Case Studies and Recent Developments in Propulsion Drive Trains of Electric Ships

Hamid Jabari[1], Amir Kiyoumarsioskouei[1*], Farkhondeh Jabari[2], Mehdi Zeraati[2] and Saeed Salarkheili[3]

[1] *Faculty of Mechanical Engineering, Sahand University of Technology, Tabriz, Iran*
[2] *Power Systems Operation and Planning Research Department, Niroo Research Institute (NRI), Shahrak Ghods, Tehran, Iran*
[3] *Faculty of Electrical Engineering, Shahid Beheshti University, Tehran, Iran*
**Corresponding author: kiumarsi@sut.ac.ir*

Manuscript received 16 March, 2024; revised 10 September, 2024; accepted 25 December, 2024. Paper no. JEMT-2403-1496.

Abstract: The electric propulsion systems in maritime industry and road transport can mitigate global warming. This paper aims to introduce cases studied in the worldwide projects from systematic, energetic, economic, and environmental points of view. In addition, some features of these technologies such as structure, operating modes, specifications of electric and hybrid propulsion systems, other numerical characteristics of these systems, and etc. are presented to introduce some benchmark test systems for future studies. Finally, systematic specifications, prime movers, power generation capacity, advantages and disadvantages of some real cases of full-electric and hybrid ships are discussed. It is proved that hybrid propulsion systems composed of renewable energy resources-based power trains such as photovoltaic panels and wind turbines, green hydrogen-based fuel cell stacks, and conventional ICEs should be coupled in ships and vessels to improve the energy-efficiency of the whole drive train and mitigate the water and air pollutants emitted from the fossil fuels-based ICEs. Hybrid drive trains typically require additional equipment such as batteries, electric generators, which can increase their weight and space requirements on vessel, potentially impacting cargo capacity. It is found that pure-electric drive trains have higher energy efficiency, zero-carbon footprints, low maintenance of electric motors, regenerative braking, and power availability for onboard systems such as advanced radar, sonar, and weapon systems, which is particularly beneficial for naval applications. Meanwhile, higher initial investment costs, charging infrastructure requirements, and limitations in range and operational efficiency of fully electric ships due to batteries energy storage capacities are disadvantages of full-electric propulsion systems.

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

http://dx.doi.org/10.22109/jemt.2024.448585.1496

---

1. Introduction

Recently, CO_2 footprints emitted by marine industry almost account for 4% of global greenhouse gases. Studies show that approximately 75% of shipping pollutants are diffused in 400km of coastal and ports, which may lead to serious threats for human health. Therefore, electrification of the maritime industry may cause a major reduction in fuel consumption and anthropogenic emissions. Moreover, conventional vehicles with internal combustion engines (ICEs) produce direct emissions. Meanwhile, pure electric and hybrid vehicles respectively produce no and less exhaust emissions than ICE based ones [1-4].

In this regard, several interesting works have been provided about marine electrification. In [5], design and control schemes of smart ships propulsion systems have been classified into mechanical, electrical and hybrid propulsion, while introducing some applicable power supply methods such as combustion processes, electrochemical energy conversion units, and energy storages. Hybridization of propulsion drive trains may cause 35% lower fuel consumption and emission footprints, while improving noise, maintainability, maneuverability and comfort. As stated in [6], small full-electric ships and large hybrid-driven vessels including passenger cruise liners, Navy ships and recreational boats saves more fuels and emit lower emissions than traditional internal combustion engines (ICEs)-based marine transportation. Authors of [7] developed a combination of ship speed optimization and energy management strategy aiming to minimize the total power consumption of the propeller in the propulsion side and the energy requirement of the onboard power grid in the demand side using the genetic algorithm. Simulations on bulk carrier under normal working conditions demonstrated that 2.6% and 9.86% fuel savings are achieved in westbound and eastbound voyages, respectively. According to [8], diesel engines, solar photovoltaic panels, wind turbines, and fuel cell stacks are main power generation technologies used in ship electrification plans. Due to severe fluctuations of solar irradiance and wind speed, energy storage devices such batteries, supercapacitors, and flywheels are also installed to participate in energy management procedure [9, 10]. Kim et al. [11] designed a DC onboard power microgrid for a 2MW pure-electric car ferry using batteries. They considered different factors such as ship operational modes, battery charge and discharge capacity selection, architecture of propulsion energy conversion system, and energy efficiency in design process. In [12], the probable failures are predicted using a weakly supervised machine learning algorithm to ensure the timely intervention of the ship crew. The balanced random forest and the multiple instance learning are developed using the event logs received from the electric propulsion drive train. The life cycle assessment of the solar PV-coupled electric ships in Brazil, India, Australia and UK is provided in [13, 14]. In [15], hydrogen fuel cell electric ships are discussed from technical points of view about onboard installation, power supply units, control, safety and related regulations.

This paper presents a comprehensive literature review on real-world propulsion drive trains of full-electric and hybrid ships and vessels focusing on systematic, economic, and environmental features of pilot cases studied or developed in different countries. Moreover, advantages and disadvantages of these projects or designs have been presented. Some applications of full-electric and hybrid prime movers in marine industry have also been introduced. In addition, various factors which should be involved in design, planning and operation of electric ships have been discussed.

Sections 2-10 of this paper provides more information about real cases designed and operated in recent years. Finally, concluding remarks and future trends are provided in Section 11.

2. Impacts of electric-propulsion systems on power quality indices

In [16], three classes of maritime microgrids are studied to compare their oscillatory behavior in three vessels equipped with high-power converters. It is assumed that electric ship 1 has a dynamic positioning unit with a twin hull and its electric propulsion system composed of two 300 kW variable-speed motors. Nominal voltage and frequency of this microgrid are 400 V and 50 Hz, respectively. The single-line diagram of the 1st ship is shown in Fig. 1.

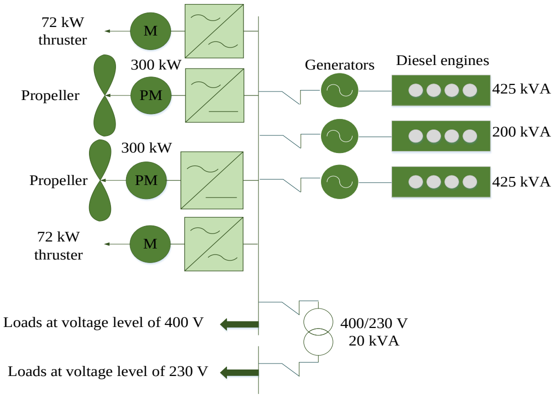


Fig. 1. The single-line diagram of the propulsion system for dynamic positioning ship

It is assumed that two generators with rated powers of 425 and 200 kVA are operated in parallel. Two 72 kW thrusters are installed for dynamic positioning purpose. A chemical tanker with a 1.187 MVA variable-speed shaft generator is studied as a maritime ship with non-sinusoidal supply (Fig. 2). Silicon-controlled rectifiers (SCRs) are combined with its drive train to stabilize the frequency. Nominal voltage and frequency are equal to 440 V and 60 Hz, respectively. A synchronous compensator is used to compensate for the distortion of the output voltage of power converter [16]. The main oscillatory resources in the marine microgrid are the rotational speed of the generator's prime mover, load fluctuations, and the weather conditions, which can be controlled using the automatic voltage regulators (AVR), governors, and the shipboard power electronic devices. As illustrated in Fig. 3, a bow thruster supplied by a 6-puls rectifier-based power converter is used in research-training ship to supply 109 kW load by a diesel engine with 376 kW power generation capacity. It should be mentioned that this diesel generator is installed to procure not only bow thruster but also other consumptions such as pumps, fans, heaters and etc.

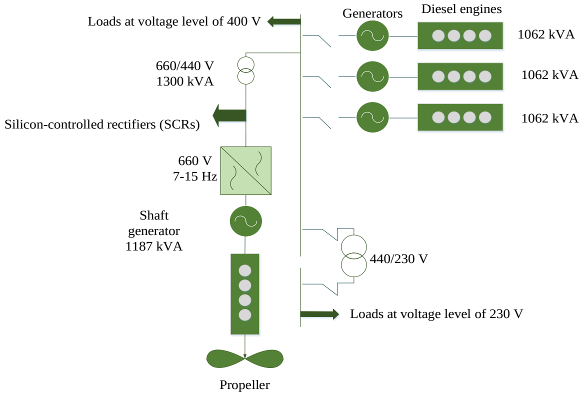


Fig. 2. A chemical tanker with a 1.187 MVA variable-speed shaft generator, synchronous compensator, and SCRs

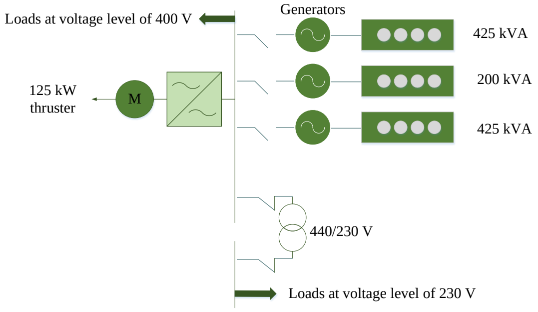


Fig. 3. A bow thruster supplied by a 6-puls rectifier-based power converter

3. Energy efficiency in AC and DC power trains

In [17], a data-oriented dynamic method is presented to evaluate the energy efficiency of a full-electric vehicle under various configurations considering its load-sharing capability. The efficiency of the entire power train is calculated from fuel injection step to the electricity consumption by the onboard loads. The efficiency of the full-electric ship is compared with conventional diesel engine-based ones and hybrid ferries. In the electric propulsion trains, a set of a prime mover and an electrical generator is used to generate AC electricity to power propeller, internal consumptions such as lighting, heating, ventilation, and air conditioning (HVAC), variable-speed electric motors, and other auxiliary loads. The electric generator can be combined with energy storage devices such as lithium-ion batteries and supercapacitors to extend the driving range of the full-electric ships. Development of power converters makes it possible to implement both DC and AC maritime power systems, as compared in Table 1 and shown in Fig. 4. Two DC/DC and DC/AC converters are used to exchange power with storage units. In the AC power train, the AC voltage with 50 or 60 Hz frequency is generated for energizing the ship switchboard. Using two bidirectional DC/DC and DC/Ac power converters, the AC power train is integrated with the energy storage unit. The AC/AC power converter is used to operate the variable-speed propulsion system. The electricity loads usually operate with 50 or 60 Hz frequency while a power transformer is required for voltage conversation in demand side. Both frequency and voltage are controlled by real-time monitoring of prime mover speed and reactive power generation and compensation. In the DC power train, the switchboard is energized by the DC voltage. The energy storage device is also coupled with the power train using the DC/DC converter. Moreover, an AC/DC rectifier such as insulated-gate bipolar transistor (IGBT) or diode is installed to convert the generator AC output into DC. The voltage source inverter makes it possible to produce the variable-frequency AC voltage for driving the propulsion system. The electricity loads are operated under system frequency and require the DC/AC inverters. In the DC power grid, the voltage is only required to be regulated not frequency.

Table 1. Comparison between AC and DC power trains

Feature	AC power supply	DC power supply
Volt-VAr control	Y	Y
Frequency control	Y	N
Synchronization	Y	N
Harmonics	Y	N
Voltage ripples	N	Y
Integration with storages	Y	N
Simple fault diagnosis	Y	N
Lower maintenance cost	Y	N

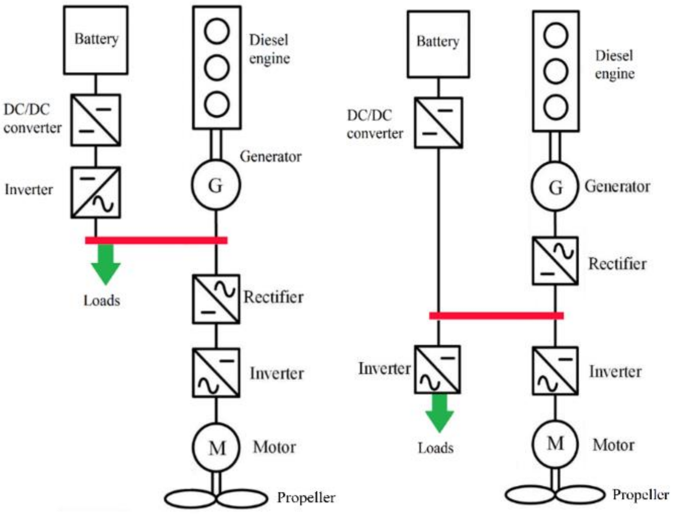


Fig. 4. Schematic representation of AC (left) and DC (right) power trains

4. Full-electric ship design process

As shown in Fig. 5, large-scale cruise ships are driven using ICEs (usually gas turbines or diesel engines) and synchronous generators. The authors of this research presented a scheme as the roadmap of designing the pure-electric or hybrid ships. Technical characteristics of a full-electric cruise are listed in Table 2.

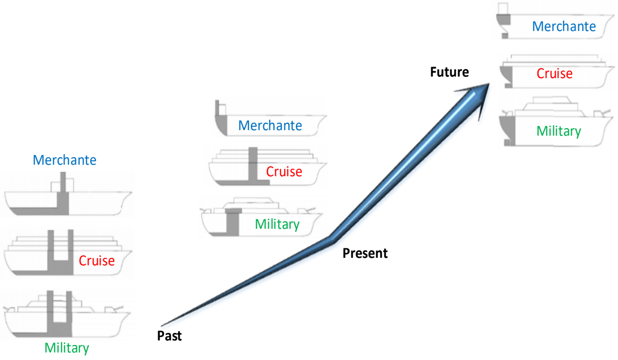


Fig. 5. Toward electrification of marine ships

The design process consists of six steps [18]:

- Conceptualization
  - Ship requirements determined by owner company
  - Technical feasibility assessment
  - Practical design scheme
- Preliminary
  - Size, configuration, main components, and single-line diagram of the ship
  - Economic-environmental aspects
  - Risk assessment
- Contract
  - Technical specifications
  - Explanatory draws
  - General requirements
  - Procurement of equipment
  - Construction plan
- Functional capabilities
  - Design, simulations, calculations, validation, performance investigation
  - Ship configuration, equipment, materials, capital and maintenance costs
- Transition
  - Yard plan
  - Zone arrangement
  - Materials list considering zone and yard plan
- Instruction activities
  - Equipment and materials list for manufacturing or importing

Table 2. Technical specifications of a pure-electric cruise

Feature	Unit	Value/Number
Gross tonnage (ship's overall internal volume)	GRT	142
life-saving appliances, including lifeboats, lifebuoys, life-jackets, life-rafts and others used by passengers and crew	-	Up to 5600 persons
Passenger cabins	-	1780
Public areas	m^2	40000
Length	m	330
Breadth at loaded waterline	m	38.4

Peak value of Draft	m	8.55
Speed capability in contract	knots	22
Propulsion unit	-	4 load commutated inverters on 2 propellers
Propeller power output	MW	2×18
Generators output power	MW	2×21+2×18
Nominal voltage on switchboard	kV	11
Cable length	m	4000
Number of secondary switchboards	-	460
Number of circuit breakers	-	23000

5. Battery-electric, diesel engines based and hybrid propulsion systems of a vessel

In [19], a battery-electric propulsion system is introduced for application in a pure electric vessel. In this full-electric drive train (Fig. 6), the ship's propellers are coupled to the electric motors. The electric motors are powered by the battery energy storage units, which can be charged from various renewable energy sources such as PVs, wind, ocean waves, shore power, etc. Some of pure-electric ships equipped with a small-scale diesel generating unit to extend the distance range when the battery cannot be recharged or for long distances.

A conventional diesel engine drive train as well as a hybrid diesel-battery propulsion system are compared in Fig. 7. In the hybrid power train, a battery is included in combination with diesel engines, which makes it possible to recharge battery via diesel engine when the total energy requirement of the vessel is less than the power product of the engine. In the battery-integrated propulsion systems, the energy storage capacity and the power rate for transferring in and out of battery are two important factors. The charge and discharge rate of the battery demonstrates the rate at which it is charged/discharged relative to its maximum capacity. For example, a discharge rate of 1 implies the battery can be completely discharged from 100% to 0% of its state of charge (SOC). The battery life time increases as its charge/discharge rate as well as depth of discharge (DOD) decrease resulting in higher price [19].

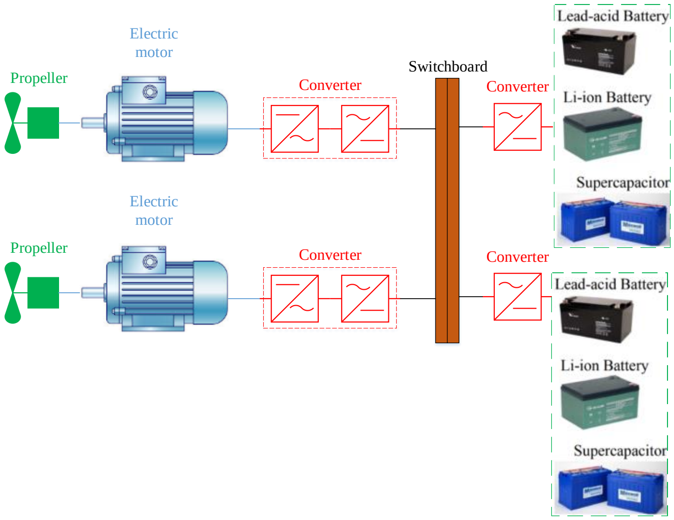
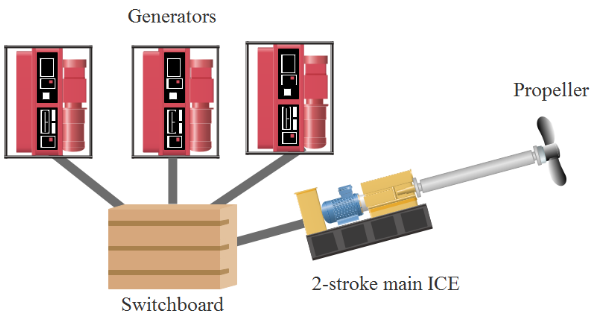
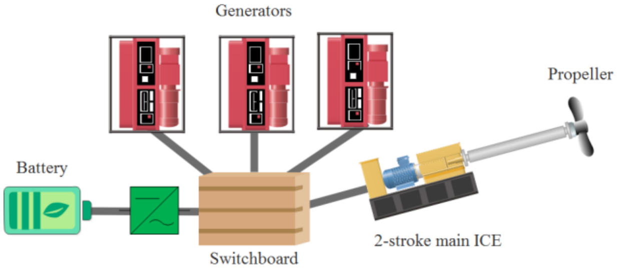


Fig. 6. The battery-electric propulsion system for a pure electric vessel



(a) The diesel engines based mechanical power train



(b) The diesel-batter hybrid propulsion system

Fig. 7. The mechanical (a) and battery-diesel hybrid (b) propulsion systems for a pure electric vessel

According to [19], the energy consumption of ferries for some typical trades depends on the routes, cargo, and distances as sample cases reported in Table 3. In Tables 4 and 5, the energy consumption of the vessels for trading cases presented in Table 3, is given for two operating conditions: (a) at vessels service speed and (b) at half of service speed.

Table 3. Sample routes for ferries

Route	Distance (nm)	Cargo
Saint Petersburg – Gdansk	532	Timber
Ponta da Madeira – Shanghai	11,100	Soya beans
Newcastle (AUS) – Osaka	4,280	Coal
Ponta da Madeira – Rotterdam	4,100	Iron ore
Hamburg – Gothenburg	326	Containers
Busan – Houston	9,800	Containers
Singapore – Piraeus	5,610	Containers
Rotterdam – Harwich	118	Lorry trailers

Table 4. Energy requirement and battery storage specifications at service speed of vessels

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container
Size	50k dwt	82k dwt	200k dwt	320k dwt	2500 teu	14000 teu	20000 teu
Service speed (knots)	13.5	14	14.5	15	18	20	22
Energy demand for travelling (MWh)	212	5314	3185	4522	198	16274	13599
Time (h)	39	793	295	273	18	490	255
Hotel (MWh)	9	222	100	109	22	2744	2040
Total energy requirement (MWh)	221	5536	3286	4632	219	19018	15639
Min. battery weight (tons)	2430	60900	36150	50950	2410	209200	172030
Min. battery volume (m^3)	2650	66400	39450	55580	2630	228220	187670

Table 5. Energy requirement and battery storage specifications at half of service speed

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container
Size	50k dwt	82k dwt	200k dwt	320k dwt	2500 teu	14000 teu	20000 teu
Service speed (knots)	6.75	7	7.25	7.5	9	10	11
Energy demand for travelling (MWh)	48	1287	843	1243	44	3583	2878
Time (h)	79	1586	590	547	36	980	510
Hotel (MWh)	18	444	201	219	43	5488	4048
Total energy requirement (MWh)	66	1731	1043	1462	88	9071	6958
Min. battery weight (tons)	730	19040	11470	16080	970	99780	76540
Min. battery volume (m^3)	790	20770	12520	17540	1060	108850	83500

It should be noted that if the operating speed of a vessel is reduced, the number of vessels required for a specific application will increase [19]. Figure 8 illustrates the example curves for speed-distance-water depth for traveling from Harwich to Rotterdam [19]. The vessel route is determined by waterways location and traffic separation strategies, which provides a total distance of 118 nm. The approximated water depth is used to calculate the energy consumption considering the effects of the shallow water resources.

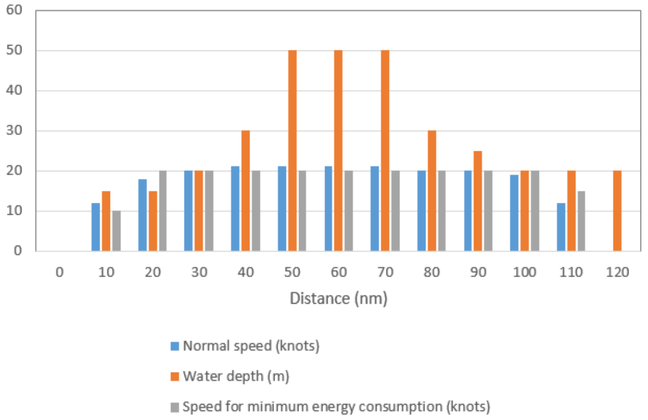


Fig. 8. Vessel speed-distance-water depth curves in typical route from Harwich to Rotterdam

The performance and efficiency of the electric ships can be influenced by normal cruising speed, water depth, and speed for minimum energy consumption across different distances. Electric ships typically operate at speeds that vary based on their design and purpose, which is called normal speeds. Common speed ranges for various types of vessels are:

- Bulk carriers: 13 to 15 knots
- Container ships: 16 to 24 knots
- Oil and chemical tankers: 13 to 17 knots
- Cruise ships: 20 to 25 knots

For electric ships, energy consumption is also affected by hydrodynamics, weight and load, and operational strategies like slow steaming. Minimum energy consumption of electric ships usually occurs at speeds lower than their maximum cruising speed due to non-linear relationship between speed and fuel consumption, where higher speeds lead to exponentially greater SFOC.

According to Fig. 8, the vessel lefts port at the speed of 5 knots in Harwich out channel. Duration of crossing from open waters was 7 h and 15 min. allowing to have sufficient time to deliver cargo in quayside and finish travel over a 12 h time interval. Secondly, the vessel speed is reduced to 8.7 knots causing an increase in crossing duration up to 14 h and 20 min. (almost twice as much as previous case). It is obvious that when speed reduces below 8.7 knots, the total energy requirement of the vessel for supplying the hotel loads and the propulsion train will increase [19].

In [19], a battery pack with 1080 m^3 volume and 990 tons weight with 22.5 million $ cost is considered for a 5000-lm cargo vessel on a 120 nm route. For a 5000-lm cargo ship, a two-stroke mechanical drive train with 500 tons weight is appropriate. Supposing that the electric motor driving the propeller has the same weight as the two-stroke engine-propeller set, this value can be subtracted from the total weight of the battery pack, which is almost 990 tons. In this case study, a fuel tank with 300 tons capacity is assumed, so no fuel needs to be carried on board. The battery pack is used for peak clipping from two-stroke internal combustion engine. When the electrical power demand is more than the power capacity of the two-stroke ICE, the power product of the main engine is adjusted on maximum value, while the additional load is supplied by the battery, as shown in Fig. 9. The ICE load periodically changes as a result of decrease and increase in propeller resistance against waves. The specific fuel-oil consumption of the ship's engines is closely related to the engine load and ship speed. The ship speed has a cubic relationship with the engine power. The sailing at lower speeds can significantly reduce the SFOC. Hence, the specific fuel-oil consumption and the speed increase when the electricity load of the propulsion system increases and vice versa.

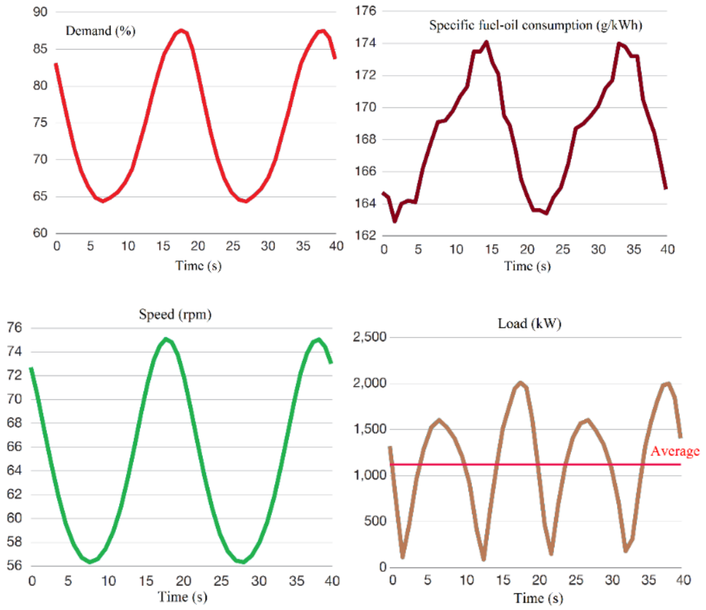


Fig. 9. Variations of energy demand, fuel consumption, speed, and propeller load

Two-stroke ICE engine load changes cyclically as a result of the increase/decrease of the vessel resistance imposed by the waves to the propeller. In this research, the minimum and maximum values of the ICE engine load are set to 65% and 87% of the specified maximum continuous rating (SMCR). The specific fuel consumption of the two-stroke engine is limited between 163 to 174 g/kWh. Turbine inlet and outlet temperatures belong to intervals 300 to 435℃ and 195 to 305℃, respectively. Moreover, mean integrated pressure (MIP) varies from 14.6 to 153.6 bar. Under adverse weather conditions, a battery pack combined with a power take-off/in PTO/PTI unit is a good choice for ensuring the reliability of power supply drive train. For example, a 50000-dwt bulk carrier with 12.2 m scantling draught, 11 m design draught, 183 m overall length, 174 m length between perpendiculars, 32.2 m breadth, wind resistance coefficient of 1, and 350 m^2 frontal area is considered for assessing battery performance during adverse weather condition. According to IMO's guideline on minimum propulsion power, the vessel performance should be investigated for the wave height of $H_s = 4\ (m)$ and the average wind speed of $V_{wind} = 15.7\left(\frac{m}{s}\right)$. Considering the minimum propulsion speed of 4 knots, the wind flow resistance can be given by (1) [20].

$$R_{A,wind} = 0.5 \times \rho \times C_w \times A_F \times \left(V_{wind}^2 - V_S^2\right) \quad (1)$$

where,

C_w: Wind resistance factor

A_F: Frontal area

V_S: Vessel speed

The wave resistance is estimated from (2) [21].

$$R_{A,waves} = 1366 \times (5.3 + V_S) \times \left(\frac{B\times T}{L_{pp}}\right)^{0.75} \qquad (2)$$

The wind and wave resistance values are obtained as 52 kN and 285 kV, respectively. When operating in adverse weather conditions, propeller loads increase and efficiency decreases. Therefore, operation at a speed of 4 knots requires an electrical power of 2.1 MW with an efficiency of 33%. When using a battery pack for procuring 20% of this power demand, it supplies 2.1×20×48 (h) = 20.2 MWh during a 48-h storm. Three scenarios 250, 500 and 1000 $/kWh are defined for battery installation cost, which results in 5, 10 and 20 million $, respectively.

6. Optimal sizing of various energy storages in PVs-diesel engines driven ships

In [22], a hybrid drive train is proposed for application in green maritime industry, as shown in Fig. 10. It consists of PV panels, DC/DC and DC/AC converters, diesel generating units, and hybrid storage technologies such as lithium-ion battery, lead-acid battery, and supercapacitors. The length, width, and height of the oil tanker as well as its deadweight are assumed to be 332.95 m, 60 m, 30.5 m, and 1,000,000 tons, respectively. The life time, rated power, and investment cost of the PV panels are respectively considered as 25 years, 145 W, and 2000 USD/kW. In addition, the energy efficiency, length, width, and thickness of each PV panel are considered to be 17%, 1.01, 0.99, and 0.25 m. The technical characteristics of the hybrid energy storage system are reported as Table 6. Optimal power and capacity of three battery storage units are obtained as Table 7. Four cases are studied to find the total investment cost of the PVs-diesel-battery driven hybrid ship either with one storage pack or three ones simultaneously. Lead-acid batteries have widely been used in marine industry for decades. They offer higher power density and less expensive compared to Li-ion and supercapacitors as advantages. But they have some drawbacks such as lower energy density resulting in larger and heavier battery packs and shorter lifecycle compared to Li-ion batteries. Li-ion batteries have also gained popularity in electric ships due to their higher energy density and longer lifecycle. Ultracapacitors offer higher power density and fast charge-discharge capabilities in marine industry. Regenerative braking and peak power delivery for maneuvering and dynamic positioning are two main advantages of these storage technology in electric ships. Lower energy density and higher investment costs of supercapacitors are their drawbacks in comparison with batteries.

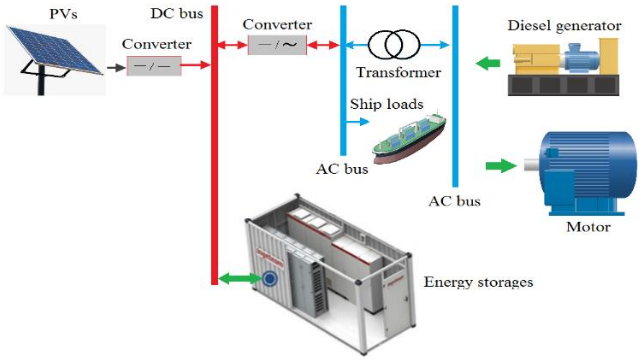


Fig. 10. The structure of the hybrid power train for optimal sizing of the li-ion battery, supercapacitor, and lead-acid battery

Table 6. Battery energy storage data

Battery	Shortest response time	Maximum response frequency (Hz)	Power cost ($/kW)	Energy cost ($/kWh)
Lead-acid	1 min.	0.0167	200	300
Li-ion	30 sec.	0.0333	1000	500
Supercapacitor	1 sec.	1	300	2000

Table 7. Power and energy capacity of battery energy storages

Battery type	Power (kW)	Energy (kWh)	Times of cycle
Lead-acid	118.63	1709.2	2387
Li-ion	43.658	1709.2	2983
Supercapacitor	130	0.042	5088

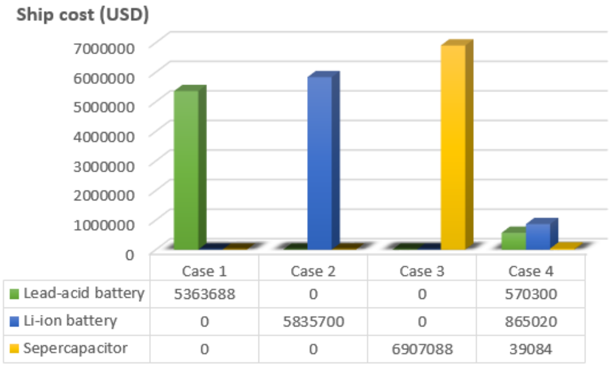


Fig. 11. The total investment cost of the hybrid electric ship at four cases studied

7. Basic components and auxiliary equipment in hybrid ships

The diesel engines used in the marine industry, usually utilize the heavy fuel oil (HFO), which is extracted from the distillation of crude oil. HFO, also known as heavy oil, marine fuel, bunker oil, furnace oil, or gas oil, is a fraction achieved from the distillation of petroleum such as the crude oil. The HFO consists of the lighter fractions as distillates and the heavier ones as residues. The crude oil extraction locations affect its impurities and chemical composition. Generally, it includes any liquid fuel for burning in a furnace or boiler to produce heating energy, or used by ICE to generate power.

Some impurities of HFO are stated as water, deposits, sodium, vanadium, oxidation materials like gums and varnishes, Sulphur, alumina salts, hydrogen sulphide, and silica. The HFO flash point is 62°F, making it dangerous to carry in huge volumes. Moreover, the viscosity of the HFO is limited to 180-700 centistokes under temperature of 50°C. The pour temperature of HFO is around 30°C, requiring to be heated while transporting from one place to anywhere inside or outside of vessels or ships. The HFO of diesel engines is stored in steel double bottom tanks and heated by passing steam through tubes embedded inside these tanks for transferring to oil purification unit and then entering main tank supplying ICE.

The oil purification subsystem composes of filtering units, settling tanker, and centrifuges. This purification infrastructure extracts a dirty oil or oil-water mixture together with sludge, which are removal from operation cycle. An oil lubrication closed cycle is run for ICE parts, where should be cooled and repeated. In a same manner, ICE is cooled by the desalinated water. The waste heat extracted from the flue gases is recovered by a boiler for generating power using the steam turbine-generator set. The single line diagram of the conventional marine propulsion systems is shown in Fig. 12 [23].

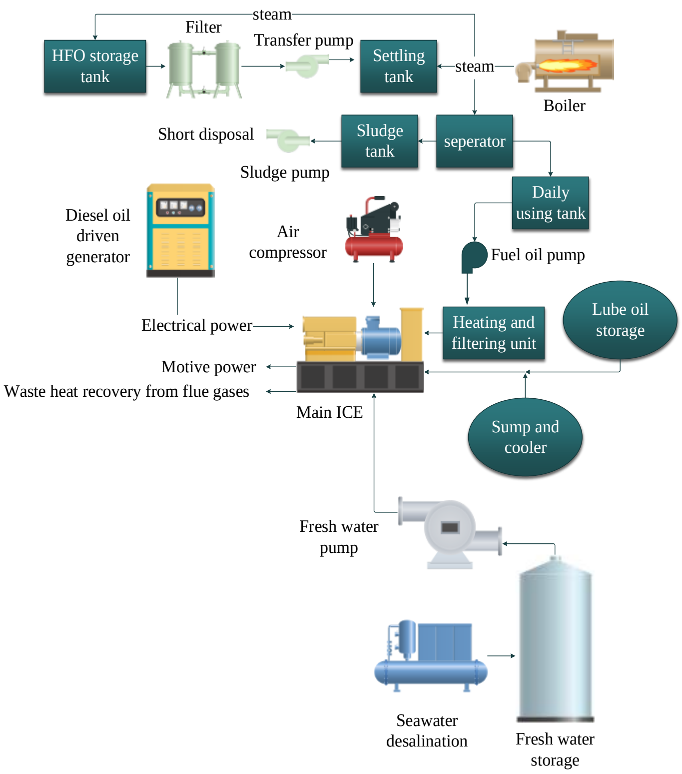


Fig. 12. The single line diagram of the conventional marine propulsion systems

Temperature of exhaust flue gases changes from 300 to 490°C. Some equipment such as ICE cylinders and fuel nozzles are heated and needed to be cooled using the pure water. A heat exchanging unit is also considered to cool the fresh water by the seawater circulating on the fresh water tubes. The pure water temperature entering the ICE is normally about 70°C and its outlet temperature reaches to 85°C. The desalinated water is not only used for domestic applications such as drinking, cooking, washing, and sanitary, but also for steam generating inside the boiler. All vessels and ships should have a seawater desalination system because it is not possible to carry all pure water demand. The temperature of seawater consumed for the fresh water-cooling process reaches to 45℃ and returns to sea. The schematic presentation of seawater and fresh water applications in marine propulsion systems is illustrated in Fig. 13.

For starting both main and auxiliary ICEs, the compressed air at 30 bar pressures should be entered to the cylinders, which turns pistons and activates combustion. At running operating condition, the compressed air pressure reduces to 7 bar aiming to control the combustion process. Therefore, some air compressors with sufficient capacities are carried by hybrid ships to ensure their reliable operation. All marine applications of air compressors are shown in Fig. 14. For lubricating the ICE parts such as its crank shaft and piston cam shafts, there is an oil lubrication unit within engine sink, as shown from Fig. 15. According to [23], it can be observed that ICEs such as diesel engines carry various auxiliary machineries to operate reliably and securely. Diesel engines with speeds up to 400 rpm can fueled by HFO, while others with a medium-speed range of <1500 rpm need less viscosity values than marine diesel oil [23].

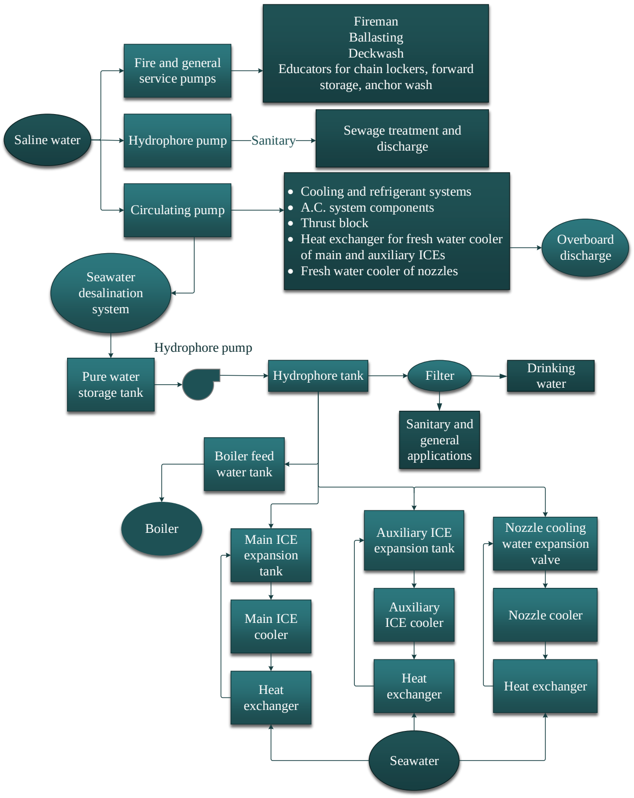


Fig. 13. The schematic presentation of seawater and fresh water circulation routes in marine propulsion systems

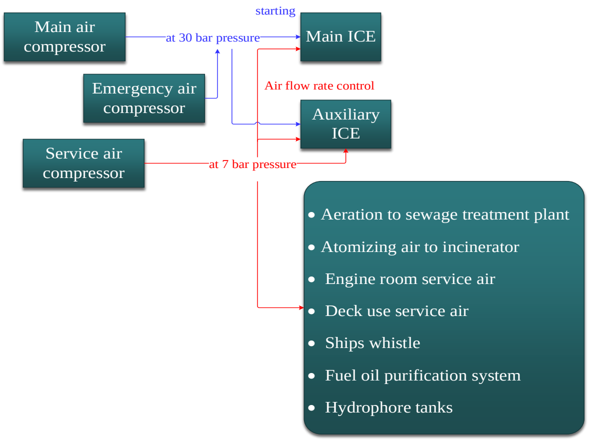


Fig. 14. All applications of air compressors in marine industry

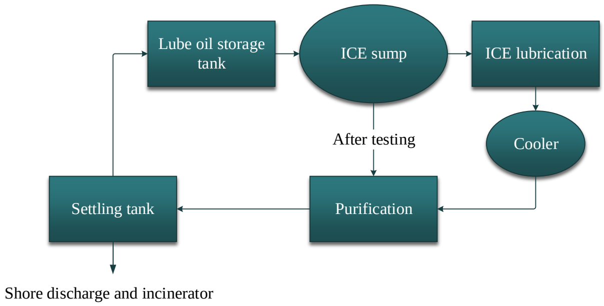


Fig. 15. The oil lubrication process

The total energy consumption of ships powered only by conventional diesel engines or by hybrid engines is complex. The main objective of the vessels or ships is to transport a cargo between two points for several days or months. Hence, some auxiliary equipment, personnel and a hotel are needed for this transport. Figure 16 demonstrates the energy flows in the marine propulsion systems. The chemical energy of the heavy fuel oil is utilized by the main ICE while the marine diesel oil is consumed by the auxiliary machinery such as the steam power plants and the pure water generation circuit. A propeller, as a hydrodynamic device, then converts this energy flow into a form useful for ship motion.

The chemical energy input of the main ICE is procured by the heavy fuel oil. The net power of the propulsion system is delivered to the shaft in the form of motive power. The largest energy losses occur in as the heat rejection by the exhaust gases, circulating cooling water, and lubricating oil loss. Generally, the thermal efficiency of the main ICE changes from 49 to 51 %. The overall energy efficiency of the entire ICE propulsion system with its auxiliaries is between 48 to 50%. The energy efficiency of the ship shaft depends on the number of bearings and the type of gearbox, which varies from 95 to 98%. The propeller efficiency is considered as 55-60%. The overall energy efficiency of the ship propulsion system varies between 25 to 30%. More details on energy efficiency of different components of diesel engines only driven ship propulsion systems are presented in Table 8. Table 9 provides a comprehensive point of view on interdependency between different parameters of ships and affected characteristics.

Table 8. Energy efficiency of different components of diesel engines driven propulsion systems

Machinery	Energy efficiency (%)	Features
Marine diesel engines	49-51	Thermal efficiency
DG set	45	Diesel engine and AC generator
Main ICE with support elements	48-50	Supporting electrical power of auxiliary equipment
Shaft	95-98	Depending on number of bearings and gears
Propeller	55-65	Based on propeller loading point
Hull	100	With minimum effective power in trial condition
Overall propulsion system	25-30	Effective/chemical power input to ship via oil

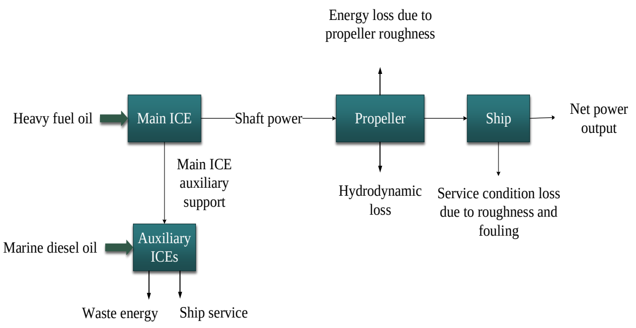


Fig. 16. The energy flows of the marine propulsion systems

Table 9. Interrelationship between the structural parameters of electric ships

Parameter	Affected by	Impacts on ship performance
Displacement	Deadweight or payload capacity	Size of vessel
Length (L)	Ship displacement speed	Resistance Longitudinal strength Hull volume Seakeeping ability or seaworthiness Maneuverability Investment cost
Breadth (B)	Length (L/B≤4 for small vessels and up to 6.5 for merchant ones)	Resistance Longitudinal strength Seakeeping ability or seaworthiness Maneuverability Investment cost
Depth (D)	Breadth (B/D between 1.7 and 2.5)	Longitudinal strength Transverse stability Freeboard Hull volume Investment cost
Draught (T)	Breadth and depth (Normally 2.5≤B/T≤3.75 and for heavily draught limited vessel reaches to 5)	Resistance Transverse stability Freeboard Seakeeping ability or seaworthiness Displacement
Depth-draught ratio (D/T)	Type of ship and freeboard	Seakeeping ability or seaworthiness
Length-depth ratio (L/D)	Type of ship and freeboard (L/D varies from 10 to 14)	Longitudinal strength Hull deflection

Some aspects, which should be considered in design of ships or vessels, are stated in Fig. 17.

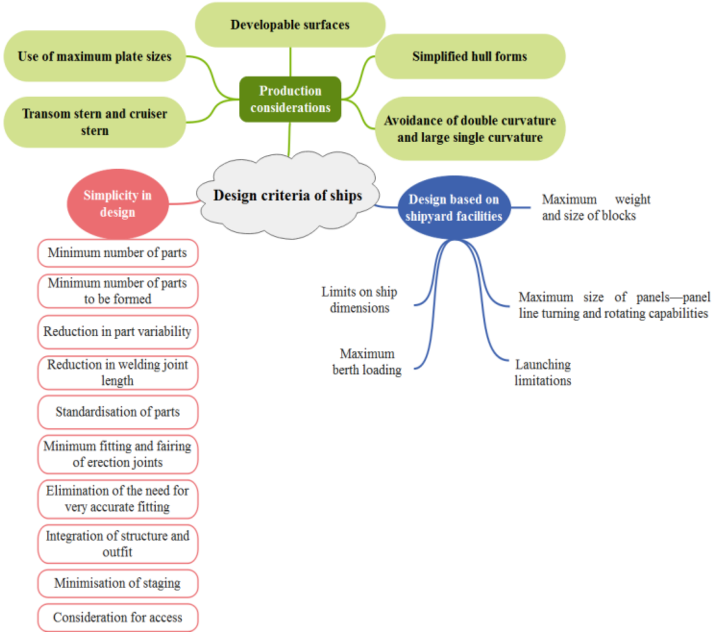


Fig. 17. Some key factors in efficient design and production of ships and vessels

8. Steam-gas combined cycle for electric propulsion of a passenger vessel

In [24], an eco-environ model is proposed for evaluation of diesel engines driven and gas-steam combined propulsion systems in passenger ships. A novel passenger ship for Holland-America line was designed with 82,897 gross tonnage [25]. Table 10 summarizes the technical specifications of the cruise ship. As reported in Table 10, the total power generation capacity is 51.48 MW, which supplies the electric propulsion system and the hotel's energy need. The electric propulsion system includes two ABB Azipod propellers coupled with two 17.2 MW electric motor drives. Maximum electrical power required for hotel is equal to 4 MW. Two operating options are considered for this cruise: (a) diesel engines driven mode and steam-gas combined cycle for propulsion system, which is shown in Fig. 18.

Table 10. The features of the cruise ship for application in Holland-America line

Total gross tonnage (g.t.)	82,897
Length (m)	285
Beam (m)	32
Draught (m)	7.8
Service and maximum speeds of ship (knots)	22 and 24
Number of passengers	2,366
Number of crew	820
Total electrical power facility (MW)	51.84

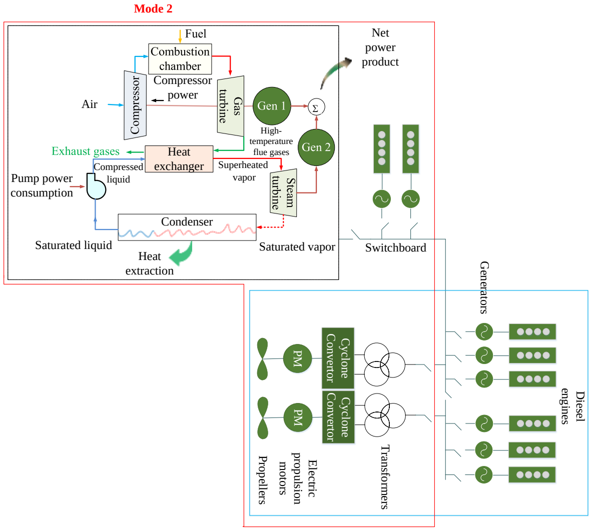


Fig. 18. The single line diagram of the diesel engines/gas-steam combined drive train of the cruise ship

As depicted in Fig. 18, six diesel engines in combination with six generators are used for driving ship in mode 1. The propellers are powered via the step-down transformers reducing the voltage level and improving the starting torque. The frequency requirement of the electric propulsion motors (PMs) is regulated by the cyclone convertors (CCs). The total generated power is equal to 51.48 MW. In mode 2, a steam-gas combined cycle cooperated with diesel units to power propellers [26, 27]. A sailing route from Vancouver port to Tokyo port (travelling distance 10,560 nm during 20 days) has been travelled [28]. In operating mode 1, the specific fuel consumption of the diesel engines is 155.6 g/kWh to generate 51.48 MW of electrical demand for the hotel loads and propulsion system [29]. In this case study, the nominal energy efficiency of the diesel engines was 41.3%. In mode 2, a combined cycle power generation train (LM2500 General Electric model) is used for driving the propellers. In this case study, the specific fuel consumption, power generation, and energy efficiency of the propulsion system were found to be155.6 g/kWh, 43.9 MW, and 54.2%, respectively [30]. In case study 2, two diesel engines with 400 kW power generation, 204 g/kWh SFC and 41.3% energy efficiency are used for providing the rest of the required electrical power [31].

9. A diesel engines and energy storage-based series hybrid propulsion system for application in mid-size ferries

Authors of [32] designed and investigated a series hybrid propulsion system shown in Fig. 19. Four ICEs fueled by the marine diesel oil are installed as the main power source. The specific fuel consumption of the diesel engines is modeled using a polynomial fuel-power curve [33, 34]. A battery energy storage with parameters listed in Table 11 is used for peak shaving [35].

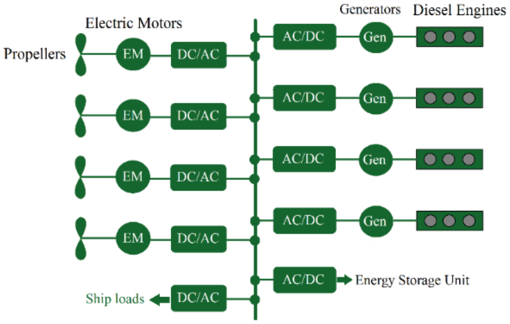


Fig. 19. The series hybrid drive train composed of diesel engines and electrical energy storage unit

Table 11. The parameters of the battery energy storage

Feature	Cell	Pack
Rated power (Ah)	41	615
Nominal voltage (volt)	3.6	720
Number of series and parallel	-	22/15

More details on battery cell resistance, charging and discharging powers as well as its maximum SOC can be found in [35]. Skeena Queen ferry is powered by 4 ICEs with power products of 6000hp, travels from Fulford harbor to Swartz port. Its passenger and cargo capacities are 92 cars and 450 passengers. Operational durations of leaving Swartz Bay, docking in Fulford harbor, leaving Fulford harbor, and docking in Swartz Bay are equal to 28, 15, 29, and 15 minutes, respectively. When operating in docking condition, battery energy storage procures on-peak electrical demand by discharging power. In sailing operating condition, diesel engines integrated with electric generators supply loads by increasing the output power of two ICEs into their generation capacities to charge battery. The lower and upper limits of the SOC of battery as well as its initial state are assumed to be 0.5, 0.9 and 0.7 p.u., respectively. According to [36], the energy transportation will be carried out using the conventional wired drive trains and the high-density energy storages such as battery packs and energy beams. It should be noted that the energy beams and wired systems enables operators to deliver electricity to loads in real time. The energy storage units with the capability of energy storing near to loads, impose the delay in transferring electricity in land, sea and air transportation infrastructure. In 2012, the storage density of the lithium-manganese batteries was 266 kWh/ton. Hence, 38,000 liters or 10,000 gallons of diesel fuel is utilized for 800 km (500 miles) transportation in $15/MWh. Hence, battery drive trains were not economical in this year. For more economic benefits of battery drive trains, higher density of storage mediums such as nuclear ones will be required instead of hydrogen and other fuels.

10. Real cases of electric and hybrid ships and vessels

In this section, a comparative analysis of recently developed full-electric and hybrid ships/vessels, and their advantages/disadvantages as well as capacity properties and applications in marine industry are presented in Table 12.

Table 12. Recent progresses on pure-electric and hybrid ships and vessels in different countries

Ref.	Ship vessel	Advantages	Disadvantages	Country year
[37]	Waterjet	• Converting 5 vessels from controllable pitch propeller to waterjet propulsion and advanced control • Supports more than 80 offshore wind farm vessels.	Limited driving time (up to one week)	Norway 2020
[38]	Battery coupled electric ship	• Long-range full-electric cargo ship • Zero-emission for protecting seawater and air • Lower transportation time and fuel consumption	Limited transit distance compared with hybrid ships	U.S. 2023
[39]	USNS Vindicator	• Four molten carbonate fuel cell stacks are used instead of diesel engines. • 2.58 MW power capacity	-	U.S. 2000
[40]	Viking Lady	H_2, liquefied natural gas, and CH_3OH are used by molten carbonate fuel cells.	For small-scale application (with 330kW power capacity)	Norway 2009
[41, 42]	Yacht	• Four 1.2 kW proton-exchange membrane fuel cell stacks are integrated with nine 20 kW lead-acid batteries. • Consumption of H_2 as a clean and renewable fuel	Suitable for short distances due to 24.8 kW power generation capacity	Japan 2003
[43]	SchIBZ	• Converting the diesel fuel into H_2 • Using H_2 by the solid oxide fuel cells	Limited power capacity (100 kW) and short transportation distance	Germany 2017
[44]	PAXell	• Diesel fuel and CH_3OH enter to high-temperature proton-exchange membrane fuel cells. • Increase power capacity by adding fuel cell stacks.	Less than 120 kW power capacity	Germany 2009

11. Concluding remarks and future trends

Maritime transportation has the great importance in the international economy, as 80% of the consumers' goods are transferred using vessels and ships. Similar to other transportation vehicles, conventional fossil fuels based ships release hazardous gasses such as CO_2, NO_x, and SO_x, which contribute to global climate change and acidification. The International Maritime Organization (IMO) estimated that ships and vessels produced 1.4 billion metric tons of CO_2 in 2020. Global carbon footprint in marine industry has grown by 4.9% by 2021. Hence, the IMO has agreed to reduce carbon emissions from marine ICEs up to 40% by 2030. In the meantime, the electrification of vessels and ships with renewable energy sources such as photovoltaic systems, wind turbines, ocean waves, tidal turbines, hydroelectric generators, and energy storage technologies like batteries, undersea compressed air storage, underwater hydro energy storage, and etc., play a key role in achieving the IMO target. This paper introduced some pure-electric or hybrid propulsion systems to present benchmark cases for future studies. In addition, some real electric and hybrid ships were introduced focusing on their structure, main drive train components, fuels, power generation capacity, pros and cons of their propulsion systems. Tidal and ocean wave energy conversion systems as well as underwater hydro turbines are promising technologies which can be deployed in specific/optimal locations, such as coastal charging stations, to recharge battery packs of ships/vessels and improve their reliability and energy efficiency. Abandoned oil and gas wells close to beaches are good candidates for developing a geothermal heat-reservoirs based power generation system and procuring energy required by the batteries of pure electric ships. Moreover, application of 100% hydrogen-burning ICEs in hybrid drive train is another solution for reducing pollutions made by natural gas fired steam-gas combined cycle. Cogeneration of hot water and heat is another benefit of a fully hydrogen-powered gas turbine which can deeply be investigated in design, development, and deployment of hybrid propulsion systems for ships and ferries.

References

[1] S. Qazi *et al.*, "Powering maritime: Challenges and prospects in ship electrification," *IEEE Electrification Magazine,* vol. 11, no. 2, pp. 74-87, 2023.

[2] J. Emblemsvag, "The electrification of the marine industry," *IEEE Electrification Magazine,* vol. 5, no. 3, pp. 4-9, 2017.

[3] M. Hayton, "Marine electrification is the future: A tugboat case study," in *Smart Rivers*: Springer, 2022, pp. 868-879.

[4] A. J. Sorensen *et al.*, "Toward safer, smarter, and greener ships: Using hybrid marine power plants," *IEEE Electrification Magazine,* vol. 5, no. 3, pp. 68-73, 2017.

[5] R. Geertsma, R. Negenborn, K. Visser, and J. Hopman, "Design and control of hybrid power and propulsion systems for smart ships: A review of developments," *Applied energy,* vol. 194, pp. 30-54, 2017.

[6] D. Paul, "A history of electric ship propulsion systems [history]," *IEEE Industry Applications Magazine,* vol. 26, no. 6, pp. 9-19, 2020.

[7] Y. He, A. Fan, Z. Wang, Y. Liu, and W. Mao, "Two-phase energy efficiency optimisation for ships using parallel hybrid electric propulsion system," *Ocean engineering,* vol. 238, p. 109733, 2021.

[8] O. B. Inal, J.-F. Charpentier, and C. Deniz, "Hybrid power and propulsion systems for ships: Current status and future challenges," *Renewable and Sustainable Energy Reviews,* vol.

156, p. 111965, 2022/03/01/ 2022, doi: https://doi.org/10.1016/j.rser.2021.111965.

[9] J. P. Trovão, F. Machado, and P. G. Pereirinha, "Hybrid electric excursion ships power supply system based on a multiple energy storage system," *IET Electrical Systems in Transportation,* vol. 6, no. 3, pp. 190-201, 2016/09/01 2016, doi: https://doi.org/10.1049/iet-est.2015.0029.

[10] M. Huang, W. He, A. Incecik, A. Cichon, G. Królczyk, and Z. Li, "Renewable energy storage and sustainable design of hybrid energy powered ships: A case study," *Journal of Energy Storage,* vol. 43, p. 103266, 2021/11/01/ 2021, doi: https://doi.org/10.1016/j.est.2021.103266.

[11] Y.-R. Kim, J.-M. Kim, J.-J. Jung, S.-Y. Kim, J.-H. Choi, and H.-G. Lee, "Comprehensive Design of DC Shipboard Power Systems for Pure Electric Propulsion Ship Based on Battery Energy Storage System," *Energies,* vol. 14, no. 17, p. 5264, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/17/5264.

[12] A. Bakdi, N. B. Kristensen, and M. Stakkeland, "Multiple Instance Learning with Random Forest for Event Logs Analysis and Predictive Maintenance in Ship Electric Propulsion System," *IEEE Transactions on Industrial Informatics,* vol. 18, no. 11, pp. 7718-7728, 2022, doi: 10.1109/TII.2022.3144177.

[13] C. Park *et al.*, "Live-Life cycle assessment of the electric propulsion ship using solar PV," *Applied Energy,* vol. 309, p. 118477, 2022/03/01/ 2022, doi: https://doi.org/10.1016/j.apenergy.2021.118477.

[14] C. Park, B. Jeong, and P. Zhou, "Lifecycle energy solution of the electric propulsion ship with Live-Life cycle assessment for clean maritime economy," *Applied Energy,* vol. 328, p. 120174, 2022.

[15] N. Shakeri, M. Zadeh, and J. B. Nielsen, "Hydrogen Fuel Cells for Ship Electric Propulsion: Moving Toward Greener Ships," *IEEE Electrification Magazine,* vol. 8, no. 2, pp. 27-43, 2020, doi: 10.1109/MELE.2020.2985484.

[16] T. Tarasiuk, P. Jankowski, V. Shagar, A. Piłat, M. Górniak, and J. Nowak, "Comparative Case Study on Oscillatory Behavior in Power Systems of Marine Vessels With High Power Converters," *Frontiers in Energy Research,* vol. 8, p. 394, 2021.

[17] P. Ghimire, M. Zadeh, J. Thorstensen, and E. Pedersen, "Data-Driven Efficiency Modeling and Analysis of All-Electric Ship Powertrain: A Comparison of Power System Architectures," *IEEE Transactions on Transportation Electrification,* vol. 8, no. 2, pp. 1930-1943, 2021.

[18] G. Sulligoi, A. Vicenzutti, and R. Menis, "All-electric ship design: From electrical propulsion to integrated electrical and electronic power systems," *IEEE Transactions on transportation electrification,* vol. 2, no. 4, pp. 507-521, 2016.

[19] [Online]. Available: https://www.caranddriver.com/features/a41103863/hydrogen-cars-fcev/.

[20] (2015). *Guidelines for the assessment of speed and power performance by analysis of speed trial data*.

[21] "Draft revised guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions," SHOPERA-project and JASNAOE, 2017.

[22] S. Wen *et al.*, "Optimal sizing of hybrid energy storage sub-systems in PV/diesel ship power system using frequency analysis," *Energy,* vol. 140, pp. 198-208, 2017.

[23] M. White, "Liquefied gas handling principles on ships and in terminals; 2," 1996.

[24] N. R. Ammar and I. S. Seddiek, "Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: case study passenger vessel," *Environmental Science and Pollution Research,* vol. 28, no. 28, pp. 37851-37866, 2021.

[25] "Oosterdam passenger vessel information," *Marine Traffic,* 2020. [Online]. Available: https://www.marinetraffic.com/en/ais/details/ships/shipid:260088/mmsi:245417000/imo:9221281/vessel:OOSTERDAM.

[26] V. Mrzljak and T. Mrakovčić, "Comparison of COGES and diesel-electric ship propulsion systems," *Pomorski zbornik,* no. 1, pp. 131-148, 2016.

[27] S. Grzesiak, "Alternative propulsion plants for modern LNG carriers," *New Trends in Production Engineering,* vol. 1, no. 1, pp. 399-407, 2018.

[28] "Cruise line and voyages," *Holland America Line,* 2020. [Online]. Available: https://www.hollandamerica.com/en_US.html.

[29] "Wartsila energy solutions," *WARTSILA,* 2020. [Online]. Available: https://www.wartsila.com/docs/default-source/power-plantsdocuments/pps-catalogue.pdf.

[30] "General Electric LM2500 power plants
" 2019. [Online]. Available: https://www.ge.com/content/dam/gepower/global/en_US/documents/gas/gas-turbines/aero-products-specs/lm2500-60hzfact-sheet-product-specifications.pdf.

[31] "Diesel generator 4000 ekW, 5000 kVA,60 Hz, and 900 rpm," *CAT,* 2012. [Online]. Available: https://s7d2.scene7.com/is/content/Caterpillar/CM20170906-16192-28043.

[32] Y. Feng, L. Chen, and Z. Dong, "Modeling, Simulation and Assessment of a Hybrid Electric Ferry: Case Study for Mid-Size Ferry," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2019, vol. 59292: American Society of Mechanical Engineers, p. V009T12A028.

[33] F. Jabari, H. Arasteh, A. Sheikhi-Fini, and B. Mohammadi-Ivatloo, "Optimization of a tidal-battery-diesel driven energy-efficient standalone microgrid considering the load-curve flattening program," *International Transactions on Electrical Energy Systems,* vol. 31, no. 9, p. e12993, 2021.

[34] F. Jabari, M. Nazari-Heris, B. Mohammadi-Ivatloo, S. Asadi, and M. Abapour, "Toward energy-efficient microgrids under summer peak electrical demand integrating solar dish Stirling heat engine and diesel unit," *Journal of Energy Management and Technology,* vol. 4, no. 3, pp. 23-29, 2020.

[35] "Autonomie Vehicle System Simulation Tool," *Argonne National Laboratory,* 2019. [Online]. Available:

https://www.anl.gov/es/autonomie-vehicle-system-simulation-tool.

[36] S. GRID, "IEEE GRID VISION 2050."

[37] "https://www.oedigital.com/news/479051-waterjets-refit-for-five-offshore-wind-vessels," 2020.

[38] "https://www.fleetzero.com/," 2023.

[39] "USNS Vindicator," 2018. [Online]. Available: https://en.wikipedia.org/wiki/USNS_Vindicator_(T-AGOS-3).

[40] "Viking Lady offshore supply vessel," 2018. [Online]. Available: http://www.ship-technology.com/projects/viking-lady.

[41] A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson, "Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship," *International Journal of Hydrogen Energy,* vol. 42, no. 1, pp. 623-635, 2017.

[42] M. F. GmbH, "First yacht with certified fuel cell propulsion," *Fuel Cells Bull.,* vol. 2003, pp. 4-5, 2003.

[43] "fischer fuel cells tested in e4ships project in Germany," *Serenergy,* 2018. [Online]. Available: http://www.e4ships.de.

[44] L. van Biert, M. Godjevac, K. Visser, and P. Aravind, "A review of fuel cell systems for maritime applications," *Journal of Power Sources,* vol. 327, pp. 345-364, 2016.