovery system. In addition, a system called SkySails power is available to generate electric power from the kite, by repeatedly letting out the kite (work phase) and returning it (rewind phase). This can be used to generate power and reduce the generator load when at anchor or at port, depending on conditions. SkySails are subject to height restrictions when approaching harbors or in the presence of other vessels. The manufacture claims SkySails kites can generate up to 5 to 25 times more propulsion power per square meter of sail area than conventional sail propulsions [36, 37]:

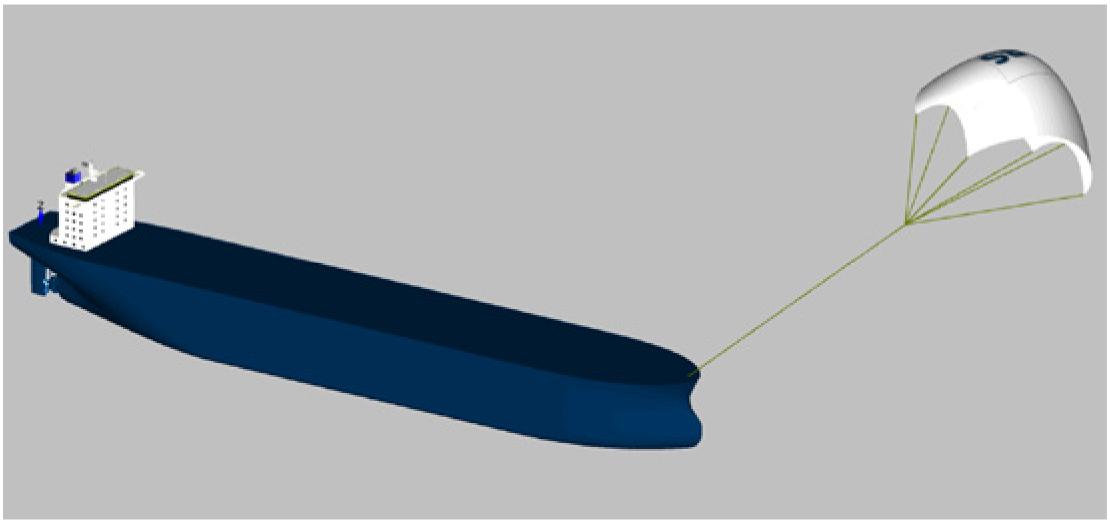


Figure 19: Sample Towing Kite System

Rigid sails are another form of sails that utilize the conventional design of a soft sail or wing sail, constructed of metal or composite materials. These are installed similar to Flettner rotor sails and are also subject to height restrictions when approaching harbors or in the presence of other vessels. The image below illustrates the design of rigid sails on the vessel *Shin Aitoku Maru* that was trialed in 1980.

Figure 20: Vessel Shin Aitoku Maru with Rigid Sails

In addition to this trial, a study was commissioned by the U.S. government on the economic feasibility of using wind-assisted propulsion to reduce the fuel consumption of U.S. Merchant Marine ships. Five different designs were considered, and the conclusion was that with the technology of the time (late 1980s), the rigid sail concept would offer the most benefits. The rigid sail analyzed in the study, "Wing Sail Concept," was a largely automated system of rigid sails supported by cylindrical masts. This system was retrofitted to a small freighter to evaluate its actual fuel gains [38].

7.1.2 FLETTNER ROTOR

The Flettner Rotor is a large cylinder mounted upright on the deck of a ship and mechanically (or electrically) spun. As wind passes at a right angle across the cylinder, the Magnus effect occurs –an observable phenomenon in which a lift force is generated on a rotating cylindrical or spherical object when in a fluid stream.

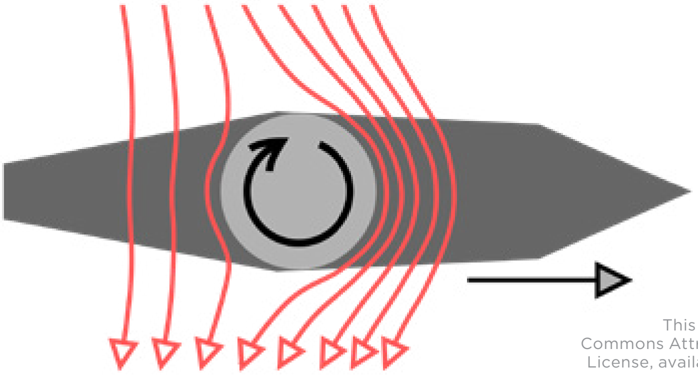


Figure 21: Magnus Effect

When wind meets the spinning rotor, the air flow accelerates on one side of the rotor and decelerates on the opposite side. The difference in the speed of the air flow results into a pressure differential which creates a lift force perpendicular to the wind flow direction. The same principle applies to rotating spheres and cylinders. The only parameter of the Flettner Rotor requiring control is the speed of the rotor's rotation, so this method of wind propulsion requires minimal operator input. In comparison to kite sails, Flettner rotors offer similar efficiency gains depending on the size of sail used versus size of the rotor. Because only the rotation speed requires control, the technology requires relatively little operator input.

In 2018, two 30-meter-tall Norsepower rotors sails were installed on a 109,647 dwt long-range product tanker owned by a European shipowner. Norsepower Rotor Sails confirmed savings of 8.2% fuel and associated CO_2 during the 12-month project. In January 2021, two 35-meter-tall Norsepower rotor sails were retrofitted onto Ro-Ro *SC Connector* operating in the North Sea. It is the world's first tilting rotor sails enabling the vessel to pass under bridge. Norsepower predicted to reduce emissions by an estimate of 25%.

Figure 22: SC Connector with Two Norsepower Rotor Sails

Rotor sails are best suited to vessels where deck space is available and there is a high proportion of time-at-sea where prevailing wind conditions are favorable. The rotor sails are installed on the deck of the vessel with vessel-tailored foundations, which are installed during a yard stay. The rotors are bolted to the foundations. When the installation of the foundations has been completed, the rotors can be lifted on the vessel and attached to the foundations during a normal harbor stay.

Additional essential components of rotor sail installation include the rotor sails, control panels, and electric power supply to each sail. The required number and size of rotor sails is dependent on the size, speed, and operating profile of each vessel [39, 40].

7.1.3 VERTICAL WIND TURBINE

In addition to using wind to assist propulsion directly, wind power can also be harvested for electric power. The Alcatraz Cruise's *Hornblower Hybrid* is a hybrid passenger vessel delivered in 2009. *Hornblower Hybrid* has 10-foot-tall vertical wind turbines installed on the top deck along with solar panels. The generated power is then stored in battery banks to power the navigation, lighting and other electronics on the ship [41].

Bonum Engineering and Consultancy of Switzerland and shipping company Bore of Finland partnered in 2019 to validate vertical wind turbine design on a vessel. The 2 m^2 wind turbine was initially tested with a nominal electrical production of approximately 2,380 kWh per year with a nominal output of 340 W at 10 m/s. The companies intend to continue testing the vertical wind turbine next with up to 10 times the previous output [42].

7.1.4 OTHER TECHNOLOGIES

Other technologies that investigated wind as a method of propulsion assist include rigid sails/solar panel combinations. Aquarius MRE is a solution developed by Eco Marine Power that combines sail power (using rigid sails) with solar power. This patented wind and solar solution is designed so that the practical limitations of using rigid sails and solar panels on ships are overcome.

At the center of Aquarius MRE is a patented rigid sail technology called the EnergySail. This device incorporates various renewable energy technologies. The EnergySail can be used as a stand-alone device or as part of an array and is positioned automatically by a computer control system developed jointly by Eco Marine Power and KEI System Ltd of Osaka, Japan. This computer system is known as the EnergySail Automated Control System. In addition to control functions for the EnergySail, the system also incorporates a management interface and a data-logging capability.

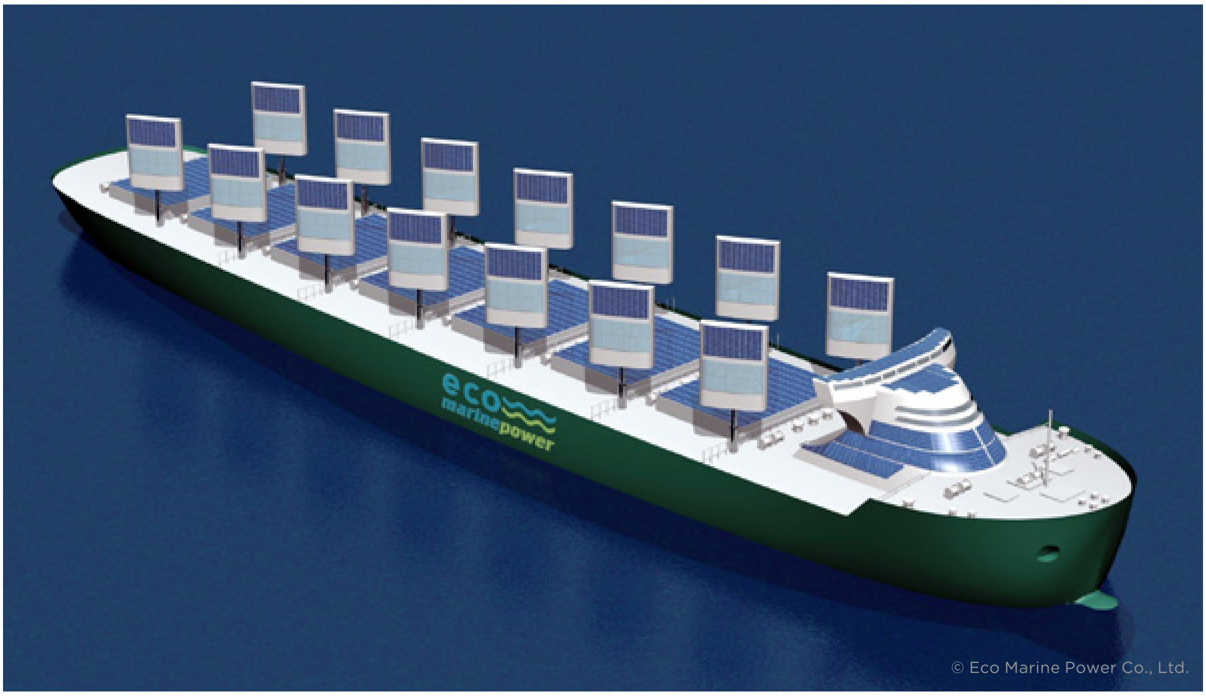


Figure 23: Aquarius Eco Ship with EnergySail System

To interface with other equipment on the vessel such as the main engines and generators, another computer system jointly developed by Eco Marine Power and KEI System - the Aquarius MAS (Management & Automation System) - is incorporated into the Aquarius MRE system architecture. This marine computer system is said to calculate vessel airborne emissions, monitor fuel consumption, log data, display system alarms and interface with a range of marine renewable energy solutions [43].

7.1.5 FUTURE RESEARCH

All of the aforementioned technologies for wind-assisted propulsion have similar challenges, namely:

- Performance depends on external factors such as the geographic location, season, availability, wind strength, consistency and direction.
- Electric power load demands
- Maintenance requirements and life expectancy of the investment
- Limited availability of components for repair and the potential for upgrades

In addition, the adoption of wind-assisted propulsion systems is a compromise between maximum efficiency gains, minimum CAPEX and space available on the deck.

7.2 SUPPORT EQUIPMENT AND SYSTEMS

7.2.1 DRIVE SYSTEM CONSIDERATIONS

When installing wind-assisted propulsion systems on a vessel, it is important to identify the supporting components associated with the drive system. The components for a wind-assisted propulsion drive system are shown in the following schematic.

In general, the machinery of wind-assisted propulsion systems consists of drive units for the thrust generating mechanism and the control system. Depending on the system type, the drive unit may be electric or hydraulic. The wind-assisted propulsion system should be arranged so that in case of failure the power supply will not be interrupted to equipment necessary for the propulsion, steering, and safety of the vessel. The main power source of power for a ship using a wind-assisted propulsion system, regardless of drive unit type, must be provided by the vessel itself.

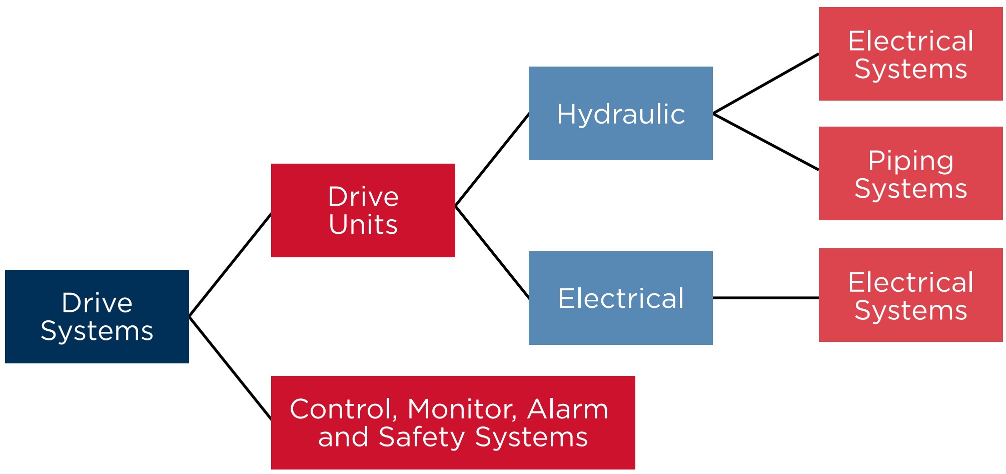


Figure 24: Components for Wind-Assisted Propulsion System's Drive System

7.2.2 CONTROL, MONITORING, ALARM, AND SAFETY SYSTEMS

Wind-assisted propulsion systems should be equipped with control, monitoring, alarm, and safety systems as appropriate for safe and effective operation.

7.3 SHIP DESIGN AND MODIFICATIONS

Depending on the type of wind-assisted system installed, the ship design and potential modifications should consider the following factors as applicable:

- Ship structure supporting the wind assist
- Navigational safety such as bridge visibility, radar blind sector and navigation lighting
- Ship stability and maneuverability
- Layout of anchoring and mooring equipment
- Electric power availability
- Impact on the operability of deck equipment such as deck cranes

7.4 REGULATION REQUIREMENTS

There are currently no international regulations specifically governing the manufacturing, installation and operation of wind-assisted propulsion systems.

ABS has published the *Guide for Wind Assisted Propulsion System Installation* addressing the requirements for the system and shipboard installation.

IMO has recognized wind-assisted propulsion technology and its potential impact on energy savings and has included the effects of wind propulsion into the Energy Efficiency Design Index (EEDI) calculation in MEPC.1/Circ. 815, in which wind-assisted propulsion is considered a method of reducing the main engine power requirement.

7.5 CREW TRAINING

For vessels with wind propulsion systems installed, crews should be trained to operate the equipment and resolve any issues that arise. Guidance documents such as operation manuals should be in place for use by the crew, and they could include information on:

- A chain of command with general responsibilities during normal operation
- All relevant operational conditions and the operational window of the wind assisted propulsion systems, including measures for emergency shut-off
- Measures for vessel maneuvering, including the operational limits of the system and measures required under extreme conditions
- Operational limitations for each mode of operation and for each change in mode of operation
- Procedure for emergency shutdown of the wind-assisted propulsion system
- Procedures to change the wind-assisted propulsion system from normal operation mode to preservation mode in case of control system failure
- Procedures for restoring the wind-assisted propulsion system after power failure or emergency shutdown

7.6 SAFETY

Installation and operation may create hazards that should be identified and mitigated by appropriate design, construction and adherence to operational procedures. At a minimum the following should be considered:

- Crew Safety – Measures should be taken to protect the crew from the potential hazards from moving and rotating parts of the wind-assisted propulsion system.
- Fire Safety - Fire protection arrangements should be examined to satisfy the regulatory safety requirements.
- Lightning Protection - Wind-assisted propulsion systems should have systems in place along with operational procedures to be protected from lightning.
- Navigation Safety - Navigation safety should be considered when operating a vessel with wind-assisted propulsion systems installed.
- Bridge Visibility - It should be demonstrated that the vessel with the wind-assisted propulsion system deployed satisfies the bridge visibility requirement under all operating situations. Where compliance is impractical, alternatives may be considered subject to the agreement of the relevant authority.
- Radar Blind Sector - It should be demonstrated that the radar blind sector requirement is compliant.
- Navigation Light - The installation of wind-assisted propulsion systems should not block navigation lights and are to comply with regulations.
- Where a helicopter deck is fitted on the vessel, the installation of the wind-assisted propulsion system is to be in accordance with the obstruction, marking and lighting requirements of a helicopter deck.

8 SOLAR

Developments in solar-module 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, but the use of photovoltaic (PV) solar technology in larger ships is slowly gaining consideration and is seen as one of the viable pathways to reducing the GHG contribution from shipping. This section provides an overview of the current and emerging solar technologies and other related topics.

8.1 CURRENT APPLICATIONS

8.1.1 CHARACTERISTICS

PV cells consist of one or two layers of a semi-conducting material, usually silicon. When light is projected onto the cell, an electric field is created across the layers that produces a measurable DC voltage. The greater the intensity of the light, the greater the DC voltage available. PV cells are often referred to in terms of the amount of energy they convert in full sunlight conditions, known as kilowatt peak or kWp. The solar cell is the basic building block of Solar PV technology. Cells are wired together to form a module (PV Solar Panel). PV Modules can be joined together to form a PV Solar Panel system (see Figure 25). A power electronic converter is often interposed between the solar panel and the load to stabilize the voltage delivered from the PV Modules to the load. In some cases, the power electronic converter will perform a DC/DC conversion, in other cases the power electronic converter will be an inverter, a specialized converter that can convert DC power into AC power.

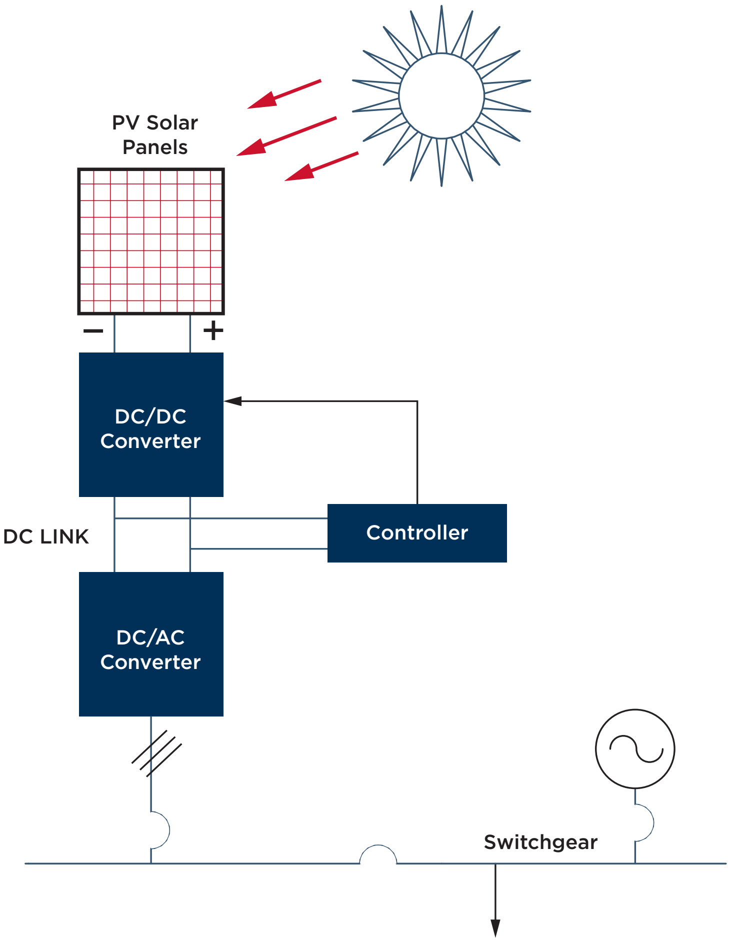


Figure 25: PV Solar Power Generation Operation [44]

Large-scale solar panel installations on vessels have been primarily on yachts and sailing boats to cover small 'hotel' loads, lighting and instrumentation equipment. The standard power production from a PV system is 100-200 watts per square meter, but technologies are becoming available to improve this rate. For large commercial vessels there have been a few installations, which were technically similar. Due to the power loads required by commercial vessels, solar systems need to cover larger areas. As a result of the physical constraints of the conversion apparatus, solar power on larger ships has been limited to assisting power plants (gensets), feed loads during harbor operations and short voyages.

Some examples of recent solar adoption include:

- **AURIGA LEADER:** A hybrid car carrier with solar power generating 0.05% of the propulsion power and 1% of its electrical usage (see picture below)
- **EMERALD ACE:** A hybrid car carrier with solar panels and 2.2 MWh of lithium-ion batteries, enabling generator-free port stays
- **PLANET SOLAR:** A solar-powered 31 m yacht equipped with 93 kW of solar panels (537 m^2) and 8.5 tons of lithium batteries. It circumnavigated the globe in 2012
- **BLUE STAR DELOS:** A ferry with a solar panel array used to investigate viability
- **PANAMANA:** A general cargo/container carrier with 2x70 MT gantry cranes. The equipment installed on the ship includes hybrid battery pack, battery charging equipment, flexible marine-grade PV panels with special mounting frames and a computer automation and management system [45].

Image courtesy of NYK Line

Figure 26: M/V Auriga Leader

8.1.2 STATE-OF-THE-ART

PV Technology for Marine Applications

Some of the most recent PV panels developed and available in the market are those made using mono-crystalline cells, with polymers of high strength. These PV solar panels are specified to withstand harsh conditions at sea, and they have been used in small vessels (e.g. pleasure craft) and in larger vessels such as ocean-going passenger ferries and cargo ships.

Future Research or Challenges for Applications

The application of PV solar technology on commercial ships has challenges related to the marine environment, including:

- The regions of operation are likely to be limited to areas where solar energy is optimal. However, PV tracking technology is extensively used for land applications and could be adopted to enhance the performance of solar energy systems on vessels.
- Adverse environmental conditions such as humidity, shading, corrosion problems (including salt deposits on the panels) and wind are issues faced by PV system technology. The limited deck space for PV arrangements on most ships keeps the potential aggregate power output low (average ~150W/m^2), even with the technology's latest advances. At present, this confines its suitability to smaller vessels [46].
- PV systems offer a comparatively low power contribution. Due to the low power output of present solar energy technology, the installation of PV cells would require the integration of storage systems to improve availability, potentially compounding space restraints and adding weight.

8.2 SUPPORT EQUIPMENT AND SYSTEMS

8.2.1 COMMON

There are key components to a marine solar panel system:

- Solar Panels
- Charging Control System
- Inverter/Converter
- Electric Cable Wiring
- Battery Pack
- Energy Storage System

In general, the installations follow a common principle, when sunlight hits a vessel's solar panels, electricity is generated. A battery pack stores the energy generated which can be used it to support the vessel's electric power needs. Most marine solar panel systems possess charging controllers to prevent the batteries from receiving higher voltage than they are capable of handling – without charge controllers, there is a risk of overcharging and damaging the battery pack. Depending on the types of appliances onboard, an inverter to convert DC into AC may be needed, as well as energy storage systems.

8.3 SHIP DESIGN AND MODIFICATIONS

8.3.1 GENERAL ARRANGEMENT

Solar panels are applicable to all types of vessels operating in areas with sunlight. To produce electricity from solar panels, a large area for installation is required and therefore only ships with ample free deck space can utilize the system (e.g. car carriers). In order for solar panels to work onboard ships and in a relatively harsh environment, they have to be more robust than land-based panels. The solar panels are intended to supplement the diesel generators and reduce their power requirements. The solar power units can produce energy both at sea and in port, but only during daylight and therefore only about 50% of the time. Solar panels can produce power in cloudy conditions, though at a lesser capacity.

8.3.2 RETROFIT OPTIONS

Solar power systems can be used to supplement traditional gensets with a variety of energy storage and power generation components such as Lithium-ion (Li-ion) batteries, supercapacitors, fuel cells, and wind power. Recent technologies considered include a hybrid design incorporating renewable sources e.g. solar as power augmentation for ships.

8.4 REGULATORY REQUIREMENTS

The International Electrotechnical Commission (IEC) has developed a standard for system design and performance of stand-alone photovoltaic systems (IEC 62124 Ed. 1.0 b:2004, Photovoltaic (PV) standalone systems - design verification). The performance test consists of a check of the functionality, the autonomy and ability to recover after periods of low charge of the battery and gives reasonable assurance that the system will not fail prematurely. The testing conditions are intended to represent the majority of climatic zones for which these systems are designed. The impact of the marine environment on the solar panels and aluminum frames requires further study including determining how frequently the marine solar panel array should be cleaned and maintained.

8.5 CREW TRAINING

The inspection and maintenance of installations onboard a ship should be carried out only by experienced personnel, whose training has included instruction on the solar panel of protection and installation practices, the requirements of this standard, the relevant national regulations/company rules applicable to the installation and on the general principles of PV classification. Appropriate continuing education or training must be undertaken by personnel on a regular basis.

8.6 SAFETY

Prior to the installation of a solar system it should be confirmed the system meets engineering and safety standards. After installation of the solar panels and prior to being energized, a system inspection is often required to ensure operation properly according to the manufacturer's instruction. The added weight of the PV solar modules and support structure on vessel stability must be accounted for in the design stages, especially for smaller vessels.

9 BATTERIES

Energy storage is the central point of an electrified power generation system and as such, battery technology is a driver of electrification of modern vessels. Batteries store and convert electrochemical energy into electrical energy and they can be designed and optimized for any specific application. Their chemistry types include lead-acid (PbA), nickel-metal hydride (NiMH), and lithium-ion (Li-ion). This section provides an overview of the current and emerging battery technologies, and other application related topics.

9.1 CURRENT APPLICATIONS

A battery cell is the basic battery unit; a battery pack comprises multiple cells. Many electrical devices require higher voltage than the basic cell voltage to operate. For example, the speed of a DC electric motor, powered directly by a battery, is approximately proportional to the battery voltage. Many electronic devices require battery voltages in excess of certain minimum values for the electronics to function. Cells can be arranged in series to generate higher voltage and higher power, as the battery pack voltage is simply the sum of individual cell voltages. Cells can also be arranged in parallel, in order to generate higher current and power. The stored energy, voltage, and lifetime of a battery are dependent on the current or power extracted from the battery. Adding more cells in parallel increases the energy, voltage, and lifetime for a given power output.

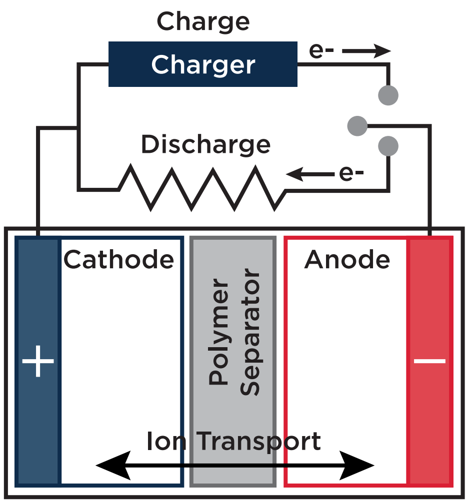


Figure 27: Schematic Representation of Li-Ion Battery Cell

9.1.1 STATE-OF-THE-ART

Modern battery technologies employ a wide range of chemical composition which directly affects their energy and power density. The key parameters for comparison of different battery technologies are (i) energy density, (ii) power density, (iii) cycle life, (iv) calendar life, (v) and the cost per unit energy stored (kWh) [47]. Volume and safety should also be considered, and to a lesser extent energy efficiency and self-discharge. Each battery type is designed based on a trade-off between energy density and power density [48]. These trade-offs vary greatly between the different technologies.

PERFORMANCE PARAMETERS: The critical parameters when selecting a battery for marine applications are the (i) cell voltage, (ii) specific energy, (iii) cycle life, (iv) specific power, and (v) self-discharge.

The **cell voltage** is a function of the chemical reaction within the battery and can vary significantly with the state of charge (SOC), age, temperature, and charge or discharge rate. The rated voltage of a battery cell is the average voltage over a full discharge cycle. Operation at high voltage can result in significantly reduced battery lifetime. Similarly, operation at a low voltage can result in cell failure.

The **specific energy** of a battery is a measure of the stored energy per unit weight. Li-ion has the highest energy density among different chemistry types. The specific energy of the Li-ion battery is approximately 3-5 times higher than that of the lead-acid battery.

Cycle life is a measure of the number of times a battery can be charged or discharged before it reaches the end of its life. Electrochemical batteries degrade with time and usage. Factors such as temperature and cell voltage also play a critical role. Li-ion has the highest cycle life and NiMH is similar. Lead-acid batteries have a significantly shorter lifetime. Lithium-titanate (LiT), a variation of lithium battery, eliminates the aging problem of Li-ion. Although LiT has a lower cell voltage and specific energy, the considerable increase in cycle life makes this battery type an attractive option for electric and hybrid propulsion systems.

Specific power is a measure of the discharge power available from a battery pack per unit weight. Lead-acid traditionally has had a high specific power and is used as the starter battery for different applications. Newer batteries, such as the Li-ion and NiMH have comparable specific power ratings.

Electrochemical cells consume energy even when they are not being charged or discharged. This energy use is a parasitic loss of stored energy and is termed **self-discharge**. The self-discharge rates can increase significantly with temperature. The self-discharge for Li-ion batteries is less than 2%, but the overall self-discharge of a battery pack can be closer to 5% due to draw of the electronic system and circuits managing the pack.

LIFETIME AND SIZING CONSIDERATIONS: Unlike many electrical and electronic devices, an electrochemical battery can have a relatively short lifetime depending on its chemistry. Marine batteries should be designed for a 10- to 20-year lifetime to match the lifespan of a vessel, which can be a challenge for battery manufacturers. Electrochemical devices, such as batteries, fuel cells, and electrolytic capacitors can degrade relatively fast as they age, especially with increased usage. In recent years, the market has shifted from relatively short-life lead-acid batteries to longer-life NiMH and Li-ion batteries. Predicting the lifespan of a battery is a complex task but the key factors affecting it are voltage, temperature, and time.

High voltage can result in breakdown of the electrolyte, increased effects of impurities, and accelerated loss of lithium from the electrodes, all of which increase the resistance reduce the storage capacity, and consequently reduce the lifetime. Lower cell voltage can increase the battery lifetime, but it also reduces the energy storage within the cell, which creates a trade-off for optimum battery use.

Operation at high temperatures can significantly reduce the lifetime and reliability of a battery, therefore it is important to implement thermal management techniques for preserving the battery packs. Operation at very low temperatures can also be a problem for some battery technologies because the electrolyte can become more viscous and have decreased conductivity. Freezing of Li-ion cells at temperatures less than -10° C reduces the amount of power and stored energy available from a battery. For this reason, manufacturers offer battery heaters for colder climates to ensure adequate performance. Ideally, the battery is heated when charged from the grid so that energy is saved for vessel propulsion at sea.

One of the biggest design challenges is the development of batteries with lifetimes comparable to that of a vessel. Factors such as voltage, temperature, and cycles affect its lifetime as discussed above. As the battery ages, there is also a reduction in the lithium available as the active materials. A lower state of charge results in lower cell voltage, which slows the degradation of the electrolyte and the loss of active lithium.

9.1.2 RESEARCH AND FUTURE DEVELOPMENT

Li-ion batteries are currently the most attractive and promising technology for hybrid and fully electric power generation systems. Therefore, much research and development are focused on improving this technology. The Li-ion technology is relatively mature, but the focus now is on developing silicon anodes, identifying new cathode materials, and improving the electrolytes used. Further efforts are also put towards recycling of batteries, advanced manufacturing, and understanding and mitigating safety issues.

Modern characterization techniques enable sophisticated analysis and understanding of the fundamentals of battery operation, which has sparked the recent advances in battery technology. The so-called “beyond Li-ion” systems have been the focus of much research in recent years. The ideas for many of these projects are established, such as lithium metal batteries with sulfur cathodes, or sodium-ion, solid state batteries, or multivalent chemistries. The significant advances in battery science during the last three decades have enabled a fresh look into these systems.

9.2 SUPPORT EQUIPMENT AND SYSTEMS

9.2.1 BATTERY MANAGEMENT SYSTEM

Battery management systems perform two primary functions. The first is to monitor the battery to determine its state of charge, state of health (ability to deliver its specified output), and the remaining useful life. These parameters are critical for optimizing the charge and discharge cycles and are communicated to the onboard diagnostics system [49]. The second function is to operate the battery in a safe, efficient, and non-damaging manner. Battery stacks are composed of cells configured in parallel or series to meet specific needs. The cell characteristics may slightly vary; therefore, it is necessary to balance the charge between cells to prevent damage and increase the lifetime of the stack.

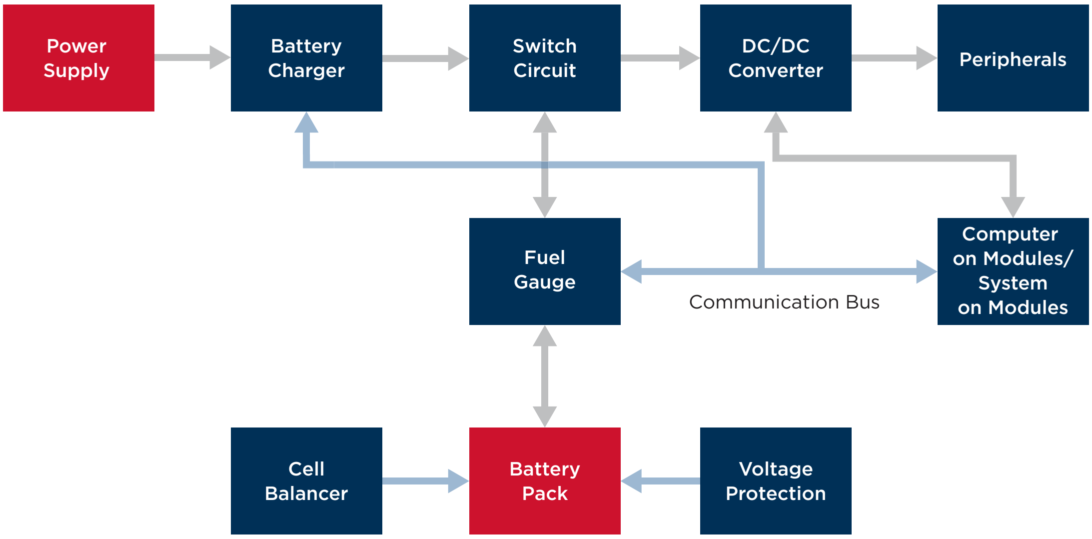


Figure 28: General Battery Management System Overview

Future batteries will rely on active cell balancing [50]. This technique involves current and voltage monitoring in each cell, as well as temperature monitoring at multiple points to ensure that all cells are operating within their design conditions. Active cell balancing offers longer lifetime, increased safety, and higher power capability for a relatively small cost increase. It is particularly important for Li-ion batteries since they are expensive and prone to damage which presents a fire risk. Advanced battery management systems can significantly improve the efficiency and lifetime of batteries, therefore are critical for electrified power generation systems.

9.2.2 BATTERY THERMAL MANAGEMENT SYSTEM

Li-ion batteries are widely used for transportation applications and will be used in marine power generation systems in the future. They have high energy density and long cycle life, but their performance and life are strongly dependent on temperature. Temperature control is achieved through dedicated battery thermal management systems (BTMS), which minimize temperature gradients and avoid any adverse effects. The most important function of a BTMS is to maintain the optimal operating temperature range and a uniform temperature distribution within the cell, module and pack at high charge/discharge rates and extreme external environmental conditions [51]. The BTMS should provide cooling to remove heat from the battery, heating to increase the battery temperature when needed, insulation to prevent rapid temperature changes, and methods to vent any potentially hazardous gases produced by the battery [52]. In addition, the BTMS should be compact, light, have low cost, high reliability, low maintenance needs, low parasitic power use, and possess simple packaging so that it can be fitted to marine applications. However, the temperature rise due to heat generation seems to be the most important issue and present challenges for designers of battery systems. Therefore, the cooling function of the BTMS is essential to the operation of the battery.

Battery cooling systems can be classified according to different attributes: (i) the cooling medium, such as air, liquid, or phase change material; (ii) the power consumption, either passive cooling that utilizes the ambient environment or active cooling using an energy source that provides cooling; (iii) contact between the cooling medium and the battery, either direct or indirect; and (iv) the thermal cycle, either using vapor compression or not [53]. BTMS with a vapor compression cycle have been primarily used in automotive applications because they can utilize the existing climate control system to cool or heat the battery.

BTMS without vapor compression cycles have not been widely used, but they have potential for high thermal performance with limited energy consumption. Cooling systems with phase change materials have the ability to absorb large amounts of heat from the battery at roughly constant temperatures through a phase change process (latent heat) with little or no energy consumption. However, these systems suffer from the low thermal conductivity of the phase change material, the continuous battery heat load after the completion of the phase change, leakage, and heterogeneity of the whole module in continuous phase change cycles. Cooling systems that use heat pipes can transfer heat more efficiently due to the higher thermal conductivity of the heat pipe than the phase change materials, but they necessitate the use of a cooling plate because of the limited contact area with the battery. Cooling systems with thermoelectric elements can control the temperature of the battery precisely by controlling the amount and direction of the current. However, they have very low efficiency and thus have received limited attention.

9.2.3 ELECTRIC MOTORS

Electric motors are well-established in marine applications and serve multiple roles on a vessel. They have an electrical conversion efficiency between 70% and 95%, and high torque and power density. Moreover, it is possible to use electric motors as generators to recover energy (e.g. shaft generator). Furthermore, electric motors are robust and reliable with reasonable cost. However, their efficiency varies with torque and speed – higher at high torque and low speed.

DC motors have a simple design and low cost due to their simple control electronics. However, they require regular maintenance due to the presence of commutators and brushes, which come in contact and are prone to wear. AC motors require complicated and costly power electronics, including an inverter as the power source to provide DC current, increasing their overall cost. Their advantages are higher power density and higher efficiency, which maximizes the range for a given battery capacity.

Three main types of AC motors have been used for transportation applications: induction, switched reluctance and permanent magnet (PM) brushless motors. Induction motors are low cost, reliable, and free from maintenance compared to DC motors, but they require dedicated control systems. Switched reluctance motors have high potential because of their simple construction and low manufacturing cost. However, their control and design are complex, and acoustic noise problems still need to be resolved. Finally, with the improvement of permanent magnet materials, PM motors have become attractive. They offer high efficiency, high power density and good reliability. However, their cost remains high due to the permanent magnetic materials. They are primarily suited for low-power applications. Future possible improvements of current electric motors include reduction in the cost of high temperature permanent magnets, the development of controllers for safer operation of subsystems, and decrease in the number of sensors in the motors [54].

9.2.4 POWER ELECTRONICS

Power electronics represent an important share of the total cost of an electrified power generation system, almost as important as the battery on a unit power basis [55]. As such, they have high potential for cost reduction. Power electronics are the link between the battery, a DC current source, and the AC motor. They include DC/AC inverters, which control the voltage output through switching devices. Control algorithms specific to each motor type ensure they operate at the highest efficiency. The efficiency of power electronics is typically between 95% and 98%. In recent years, the performance of semiconductor switching devices has significantly improved with associated improvements in cost and reliability.

Magnetic components and capacitors have progressed as well and now can be used in high frequency power electronics. Components such as diodes and switches must be resistant to both high temperatures and vibration. Inverters can be simplified and, ideally, integrate electromagnetic interference filters as well as being fault tolerant. The main challenge remains the development of higher resistance to heat (or improved cooling systems) and the reduction in the number of devices to reduce space requirements.

9.3 SHIP DESIGN AND MODIFICATIONS

9.3.1 GENERAL ARRANGEMENT

The vessel will require a dedicated location and space for the batteries. This space will be isolated from other machinery and equipment to address the proper precautions, such as fire safety, ventilation, and control accessibility. The ABS *Guide for Use of Lithium Batteries in The Marine and Offshore Industries* provides requirements and reference standards for the effective installation and operation of lithium battery systems for owners, operators, shipyards, designers, and manufacturers.

The location and application of battery spaces also influence the hazardous areas of the vessel. Depending on the battery design and chemistry, flammable gases may be released in abnormal operations. This may require the designation of hazardous areas and will affect the vessel design, installed electrical equipment, access points, and ventilation.

9.3.2 RETROFIT OPTIONS

Providing a dedicated internal space may be more challenging in retrofit applications. Batteries and supporting equipment can be arranged in containers to provide equivalent separation to a dedicated space.

9.4 REGULATORY REQUIREMENTS

Currently, the IEC and UL have developed standards (IEC 62619, IEC 62620, UL 1642, etc.) for lithium batteries addressing the requirements for cell construction and established testing requirements for the use in industrial applications.

Lithium batteries and lithium metal batteries are listed in the IMO International Maritime Dangerous Goods (IMDG) Dangerous Goods List (DGL) under the Class 9 Miscellaneous Dangerous Goods label. Special Provision 188 has 8 specific requirements for lithium batteries:

- SP 188.1/2 Lithium Content/Watt Hour Rating
- SP 188.3 Battery/Cell Test
- SP 188.4 Package
- SP 188.5 When Installed in Equipment
- SP 188.6 Package Marking
- SP 188.7 Package Drop Test
- SP 188.8 Package Gross Mass

There is scant literature that specifically regulates the design, construction and installation of lithium batteries for marine applications. ABS published the *Guide for Use of Lithium Batteries in the Marine and Offshore Industries* to address these gaps. This Guide refers to several standards and other references, such as those by the IEC, UL, and found in the IMDG.

9.5 CREW TRAINING

Crews should be trained to operate and maintain the energy storage system (ESS) installed. The Operation and Maintenance Manual and detailed firefighting procedures are to be kept onboard for easy reference by the crews.

9.6 SAFETY

Fires are a major risk on marine vessels. With the advent of hybrid electric power generation systems, fires originating in the battery system need to be understood and prevented. The risk and hazard of battery fires associated with the battery cell and power system are closely related to the size and capacity of the battery pack.

Li-ion battery packs are the most susceptible to fires due to their high energy density and high charge and discharge rates, which is what makes them suitable for marine power generation applications. A Li-ion battery that is operated at extreme conditions and exposed to impact can rupture, spark, and emit toxic and flammable gases, which can be ignited to sustain a steady combustion [56]. Although regular battery systems have a low probability of self-ignition, they are vulnerable to external thermal, mechanical, and electrical impacts that may occur during extreme operating conditions or incidents [57].

THERMAL IMPACT: Marine hybrid electric power generation systems are expected to be used in the same way as conventional internal combustion engines, in extreme hot and cold environments. Extreme hot or cold temperatures have an adverse effect on the battery performance and lifespan. In addition, high temperature conditions may cause some unwanted chemical reactions in the battery and lead to overheating [58]. In cases of poor thermal dissipation, overheating can trigger thermal runaway which can lead to battery fire. Thermal runaway is a widely observed phenomenon referring to an overheating event in which exothermic chain reactions take place and overcome the cooling function of the battery pack [59]. In Li-ion batteries, thermal runaway is manifested through a dramatically increasing battery temperature (greater than 10° C/min) or the activation of the safety vent, which indicates that exothermic thermochemical and electrochemical reactions have been triggered. Battery thermal runaway is usually accompanied by a large amount of dark smoke, hot sparks, and visible flames [60].

MECHANICAL IMPACT: Most commercial Li-ion battery cells are relatively fragile without the protection of the battery module and pack enclosure. Therefore, it is important that they be located in areas that minimize the risk of mechanical damage.

ELECTRICAL ABUSE: Fast charging and discharging combined with the high performance of hybrid electric power systems can increase the fire risk. Li-ion batteries are designed to receive and store a specific amount of energy in a specific amount of time. Exceeding these limits, which may be a result of rapid charging or overcharging, may degrade their performance or result in permanent failure. Electrical abuse is usually accompanied by Joule heating, which generates heat, and internal chemical reactions, which may lead to internal short-circuit. Appropriate design of the battery management system should mitigate these risks. Besides the failure of battery cells, fire incidents can be caused by poor design and manufacturing of electronic control systems, battery management systems, and power transmission control systems.

10 SUPERCAPACITORS

Supercapacitors (also "ultracapacitors"), or to be technically correct, electronic double layer capacitors (EDLC), form a subset of the general category of electrochemical energy storage devices, specifically electrochemical capacitors (ECs). To clarify any concerns over name or nomenclature, the term ultracapacitor is a more colloquial term for the symmetric, carbon-carbon, EC. "Supercapacitor" was the original name given to this class of extremely highly specific capacitance devices, but since NEC Tokin trademarked that name in 1975, during the early days of EDLC development, it has been replaced with ultracapacitor in general usage. Even today the term supercapacitor continues to be used for the class of asymmetric, or carbon-metal oxide, ECs [61]. This section provides an overview of the current and emerging supercapacitor technologies and application related topics.

10.1 CURRENT APPLICATIONS

The commercial use of capacitors for energy storage is a relatively new concept made possible by the development of the EDLC. The EDLC is an electrochemical capacitor commonly referred to as a supercapacitor or ultracapacitor. Another type of capacitor that is often associated with the supercapacitor is the lithium-ion capacitor (LIC) [62].

An EDLC is constructed of two electrodes surrounded by a common electrolyte as shown in Figure 29 below. Essentially, the EDLC consists of two capacitors in series separated by an ion-permeable membrane, where each of the capacitors is constructed of a polarized electrode and opposite-polarity ions in the electrolyte. As is often the case, both electrodes are constructed of the same material and consequently, the EDLC is known as a symmetrical capacitor.

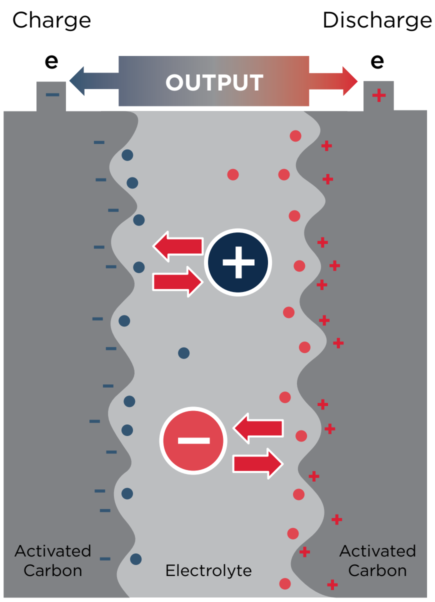


Figure 29: EDLC Construction

An LIC is constructed of two electrodes surrounded by a common electrolyte as shown in Figure 30, below. The LIC is a hybrid electrical energy storage device, which combines the EDLC's cathode and a lithium-ion battery's anode. The LIC maintains the EDLC's advantages in conjunction with lithium-ion battery's features, e.g. high energy density. In the case of a LIC, the two electrodes differ in material and construction. LICs are also known as asymmetrical capacitors.

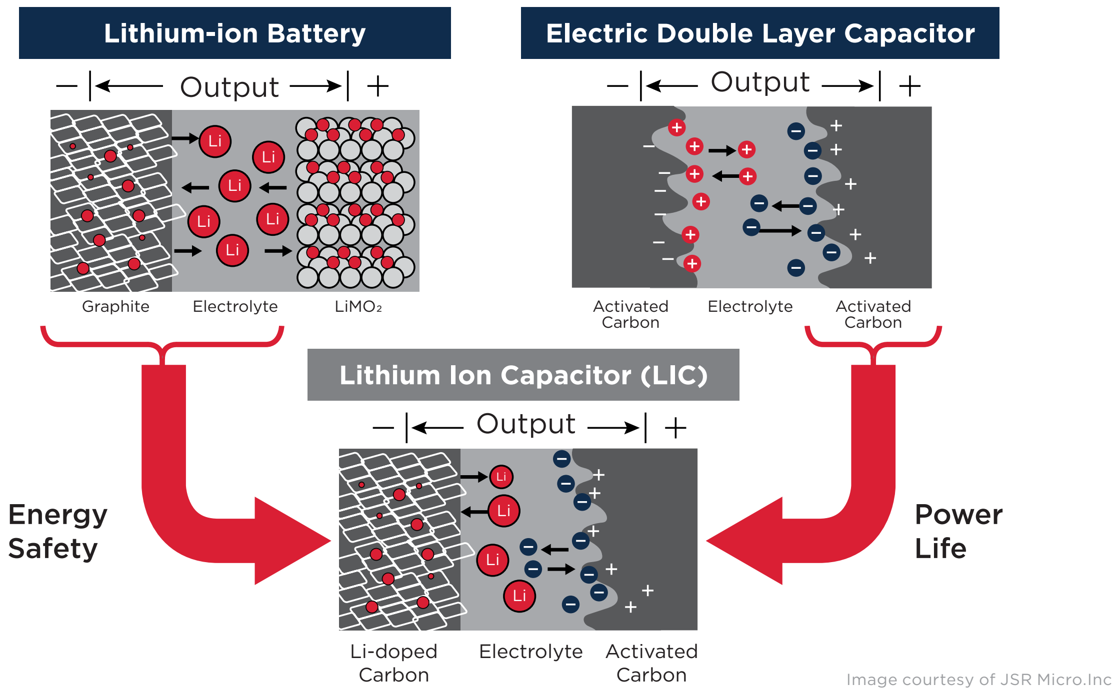


Figure 30: Lithium-Ion Capacitor Construction

10.1.1 CHARACTERISTICS

A supercapacitor is a high power density, non-chemical reaction based, electric energy storage device.

10.1.2 CONSTRUCTION

Supercapacitors are constructed in a modular and scalable fashion. Each supercapacitor is made of elements (the basic unit), modules (combinations of elements), and packs (connected modules). These options in construction allow for flexibility to achieve the desired voltage and current characteristics.

10.1.3 CHARGE / DISCHARGE TIME

The charge and discharge time of a supercapacitor or ultracapacitor can be compared to that of any ordinary capacitor. However, high charging and discharging currents can be achieved due to the minimal internal resistance offered by the supercapacitor.

10.1.4 SPECIFIC POWER

The specific power of a supercapacitor/ultracapacitor is the highest output power divided by its total mass. Supercapacitors' specific power is known to be 10 times the specific power of batteries. This property is useful in applications where quick energy bursts are required. The trade-off is the lower relative specific energy: they can provide higher power but for shorter periods of time.

10.1.5 SAFETY AND LIFE CYCLE

Supercapacitors offer benefits relative to other energy storage systems. While batteries have thermal limitations and hazards due to excessive heating, supercapacitors are relatively cool due to their low resistance. They also offer a virtually limitless cycle life. This property is useful where energy release and storage are carried out very frequently.

10.1.6 STATE-OF-THE-ART

Supercapacitors and LICs are suitable for applications calling for a quick delivery of energy, referred to as pulsed power applications. Similar to pulsed power applications are applications where there is a need for a rapid and repeated bi-directional exchange of energy between an electrical network and a load. In pulsed power applications, capacitors are charged as quickly as possible and limited only by the capabilities of the electrical network and can quickly deliver the stored energy in a high power pulse. Charging times could be seconds or minutes, while discharge times could be micro or Nano seconds.

In bidirectional energy exchange applications, capacitors may be initially charged to some fraction of their energy storage capacity and then float on the electrical network, delivering stored energy when needed and absorbing excess or regenerative energy when available. Another application of capacitors is the delivery of stored energy to an electrical network when normal sources of power are not available. Although capacitors do not store as much energy as do batteries, they may be capable of delivering enough energy to an electrical network to allow it to ride through a temporary interruption of normal electrical power until such time as another source of electrical power may come on line to assume the load.

Currently, supercapacitors and LICs are a leading energy storage choice in applications where a fast rate of charge or discharge is required or where the required cycle life is high. Supercapacitors and LICs have excellent performance capabilities allowing for management of peak power and average power demands of power grids or to act as backups for primary energy supplies such as diesel generators, gas turbine generators or fuel cells.

10.1.7 EXAMPLE APPLICATIONS

Supercapacitors are used in different electric power system applications and in different industries such as the automotive, electronic, wind, marine and offshore industries for:

- Load-leveling
- Peak-shaving
- Transient power source
- Heave compensation
- Dynamic Breaking or the KERS (Kinetic Energy Recovery System).

In the case of KERS, the automotive industry is making use of this approach by using electrical generators that change kinetic energy into electrical energy. This electrical energy is stored in supercapacitors and is later used to supply power required for acceleration. This also can be utilized in marine vessel applications.

10.1.8 RESEARCH AND FUTURE DEVELOPMENT

The future of supercapacitors is promising, e.g. there is a plan to combine double-layered interface with existing technologies for energy storage. The addition of electrochemical capacitor to applications that run on other hybrid devices has spurred great improvements in performance of charge and discharge life cycles.

With the supercapacitors' characteristics of a nearly unlimited cycle life, immunity to thermal runaway, and symmetrical and rapid charging/discharging rates, their use is likely to increase on vessels that experience rapid changes in electrical load such as those with dynamic positioning systems, cranes, active heave compensation, or that drill, mine or pump cargo.

Other industries have demonstrated this technology in electric vehicle and hybrid applications. Several cities that use hybrid technologies for their public transit systems have seen improvements in charge cycles and energy storage mechanisms. These improvements can be adopted in the marine industry as well.

Such rapid charging and energy storage facilities have already entered the market, causing a shift in the thinking on storage capabilities.

The combination of supercapacitors and other hybrid technologies (batteries, fuel cells) shows promise as the benefits of each technology can offset the limitations of the others.

10.2 SUPPORT EQUIPMENT AND SYSTEMS

10.2.1 SUPERCAPACITOR MANAGEMENT SYSTEM

A supercapacitor management system provides operational, system monitoring and safety features to support the integration of a supercapacitor system with the vessel electrical distribution system. Its function includes balancing power between each element, module and pack. The system monitors the entire system including voltage, current, and temperature. Based on the parameters monitored, the system will have protective features to alert operators or take actions to minimize or prevent abnormal operations.

Additional protective features are usually incorporated to prevent overload and short circuit. The system also provides linkage to the vessels power management system for overall electrical system operations.

10.2.2 POWER ELECTRONICS

The super capacitor system can be connected to the vessels electrical system via multiple methods. This depends on the vessel's electrical network configuration. Since the output of the supercapacitor is DC, power electronics are used to either convert (DC to DC), or invert (DC to AC) for proper connection to the vessel's switchboards.

10.2.3 SAFETY SYSTEMS

The supercapacitor system requires safety systems to support normal operations, and to prevent abnormal operations. Linked in with capacitor management system is the need for cooling, ventilation and fire safety systems.

The supercapacitor arrangement also needs to consider the safety of onboard personnel. This includes appropriate warning labels addressing the danger of the system as well as interlocks and safety mechanisms to prevent electric shock to personnel.

10.3 SHIP DESIGN AND MODIFICATIONS

10.3.1 GENERAL ARRANGEMENTS

The vessel will require a dedicated space/location for the supercapacitors. Similar to battery applications, this provides added safety benefits by isolating the components from other machinery and equipment. A dedicated space allows proper fire safety, ventilation, and access control. Additional fire extinguishing systems should be paired with the supercapacitor based on the cell electrolyte chemistry.

The location and application of supercapacitors spaces will also have an impact on vessel hazardous areas. Depending on design and chemistry, flammable gases may be released in abnormal operations. This may require designation as a hazardous area and will have additional impact on vessel design, installed electrical equipment, access points, and ventilation.

10.3.2 RETROFIT OPTIONS

Providing a dedicated internal space may be more challenging in retrofit applications. Supercapacitors and supporting equipment can be arranged in containers or similar apparatus to provide an equivalent separation to a dedicated space.

10.4 REGULATORY REQUIREMENTS

In response to the scant literature that specifically regulates the design, construction and installation of supercapacitors, in 2018 ABS released the *Guide for the Use of Supercapacitors in the Marine and Offshore Industries*. This Guide refers to several standards and other references, such as IEC, UL 810A, NFPA 70, etc.

For transportation, United Nations UN 3499 CAPACITOR should be consulted. In many application cases, supercapacitors depending on their chemical composition, are rated non-hazardous under the OSHA hazard communication standard (29 CFR 1910.1200), since they are considered “an article” [63].

10.5 CREW TRAINING

For vessels with supercapacitors installed onboard ship, the crews should be trained to operate and maintain the ESS installed. The Operation and Maintenance Manual and detailed firefighting procedures are to be kept onboard for easy reference by the crews.

10.6 SAFETY

Though, supercapacitors do not have the same type of safety concern as Li-ion batteries regarding mechanical impact and potential explosive condition, supercapacitors may release electrolytes that may be toxic or moderately dangerous to skin absorption; therefore, care and first aid measures are to be considered for personnel safety.

11 CARBON CAPTURE

While combustion of some of the zero-carbon fuels, such as ammonia and hydrogen, do not emit CO_2, other carbon-based fuels, harvested or renewably produced, produce CO_2 in proportion to the carbon content of the fuel.

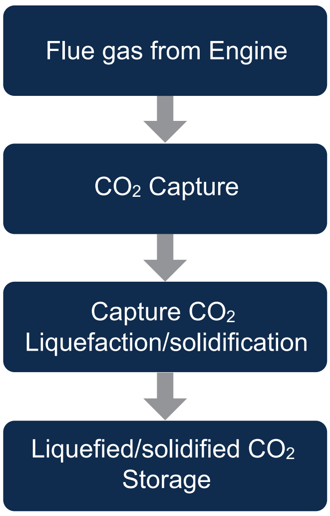
Carbon Capture and Storage (CCS) is the process of capturing waste CO_2 usually from large point sources such as power plants or cement factories and transporting it in liquid or vapor form to a storage site. The Intergovernmental Panel on Climate Change (IPCC) considers CCS an important method of reducing global CO_2 emissions. Most studies concerning carbon capture focus on onshore power plants using fossil fuels such as coal and natural gas. CCS may be a method for reducing carbon emissions from vessels. CCS for shipboard application refers to a set of technologies that can be used to remove CO_2 from vessel exhaust gas and store it for subsequent disposal or use.

11.1 CURRENT APPLICATIONS

Over the last 20 years many research groups around the world have explored carbon capture technologies to increase efficiency and reduce the size and cost of the system. CO_2 has been safely transported and used in many industries for decades and can be moved by ship, truck or pipeline.

Due to its footprint, the majority of the carbon capture systems have been designed and demonstrated in electric power plants. But it is possible to deploy CCS technologies onboard vessels to capture, store and transfer CO_2 to shore for use.

There are three major types of CO_2 capture systems: post-combustion, pre-combustion, and oxyfuel combustion. Pre-combustion removes carbon from the fuel prior to combustion and oxy-fuel combustion combusts with oxygen to produce a flue gas that mainly consists of hydrogen and carbon. Consequently, the pre-combustion and oxy-fuel combustion carbon capture systems require integration into the fuel supply and power generation systems and require a total redesign. The post-combustion process captures CO_2 from flue gas produced after the combustion and therefore can be added to the conventional design with minimal alteration. Retrofit to vessels as a standalone system is relatively straightforward.



There are two steps to separate CO_2: capture and desorption/regeneration. In capture, the CO_2 is absorbed into a liquid or solid by contacting the CO_2 source with the absorber. In the desorption/regeneration step, CO_2 is selectively desorbed from the absorber, resulting in a flow of pure CO_2 gas, with the original capture absorber material regenerated for further use [64].

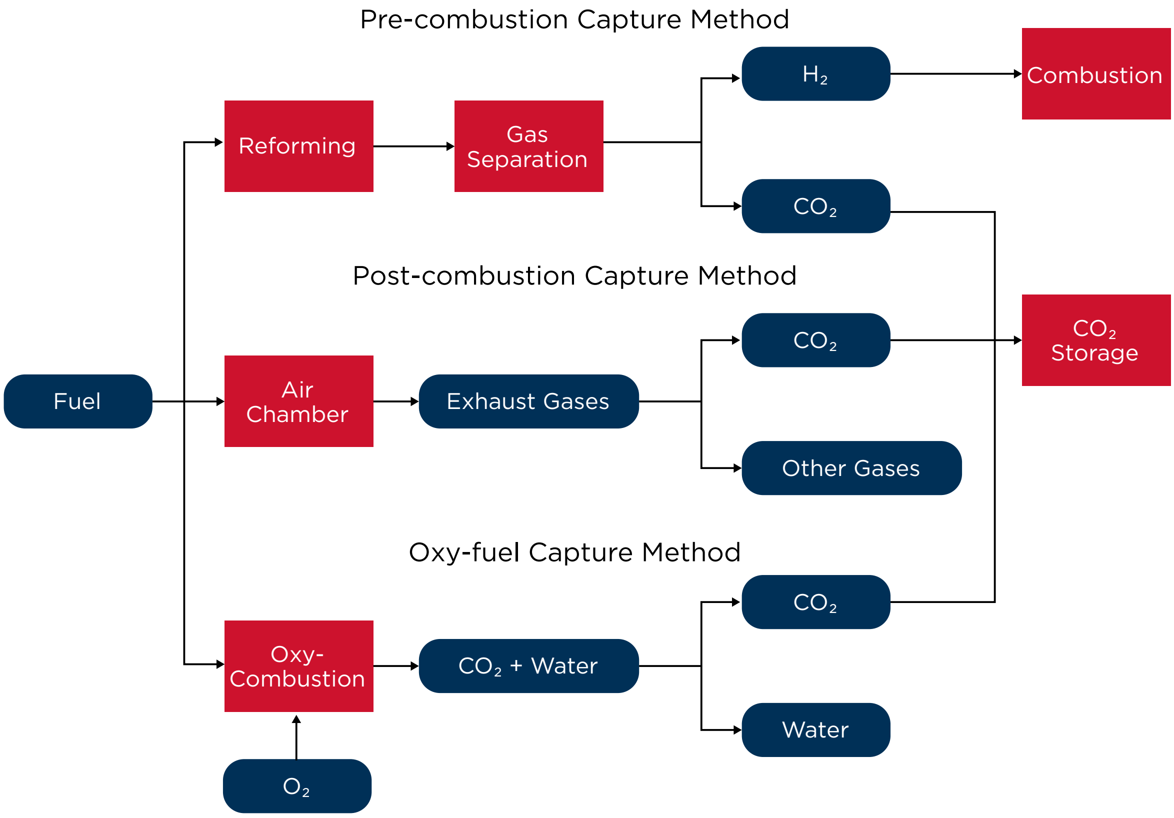


Figure 31: Three Carbon Capture Methods

The challenge in the marine environment is the handling and storage of captured CO_2. The process requires significant power to liquefy or solidify the captured CO_2 for storage. Storing CO_2 in gaseous form onboard is not a viable option due to space requirements.

CO_2 transforms from a gas to solid directly when cooled and solidifies at -78° C in ambient pressure. It can also be solidified by interaction with other chemicals [65].

To transport CO_2 in a liquid state it needs to be contained at 0.7MPa and -50° C [66]. If the liquefied CO_2 is to be stored onboard, the storage space should be considered based on the expected capture during voyage; 1 tonne of liquified CO_2 occupies slightly less than 1 m^3 volume.

11.1.1 RESEARCH AND FUTURE DEVELOPMENT

Mitsubishi Heavy Industries (MHI) recently conducted a concept study focused on installing a marine carbon capture and storage unit on a very large crude carrier [67]. The system was comprised of four towers for cooling the exhaust, absorbing CO_2, treating the exhaust, and regenerating the CO_2, in addition to the required liquefaction and storage facilities. The objective of the project was to investigate onboard production of methane or methanol by combining hydrogen from water electrolysis with the captured CO_2. MHI reported the CO_2 capture rate at about 86%, and a 20 year return due to the high CAPEX and OPEX.

The U.K.'s department for transport recently funded a project by PMW technology with an A3C carbon capture process, partnered with a naval architect company, Houlder Ltd. to study the potential for using carbon capture technology in shipping [68]. They will use their A3C carbon capture process to extract CO_2 from marine exhaust gases by freezing, then sublimating the CO_2. The CO_2 will then be liquified and stored in tanks onboard the ship.

Presently, carbon capture technology faces technical and economic challenges for marine application. However, it still has potential to be an effective method of reducing GHG emissions for future vessels, especially in conjunction with low-carbon fuels. Further technical advances are expected to reduce the scale, cost and complexity of the carbon capture technology.

11.2 REGULATION REQUIREMENTS

In general, regulations and policies for carbon capture are mostly in development, with Europe being a notable early adopter. The European Union's carbon capture directive on Geological Storage of Carbon Dioxide came into force in 2009, providing regulatory requirements for storage.

The U.K. Department of Energy and Climate Change also has projects in motion to support the relatively new technologies and in the U.S. the Environmental Protective Agency (EPA) is working on developing regulations to track national carbon capture activity and ensure safe practice.

12 HYBRID AND COMBINED SYSTEMS

The IMO GHG regulations and global energy security concerns have spurred the introduction of electrified power generation and propulsion systems in marine vessels. Electrified power generation offers certain benefits such as high efficiency, reduction or even elimination of local emissions, high power, and a reduction of noise and vibration. However, electrified vessels also face significant challenges, such as the long charging time and cost of batteries, lack of charging infrastructure at ports, and the resource depletion of certain battery materials. The impact of charging electrified vessels from the grid is largely unknown and market acceptance is also a hurdle for adoption. Nevertheless, electrified vessels have a high potential for technological improvement, which has drawn the attention of equipment manufacturers and regulatory bodies.

Hybrid electric power systems provide opportunities to utilize different energy storage and power generation components. Lithium-ion batteries, supercapacitors, flywheel energy storage, fuel cells, solar and wind power can be used to supplement or in some cases replace traditional gensets over varying operational scenarios such as at sea, during maneuvering, and docking. This diversity of available electric power sources helps to improve operational flexibility and reliability by selectively using generators as needed and operating them at their efficient load points. For example, vessels engaged in long, low power transits such as a river or a canal passage require multiple generators to run in parallel for reliability purposes. The use of the appropriate energy storage system can reduce generator reliance by using the battery to prevent a loss of power. Energy storage technologies can offer a similar function in vessels during dynamic positioning and cable/pipe laying operations. Other uses of energy storage are load leveling such as active heave compensation of drilling derricks and crane systems.

12.0.1 OPTIMIZATION OF POWER CONSUMPTION

The inclusion of alternate power generation and energy storage technologies allows a minimum number of generators to be run thus offering the opportunity to optimize the number and the operating points of generators for different operating scenarios. Maintenance costs can be reduced according to the operating hours of equipment as well as by limiting the start/stop cycles of certain components.

12.0.2 EFFICIENCY IMPROVEMENT AND EMISSIONS REDUCTION

Hybrid electric power systems can improve the fuel economy and reduce the emissions of a vessel by several critical factors: (i) the energy storage devices and electric motors enable the selective use of the internal combustion engines on the vessel, which directly reduces the emissions and carbon footprint of the vessel; (ii) since power is generated from electric motors, the operating points of the engine can be optimized for minimum fuel consumption and emissions; (iii) the addition of the energy storage devices and electric motors enables the downsizing of the engines onboard; and (iv) the energy storage devices can offer purely electric power generation and propulsion to the vessel, which results in zero emissions operation in ports and other environmentally sensitive areas.

Hybrid-electric power systems have the potential to improve reliability, operational efficiency, fuel consumption rates, environmental footprints and maintenance costs when compared to traditional electric power systems.

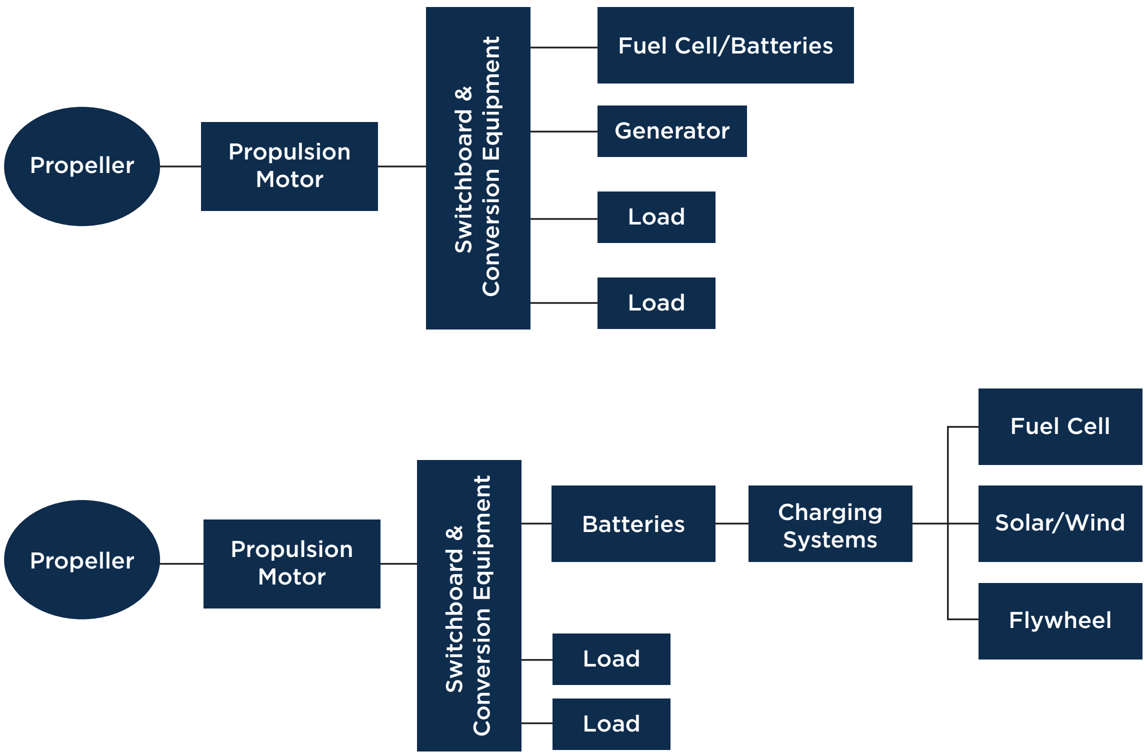


Figure 32: Example Architectures of Hybrid Electric Systems

12.1 CURRENT APPLICATIONS

12.1.1 STATE-OF-THE-ART

SEACOR Marine recently investigated the installation of a hybrid system using Li-ion batteries in its Offshore Supply Vessel *SEACOR Maya*. With its design and components tested and approved for hybrid power integration, the vessel was converted at Bollinger Shipyards in Morgan City, Louisiana and was followed by sea trials in May 2018. The hybrid power solution on *Maya* has the potential to reduce fuel consumption by as much as 20%. As a result of this performance, SEACOR Marine plans to adopt more vessels with hybrid power systems in the future. ABS provided an initial approval in principle (AiP) for the design and classification of the *SEACOR Maya*.

Harvey Gulf International Marine recently retrofitted two offshore supply vessels (OSV) with a battery/converter system in 2019 that are also powered by dual-fuel engines using LNG and MDO. *Harvey Energy* started operation in March 2015, was the first OSV in North America being powered primarily by LNG, serving Shell in its deepwater offshore operations in the Gulf of Mexico.

Harvey Gulf contracted Wärtsilä to supply an energy storage system, energy management system, transformer and drive, all mounted inside a single container for the retrofit of *Harvey Energy*. The 5,312-dwt OSV is currently powered by three Wärtsilä 6L34DF dual-fuel gensets providing 7,530 kW (10,100 hp) fueled by Wärtsilä's LNGPac system – a complete fuel gas handling system for LNG vessels. Wärtsilä's hybrid solutions are based on a 'first-of-its kind' fully integrated hybrid power module. This combines engines, an energy storage system using batteries, and power electronics optimized to work together through an innovative, Wärtsilä-developed energy management system. The solution marks a new benchmark in marine hybrid propulsion. The installation of a Wärtsilä 1,450 kW battery hybrid solution is anticipated to reduce the *Harvey Energy*'s exhaust emissions, fuel consumption, and noise level. The overall fuel cost savings are expected to be in the range of 10 to 20%, according to Harvey Gulf International Marine, LLC. It is also projected that the battery capacity will be sufficient to sail in and out of harbor on electric power with fewer engines running, while also supplementing hotel load electricity when docked, reducing noise and pollution levels while in port. Furthermore, the ability to operate on battery power will assist redundancy during critical dynamic positioning operations at the offshore platform.

Figure 33: Harvey Energy OSV

ABS was selected to provide technical reviews and survey verifications of vendor-supplied equipment and installation aboard the *Harvey Energy* and issued the ABS class notation ESS-LiBATTERY. *Harvey Energy* is one of five LNG-fueled platform supply vessels (PSVs) in operation in Harvey Gulf's fleet.

Wärtsilä recently introduced a hybrid propulsion system (Wärtsilä HY) that combines a diesel engine, batteries, a generator, and DC power electronics and can be configured in a series or parallel architecture (Figure 34). In the parallel configuration, the engine and shaft generator are both connected to the propeller through a gearbox; in the series configuration, the diesel engine is only coupled to a generator to produce electric power, without driving the propeller, which is electrically driven.

Figure 34: Wärtsilä HY System Installed in a Harbor Tug Vessel

This hybrid system was installed on a 90 tbp harbor tug in 2018 that is used for ice-breaking operations in the North Baltic Sea. Wärtsilä reported that each component of the system was designed to be hybridized, and the entire system is controlled to maximize energy efficiency, performance, lifetime, and safety, while minimizing emissions and exhaust.

The Wärtsilä HY system is marketed as a configurable integrated power module, and Wärtsilä has proposed a smart approach to the design of the system. This approach is based on (i) identification of the ship type and mission, (ii) system selection and optimization based on a balance between stationary and transient loads, (iii) initial tuning based on early data collection, and (iv) periodic monitoring and tuning during the life cycle of the vessel.

MAN ES introduced its HyProp ECO hybrid propulsion system aiming to control the power delivered to the shaft in the most efficient manner. The HyProp system can integrate four-stroke medium/high speed engines, auxiliary gensets, energy storage systems, electric motors, gearboxes and propellers using an energy management system and the associated transformers, switchboards, and variable speed drives. Based on data from MAN, the HyProp system can reduce fuel oil consumption by up to 15% (MAN, 2018).

12.1.2 RESEARCH AND DEVELOPMENT

The market for marine hybrid power generation and propulsion systems is expected to reach $7.5 bn by 2027 (Transparency Market Research), driven by the IMO regulations for GHG reduction. Therefore, manufacturers are expected to invest in research and development of hybrid systems to extend their applications to tugboats, offshore support vessels, ferries, military vessels, yachts, and cruise ships. Hybrid systems will vary in size and power output depending on the application, ranging from 150 to 4,000 kW.

Research and development efforts associated with hybrid systems are focused on their key components: energy storage systems (batteries and supercapacitors), electric motors, and power electronics.

Li-ion batteries are currently the most attractive and promising technology for hybrid and fully electric power generation systems. Therefore, many research and development efforts are focused on improving this technology. The Li-ion chemistry is fairly mature, but research is needed to develop silicon anodes, identify new cathode materials, and improve the electrolytes used. Additionally, efforts are also needed for recycling of batteries, advanced manufacturing, and understanding and mitigating safety issues.

Future possible improvements of current electric motors include reduction in the cost of high temperature permanent magnets, the development of controllers for safer operation of subsystems, and reduction in the number of sensors in the motors.

In recent years, the performance of semiconductor switching devices has significantly improved with associated improvements in cost and reliability. Magnetic components and capacitors have progressed as well, and now can be used in high-frequency power electronics. Components such as diodes and switches need to be resistant to both high temperature and high levels of vibrations. Inverters can be simplified and, ideally, integrate electromagnetic interference filters as well as being fault tolerant. The main challenge remains the development of higher resistance to heat or better cooling systems and size reductions so that they can be more space efficient.

12.2 SUPPORTING EQUIPMENT

12.2.1 COMMON - BATTERIES

Batteries can be optimized for a particular application, as their use can dictate the material selection. For example, batteries used for a purely electric propulsion system are optimized for a wide operating range, while batteries used for hybrid systems are optimized for a narrow operating range in order to maximize the number of discharge cycles.

Recent advances in Li-ion batteries have allowed the development of modern hybrid and electric propulsion systems. Lithium is the lightest metal, and the Li-ion battery has many advantages over other technologies, such as higher energy density, higher cell voltage, and longer life. A number of variations of Li-ion chemistry have been developed and used in commercial products. Early Li-ion chemistry types used cobalt and manganese as the main metals, and the choice and mix of materials can significantly influence the energy density, lifetime, safety, and cost. Manufacturers such as Panasonic, LG Chem, and AESC, among others are offering a wide range of batteries that have been used primarily in electric and hybrid propulsion systems for automobiles.

12.2.2 FUEL-SPECIFIC EQUIPMENT

Any fuel-specific equipment used in hybrid power systems is dictated by the fuels used in the internal combustion engines of the system. Current hybrid systems employ either diesel or dual-fuel diesel/LNG engines. For the diesel engines used, the fuel delivery system is similar to the conventional systems used in existing auxiliary engines. For the dual-fuel engines used, the fuel storage and supply system are similar to that of dual-fuel vessels, and includes the LNG storage, containment, and gas supply systems.

12.3 SHIP DESIGN AND MODIFICATIONS

Vessels with hybrid and combined systems will have unique designs and dedicated space for the equipment in the combined system. Please refer to other sections for specific requirements.

12.4 REGULATORY REQUIREMENTS

Please refer to specific regulatory requirements for each component of the hybrid and combined systems and the ABS *Guide for Hybrid Electric Power Systems for Marine and Offshore Applications*.

12.5 CREW TRAINING

For vessels with hybrid and combined systems installed onboard ships, the crews should be trained to operate and maintain the associated ESS installed. The Operation and Maintenance Manual and detailed firefighting procedures are to be kept onboard for easy reference by the crews.

12.6 SAFETY

Safety concerns for each individual compartment of the hybrid and combined system is discussed in the previous sections. However, in the hybrid and combined system, the safety risks can be complicated and will require a specific risk assessment to evaluate and assess.

13 ABS ROLES

ABS has developed guidance and technology requirements for many of the areas addressed in this Advisory. High-level overviews of industry issues, technologies and topics are included in ABS Advisories. Industry requirements are provided in ABS Guides and Rules. These are developed to address the safety concerns and operational requirements for evaluating the readiness of technologies for the foreseeable future.

ABS *Advisory on Exhaust Gas Scrubber Systems*

ABS *Advisory on Gas and Other Low Flashpoint Fuels*

ABS *Advisory on Hybrid Electric Power Systems*

ABS Advisory on *Marine Fuel Oil*

ABS *Advisory on NOx Tier III Compliance*

ABS *EU Monitoring Reporting and Verification of CO2 Debrief*

ABS *Guide for Direct Current (DC) Power Distribution Systems for Marine and Offshore Applications*

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

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

ABS *Guide for Wind Assisted Propulsion System Installation*

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

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

14 LIST OF ACRONYMS

ABS	American Bureau of Shipping
AC	Alternating Current
AiP	Approval in Principle
ASTM	American Society of Testing and Materials
BOG	Boil-Off Gas
BOR	Boil-Off-Rate
BTMS	Battery Thermal Management System
CAPEX	Capital Expenditure
CFR	Code of Federal Regulations
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
COGES	Combined Gas turbine Electric & Steam system
DC	Direct Current
DWT	Deadweight Tonnes
EC	Electrochemical Capacitors
EDLC	Electric Double Layer Capacitor
EGR	Exhaust Gas Recirculation
ESS	Energy Storage System
EU	European Union
GHG	Greenhouse Gas
GT	Gross Tones
HFO	Heavy Fuel Oil
HSQE	Health, Safety, Quality and Environmental
IACS	International Association of Classification Societies
IEC	International Electrotechnical Commission
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization
ISO	International Organization for Standardization
LIC	Lithium-ion Capacitor
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSHFO	Low Sulfur Heavy Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MSC	Maritime Safety Committee
MSDS	Material Safety Data Sheet
MT	Mega Tonne
MW	Mega Watt
NFPA	National Fire Protection Association
NOx	Nitrogen Oxides
NRC	Nuclear Regulatory Commission (US)
OPEX	Operating Expenditure
OSHA	Occupational Safety and Health Administration
PEM	Proton Exchange Membrane
PV	Photovoltaic
SCR	Selective Catalytic Reduction
SOLAS	International Convention for the Safety of Life at Sea
SOx	Sulfur Oxides
STaGE	Steam Turbine and Gas Engine
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
Tcf	Trillion Cubic Feet
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UR	Unified Requirements
US	United States

15 REFERENCES

1. Life Cycle GHG Emission Study on the use of LNG as Marine Fuel. Thinkstep on behalf of SEA/LNG and SGMF. April 10, 2019.
2. The climate implications of using LNG as a marine fuel. International Council on Clean Transportation (ICCT). January 2020.
3. Woodford, C. (2019, November 25). How do steam turbines work? From https://www.explainthatstuff.com/steam-turbines.html
4. Steam Inlet Temperature, https://www.sciencedirect.com/topics/engineering/steam-inlet-temperature
5. ABS Setting the Course to Low Carbon Shipping: Pathways to Sustainable Shipping, 2020
6. Mitsubishi Heavy Industries Technical Review Vol. 53 No. 2 (June 2016) https://www.mhi.co.jp/technology/review/pdf/e532/e532003.pdf
7. INT-NAM 2011 Marine Steam Turbines
8. Catalog of CHP Technologies, https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies_section_4._technology_characterization_-_steam_turbines.pdf
9. Fundamentals of Gas Turbine Engines, EZ-pdh.com, Ezekiel Enterprises, LLC.
10. Marine Gas Turbines by H. K. Kayadelen and Y. Üst
11. Biodiesel for Gas Turbine Application – An Atomization Characteristics Study by Ee Sann Tan, Muhammad Anwar, R. Adnan and M.A. Idris
12. Research publication on the use of biodiesel fuel for gas turbine Combustors by Dóra Szalay, Hitoshi Fujiwara, and Michael Palocz-Andresen
13. "World Nuclear Association - Nuclear-Powered Ships," [Online]. Available: https://www.worldnuclear.org/information-library/non-power-nuclear- applications/transport/nuclear-powered-ships.aspx. [Accessed 29 November 2019].
14. S. G. a. R. Rosner, "Nuclear Reactors: Generation to Generation," American Academy of Arts and Science, 2011.
15. [Online]. Available: https://nrc.gov.
16. [Online]. Available: https://nuclearstreet.com.
17. [Online]. Available: https://nuclear-power.net.
18. [Online]. Available: https://world-nuclear.org.
19. [Online]. Available: https://www.euronuclear.org.
20. [Online]. Available: https://www.seaborg.co/the-reactor.
21. [Online]. Available: https://en.wikipedia.org/wiki/Breeder_reactor.
22. [Online]. Available: https://terrapower.com.
23. US Office of Nuclear Energy, 9 8 2018. [Online]. Available: https://www.energy.gov/ne/articles/southern-company-and-terrapower-prep-testing-molten-salt-reactor.
24. [Online]. Available: https://www.moltexenergy.com.
25. [Online]. Available: http://www.elysiumindustries.com/technology.
26. [Online]. Available: https://static1.squarespace.com/static/597ac945725e255e16e7e607/t/5bc42a6a9140b74027bc768c/1539582572678/IAEA-SMR-Booklet+%5BElysium+Industries+MCSFR%5D.pdf.
27. [Online]. Available: https://www.arcnuclear.com/arc-100-reactor.
28. [Online]. Available: https://static1.squarespace.com/static/5b980789a9e0284111acc818/t/5bffefa60ebbe8bc1dd4250c/1543499704783/arc-100-product-brochure..
29. [Online]. Available: https://www.iaea.org/topics/small-modular-reactors.
30. S. Pais, "Plasma Compression Fusion Device". United States Patent 20190295733.
31. "Marine Engine Programme," MAN Energy Solutions, 2019.
32. M. S. Ferro, "Right of innocent passage of ships carrying ultra-hazardous cargoes," Nuclear Law Bulletin No. 78, pp. 5-18, December 2006.
33. Code of Safety for Nuclear Merchant Ships," Resolution A.491 (XII), 1981.
34. S. T. D. H. S. H. E. Dedes, Possible Power Train Concepts For Nuclear Powered Merchant Ships, Southampton, 2017.
35. J. Jacobs, "Nuclear Short Sea Shipping - The integration of a helium cooled reactor in a 800 Teu Container Feeder," University of Delft.
36. SkySails Technology Information, 2018
37. Ship Technology, MS Beluga SkySails - Cargo Ship, https://www.ship-technology.com/projects/msbelugaskysails/, 2005

38. ABS Setting the Course to Low Carbon Shipping: 2030 Outlook, 2019
39. Norsepower Rotor Sail Solution, 2018
40. Maersk Tankers, Norsepower Rotor Sails confirmed savings of 8.2% fuel and associated CO_2 in Maersk Pelican project, https://maersktankers.com/media/norsepower-rotor-sails-confirmed-savings, 2019
41. Alcatraz Cruises' Hornblower Hybrid is a Model of Alternative Energy Innovation, https://www.alcatrazcruises.com/blog/2018/07/18/alcatraz-cruises-hornblower-hybrid-is-a-model-of-alternative-energy-innovation/
42. Vertical Turbine Developed for Onboard Renewable Energy, https://www.maritime-executive.com/article/vertical-turbine-developed-for-onboard-renewable-energy
43. Wind and Solar Marine Power, https://www.ecomarinepower.com/en/products/8-products-services-and-consulting/15-wind-and-solar-marine-power, 2020
44. ABS Advisory on Hybrid Electric Power Systems, 2017
45. EcoMarinepower, https://www.ecomarinepower.com/en/news/149-ship-solar-power-system-installed-on-large-general-cargo-ship-mv-panamana
46. Solar Panels For Boats: What You Need To Know | EnergySage, https://news.energysage.com/solar-panels-for-boats/
47. Burke, A., Jungers, B., Yang, C. and Ogden, J., 2007. Battery Electric Vehicles: An assessment of the technology and factors influencing market readiness. Public Interest Energy Research (PIER) Program California Energy Commission.
48. Fotouhi, A., Auger, D.J., Propp, K., Longo, S. and Wild, M., 2016. A review on electric vehicle battery modelling: From Lithium-ion toward Lithium–Sulphur. Renewable and Sustainable Energy Reviews, 56, pp.1008-1021.
49. Ling, Z., Zhang, Z., Shi, G., Fang, X., Wang, L., Gao, X., Fang, Y., Xu, T., Wang, S. and Liu, X., 2014. Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules. Renewable and Sustainable Energy Reviews, 31, pp.427-438.
50. Li, Y., Yang, J. and Song, J., 2017. Design principles and energy system scale analysis technologies of new lithium-ion and aluminum-ion batteries for sustainable energy electric vehicles. Renewable and Sustainable Energy Reviews, 71, pp.645-651.
51. Adair, D., Ismailov, K. and Bakenov, Z., 2014. Thermal Management of Lithium-ion Battery Packs.
52. Pesaran, A.A., 2001. Battery thermal management in EV and HEVs: issues and solutions. Battery Man, 43(5), pp.34-49.
53. Teng, H. and Yeow, K., 2012. Design of direct and indirect liquid cooling systems for high-capacity, high-power lithium-ion battery packs. SAE International Journal of Alternative Powertrains, 1(2), pp.525-536.
54. Wang, X., Li, M., Liu, Y., Sun, W., Song, X. and Zhang, J., 2017. Surrogate based multidisciplinary design optimization of lithium-ion battery thermal management system in electric vehicles. Structural and Multidisciplinary Optimization, 56(6), pp.1555-1570.
55. Offer, G.J., Howey, D., Contestabile, M., Clague, R. and Brandon, N.P., 2010. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy policy, 38(1), pp.24-29.
56. Evarts, E.E., 2015. To the limits of lithium. Nature, 526(7575), p.S93.
57. Sun, P., Bisschop, R., Niu, H. and Huang, X., 2020. A Review of Battery Fires in Electric Vehicles. Fire technology, pp.1-50.
58. Wang, Q., Mao, B., Stoliarov, S.I. and Sun, J., 2019. A review of lithium ion battery failure mechanisms and fire prevention strategies. Progress in Energy and Combustion Science, 73, pp.95-131.
59. Drysdale, D., 2011. An introduction to fire dynamics. John Wiley & Sons.
60. Larsson, F., 2017. Lithium-ion battery safety-Assessment by abuse testing, fluoride gas emissions and fire propagation. Chalmers University of Technology.
61. Textbook: Ultracapacitor Applications, IET Power and Energy Series 59
62. ABS Advisory on Hybrid Electric Power Systems 2017
63. Ultracapacitor Safety Data Sheet, https://www.maxwell.com/images/documents/Safety_Datasheet_3000389_EN_4.pdf
64. Pearson, R. J. et al., (2011). Energy Storage via Carbon-Neutral Fuels Made from CO_2, Water and Renewable Energy. Proceedings of the IEEE, 100(2), 440-460.
65. Peilin Zhou, Haibin Wang, Carbon capture and storage—Solidification and storage of carbon dioxide captured on ships, Ocean Engineering, Volume 91, 2014, Pages 172-180, ISSN 0029-8018.
66. Ship Transport of CO_2 (2004). IEA Greenhouse Gas R&D Programme. Mitsubishi Heavy Industries
67. https://www.rivieramm.com/opinion/opinion/could-onboard-carbon-capture-really-work-55436
68. Blenkey, Nick. "U.K. Project Looks at Potential of Carbon Capture for Shipping." Marine Log, 15 Apr. 2020, www.marinelog.com/technology/u-k-project-looks-at-potential-of-carbon-capture-for-shipping/.

CONTACT INFORMATION

NORTH AMERICA REGION
1701 City Plaza Dr.
Spring, Texas 77389, USA
Tel: +1-281-877-6000
Email: ABS-Amer@eagle.org

SOUTH AMERICA REGION
Rua Acre, nº 15 - 11º floor, Centro
Rio de Janeiro 20081-000, Brazil
Tel: +55 21 2276-3535
Email: ABSRio@eagle.org

EUROPE REGION
111 Old Broad Street
London EC2N 1AP, UK
Tel: +44-20-7247-3255
Email: ABS-Eur@eagle.org

AFRICA AND MIDDLE EAST REGION
Al Joud Center, 1st floor, Suite # 111
Sheikh Zayed Road
P.O. Box 24860, Dubai, UAE
Tel: +971 4 330 6000
Email: ABSDubai@eagle.org

GREATER CHINA REGION
World Trade Tower, 29F, Room 2906
500 Guangdong Road, Huangpu District,
Shanghai, China 200000
Tel: +86 21 23270888
Email: ABSGreaterChina@eagle.org

NORTH PACIFIC REGION
11th Floor, Kyobo Life Insurance Bldg.
7, Chungjang-daero, Jung-Gu
Busan 48939, Republic of Korea
Tel: +82 51 460 4197
Email: ABSNorthPacific@eagle.org

SOUTH PACIFIC REGION
438 Alexandra Road
#08-00 Alexandra Point, Singapore 119958
Tel: +65 6276 8700
Email: ABS-Pac@eagle.org

ABS

TX 11/20 20219