A Review on Propulsion Drive Trains of Electric Ships: Structures, Challenges and Opportunities

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Development of marine industry has caused a significant increase in fuel consumption of global shipping as well as pollutant greenhouse gases. It is forecasted that marine industry will account for 20% of global carbon footprint, 9% of SOX emissions, and 15% of NOX pollutants by 2050. Studies reveal that carbon, nitrogen and sulfur oxides deteriorate seawater quality, which may diffuse in air and affect human health. In this regard, renewable energy sources and storage units are capable to save more energy and mitigate pollutants emitted from fueling internal combustion engines (ICEs). This paper aims to present a comprehensive study on electric ships' structure and operating modes, prime movers, energy sources including non-renewables and clean ones, benefits and challenges in electrification of marine industry. It is found that electric ship propulsion drive trains typically consist of electric motors, power electronic devices such as inverters and converters for flowing electricity from battery or fuel cell to electric motor, battery energy storages, and controllers for managing speed, torque, and direction of motor rotation. Some challenges of electric propulsion systems are the weight and space required for batteries, overheating of motors and power electronic devices, and lower energy density of storage compared to traditional fossil fuels-based ones. The main advantages of marine transport electrification include less greenhouse gas emissions and ecological footprints, lower operation and maintenance costs of electric motors compared to marine-scale diesel engines, noise reduction, and the improved maneuverability as a result of better torque control during navigating through congested waterways.

Keywords: *Electric ships, Propulsion systems, Marine industry, Emission footprints, Internal combustion engines (ICEs), Controllable pitch propeller (CPP).*

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1. Introduction

During 2017-2020, the global growth of the gross domestic product (GDP) has been reduced from 3.28% to -3.6%, as illustrated in Fig. 1. In 2020, some issues such as COVID-19 pandemic, tariff between China and US, UK decision for leaving European Union affect the world economic growth. Meanwhile, maritime industry is an important part of blue economy, which provides food, supports tourism, facilitates maritime transportation, and generates electricity using renewable energy sources such as waves, tides, and river and ocean currents. Trends and geography of world seaborne trade in 2020 is shown in Fig. 2. It is obvious that Coronavirus spread and oil prices disrupted global maritime trade intensifying supply chain crisis. Structure of many ships and vessels operated worldwide have not been updated. Hence, a huge volume of pollutants gases and substances is exhausted to seawater and air over their operation.

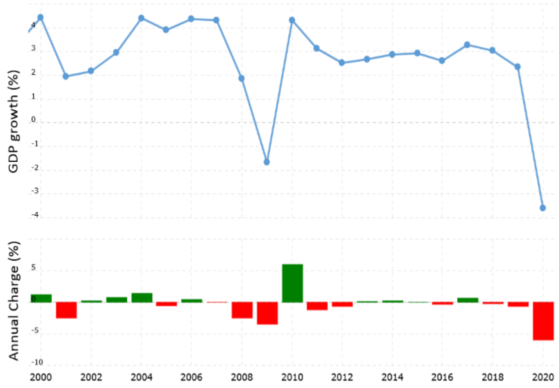

Fig. 1. The world GDP growth [1]

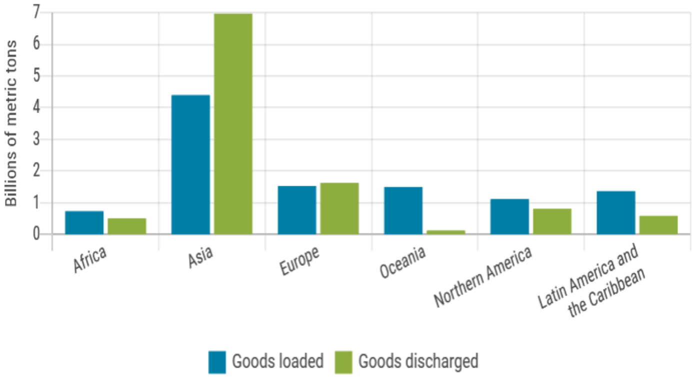

Fig. 2. Trends and geography of world seaborne trade in 2020 [2]

Hence, international marine organization (IMO) has regulated a number of rules and standards on NO$_x$ emission level and Sulfur content of fuel, energy efficiency design index (EEDI) and ship energy efficiency management plan (SEEMP) for environmental protection.

Electrification of hydraulic ocean transportation has recently been increased using internal combustion engines (ICEs), electric propulsion systems, energy storage technologies, and renewable energy sources (RES). The structure of the hybrid ships is depicted in Fig. 3.

In a hybrid propulsion system, a set of ICE and electric-drive motor (EM) is used to provide the energy demanded for the ship transportation as well as its internal consumptions such as lighting, cooking, electric chillers, water heaters, potable water producer or desalination unit, washing machines, and etc. A battery pack is also installed on the power drive train to be charged by the surplus energy. The electrical power produced by the electric motor is utilized by the ship propeller. Moreover, renewable energy sources such as wind farms, photovoltaic (PV) arrays, ocean wave energy, tidal power generation, undersea hydro turbines, and energy storage units are usually used to procure the electrical load of the charging stations in a secure and reliable manner. The type of fuel utilized by the internal combustion engine, the generator type and size as well as the battery power and energy capacities depend on the type, purpose and size of the ship or vessel.

During daytime, the battery pack can be charged from the PV array mounted on the deck of the ship. It should be mentioned that greenhouse gases are exhausted during operation of ICEs and conventional fossil fuels based thermal power generation units. In 2010, "Greenline 33 Hybrid Yacht" was designed and operated by Italian and Slovenian engineers. It composed of a battery, PVs, and a diesel engine for operating in full-electric and diesel-only modes [3]. In 2015, "Savannah" with a 4-stroke engine, 3 generators, and a 1-MW lithium-ion battery was developed by a Dutch manufacturer. Three operating mode was considered for this hybrid ship: diesel-engine propulsion mode, diesel-EM hybrid mode, and full-electric driving mode [4]. Mechanical drive trains with ICEs are mainly operated at higher speeds and peak energy demands, while EMs are driven under lower speeds conditions. This causes a reliable and stable operation of hybrid ships in long-term periods.

In 2017, a supercapacitor is integrated with a lithium-ion battery to lunch a full-electric ship with two EMs [5]. California air resources board announced an aluminum catamaran ship called "Water-Go-Round", in 2018. It was driven by hydrogen fuel cells and lithium-ion batteries [6]. In Section 2, mechanical and electrical propulsion systems of hybrid ships are discussed.

In [7], three diesel-electric ferries were analyzed in full electric and hybrid operating modes. In hybrid mode, a diesel engine powers an electric motor, while using a battery energy storage in full-electric mode. It is proved that on-board diesel engines have less contribution in underwater radiated noise. Wang et al. [8] optimally designed a hybrid electric propulsion system for a polar mini-cruise ship considering the annual fuel consumption, life-cycle cost, and the annual full-electric sailing time. It is demonstrated that the diesel engine and battery parameters as well as the gear ratio affect the hybrid electric propulsion system significantly. Authors of [9] considered the battery degradations in the real-time optimum control of the liquefied natural gas (LNG)-fueled hybrid ships. Moreover, the state of health as well as the total electrical power demand have been forecasted by the extended Kalman filter. In [10], optimum storage capacities of battery and supercapacitor are found aiming to minimize the capital investment, operation and maintenance costs considering the total power demand of the electric ship as well as their state of charge and power limitations. In [11], the optimum size of fuel cell stacks and battery in a hydrogen-fueled all-electric ship is obtained by minimizing the total capital investment, fuel consumption, and occupied volume of the propulsion drive train while enhancing the personnel electrical safety. In [12], use of onboard electrical energy storage devices is discussed as a load leveling solution when sailing in irregular waves conditions. Moreover, effects of underwater radiated noise on shop propulsion load and fuel consumption is studied in [13]. Gao et al. [14] proposed a ship voyage and energy dispatch strategy that affected by emission control policy in coastal regions. They proved that it is possible to achieve 6% reduction in ship operation cost and 8.3% mitigation in SO$_2$ footprints by involving the emission control scheme. The information gap decision theory should be applied to the optimal battery sizing approach for modeling both risk-aversion and risk-seeker uncertain operating scenarios such as weather conditions and wave-induced loads [15]. In [16], a methanol-fueled solid oxide fuel cell (SOFC)-sCO$_2$ cogeneration system is proposed for powering the propulsion drive trains of the full-electric ships. It is demonstrated that this power train is suitable for container ships with simple design and less complexity compared with SOFC-gas turbine. Feng et al. [17] integrated a carbon capture and storage unit with a natural gas-fired engine and an organic Rankine cycle (ORC) for application in cargo ships. To enhance its energy efficiency and flexibility under low and medium demands, an exhaust gas recovering scheme is applied to power generation unit. The capital investment, operation and maintenance costs of the propulsion drive train as well as the payback period and emission mitigation could be compared with traditional coal, diesel and gas oil ships [18]. In [19], a large container ship is driven by two heavy fuel oil and LNG-fueled dual-fuel engines as well as an onboard carbon capture unit. It is recommended to evaluate the economic and environmental aspects of the NH$_3$ supply chain for ultra-large ocean-going container ships [20].

As reviewed in recently published works, there is a limited number of papers on electrification of marine industry. Hence, this paper aims to present a comprehensive review on pure-electric, mechanical and hybrid drive trains from systematic viewpoint. Moreover, several commercial samples of PVs, fuel cells and battery integrated electric ships and ferries are introduced. Main applications, advantages and limitations of such propulsion drive trains are also stated.

Other sections of this paper are organized as follows: In Section 2, the full-electric and hybrid propulsion systems are reviewed focusing on the mechanical drive trains, electric drive train, and hybrid ones while stating the advantages and disadvantages of equipment or the whole propulsion system. A taxonomy of commercial photovoltaic, fuel cells and battery-driven electric ships are also presented in Section 2. Finally, concluding remarks and future trends are provided in Section 3.

2. Propulsion systems of hybrid and full-electric ships

In the marine industry, several key features should be considered during the design and development of the hybrid propulsion systems:

- Fuel consumption;

- Greenhouse gases emitted from ICEs, conventional thermal power plants, which operated for procuring energy demanded by ships charging stations;
- Noise radiations and vibrations;
- Maintenance cost of ICEs;
- Investment costs.

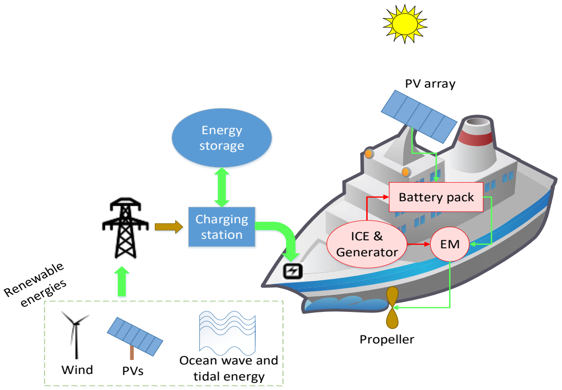

Fig. 3. Electrification of hybrid ships and vessels using RES and ICEs

The fuel consumption of the mechanical propulsion system (ICE plus generator) depends on type, size and operating condition of ICE. Operating point of ICE is determined based on energy demanded for transportation and internal loads of ships such as air conditioner, seawater desalination unit, lighting, cooking, washing, etc. In subsections 2.1-2.3, a systematic review of mechanical, electrical and hybrid drive trains of ships is presented.

2.1. Mechanical drive trains

A typical mechanical propulsion system of hybrid ships is shown in Fig. 4. Diesel engines and gas turbines are mainly used as ICEs to produce power demanded by propulsion unit. A propeller is supplied by ICE either directly or via a gearbox. Generally, diesel engines and gas turbines are selected as alternative prime movers. The AC bus is used to model the power exchange between the charging station of hybrid ships and the local electricity network. In large-scale cargo vessels, gearbox is not installed on drive train pack and low-speed diesel engines are usually used as the prime mover. In the small-scale ships, which equipped with high-speed diesel units, a gearbox is required to decrease the engine speed and reverse the shaft rotation. There are several types of propellers: fixed pitch propeller (FPP), water jet, surface piercer, whale tails, and magnetic hydrodynamic unit, and controllable pitch propeller (CPP) [21, 22]. Among all types of propellers, the FPP is mostly coupled with the gearbox for stopping the engine and reversing the shaft rotation [23].

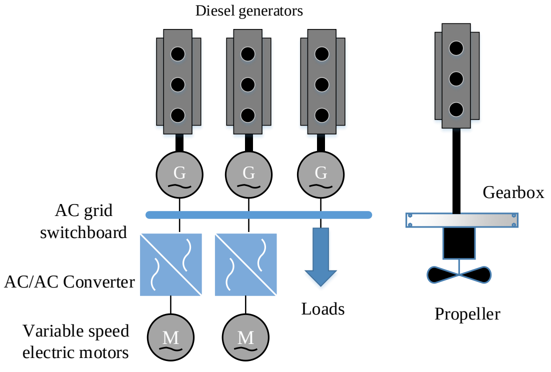

Fig. 4. A typical mechanical drive train of hybrid propulsion system

The fuel consumption and power generation of the diesel engine depend on gearbox, propeller and vessel's resistive behavior. These factors are involved in propeller curve of electric ships. The specific fuel consumption of the diesel engines is a nonlinear function of its power product. According to Table 1, the SFCs of diesel engines are provided at discrete operating intervals and can be modeled as 3rd and 5th order polynomials and cubic spline interpolation [24, 25]:

- **Diesel unit with 2 MW capacity**
  - 3rd order polynomial

$$SFC(P_i) = -4.478\times10^{-7}P_i^3 + 0.0009921\times P_i^2 - 0.6862\times P_i + 348.8 \tag{1}$$

  - 5th order polynomial

$$SFC(P_i) = -2.446\times10^{-12}P_i^5 + 8.092\times10^{-9}P_i^4 - 1.034\times10^{-5}P_i^3 + 0.006448P_i^2 - 1.999P_i + 454.4 \tag{2}$$

- **Diesel unit with 1 MW capacity**
  - 3rd order polynomial

$$SFC(P_i) = -3.428\times10^{-8}P_i^3 + 0.0001618\times P_i^2 - 0.2762\times P_i + 378.9 \tag{3}$$

  - 5th order polynomial

$$SFC(P_i) = 3.507\times10^{-14}P_i^5 - 1.739\times10^{-10}P_i^4 + 2.655\times10^{-7}P_i^3 - 4.494\times10^{-5}P_i^2 - 0.2305P_i + 379.3 \tag{4}$$

Table 1. The specific fuel consumption of diesel units at discrete operating intervals [24]

Unit 1 with 2000 kW power production capacity		Unit 2 with 1000 kW power generation capacity	
Load (kW)	SFC (g/kWh)	Load (kW)	SFC (g/kWh)
360	300	135	280
615	260	200	240
830	240	280	220
1025	230	360	210
1470	215	415	206
1680	208	530	202
1795	204	805	202
1840	203	940	206
2000	202	1000	210

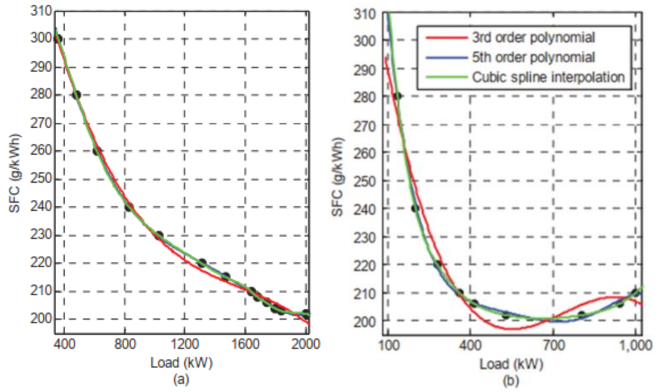

Fig. 5. Comparison between 3rd and 5th-order polynomials, and cubic spline interpolation applied to SFC-load curves for (a) 2MW and (b) 1MW diesel units in mechanical propulsion systems

The fuel consumption of the diesel engines increases when they are overloaded. Hence, a broad operating area of these units should be achieved using the sequential turbocharging, a waste gate, or variable turbine geometry. The main challenge with the fixed pitch propeller is to balance the vessel's resistive load, diesel engine, gearbox, and the propeller so that the diesel unit is operated in a safe, economic, and reliable manner. Minimum speed of the ship is restricted by the minimum speed of diesel engine. This challenge can be controlled using a controllable pitch propeller. Under a certain shaft speed, the propeller thrust and the power absorbed by the diesel unit are reduced if the pitch reduces. In addition, the thrust can be reversed while reversing the pitch with no need to reverse the diesel engine or gearbox [26].

2.1.1. Application of FPP and CPP in mechanical drive trains

If the hybrid ship is equipped with the fixed pitch propeller, the propeller, resistive loads of the ship, and gearbox affect the fuel consumption and power generation point of the diesel engine. The most important challenge of the FPP in hybrid ships is to balance the ship, gearbox, and propeller resistive loads with the power production of the diesel engine. In other words, the minimum speed of the ICE engine affects the minimum speed of the ship. Unlike the FPPs, the controllable pitch propeller improves the energy efficiency of the propulsion system for controlling and optimizing the ship speed. Moreover, they enable the mechanical power trains to smoothly maneuver from ahead mode to reverse by inversing the CPP. In addition, the energy efficient application of ICE in each propeller operating condition such as cruising, traveling, maneuvering from ahead to reverse mode, and etc. can be stated as the CPPs advantages.

2.1.2. Pros and cons of mechanical propulsion drive trains

Mechanical propulsion drive systems are usually energy efficient under 80-100% of their nominal speed. At this speed range, the diesel engines have their optimum performance from energy efficiency and fuel consumption points of view. These systems have three main power conversion components as ICE, gearbox, and propeller, which results in lower energy conversion losses. It should be noted that NOx pollutants emitted from the high-speed ICEs is higher than those produced by the low-speed engines. The diesel fuel consumption and the greenhouse gas emissions will be reduced by the waste heat recovering from the flue gases aiming to produce electricity and heat as byproducts [27]. Some important challenges of the mechanical propulsion can be summarized as follows [28]:

- ✓ The maneuverability of the hybrid propulsion systems is affected by the ICE's operating point, which can be improved by CPPs.
- ✓ The ICE's higher loading increases the maintenance requirement and cost of the mechanical propulsion drive trains. Hence, the CPPs decreases their dynamic loads and the equipment failure rates.
- ✓ These propulsion units usually have lower fuel consumption efficiency and higher NOx footprints under more than 30% speed drops from the rated speed.
- ✓ Over the acceleration of the diesel engines-assisted electric ships, the higher volume of emissions is released due to the higher dynamic loading of the ICE.

2.2. Electric drive trains

The electric propulsion systems are introduced as the emission and fuel-efficient solution in pure electric ships and hybrid ones. A central power management unit controls the load-generation balance criterion for both propulsion systems and hotel energy demands ensuring the lower fuel consumption and emission production of the ICEs in the presence of electric propulsion drive trains [29]. The single line diagram of the typical electric drive train is illustrated in Fig. 6.

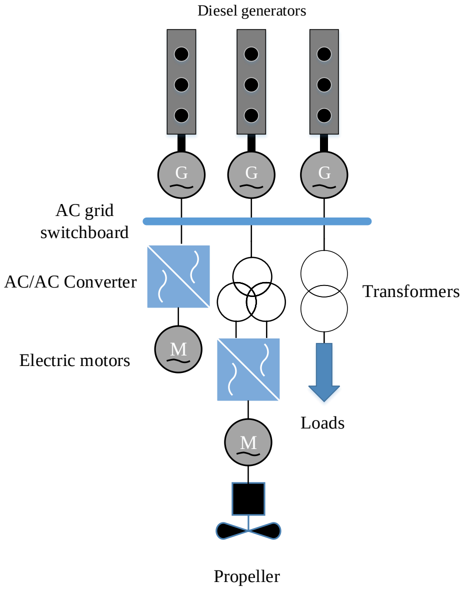

Fig. 6. The schematic representation of the electric drive trains

As discussed, the greenhouse gas emissions of the electric propulsion systems are less than the NOx footprints of the mechanical drive trains. According to [23], a cruise ship, which is equipped by an electric drive train with 20 MW-power generation capacity per shaft, needs to be assisted by 5 diesel engines running at speed of 720 rpm. While, another one composed of a mechanical propulsion infrastructure with 20 MW power generation capacity should be coupled either with two ICEs running under maximum 500 rpm speed with four-stroke diesel units or 80 rpm using two-stroke diesel engines. The average emission footprints of the diesel generators are almost 9.7, 10.5, and 14.4 g/kWh in case of full-electric, 4-stroke and 2-stroke mechanical propulsion systems, respectively.

In the electric propulsion systems, the diesel engines operate near to their nominal working point resulting in lower fuel consumption and emission production. In contrast to mechanical propulsion systems which operates under lower speeds, the diesel engines used for electrical drive trains works under their nominal speeds. Lower radiative noise is another advantage of these systems because of no need to mechanical transmission link from ICEs to propellers. Meanwhile, the electrical propulsion trains have some challenges as:

- ✓ Use of AC/AC and AC/DC power electronic converters as well as electric motors, the total energy losses of the electric drive trains and the specific fuel consumption of the diesel engines increase, especially when operating at high speeds.
- ✓ The electric propulsion systems usually use the fixed pitch propellers due to maximum torque generation capability of variable-speed drive electric motors at each operating speed.
- ✓ The frequency and voltage drop under fault situations may lead to failure of electric propulsion systems or their switching off reducing the reliability of propulsion systems.

2.3. Hybrid drive trains

As mentioned in section 2.2, the energy losses of the electrical drive trains cause the higher fuel consumption under part-load operating condition of electric propulsion systems. The surplus electrical power may also cause more weight, volume and higher investment cost. Hence, a hybrid propulsion train is cost-environment effective solution for low-speed shipping applications. The typical hybrid propulsion system is shown in Fig. 7. In the hybrid power train, the mechanical propulsion system procures the energy requirement at high-speed condition. Moreover, the electric motor-gearbox set and the electric motors directly coupled with shaft, drives the propellers and supplies the hotel electrical loads under lower speed modes. One of the important advantages of the hybrid propulsion systems is to improve the ship top speed and reduce the ICE thermal loading, fuel consumption, and emission footprints. Some practical samples of hybrid propulsion trains are introduced as naval frigates and destroyers [30, 31], towing kites [32], offshore vessels [33]. In [31], the gas turbines are used as the prime movers of the hybrid propulsion systems with lower specific fuel consumption than that of diesel units, which leads to higher fuel savings and lower greenhouse gases emissions. Authors of [34] described a novel FREMM class of frigates designed by Italian and French Navies. This frigate with hybrid drive train is applicable for war and consist of one gas turbine unit and two electric motors. A simulator software is also developed by University of Trieste to virtually test and train its behavior.

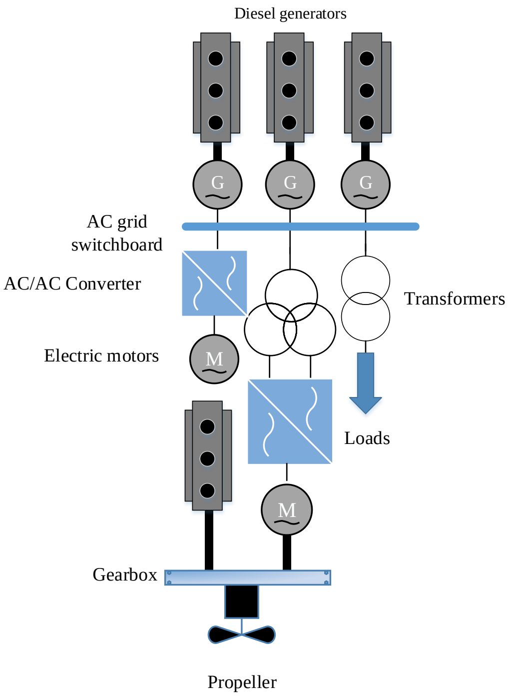

Fig. 7. The concept of hybrid propulsion systems

2.3.1. Electrical drive train with multiple energy resources

The electrical drive trains with multiple energy resources are illustrated in Fig. 8. In this case study, three classes of mechanical and electrical prime movers are installed in propulsion systems to drive ships:

- ✓ Thermal units such as diesel engines, steam turbines, gas turbines, or a combination of these units;
- ✓ Electro-chemical power producers such as fuel cell technology;
- ✓ Energy storage facilities such as compressed air energy storage, battery, superconducting magnetic energy storage, supercapacitors, and etc.

As obvious from Fig. 8, an energy storage unit should be coupled with electrical drive train at three schemes:

- ✓ Connect to main switch board using a DC/AC power convertor
- ✓ Connection of energy storage device to low-voltage bus using an AC/DC rectifier
- ✓ Connect to DC port of propulsion converter using a DC/DC converter

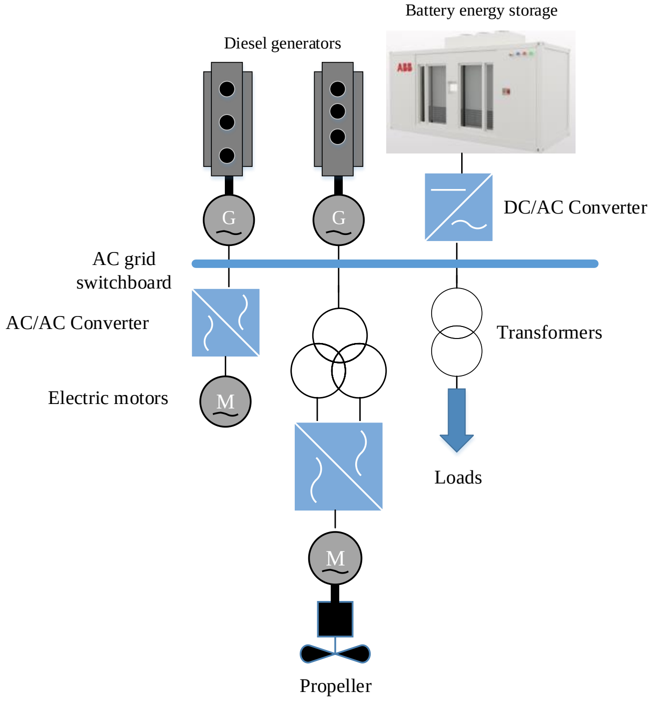

Fig. 8. The electrical propulsion system with multiple power generation units

The advantages of using multiple energy sources in electric ships can be summarized as follows [35]:

- ✓ When the ICEs are operated under a part-load mode, it is possible to off some of them and procure the electrical demand by the energy storage device. Then, it can be charged by the ICEs while the required power is less than the output power of the ICEs at fuel-cost effective operating point. In other words, the energy storage unit is recharged by the surplus power generated by the diesel engines or gas turbines. Hence, fuel saving, noise reduction, emission mitigation, and human comfort will be resulted from participation of energy storages in ship's electrical demand flattening strategies [36].
- ✓ The energy storages such as batteries can be charged during off-peak demand periods and discharged over the on-peak load time intervals. Therefore, the specific fuel consumption and the pollutants emitted from ICEs will be reduced significantly [37].
- ✓ The battery energy storage can be charged during the regenerative braking mode of the ship. In existing electric ships with battery storages, the regenerative braking power is lost in resistive loads of braking systems. Moreover, most of ships usually do not stop quickly [38].
- ✓ When a failure occurs in ICEs operation, the battery pack procures supports the electrical drive train. Hence, back-up diesel engines or other ICEs is not required for higher reliability. And availability of drive trains [39].

Parallel operation of batteries in hybrid energy production board may cause some challenges as follows [40]:

- ✓ It should be charged at low-demand periods and discharged at of-peak or mid-peak time intervals by a control scheme aiming to reduce the specific fuel consumption of the diesel engines or other types of ICEs.

- ✓ The energy demand changes may lead to a significant increase in fuel consumption and emission footprints of ICEs. Therefore, a control loop is needed for economic-environmental dispatch of energy demand between battery storage and ICEs.

In hybrid propulsion systems with multiple energy suppliers, energy efficiency is higher than that of other types of propulsion systems as a result of [41-43]:

- ✓ It is possible to supply demand from various sources of energy, ICEs, and storage technologies. Hence, if a failure occurs in one of these units, ship loads can be supplied by others without stopping ship.
- ✓ At peak load periods, battery storage can participate in energy procurement process by discharging power.

Figure 9 shows the single line scheme of the hybrid propulsion systems in the presence of multiple energy resources. As obvious from this figure, the electrical power supply is operated under the low demand hours, while the ICEs may be switched off for fuel saving and emission reduction purposes [44, 45].

The solar, wind and fuel cell are three main sources of energy which have been used in full-electric and hybrid ships. The reliability, power quality issues and the stable operation of electric ships are emerged due to uncertain nature of these resources. The main objective of the ship propulsion system is to drive the propellers using the reliable and continuous power supply. Hence, different control strategies are required due to various hotel loads and propelling energy demand with different voltage and frequency levels, which must be managed in a limited physical space [46].

In photovoltaic-assisted electric ships, solar irradiance is converted into electrical power, which can be used for charging battery when sunlight is coefficient and discharge battery at peak load intervals. Due to fluctuations of solar irradiations, PVs are usually installed in electric ships as auxiliary power supply unit. The solar PVs and battery energy storage are usually combined for application in small or medium-scale electric ships [47, 48]. Table 2 describes the structure and energy resource characteristics of the solar driven electric ships.

Table 2. Commercial samples of PVs integrated electric ships

Refs.	Physical structure description	PVs specification	Energy storage	Applications and advantages
[49]	Vessel length: 35 m Vessel width: 15 m Maximum speed: 14 knots	A PVs farm with 93 kW power generation capacity in 537 m^2 area	8.5 t Li-ion batteries	Peak load flattening by batteries
[50, 51]	Length: 14 m Width: 6 m Vessel speed: 3.5 knots	48 PV panels	3600 pounds batteries	PVs and batteries are main and auxiliary sources of energy.
[52]	Length: 200 m Width: 33 m Weight: 19,000 t	328 PV panels Rated power of PVs: 40 kW	-	Partial load procurement by PVs Applicable for carrying 6200 cars
[53, 54]	Length: 200 m Width: 32 m Weight: 19,000 t Maximum speed: 22.4 knots	Use of 768 PV panels Rated power of PVs: 160 kW	Li-ion batteries with 2.2 MWh energy capacity	Carbon mitigation Higher energy efficiency
[55]	Length: 110 m Width: 19 m Weight: 1665 t Maximum speed: 13 knots	135 PV panels with 37 kW power capacity 20 kW AC/DC inverters	128 kW Li-ion batteries	Energy consumption of lighting system is procured by PVs. Capable of holding 800 cars
[56]	Length: 21 m Width: 10 m Maximum number of passengers: 100 Maximum speed: 10 knots	Wind and solar PVs are installed for energy procurement process.	-	PVs and ICE cooperated for supplying demand.
[57]	Length: 33 m Width: 10 m Maximum speed: 8 knots	70 PV panels with rated power of 19.6 kW	-	Annual power generated by PVs is about 18 MWh. Annual carbon emission reduction is 16 t.
[58, 59]	Length: 183 m Width: 32 m Weight: 15000 t Maximum speed: 10 knots	540 PV panels with power generation capacity of 143 kW	750 kW Li-ion batteries	Capable of holding 5300 cars Carbon emission reduction by 1.5% Fuel saving by 1.8%

Due to fluctuations of solar radiations and ambient temperature impacts on PVs power products, the reliability and stability of the electric drive ships/vessels are reduced specially in cloudy sky conditions [60]. In this situation, battery packs can flat the power generation curve of the PVs-assisted drive train. A battery management system is also required to compensate for the switching energy losses during the power charge/discharge modes [44]. In case of insufficient power generation of PVs and battery, ICEs such as diesel engines, gas turbines, steam turbines, or a combination of these units can economically be dispatched to supply electricity loads and energy requirement of propellers by minimum fuel consumption and CO_2 production [23, 61]. As reported in Table 2, the first PVs-assisted electric ship was made in China, which was able to carry 5300 cars. The PVs power production facility can supply the ship lighting electricity demand in stand-alone operating mode, when the solar irradiation density is sufficient. The DC power generation of the PV panels should be converted to AC using the DC/AC inverters and transformers for supplying the vessel/ship electricity demand. The energy losses of DC/AC power electronic converters and inverters should be considered in sizing PVs, ICEs and battery [62, 63].

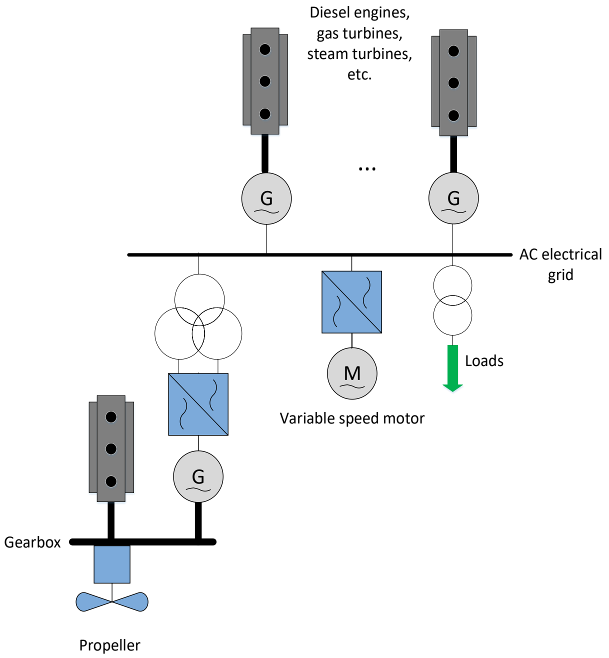

Fig. 9. The hybrid propulsion systems with multiple energy resources

The wind energy is another cost-effective power generation solution for small and medium-scale vessels and ships. In recent years, sails and ICEs together with fuel cells and batteries are used for powering modern ships/vessels [64]. Aerofoil sail, skysail, and Flettner rotor sail are some of conventional ones applied to wind energy based propulsion systems [65, 66]. Although the power generation of the Flattener rotor sails is less fluctuated and higher than that of aerofoil soil and skysail, they have some issues (such as their large sizes) for landing/launching kites. In Flettner rotor sails, a cylindrical rotating part works by a magneto-motive force for powering propellers using wind energy. Some technical criteria such as weight, intensity and size of sails should be considered in selecting and designing sails. Moreover, higher energy efficiency and flexible control strategy under different weather conditions are main factors in wind integrated electric ships. The sail energy efficiency depends on the weather/sea conditions and the wind energy conversion infrastructure. At low wind speeds, the power output of the wind assisted propulsion system reduces causing a decrease in its energy efficiency. Hence, a controller is installed to optimally dispatch loads between ICEs considering the variable wind power avoiding the wind power shortages and the ICEs power surplus [67]. In the skysail ships, the drag force required for pulling them is provided by flying the skysails in front of them. A towing line, a controller and a launch unit are main components of these ships to convert wind power to electricity and control the wind integrated propulsion systems. Recently, some automatic control systems are designed and developed in sails-driven electric ships to balance loads using sails power products and ICEs. The objective of these works is to minimize the total fuel consumption of the main engines (diesel/gas turbine/steam turbine, etc.) aiming to mitigate emissions and maximize economic savings associated with the fuel utilization reduction.

Another renewable energy source, which usually used in electric ships, is fuel cells. Some technical constraints such as the overall energy efficiency, simplicity of design and development, power and energy densities, fuel type and processing equipment should be considered in selecting the fuel cell assisted ship propulsion systems. Low-temperature fuel cells usually work using pure hydrogen, while high-temperature ones with solid oxide electrolyte operate by alternatives such as CO and CH_4. In high-temperature fuel cells, it is needed to convert alternative fuels into pure hydrogen. The most important criterion for the commercial applications of fuel cells in marine industry is their low power product range. A project funded by European Union demonstrated that this limit should be at least 500 kW for making fuel cells applicable in large sea-going ships. Current fuel cells can supply 350 kW demand and are suitable for installation in vessels as auxiliary energy sources. The main components of the fuel cells assisted electric propulsion systems is shown in Fig. 10. As obvious from this figure, a fuel tank and a fuel reformer are coupled with a number of fuel cell stacks to convert methane/CO into pure hydrogen gas. The DC power output of the fuel cell stacks is measured and then controlled by a central management system to economic-environmental dispatch of batteries, main ICEs using DC/DC converters and DC/AC inverters. Finally, DC and AC loads as well as electric propulsion motors are supplied by power outputs of these electronic devices. In recent years, several projects have been funded by US and Norway's research councils to develop fuel cells based electric propulsion systems in marine industry. In this context, "Vindicator" and "Viking Lady" are two warships with 330 kW fuel cell stacks. Another commercial passenger ship is "Alsterwasser" used in Hamburg's inner waterways. Some of fuel cells-based ships are introduced in Table 3. As discussed in Table 3, diesel fuel, liquefied natural gas, and carbon monoxide, methane, methanol or other biofuels are suitable alternative energy sources which can be applied to high-temperature fuel cell stacks in large-scale ocean-going ships.

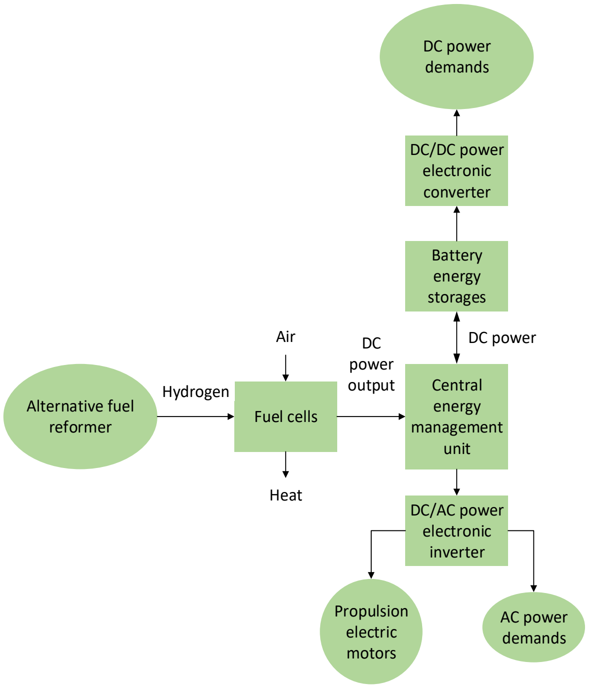

Fig. 10. The schematic block diagram of the fuel cells assisted electric propulsion systems

Fluctuations of solar irradiations and wind speeds have caused their application is limited to weather conditions resulting in uncertainty of their power products. Hence, integration of solar and wind technologies and installation of energy storage devices such as Li-ion batteries may solve this problem. Meanwhile, ICEs such as diesel engines or gas turbines can improve the reliable and stable operation of the renewables-assisted propulsion systems. The general overview of the solar-wind-diesel propulsion systems are depicted in Fig. 11.

Table 3. A taxonomy of commercial fuel cells based electric ships

Ship/vessel	Fuel cell	Alternative fuel	Power capacity	Advantages
Vindicator [68]	Molten carbonate fuel cells	F76 diesel fuel	2.5 MW	Four fuel cell stacks are used instead of 4 diesel engines.
Viking Lady [69]	Molten carbonate fuel cells	H_2 Liquefied natural gas CH_3OH	330 kW	Three fuel types are utilized in power generation to improve reliability and efficiency.
SchIBZ [70]	Solid oxide fuel cells	Diesel fuel	100 kW	Diesel fuel enters reformer to be converted into H_2 and then used by solid oxide fuel cells. Rated power of this plant is almost 500 kW.
PAXell [71]	High-temperature proton-exchange membrane fuel cell	Diesel fuel CH_3OH	120 kW	It is possible to increase power output by fuel cell stacks.
Boat [72]	A tourist boat with 20 m length, which made by South Korea using proton-exchange membrane fuel cell.	Hydrogen	50 kW	Installation of Li-ion batteries in combination with proton-exchange membrane fuel cell improves efficiency of propulsion systems.
Yacht [73, 74]	Proton-exchange membrane fuel cell	Hydrogen	4.8 kW	Use of 4 proton-exchange membrane fuel cells with 1.2 kW power capacity and 9 lead-acid batteries with 20 kW capacity for continuous energy supplying.
NedStack [75]	Proton-exchange membrane fuel cell	Hydrogen	60 kW	Use of 2 Proton-exchange membrane fuel cells with 30 kW rated power.

Table 4. Commercial marine-scale battery energy storages

Ship/vessel	Battery type and capacity	Ship capacity	Maximum speed (knots)	Length (m)	Manufacture	Country/year
Alsterwasser [76]	Lead-gel/200 kWh	100 passengers	8	25	Zemships	Germany 2008
Viking Lady [77]	Li-ion/0.5 MWh	25 passengers	15.5	92	Eidesvik	Norway/2009
Deutschland [78]	Li-ion polymer/1.6 MWh	1200 passengers and 365 cars	18.5	142	Scandlines	Germany 2014
BB Green [79]	Li-ion/200 kWh	100 passengers	30	22	European Union funded project	Netherlands 2015
Aditya [80]	Li-ion/50 kWh	75 passengers	7.5	21	Water transport Department in Kerala	India/2016
Elektra [81]	Li-ion/1 MWh	375 passengers and 90 cars	11	98	Finferries	Finland/2017
Enhydra [82]	Li-ion/160 kWh	600 passengers	13	39	Red and White Fleet	USA/2018
Ellen [83]	Li-ion/4.3 MWh	200 passengers	21	60	European Union Horizon 2020	Denmark 2019
Yungang Electric Tug No. 1 [84]	Li-ion/5 MWh	300 passengers	13	35.5	Lianyungang Port Holding Group	China/2021
Medstraum [85]	Li-ion/1.524 MWh	147 passengers	23	Not reported	Corvus Energy	Norway/2022

Table 5. Opportunities and challenges of electric ships/vessels

Propulsion system type	Benefits	Limitations
Full electric prime mover	Lower noise Near-zero emissions No risk of oil leakage or spillage Less moving parts Lower maintenance cost No need to change or charge oil Higher fuel cost saving	Driving range is limited to maximum state of charge of battery pack. Higher weight of battery bank in case of large-scale ships Speed is limited by the size of the battery charger. Electronic devices installed on board are prone to corrosion and failure.
Hybrid propulsion systems	More energy sources such as solar PVs, wind turbine, undersea hydro turbine, and ICEs Driving range is supplemented by ICE and RES based drive train	Higher investment and maintenance costs Higher pollutants emitted from ICEs in comparison with full-electric propulsion systems
Lithium-ion batteries based electric or hybrid ships	Higher energy density Capable to recover energy Higher reliability of propulsion system	Higher capital investment and maintenance costs compared to those do not use batteries Slower dynamic response
Fuel cell technology-based ships or vessels	Fuel cells are more compact. Silent and smooth alternative in energy conversion process Relatively long usage time No noise and visual pollutions Good power quality Hydrogen fuel cells are more environmentally friendly compared to ICEs due to carbon capture issue High energy efficiency (>80%)	Higher investment cost due to expensive catalysts Storage and transportation of hydrogen Higher risk of hydrogen ignition due to its flammable property

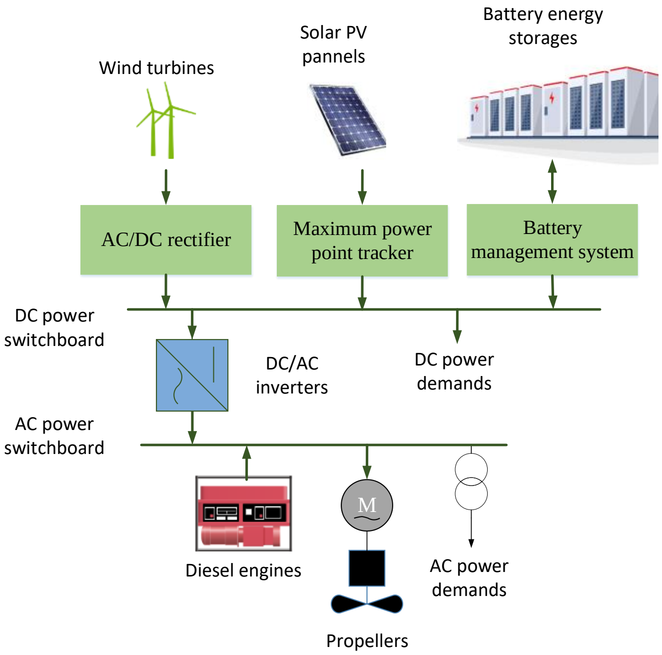

Fig. 11. The typical solar-wind-diesel propulsion systems

According to [86], "Aquatanker" is a zero-energy marine carrier designed for transportation of huge volume of desalinated water. Its length and width are equal to 400 and 31 m, respectively. Moreover, its maximum speed is 15knots. This green ship is equipped with wind sails and solar PV panels. Experimental analyses revealed that its fuel consumption and emission footprints are almost 50% less than those of conventional ones. Another commercial green ship is "Solar Sailor" which was produced for transportation of maximum 100 passengers. The diesel fuel saving and pollution reduction of this wind-solar driven ship are 250 kL and 670 t, respectively. US also developed a solar-wind-diesel-fuel cell hybrid ferry ship that named "Hornblower Hybrid". As obvious from Fig. 11, a battery energy storage is also supplied by DC power output of fuel cell stacks to procure DC electricity demands at peak load periods. Table 4 summarizes battery technologies made by different countries for electrification of ships or vessels and can be used in hybrid propulsion systems.

Some benefits and challenges of hybrid and full electric ships which composed of renewable energy resources and energy storages can be summarized as Table 5.

3. Concluding remarks and future trends

In this paper, a review on renewable energy resources-based ships and vessels was presented. In addition, main component, structure, and performance of mechanical, electrical and hybrid propulsion systems were discussed. Advantages and limitations of these drive trains were introduced. Some commercial products made by different manufactures were compared from various points of view such as scale, technology type, capacity, production year, pros and cons. Although several remarkable efforts have been carried out on design, development and deployment of solar, wind, fuel cell, battery assisted hybrid ship propulsion systems, there are some technical and economic challenges in reliability, stability, energy-secure operation of these facilities. In this regard, corrosion of ship equipment due to gross water usage, lower energy efficiency of solar PV panels, optimal sizing of wind turbines and PV panels in a limited deck space, design and application of appropriate controllers in wind, solar, battery energy management systems with consideration of unstable weather conditions as well as uncertainties associated with electrical demands and output power of wind turbines and solar PV panels are some of these challenges. Moreover, because of needs to DC/DC converters, DC/AC inverters, and AC/DC rectifiers in supplying DC and AC loads of electric ships, power quality issues should be taking into account in planning and operation of ferries, vessels and ships. Higher capital investment costs of renewables integrated propulsion systems with controllers, communication infrastructure and stabilizers make it vital to optimally allocate renewable energy resources in marine industry. In fuel cell hybrid drive trains, hydrogen production, transformation and conditioning costs should be considered in decision making process. Fuel logistic costs, which is associated with transferring fuel from production side to consumption or storage parts, as well as the energy conversion costs of the main engines (diesel generators, gas turbines, steam turbines, fuel cells, etc.) and auxiliary devices are other economic factors in marine studies. It should be noted that battery energy storages have three main roles in electrification of marine industry. They can be used as auxiliary energy sources, for participation in mid or long-term load flattening strategies, and for short-term ship's load-generation balance program. Three conventional types of energy storages applied to full-electric or hybrid ships are batteries, ultracapacitors and flywheels. As future trends, design structure and performance of other types of energy storages which can be used in marine industry and electric ships will be studied. Moreover, feasibility of demand-side management strategies such as peak-clipping and valley filling will be simulated on a real large-scale ocean-going ship to maximize fuel saving and emission reduction. As another future scheme, feasibility of hydrogen turbines applications in hybrid propulsion systems should be investigated from energetic, exergetic, economic and environmental points of view considering various sources of uncertainties such as AC and DC loads, solar irradiance, wind speed, single or multiple failures in mechanical or electrical components of drive trains. Under similar solar irradiations, ship loads value, weather conditions, and other ship operational criteria, the energy efficiency and power output of the solar dish Stirling heat engines should be compared with those of PV panels to introduce them as future approaches for electrification of small-scale vessels. Technical and economic limitations of different types of propulsion systems in design, development and deployment of full-electric and hybrid ships were discussed. Hence, optimal integration of renewable energy resources, lithium-ion batteries, fuel cells, and ICEs to build an energy-efficient and reliable energy conversion pack for driving future ships and vessels imply several costs, environmental and technical constraints, which should be considered in long-term planning analysis of their applications. Moreover, risk-seeker and risk-aversion strategic decision-making schemes are required to model the unstable weather conditions as well as the fluctuated electrical demand of the ship/vessel hotel. In addition, design and optimal operation of the robust controllers may cause a significant improve in the energy efficiency and reliability of the whole drive train.

Development of charging stations for electric ships and vessels is essential for transitioning to low-carbon maritime transportation. Moreover, application of green fuels such as hydrogen in ICEs such as gas turbine should be assessed. The hydrogen fell cells can also be utilized to convert H_2 into electricity for driving the electric motors. Some advantages of H_2 fuel cell ships, vessels and ferries includes:

- Longer operational range compared to battery-assisted ones making it possible to travel without frequent refueling
- Faster refueling than charging battery
- Zero-carbon footprint in H_2-air combustion process
- Lower noise during operation causing higher comfort for crew.

Green fuels such as biofuels, hydrogen, ammonia, and synthetic natural gas can be utilized by electric ships but safety regulations and refueling stations should be considered in design and development of these vehicles.

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