Waterborne Transport. Hybrid Power Supply for Electrification of Port Infrastructures, Shore-to-Ship Power, and Ship Power and Propulsion

Juan Camilo Gomez Trillos and Urte Brand-Daniels

Abstract Hybrid power supply systems integrate the use of different power sources, converters and/or storages for the electrification of maritime applications in order to reduce environmental impacts and contribute to resilience. In the area of port infrastructure, there have been approaches to the hybridisation of RTG cranes, tugs and drayage trucks, which have been equipped with batteries in addition to combustion engines. These approaches can contribute to a reduction in fuel consumption of up to 40% and thus to a reduction in greenhouse gas emissions and air pollutants. With regard to shore-to ship power, there are promising solutions despite the lack of harmonised standards, such as charging with lithium-ion batteries due their high efficiency and power density, as well as battery swapping due to short recharging times and the flexible use of energy from the grid. In the area of hybrid power and propulsion systems, the comparison of diesel engines, fuel cells and batteries shows that diesel engines have lower investment costs, but also lower efficiencies of up to 52% compared to fuel cells with 60%. However, according to the EU HySeasIII project, fuel cells combined with batteries can contribute to a significant reduction in GHG emissions of up to 80%.

Keyword Battery storage · Decarbonization · Energy efficiency · Fuel cells · Maritime sustainability · Resilience

List of Abbreviations

AC	Alternative current
APS	Automated plug-in system
BC	Black carbon
BE	Battery electric
BESS	Battery energy storage system

J. C. G. Trillos (✉) · U. Brand-Daniels
Institute of Networked Energy Systems, German Aerospace Center (DLR), Oldenburg, Germany
e-mail: Juan.GomezTrillos@dlr.de

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CAPEX	Capital expenditures
CCCC	China communication construction co.
CP	Controllable pitch
DBE	Diesel battery electric
DC	Direct current
DCS	Data collection system
DE	Diesel electric
DoD	Depth of discharge
DWT	Deadweight tonnage
EGR	Exhaust gas recirculation
EMSA	European maritime safety agency
ESS	Energy storage system
EU	European Union
FP	Fixed pitch
GHG	Greenhouse gas
GM	Generator/motor
GT	Gross tonnage
HC	Hydrocarbons
HFCBE	Hydrogen fuel cell and battery electric
HFO	Heavy fuel oil
hp	Horsepower
HT-PEMFC	High temperature proton exchange membrane fuel cell
HVSC	High voltage shore connection
IAPH	International association of ports and harbours
IMO	International maritime organization
km	Kilometer
KPI	Key performance indicator
kV	Kilovolts
kW	Kilowatt
LCA	Life cycle assessment
LCC	Life cycle costing
Li-ion	Lithium-Ion batteries
lm	Lane meters
LT-PEMFC	Low temperature proton exchange membrane fuel cell
LVSC	Low voltage shore connection
MARPOL	International convention for the prevention of marine pollution from ships
MDO	Marine diesel oil
MGO	Marine gasoil
MW	Megawatt
MWh	Megawatt-hour
NMC	Nickel-manganese-cobalt Li-Ion battery
NMCA	Nickel-manganese-cobalt-aluminium
NOx	Nitrogen oxides
OPEX	Operational expenditures

OPS	Onshore power supply
PGM	Platinum-group metals
$PM_{2.5}$	Particulate matter 2.5 µm
PMS	Power management system
RoPax	Roll on/roll off and passenger ferry
RoRo	Roll on/roll off ferry
RTG	Rubber tired gantry crane
SBC	Shore-side battery charging
SBC-BS	Shore-side battery charging—battery swapping
SFOC	Specific fuel oil consumption
SPB	Shore-side power banks
SOFC	Solid oxide fuel cell
SOx	Sulphur oxides
SSE	Shore-side electricity
STS	Shore-to-ship
TEN-T	Trans-European transport network
TEU	Twenty-foot unit container

1 Introduction

Worldwide seaborne trade totaled 12,027 million tons in 2022, declining slightly by 0.4% in that year. However, a growth rate of 1.2% was recorded for 2023 and an expansion beyond 3% between 2024 and 2028 is expected (United Nations Conference on Trade and Development 2023). A growth trend will likely continue in the future. In addition to freight transport, maritime passenger transport is also growing, although it was significantly affected by the COVID pandemic. The passenger volume reached 31.7 million passengers in 2023, surpassing by 7% the pre-pandemic level in 2019. Moreover, a 10% increase in capacity is forecasted for the years 2024 through 2028 (Cruise Lines International Association 2024).

The Fourth Greenhouse Gas (GHG) Study by the International Maritime Organization (IMO) estimates that maritime shipping contributed approximately 2.8% to the global anthropogenic CO_2 emissions in 2018 (Faber et al. 2020). More recent statistics from the IMO Data Collection System (DCS) platform gives account of a fuel consumption totaling 212.3 million tons in 2021, resulting in estimated emissions of 660 million tons CO_2 after considering emission factors for different fuels (Marine Environmental Protection Comittee 2022). In comparison, worldwide anthropogenic CO_2 emissions were estimated at 36,816 million tons (Ritchie and Roser 2024). While operational and technical measures have led to decrease in energy intensity and higher efficiency, these gains have been outpaced by the growth of the sector, therefore leading to increase of the of the total emissions produced by this industry, what could lead to a higher impact in the future and a higher share of the total CO_2 emissions. In addition, maritime transportation has considerable challenges for its transition and a complete fleet renovation or retrofitting is expected to take several decades.

Although ships and their propulsion systems are often cited as the main source of emissions, the issue is much more complex. The maritime sector involves not only the water transportation activity itself, but also the activities occurring while ships are at berth as well as the handling of cargo and passengers at ports which can contribute massively to the environmental impact (Park 2022). On one side, the IMO is responsible for developing and maintaining international regulations for maritime shipping at international level. On the other side, port infrastructure and their regulations tend to be managed locally by each country. This leads to different regulations in force both on board or on shore.

In addition to the considerable pollution caused by cargo handling and passenger activities at ports, ships at berth have also considerable emissions. At berth, although the ship propulsion is not operating, other systems onboard require power. Often these systems are lighting, air conditioning, electronic systems and any load due to cargo handling. Thus, it is estimated that ships at berth emitted between 7.9 and 10.7 million tonnes of CO_2eq emissions per year between 2018 and 2023 in the EU, which represent a share of between 6.1 and 7.2% of the total emissions of ships bigger than 5000 gross tonnes in the EU (EMSA 2024). However, although ocean-going vessels at port are important contributors to local air pollutants and GHG emissions, some research also has shown that harbor crafts, cargo-handling equipment and heavy-duty diesel vehicles have also relevant emissions, comparable or even higher than those of the ships berthed at port, depending on the analyzed pollutant (Park 2022). Against this background, several of these technological options are being tested, developed and adopted both on as well as offshore to reduce local pollution and in addition GHG emissions of maritime transportation, including electrification, hybridization, and the use of renewable energy sources.

Hybrid power systems, which integrate the usage of multiple power sources, converters and/or storages, offer a promising solution for reducing local pollution and GHG emissions while also improving efficiency. In addition, electrification has been seen as one alternative to integrate renewable energies into the energy supply for waterborne transportation. Typically, hybrid power systems consist of internal combustion engines and energy storage systems including technologies like batteries, supercapacitors or flywheels. Other solutions may include fuel cells or other power-generation technologies (Geertsma et al. 2017; Damian et al. 2022; Inal et al. 2022). On the other hand, hybridization leads to the electrification of operations by the use of multiple power sources that can be integrated as required. It also enables the integration of energy storage systems which, depending on the system specifications, can be used as devices for peak shaving, load balancing and, in some cases, fully electric operation (Kalikatzarakis et al. 2018). In addition to a possible reduction in environmental impacts, this can also increase resilience, e.g. by enabling flexibilization, redundancy, storage options and, to a certain extent, independent operation.

The next subchapters will explore the state of the art of possible hybrid solutions in three key areas going from land to the shore by encompassing freight-handling infrastructure and vehicles/vessels at ports, shore-to-ship power technologies and onboard ship power and propulsion systems. In the latter case, selected key performance indicators (KPIs) for technologies such as traditional internal combustion engines, fuel cells and Li-ion batteries are explained and their possible developments partly up to 2050 are shown. The description of the state of the art will be finally exemplified with a case study of a hydrogen fuel cell and battery hybrid ferry concept previously developed in the project HySeas III.

2 Hybrid Power Solutions at Ports

Ports require extensive freight-handling infrastructure and vehicles. The construction and operation of both infrastructure and vehicles demand significant resources and can lead to considerable air pollution and in general environmental impacts. Traditionally, ports rely on local electrical grids for lighting, and to certain degree for equipment operation. On the other hand, Fossil fuels are used for heavy machinery like cranes and container handling equipment. With the need to reduce the emissions, minimize the local pollution and move towards sustainability, ports are increasingly electrifying their operations and integrating renewable energy sources like photovoltaic panels and wind turbines into their energy supply.

According to a survey of the International Association of Ports and Harbours (IAPH), 45% of the port investments in solar and wind energy are being executed timely, although also 46% of the surveyed replied that they currently do not have any planned investments in this subject (Notteboom and Pallis 2023). Energy Storage Systems (ESS) such as electrochemical batteries are also being used for the storage of fluctuating renewable energies and ensure a constant power supply and peak shaving, both for stationary as well as for mobile applications (Kermani et al. 2021). Alternative fuels or complete electrification are also envisioned to replace fossil fuels used in the operation.

In this context, hybrid solutions that combine multiple generation and storage technologies are becoming increasingly relevant as a potential alternative to systems powered only by fossil fuels. In the next section, the hybridization trends of three vehicles types commonly used in freight ports, rubber-tired gantry cranes, tugs and drayage trucks, will be analyzed exemplarily.

2.1 Rubber Tired Gantry (RTG) Cranes

Rubber Tired Gantry (RTG) cranes are used to move and store containers at ports. RTG cranes are mainly powered by diesel engines coupled with electric generators to provide the power to lift the containers (Starcrest Consulting Group LLC 2012; Antonelli et al. 2017). A typical RTG Crane is shown in Fig. 1, where the exhaust of the diesel engine can be seen as a vertical rising pipe to the right of the crane. The potential energy of the containers lifted is later dissipated during descent in resistive loads (Antonelli et al. 2017). Adding an energy storage allows the storage of the—otherwise—dissipated energy for further use later as lifting power. As the power for lifting containers can be partially supplied by the energy storage, a smaller generator can power the RTG crane and operate at an optimal point. This contrasts with the traditional operation for which the generator has to operate at multiple operational points. Statistics on the emissions of RTG cranes at the Ports of Long Beach and Port of Los Angeles, where some hybridization was tested more than a decade ago, show that approximately 11% of nitrogen oxides (NO_x) emissions and 9% of particulate matters (PM) from cargo handling equipment is emitted by RTG cranes (Starcrest Consulting Group LLC 2012).

Several projects have tested hybridization as one alternative to decrease the emissions and fuel consumption of these cargo-handling equipment. Recent research carried out by Antonelli et al. analyzed the typical operational loads of RTG cranes in the port of Livorno in Italy and potential savings that a hybrid system including electrochemical storage or supercapacitors combined with traditional diesel internal combustion engines could offer (Antonelli et al. 2017). By means of the collected data and simulations, this study identified the possibility of downsizing the internal combustion engine installed in the RTG crane from the original 414 kW. The main advantage of this is the operation of smaller engines for longer time at the design point. However, smaller engines have often poorer fuel specific fuel consumption

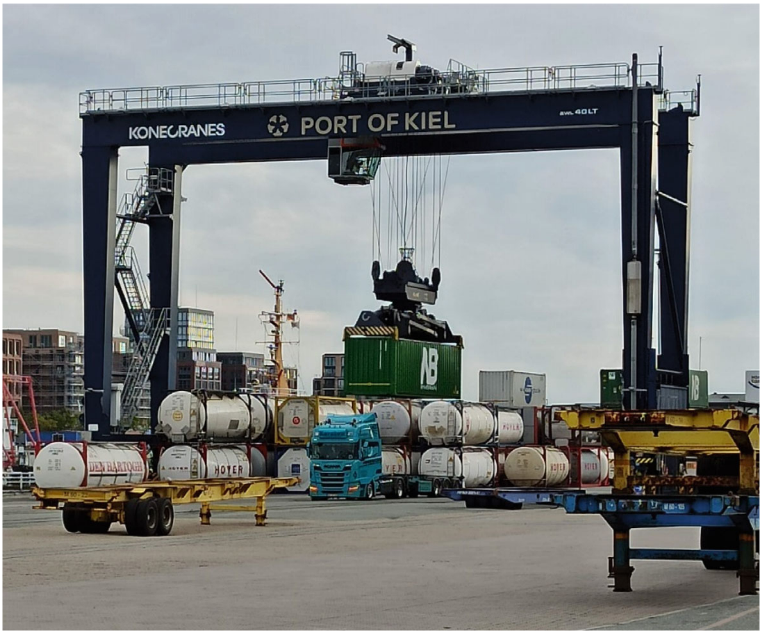

Fig. 1 Typical RTG crane at the Port of Kiel, Germany. The crane shown is not hybrid but has a similar function as the one shown in the figure (own figure)

compared to the bigger engines, what partially offsets the savings of operating the engines at their design point. The authors also analyzed the integration of 83.2 or 44.4 kWh Li-ion batteries with different cell chemistries. With the integration of lithium batteries in hybrid systems compared with systems only including internal combustion engines, the authors identified possible fuel savings from 30 to 60%, depending on the ICE engine sizing (Antonelli et al. 2017). Some costs analyses were carried out by the same authors by comparing a typically 414 kW ICE powered RTG crane with hybrid versions including 414, 165 kW or 36 kW engines in combination with batteries or supercapacitors. The main findings showed that the RTG versions with unmodified engine size have an estimated decrease in fuel costs of around 30%, whereas the engine-downsized versions manage to decrease the fuel costs down to 60%. Although the hybrid RTG versions with unchanged engine size result in a higher purchase cost, hybrid RTG cranes break even within 3–6 years due to the fuel savings (Antonelli et al. 2017). Other analyses carried out by Vlahopoulos and Bouhouras in 2022 confirm the aforementioned results with reductions of up to 33% of fuel consumption and payback times between 1.3 and 3.42 years (Vlahopoulos and Bouhouras 2022).

The implementation of hybrid RTG cranes is transitioning from a research topic into industrial application. Industrial equipment manufacturers already offer hybrid options as part of their standard RTG crane portfolio, claiming fuel savings of up to 40% depending on the operation (Liebherr 2019; Konecranes 2024). Some specifications of the Energy Storage Systems (ESS) installed on hybrid RTG cranes powered by battery systems are summarized in Table 1, with Battery Energy Storage Systems (BESS) systems of comparable size to those mentioned by Antonelli et al. (Corvus Energy 2024a).

Table 1 Reference projects of hybrid RTG cranes of the company Corvus Energy (2024a)

Year	Country	ESS capacity [kWh]	Number of RTG cranes	Location
2015–2016	China	94	20	Hybrid RTG Cranes of China Communication Construction Co. (CCCC) in the ports of Yangshang, Yidong and Waigaoqiao
2018–2020	China	79	48	Hybrid RTG Cranes of China Communication Construction Co. (CCCC) in China
2020	United States of America	170	25	25 hybrid RTG cranes in the of South Carolina

2.2 Tugs

Tugboats or simply tugs are vessels assisting other ships during maneuvers by pulling or pushing them (Wärtsilä 2024). Often these ships have a high power-tonnage ratio allowing them to generate significant thrust at low speed, what is commonly named bollard pull. A typical load profile of a tugboat shows that the engine load is much higher (ten-fold) when assisting another ship than during loitering or waiting (Vu et al. 2015). In efforts to reduce the air pollutants and GHG emissions, tugboats are being progressively electrified or hybridized.

Some industrial electric and hybrid solutions are already available in the market. The company DAMEN offers an electric tug fitted with battery packs with a storage capacity of around 2800 kWh (DAMEN 2024). Wärtsilä has also disclosed the production of thrusters for a 5000 hp (3728 kW) hybrid tug to be used in the Chinese market (Wärtsilä 2022). In addition, the company Rolls-Royce also disclosed the production of an LNG tugboat powered by two 1492 kW MTU gas engines, 2 $\times$ 500 kW electric motors and additionally onboard batteries with 904 kWh capacity for peak shaving during acceleration, maneuver or for electricity supply onboard (Rolls-Royce 2024). The specifications of the tugboats depend on operational aspects and particularly on the bollard pull required for the particular operations and cannot be generalized. More information on ship propulsion and power systems for ships will be explored in subchapter 11.4 (On Board Hybrid Ship Power and Propulsion).

In a study carried in 2010 and in the port of Los Angeles and Long Beach, reductions of emissions and fuel consumption of a hybrid power electric propulsion tugboat compared to a conventional were analyzed (Jayaram et al. 2010). The emissions of PM2.5, NOx and CO_2 emissions for the hybrid tug compared to a conventional tug were found to be 73%, 51% and 27%, respectively. In addition, fuel savings of about 25–28% in favor of the hybrid alternative were described. However, most of the impact was attributed to the use of gensets for propulsion rather than the onboard BESS. Moreover, according to a document published by Siraichi et al. in 2015, the implementation of the hybrid tugboat Tsubasa including 300 kWh lithium iron phosphate BESS onboard led to reductions of 20% in the fuel consumptions as well as in the CO_2 emissions for the operation of the ship compared to a conventional tugboat (Siraichi et al. 2015). According to the commercial producer of Tugboats DAMEN, it's model ASD TUG 2810 Hybrid can provide fuel savings of up to 30% and reduce the NOx, PM, HC and CO emissions by up to 42, 39, 44 and 46%, respectively (DAMEN 2014).

2.3 Drayage Trucks

Drayage refers to short distance transportation of goods, typically containers, within ports or surrounding areas. Containers are often unloaded from or loaded onto a vessel by one or multiple quayside cranes, with a frequency of around one to three minutes. The step either prior or subsequent to this process involves large fleets of trucks, conveying containers from or to the quayside cranes. For example, heavy-duty diesel trucks including drayage trucks accounted for 32, 43, 37 and 49% of the total NO_x, particulate matter ($PM_{2.5}$), carbon monoxide (CO), sulphur oxide (SO_2) and CO_2eq emissions by pollutant at the Port of New York and New Jersey in 2019, respectively (Park 2022).

As in the other cases presented, hybrid solutions are being explored, tested and implemented. Within a demonstration project in the port of Los Angeles in 2017, the company Kenworth developed a hydrogen fuel cell and lithium-ion battery class 8 truck with a 100kWh battery pack and 85 kW fuel cell from the company Ballard. The power of the entire system was rated at 360 kW/480 hp and the range of operation was estimated at 320 km (WaterstofNet 2018a). The company US Hybrid also tested a drayage truck with an 80 kW fuel cell and 30 kWh battery achieving a system power of 367 kW and a torque of 3930 Nm. The estimated range for the truck is 320 km with onboard hydrogen capacity of 25 kg (WaterstofNet 2018b). Furthermore, US Hybrid has also launched a hybrid natural gas-powered drayage truck with over 85 kWh battery capacity and a 8.9-L gas engine and an on-board battery charger of up to 20 kW (US Hybrid 2022). This engine is smaller than the 15-L used in the non-hybrid versions. The range of the truck is around 1000 miles (1600 km) with both compressed natural gas and battery and up to 35 miles (56 km) only with battery. The truck traction power is 340 hp (253 kW). According to the press releases of US Hybrid, the fuel economy of the hybrid drayage truck is as much as double as that of the original 15-L gas engine. However, no absolute numbers have been disclosed.

2.4 Section Concluding Remarks

Hybrid power technologies are being used to mitigate pollution and GHG emissions at port. Solutions for RTG cranes, tugs and drayage trucks were introduced in the former section. Hybridization contributed to the reduction of typically between 20 and 40% of the fuel consumption for RTG and tugboats and drayage trucks. At the same time significant reductions in air pollutants were also described. While specifications vary for each of these applications, a growing trend in the implementation of hybrid systems emerges, as these can decrease fuel consumption, air pollution and GHG emissions. Moreover, established producers of industrial equipment are already offering hybrid options in response to the demand of more sustainable port operations.

3 Hybrid Shore-to-Ship Power Solutions

When ships are berthed at port, they require energy to power their electrical and heat (or cooling) loads. These loads are often referred as hotel loads and frequently not bound to the propulsion system. Electrical loads are typically supplied by onboard diesel generators. Depending on the ship type and size, the hotel loads can fall in a range in the order of hundreds of kW for small ships to the order of tenths of MW for big cruise ships, the latter consuming considerable amounts of electricity for onboard equipment like air conditioning, lighting and other electrical loads. In fact, 25% of the available energy on board of cruise vessels is used for hotel loads (Marzi and Broglia 2019). Typically, diesel generators run on fossil fuels like heavy fuel oil (HFO), marine gasoil (MGO), marine diesel oil (MDO), hydrotreated vegetable oil or even natural gas. Depending on the fuel they burn, these generators can produce considerable amounts of air pollutants, particulate matter and GHG emissions. Although influenced by the manufacturer, engine size, operational point and fuel, typical specific fuel oil consumption (SFOC), falls into the range 180–210 g fuel oil/kWh of electricity generated, which leads to CO_2 emissions of between 575 and 670 g CO_2/kWh of electricity produced onboard (MAN Energy Solutions 2024). In addition, assuming an engine is Tier III—MARPOL Annex VI compliant, the NO_x emissions would be between 2.0 and 3.4 g/kWh (Marine Environmental Protection Comittee 2021). Particulate matter (PM) and black carbon (BC) emissions are in practice below 100 mg/kWh and 50 mg/kWh. However, NO_x, PM and BC emissions are highly dependent on the engine load, being often higher at partial load, which is often the case when ships are berthed (Kuittinen et al. 2024). Therefore, ships at berth are also considerable sources of air pollution and GHG emissions. For comparison, the GHG emissions of PV electricity ranges from 25.2 to 43.6 g CO_2eq/kWh and emissions for the production of electricity from fossil fuel generators can emit up to 1 kg of CO_2eq/kWh of electricity (Stucki et al. 2023).

Shore-Side Electricity (SSE), also known as Shore-to-Ship (STS) power, Onshore Power Supply (OPS) or—in a more traditional way—cold ironing, refers to the supply of electricity from shore to ships while they are berthed. The shore electricity supply allows to turn off the onboard generators, thus reducing the local air pollution. An additional benefit of SSE is the reduction of the net GHG emissions, as long as the electricity supplied from the shore grid or shore-based power supply has lower emissions than that generated onboard. This is particularly the case if renewable energies make an important part of the electricity generation matrix onshore.

According to Article 9 of the EU Regulation 2023/1804, SSE should be available for all passenger seagoing container and passenger ships in Trans-European Transport Network (TEN-T) maritime core ports by the beginning of 2030. This regulation targets container ships, RoRo ferries and passenger ships with a Gross Tonnage (GT) beyond 5000 GT, for which SSE should be used in at least 90% of the port calls (European Parliament and the Council of the European Union 2023). As a result, new solutions for SSE and practical use cases are expected to be developed or rather implemented in the following years.

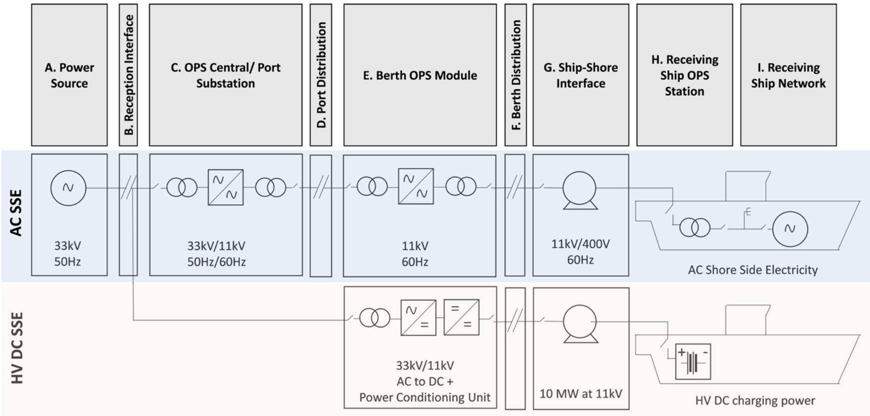

Fig. 2 Architecture of SSE systems considering main component blocks considering AC or DC electricity supply. Adapted from European Maritime Safety Agency (EMSA), 2022ab

The European Maritime Safety Agency (EMSA) produced already guidelines on the subject of SSE equipment, technology, planning and safety (European Maritime Safety Agency (EMSA) 2022a, b). EMSA so far considers different options of electricity supply to ships, including Onshore Power Supply (OPS), Shore-Side Battery Charging (SBC), SBC Battery Swapping (SBC-BS), Shore-Side Power Banks (SPB) and Port Generators.

Figure 2 shows the most important infrastructure components for SSE, focusing on the options OPS and SBC. Additional options using AC and DC SSE supply are shown. SSE consist systems of different components both onshore as well as onboard. Other configurations are also possible.

The different options will be explained to the light of hybrid power systems in the following sections and are described in detail in the current guidelines developed by EMSA (European Maritime Safety Agency (EMSA) 2022a, b). Although the options OPS, SBC and SBC-BS are not necessarily hybrid in nature, they will be explained to understand their differences compared to the other hybrid alternatives.

3.1 Onshore Power Supply (OPS)

OPS consist of the supply of electrical power to ships at berth from a shore-side source, such as the national grid or a local generation system. With this solution, the electricity generation from auxiliary engines onboard can be replaced and the generators turned off while at berth. Two types of OPS are existing; namely, High Voltage Shore Connection (HVSC) and Low Voltage Shore Connection (LVSC). HVSC is suited for ships with high power demand, such as container or cruise ships. It includes a centralized frequency conversion at port substation. However, both the shore side and ship side must be designed and equipped to handle high voltage electricity. The supply on the shore side can be occur at a voltage of 6.6 or 11 kV. Ships must have step-down transformers to adapt the voltage to the one of the distribution networks onboard. In contrast, LVSC is suitable for ships with lower power requirements or not equipped with a step-down transformer onboard. Typical applications of LVSC are service and working vessels or tankers.

A key consideration is frequency conversion, which is necessary in some locations where the local grid operates at 50 Hz, like Europe, Africa or Asia. Most of the ships worldwide have distribution grids operating at 60 Hz, requiring frequency conversion due to incompatibility when ship and local electricity grids have different frequencies. Frequency conversion entails additional costs for SSE infrastructure. The use of OPS could effectively reduce CO_2eq emissions and local air pollutants emissions at ports like SO_x, NO_x and particulate matter emissions, especially if the shore-side electricity is generated with renewable sources.

OPS can be hybrid or non-hybrid depending on the power source (Fig. 2a), which may include the national grid, port generators, renewable energy plants, electrical energy storage or emergency back-up units.

3.2 Shore-Side Battery Charging (SBC)

Shore-Side Battery Charging (SBC) builds on OPS to charge onboard BESS using AC or DC shore power supply. This option is increasingly relevant, as the fleet of hybrid and electric ship fleets is growing. Key features of SBC include fast charging capabilities, in some cases using high-voltage direct current (HVDC), for instance 2 MW at 1 kV DC. Moreover, greater flexibility in the internal ship arrangement, as components like transformers can be on land, an important feature for ships which internal spaces are occupied by battery compartments. Finally, depending on the shore-side electrical power source, these systems can provide reduced GHG emissions and reduce local pollution. Among the challenges are fire hazards due to battery overheating and thermal runaway, interconnectivity and interoperability between the onboard management system and shore-side charger and lack of standardized solutions.

The electrical connection in SBC can be either wired (AC or DC) or wireless (capacitive or inductive power transfer). Wireless charging offers some advantages like reduced exposure to mechanical wear and corrosion and simplified docking procedures, which are convenient for ships with opportunity charging like ferries, for which charging time is limited and connection and disconnection times can make charging unfeasible. However, the lower efficiency compared to wired charging options is a major obstacle to the widespread use of wireless charging systems (Khan et al. 2022).

One example of SBC can be found in the port of Oslo, where the company Cavotec installed in 2020 an Automated Plug-in System (APS) for e-ferry charging (see Fig. 3). The system is suitable for ferries with a charging connection in the bow,

Fig. 3 Automatic plug-in system of the company Cavotec for charging of e-ferries. *Source* Courtesy Cavotec (2024)

minimizing the space for onboard and shoreside equipment and maximizing the possible charging time during passenger boarding and offboarding. This system has been implemented for the electrification of the e-ferry service between Oslo City Hall Pier to Nesodden in Oslofjord providing charge service to the ferries MS Dronningen, MS Kongen and MS Prinsen (Cavotec 2020).

3.3 Shore-Side Battery Charging—Battery Swapping (SBC-BS)

In the case of SBC-BS, the ships' BESS are not recharged on board, but completely replaced (swapped). This reduces the turnaround times of electric/plug-in vessels at berth, eliminating the need of wait for recharging and enabling greater flexibility. For smooth operation, modularity and standardization are important prerequisites. In addition, the infrastructure of the interface between ship and shore should ensure fast and safe handling of the battery module units (European Maritime Safety Agency (EMSA) 2022a, b).

Some examples of this solution are already available. In 2023, Singapore has launched their first fully-electric cargo vessel called Hydromover with swappable batteries (Offshore Energy 2023). A photo of this vessel is shown in Fig. 4. The battery system called PrwSwäp includes 70 kWh $\times$ 6 NMC Li-ion batteries and is connected through cloud-based service and management provided by the company of

Fig. 4 A photo of the Hydromover, a fully-electric cargo vessel with interoperable swappable battery solution. *Source* Courtesy Yinson Green Tech (Offshore Energy 2023)

Shift Clean Energy from Vancouver. The lightweight, 18.5 m long vessel transports up to 25 tons of cargo. The improved energy efficiency and lower maintenance costs should save up to 50% of operating costs. The battery can be replaced within minutes to minimize downtime. The vessel also had to undergo a comprehensive risk assessment in relation to the operation and swapping of batteries to ensure compliance with international safety standards in the maritime industry.

A swappable battery container for inland shipping was also announced in 2021 by the company Wärtsilä. The battery containers are installed on the 104 TEU inland container vessel Alphenaar, which is powered simultaneously by two 20-foot containerized battery banks onboard (Wärtsilä 2021). According to representatives of the company developing these systems, this concept can allow the reduction of the emission of 1000 tons of CO_2 and 7 tons of NO_x per year. Each of the containers include 45 battery modules totaling 2 MWh and are charged with certified green energy at dedicated charging stations (Port of Rotterdam 2021; Zero Emission Services 2021).

3.4 Shore-Side Power Banks (SPB)

OPS, SBC and SSB-BS are not necessarily hybrid. An extension of the SBC and a hybrid solution are Shore-Side Power Banks (SPB). Power banks or shore side Electrical Energy Storage (ESS) units in containers are used to temporally store on-site electricity, which in some cases comes from renewable sources (European Maritime Safety Agency (EMSA) 2022a, b). This can push simultaneously the deployment of renewable energy sources in the port area and handle fluctuating/irregular electricity production (e.g., renewable energies). For instance, overnight charging or charging during off-peak hours can decrease the stress on the local grid and increase the use of cheaper electricity. Moreover, other services in the port area could be provided by power bank energy as the containerized storage units can be deployed anywhere and moved around the port. Given the challenges, the maintenance and safety care of a large number of containers that are associated with particular fire hazards, are mobile and have complex interoperability, can be costly (European Maritime Safety Agency (EMSA) 2022a, b). Finally, due to the low energy density of batteries, container energy banks require many units per MWh, which at the same time means a high space requirement that can be very expensive in port areas due to space scarcity. One example of SPB is the charging system implemented for the Amherst Islander II (fully electric) and Wolfe Islander IV (hybrid) passenger and car ferries operating in the Ontario lake in Canada. Due to the limited charging times, the ferries require fast charging. However, the local grids of Millhaven and Stella harbors have limited capacity. For this reason, each of the SBC stations servicing these ferries are equipped with a dedicated 3.0 MWh BESS (Leclanché 2022). These SBC systems charge the onboard 1.9 MWh (Amherst Islander II) and 4.6 MWh (Wolfe Islander IV) batteries. The BESS onshore are charged by the harbor grid and are connected to the ferry through DC-DC converters with a capacity of 1800 kW. In this way, the power drained from the local grid decreases from 1800 to around 1000 kW. Additionally, the BESS can also provide peak-shaving services during high consumption periods in the harbor area.

Another example is provided by a research project in the ports of Kiel in Germany and Gothenburg in Sweden. The EU-funded Sea Li-ion research project led by the shipping company Stena and BatteryLoop explored the possibility of reusing lithium-ion batteries from the automotive sector for a stationary ESS that supplies electricity for electric ferries in the ports of Kiel and Gothenburg (Powertrain International Web 2022). The classification society DNV also supported this project. So far, only the design of the ESS, the evaluation of the recycling potential of lithium-ion batteries, the impact of the ESS on the electricity grid and a business case for electric ferries and ESS in the Port of Gothenburg have been analyzed, but the aim is to make the system a reality by 2030 and to operate the RoPax ferry "Stena Elektra" between Gothenburg and Frederikshavn with it. The business case in the port of Gothenburg has shown that there is currently sufficient electricity in the port. However, placing an ESS in the port creates opportunities to free up electricity supply capacity for other system services and support the electricity grid. According to estimations of the project, 5% of the total electricity consumption in Gothenburg would be required to charge a ferry (Powertrain International Web 2022). In other ports, however, an ESS might be necessary to enable the charging of electric ferries without compromising grid stability or building additional infrastructure.

3.5 Port Generators

A final hybrid option discussed in the existing literature is port generators that utilize micro-generation (European Maritime Safety Agency (EMSA) 2022a). These systems aim to provide mobile and flexible electrical energy “on site”, especially in the case of ports with limited access to the electricity grid or insufficient power for the demand placed by berthing ships. Some examples include hydrogen fuel cells or LNG hybrid power production barges, which can serve as port generators. A relevant consideration is the required space for the installation of the power generation units and safety aspects such as hazardous areas, low flash point or toxic fuels. Furthermore, the sustainability of such solutions can only be guaranteed depending on the energy sources used (e.g., green hydrogen) (European Maritime Safety Agency (EMSA) 2022a, b).

One example can be found at the Kirkwall pier in Scotland, where a 75 kW hydrogen fuel cell supplied by Arcola Energy was placed to provide electricity for ships and other activities. Moreover, the heat as by-product of the fuel cell is used for nearby buildings. The hydrogen is produced by electricity from 900 kW wind turbines and tidal turbines on the island of Eday and shipped to Kirkwall (BIG HIT Project 2024; Surf ‘n’ Turf Project 2024). The initiative was part of Surf ‘n’ Turf’s community renewable energy project, funded by Local Energy Scotland and the Scottish Government’s Local Energy Challenge Fund, managed by Community Energy Scotland and supported by partners EMEC, Orkney Islands Council, Eday Renewable Energy and ITM Power.

3.6 Concluding Remarks

In the previous section, several options for the shore-side supply of electricity to ships were discussed, including OPS, SBC, SBC-BS, SPB and port generators. Some publications have analyzed these alternatives with regard to different criteria (Khan et al. 2022; Mutarraf et al. 2022). For instance, Khan et al. (2022) evaluated different SSE options, including SBC, SBC-BS and power banks in the sense of hydrogen production, based on six parameters: cost, efficiency, environmental impact, recharge time, durability and reliability. Based on their assessment, Khan et al. could show that SBC with lithium-ion batteries performed best in terms of their high efficiency and power density. Battery swapping is a promising solution to save time (low recharging time) and utilize energy from the grid when demand is lower, but further improvements are needed to simplify the process. Finally, the hydrogen production system enables an external supply, which leads to a flexibility of the port and increases the continuity of the service.

Even though various SSE options are available and first examples of implementation exist, the power supply is still primarily provided by the conventional variant of the power systems on board. On the one hand, this has to do with the fact that there are no uniform standards especially for hybrid solutions like SBC as well as for electric vehicles (EV) and DC charging in the marine context. Moreover, the diffusion of electrically powered ships (especially larger vessels) still does not seem to be progressing as quickly as originally thought due to high costs, long charging times, system complexity, local grid conditions and a lack of charging infrastructure, which suffers the common chicken and egg problem. In particular, the low cost of MDO and HFO seems to be an important argument in favor of generating electricity on board instead of building infrastructure for SSE. However, an improved energy management system, e.g. in the form of energy storage systems that can absorb peak loads and use cheaper electricity at times of higher load, could help to improve the efficiency and reduce the ship's overall electricity costs (Tang et al. 2018; Kumar et al. 2019).

4 On Board Hybrid Ship Power and Propulsion

In the past sections, different hybrid solutions for ports and shore-side electricity were described. This section will be focused on the power and propulsion systems of ships.

Internal combustion engines consuming HFO and MDO are ubiquitous in most of the ships for propulsion and for the supply of electricity onboard. Nevertheless, concerns about air pollution and global warming potential have prompted the industry to explore alternatives to increase efficiency, reduce the environmental impacts and decrease operating costs, while maintaining safety and performance in the operations. Three not mutually exclusive approaches to minimizing these problems are (Geertsma et al. 2017):

- Abatement technologies: Engine modifications, exhaust gas recirculation (EGR), fuel water emissions, waste heat recovery systems, sulfur scrubbers and selective catalytic reduction (SCR) to combat air pollution. These technologies have largely been used to tackle NO_x emissions, which are regulated by the MARPOL VI annex and classified under different "tiers". Used so far to combat air pollution, these systems offer only a limited effect when it comes to reducing GHG emissions because gases like CO_2 are not captured or transformed in the process. Often, these systems increase the CAPEX and OPEX of ships.
- Alternative fuels: Replacing the current fossil fuels by other fuels like methanol, biodiesel, ammonia, hydrogen, among others. Depending on the pathway used to produce the alternative fuels, the net effect of these can be favorable or not in terms of air pollution and GHG emissions compared to the use of their fossil-based fuels counterparts. Additionally, these substances are at the moment mainly derived from fossil fuels and availability of renewable-based alternatives is still limited.

- Hybrid power systems: Design that integrates multiple power sources to provide efficient and innovative propulsive power. It can typically consist of a combination of internal combustion engines (such as marine diesel engines) and often ESS including batteries, supercapacitors, or flywheels. The designs are not limited to use diesel engines, but can also utilize fuel cells or any other generation technologies as power sources. One benefit of electrical propulsion is its higher efficient at low speed. Nevertheless, additional electrical components can introduce losses of between 5 and 15% of the propulsive power.

In the remainder of this subchapter, hybrid power and hybrid propulsion systems will be explored. The typical propulsion and power systems will be first introduced, followed by the hybrid power and hybrid propulsion systems.

4.1 Propulsion and Power Systems Options

Various designs can be categorized based on the type of propulsion and how it is powered. This situation is illustrated in Fig. 5, where the different options are shown. The option for shore-side electricity discussed in the previous section are also depicted for the different alternatives. Notice that two types of hybridization are possible: either the propulsion can be hybrid by using more than one driver (Fig. 5c and e) or the power supply can be hybrid obtaining power from different generation options (Fig. 5d–f). These two options can be as well combined (Fig. 5e).

The following sections describe different variations as presented in Fig. 5.

4.1.1 Mechanical Propulsion

The most typical option consists of a prime mover like a diesel engine or a gas turbine which is mechanically coupled in a direct way or through a gearbox to a propulsor (often a propeller). A separate electrical AC network supplied often by diesel generators provides electrical power for onboard electrical loads. If both ship and port have the necessary interfaces and infrastructure, shore-side electricity (SSE) may supply electricity for the onboard loads while at berth. A schematic representation of this option can be seen in Fig. 5a, where propulsion and the electrical loads are not coupled. Hybridization is not present in the propulsion or power system of this configuration.

This type of propulsion system reaches its maximum efficiency at design speed between 80 and 100% of the top speed. The advantages of this configuration include low conversion losses due to fewer conversion steps (main engine, gearbox and propeller), low complexity and low purchase cost compared to other options. However, some disadvantages are limited maneuverability due to the operational envelope of the propulsion engine, higher maintenance requirements under dynamic loads, poor fuel efficiency and high emissions at speeds below 70% of maximum

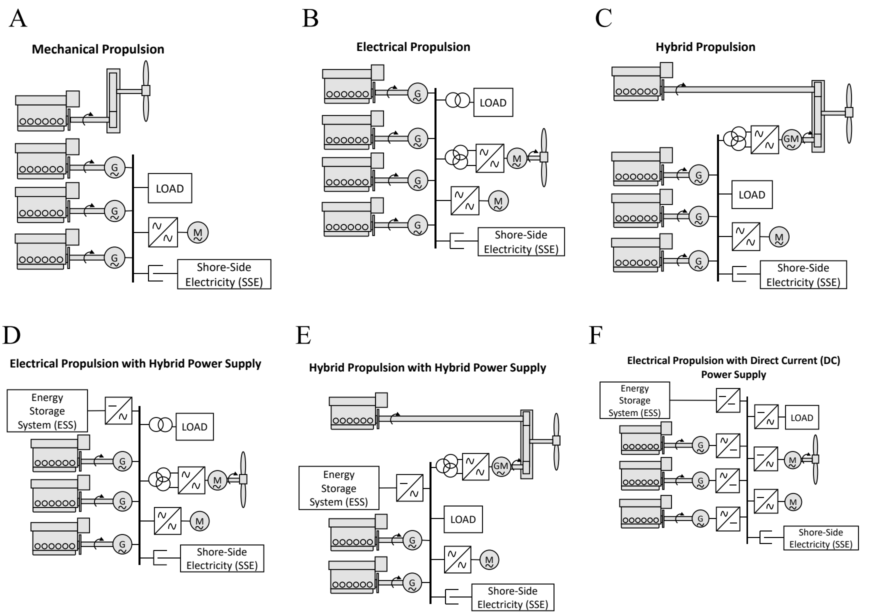

Fig. 5 Schematic comparison of different ship propulsion and power systems. Adapted from Geertsma et al. (2017) by adding Shore-Side Electricity (SSE)

speed, reduced availability in case of drive train failure leading to loss of propulsion, high NO_x emissions under certain operating conditions as well as noise and due to the transmission system.

Mechanical propulsion is the preferred application for ships operating at a single speed, typically cargo ships and fast crew suppliers. For other ship types that operate at low power in their operational envelope, like tugs or offshore vessels with dynamic positioning (DP), this type of propulsion result in a poor performance in terms of fuel consumption and emissions. In these cases, electric or hybrid solutions may be more suitable.

4.1.2 Electrical Propulsion

Figure 5b illustrates a typical electrical propulsion, which consists of multiple diesel engines coupled to electrical generators and integrated through a high voltage electrical bus. Propulsion motor drives and hotel loads are electrically fed from this bus, often requiring transformers and power electronic converters (Geertsma et al. 2017). As in the former case, if both ship and port have compatible interfaces and infrastructure, shore-side electricity (SSE) may supply electricity while at berth and the onboard generators can be shut down.

Electric propulsion is a fuel-efficient solution when the hotel load is significant compared to the propulsion load and the operating profile is diverse. The number of running engines and their operation is controlled by a power management system (PMS) matching the power required by propulsion and hotel load with the power produced by the generators. Important benefits of these systems include:

- Lower NO_x emissions, as these systems make use of more engines operating often at the design point, at which they typically produce less NO_x emissions.
- Reduced maintenance loads are reduced as the engines are shared by propulsion and hotel load.
- Lower noise and vibration are produced in the absence of transmission systems.
- High system availability, due to redundancy of engines and the possibility to operate in a broad operational envelope.
- Mechanical transmission requires a shaft to transfer the mechanical power produced by the engine to propellers. Electrical propulsion does not require a shaft connecting engine and propeller, so the absence of shaft-line along the ships allows more design-freedom.

In contrast, the main disadvantages of these systems are:

- Increased losses due to more power conversion stages, which leads to higher specific fuel consumption (SFC) near top speed.
- Poor fuel consumption and high emissions due to engines running at low part load in applications like Dynamic Positioning (DP) to achieve high availability.
- Susceptibility to voltage and frequency swings that can occur due to changing loads, which in turn can switch off electrical systems with the consequence of reduced reliability and availability.

Electrical propulsion is broadly used on cruise ships, ferries, drilling or offshore vessels with dynamic positioning, cable layers, icebreakers and naval vessels. Aspects like the redundancy of the engines, which is offered by these systems, have been particularly relevant for applications like DP, where maintaining the position even in fault conditions is necessary. Redundancy provides spinning reserve that guarantees the availability of power.

4.1.3 Hybrid Propulsion

Figure 5c illustrates a hybrid propulsion system, which combines a mechanical drive with an electrical motor. The electrical motor provides the power to drive the propulsion system at low speeds. At high speeds, the mechanical drive takes over and provides primary propulsion. In addition, the electrical motor can also act as generator to supply electricity to the loads (Geertsma et al. 2017). Therefore, this item is tagged as GM (Generator/motor). As in the two former cases, shore-side electricity (SSE) can supply electricity while at berth, provided that the corresponding interfaces and infrastructure is present onboard as well as onshore.

The main advantage of hybrid propulsion is the combined benefits of electrical and mechanical propulsion, often requiring a trade-off between their features, like efficiency, noise reduction and fuel consumption. Main applications for hybrid power systems are naval ships, towing vessels and offshore vessels. Hybrid propulsion can be provided by non-hybrid power systems, as in many cases the prime movers of the systems are diesel engines.

4.1.4 Electrical Propulsion with Hybrid Power Supply

Illustrated in Fig. 5d, a distinctive aspect in this case is the connection of all the power sources or ESS through an electrical bus bar. This contrasts with hybrid propulsion or purely mechanical propulsion, for which the propulsion engines directly provide mechanical power to the propulsion system. The onboard ESS allows the storage of electricity produced by the generators or even by shore-side electricity supply. By storing electricity from the grid onboard for later use in propulsion, the fuel consumption of the engines can be reduced (Geertsma et al. 2017). If the shore-side electricity charging the ESS is from low-GHG sources, such as renewables, the net GHG emissions of the ship can be reduced, not only while it is berthed but also during propulsion, this being an advantage over mechanical or electrical propulsion. Moreover, a combination of two or more types of power sources can be achieved, including:

- Combustion-based power supply based on diesel engines, gas turbines or steam turbines connected to an electrical generator.
- Electrochemical power supply from fuel cells
- Stored electrical power supply from energy storage systems, such as batteries, flywheels or super capacitors.

While the application of hydrogen fuel cells in ships has been so far been limited mainly to submarines and demonstration projects, the usage of battery energy storage for propulsion systems is becoming increasingly widespread. Different variants are available, depending on how the storage system is connected to the electrical system:

- At the main high voltage bus bar through an AC/DC converter (Option shown in Fig. 5d)
- At the low voltage bar through an AC/DC converter
- Directly using a DC/DC converter to the direct current link of the propulsion converter.

One of the main benefits is that the ESS can provide power when the operation of other generators at partial load is inefficient and can then be recharged by operating any generation source at its optimum operating point. Additionally, load balancing and peak shaving are possible with ESS, so that efficient operating points are maintained. Onboard storages enable recharging from shore-side reducing fuel consumption and local emissions. The integration of renewable sources can decrease the global warming potential of the ship's energy supply.

ESS can store the energy generated by braking motors, as it is the case with heavy crane installations and offshore vessels with heave compensation. Furthermore, ESS can provide backup power in case of failure of other generators, replace spinning reserves and enhance the availability of the propulsion, which is crucial for applications using DP.

Challenges include the complex control strategies compared to mechanical or electrical options and the additional maintenance and purchase costs. The higher costs can be partially offset by the ability to downsize some components due to redundancies and reducing component size through peak shaving.

The main applications so far are tugs, ferries and offshore vessels. An interesting example is the MV Hallaig, which demonstrated 35% fuel savings in the trial phase compared to a mechanical propulsion system. Around 24% of the fuel savings were due to overnight charging using electricity from the grid and 11% to optimizing operation with the energy management system (Geertsma et al. 2017). Some studies have found fuel savings between 7.9 and 17.6% for different types of ships (Karvounis et al. 2022).

4.1.5 Hybrid Propulsion with Hybrid Power Supply

This option combines the exceptional efficiency of direct mechanical drive and the flexibility of ESS for electrical supply, as found in Fig. 5e. By storing electricity from onboard generators, shore-side electricity or both, this option can reduce the net GHG emissions if the GHG emissions of the shore-side electricity are low. At low propulsion power, an electric drive propels the ship conveying power from electrical generators or the ESS. At high speeds, the mechanical drive takes over as prime mover. The electric drive can also work as generator supplying electricity to onboard electrical loads or for storage in the ESS. Therefore, the generator/motor is labelled "GM" in Fig. 5e.

Therefore, this alternative aims at combining the high efficiency of mechanical propulsion at high speed with those of the electrical propulsion with hybrid power supply at low speed. Main challenges are complicated control strategies and costs. Hybrid propulsion with hybrid power supply is being researched for tugs and yachts.

4.1.6 Electrical Propulsion with DC Hybrid Power Supply

DC grids offer several benefits over traditional AC grids, including lower fuel consumption and emissions at partial loads, lower noise levels and improved resilience to interference as the frequency does not play a role in the stability of the grid. This is because engines can operate at variable speeds in DC grids, reducing mechanical and thermal loads, in contrast to AC grids in which engines have to operate at a constant speed despite changes in the loads. Additionally, DC architectures require fewer and smaller switchgears and are less prone to faults spreading throughout the onboard grid. In turn, implementing a DC grid has the disadvantages of requiring extensive power electronic converters with high costs, fault protection systems and complex control strategies (Geertsma et al. 2017). This particular type of propulsion system together with DC hybrid power supply is demonstrated in Fig. 5f, where all the electricity is converted to direct current and fed to the busbar, before being reconverted back to AC for onboard electrical loads and propulsion.

DC power supplies are commonly used in submarines in combination with battery packs for air-independent propulsion. The technology has also been tested in ferries, offshore vessels, drilling ships, research vessels and wind farm support vessels. DC is also being used in the first completely electrical vessel, MF Ampere in Norway (Geertsma et al. 2017).

4.2 Trends of Hybrid Power and Propulsion Systems

A top-down picture of the topic of hybridization of power supply for ships will be presented in this section. The statistics for this section were inferred indirectly from data on the electrification of ships. Therefore, the focus here is mainly on ships with onboard ESS and in line with hybrid power supply (Fig. 5d and e). As of August 2024, and according to data of the class society DNV, 944 ships fitted with batteries are in operation and 451 on order (DNV 2024). The ships are categorized as hybrid, plug-in hybrid and pure electric, with a slightly different categorization in comparison with the previous section. Hybrid and plug-in hybrid refer to ships combining batteries with other power systems, having in the latter case the possibility of charge from shore. Pure electric refers to operation relying entirely on onboard batteries. Figure 6a shows that an important share (37%) of the ships fitted with onboard batteries are car/passenger ferries, followed by ships for other activities (20%), offshore supply vessels (11%) and fishing vessels. Moreover, Fig. 6b shows that most of the ships operate either in Europe excluding Norway (35%) or specifically in Norway (33%) with the rest elsewhere. Norway is a remarkable case for electrification of car/passenger ferries and the biggest market of this type of ship in Europe. In terms of different applications and as shown in Fig. 6c, 64% of the ships are hybrid, 17% are plug-in hybrid and 19% are fully electric. Finally, Fig. 6d shows that around 50% of the fleet operating with batteries is not more than four years old or was fitted in the last four years, with the ordered fleet being around one third of the current fleet by ship number.

The statistics reveal that hybrid, plug-in hybrid and pure-electric ships are gaining relevance. While, car/passenger ferries dominate the trend, similar solutions are being adopted for other ships. A big share of this trend is taking place in Europe. Finally, the orders of future ships fitted with hybrid, plug-hybrid and pure electric onboard power systems for the following years are comparable to the existing ships fitted with this solution, showing an increasing adoption.

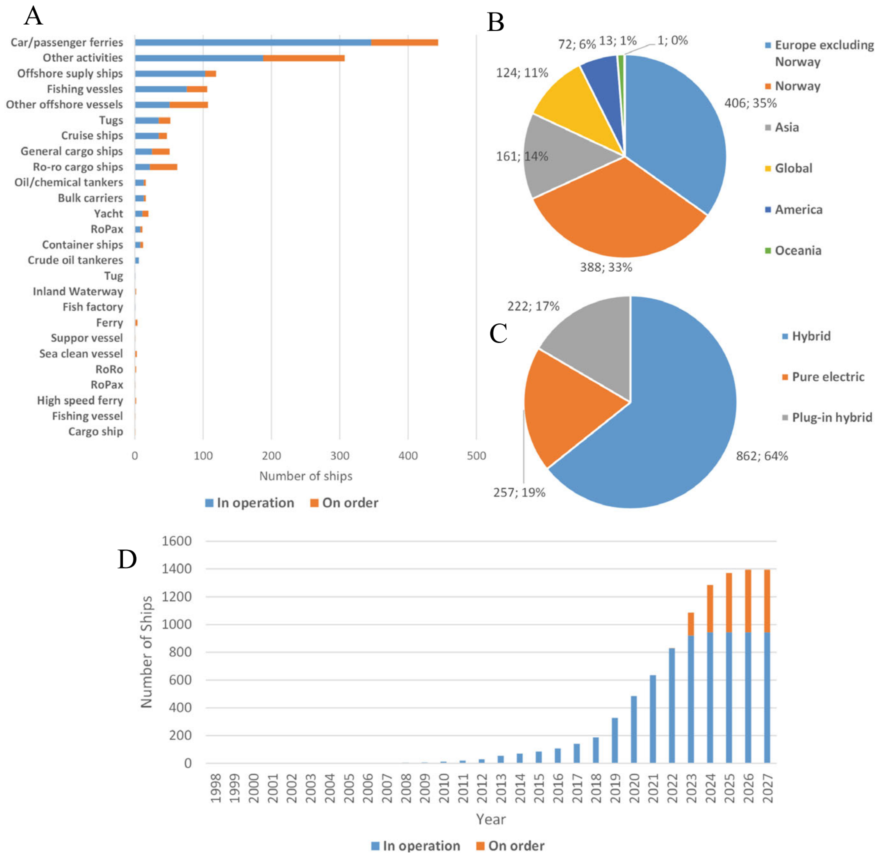

Fig. 6 Statistics on ships fitted with onboard batteries. The statistics are shown by ship type (**a**), location (**b**), type of power system (**c**) and number of ships per year (**d**). Own plots with data extracted from the Alternative Fuels Insight Platform of the classification society DNV (2024). Status 28.08.2024

4.3 Key Performance Indicators (KPIs) of the Components of Hybrid Power Supply Systems

Following the classification of the different propulsion and power systems for ships, a description of the KPIs will be presented in the following section. The section will start by describing the typical features of propulsion systems for ships. Later, the technical and economic features of diesel engines, fuel cells and batteries as important components of most of the hybrid power systems will be described and contrasted.

4.3.1 Ship Propulsion Requirements

Ships and their propulsion plants are traditionally optimized for their operation under calm water conditions. The power required by the propulsion system at constant speed depends on ship's frictional, residual and air resistance. Additionally, the acceleration required by the operational conditions may also drive the selection of the propulsion and power system. Ships requiring more acceleration demand a higher power-to-displacement ratio. However—and specially for cargo ships—lowering the fuel consumption has resulted in low power-to-displacement ratios, accelerating slower than previous designs (MAN Energy Solutions 2018). Off-design conditions related to rough weather or waves are handled in the design phase by adding a sea margin typically comprised in the range of 15–25% of the power required in calm water conditions (Taskar et al. 2016).

Table 2 highlights the diversity of ship types, engine speeds, and main engine power. The broad range of typical main engine power is largely due to variations in speed, size and engine types, even within each ship category.

4.3.2 Internal Combustion Engines, Fuel Cells and BESS

Most of the hybrid solutions so far envisioned for ships include either the traditional diesel engines combined with BESS or fuel cells. The main features of these systems will be introduced in the following sections.

Internal Combustion Engines

Both Diesel and Otto cycles can in general be used to produce mechanical power for propulsion. However, the Diesel cycle offers some advantages related to higher efficiency, fuel quality and higher compression ratios (Hannemann 2024). Being more common, the following section will describe some KPIs for diesel engines. KPIs for diesel engines depend heavily on the size and type of engine. Medium speed four-stroke engines have a higher specific power and a higher power density than low-speed two stroke engines. However, the latter have a superior fuel economy and therefore a higher efficiency. Exemplary values for two- and four-stroke diesel engines are summarized and compared in Table 3 (MAN Energy Solutions 2018).

Fuel Cells

Although hydrogen fuel cells have found so far limited applications for ships, these devices are being increasingly studied and tested. A summary of KPIs for different fuel cell (FC) technologies can be found in Table 4.

Future technology targets as defined by the Clean Hydrogen Joint Undertaking in the EU can be found in Table 5. It is noticeable that the FC module CAPEX for heavy duty vehicles are estimated to be lower than those for maritime applications. CAPEX for maritime applications are expected to be around 1000 EUR/kW by 2030 in comparison with heavy duty vehicles, for which CAPEX are expected to be below 100 EUR/k. In addition, the system lifetime is expected to be longer for maritime

Table 2 Typical characteristics of different ship types.

Category	Type	Propeller	Main engine type	Size factor	Speed (kn)	Typical main engine power (MW)
Tanker	Crude oil	1 FP	2-stroke	dwt	13–17	10–35
	Gas tanker/ LNG carrier	1 FP	2-stroke, steam turbine	dwt/cubic meter (cbm)	16–20	2–45
	Product	1 FP	2-stroke	dwt	13–16	2–12
	Chemical	1 FP	2-stroke	dwt	15–18	3–20
Bulk carrier	Ore carrier	1 FP	2-stroke	dwt	14–15	3–32
	Regular	1 FP	2-stroke	dwt	12–15	5–64
Container ship	Liner carrier	1 FP or 2 FP	2-stroke	teu	20–23	10–80
	Feeder	1 FP or 1 CP	2 or 4-stroke	teu	18–21	< 12
General cargo ships	General cargo	1 FP	2 or 4-stroke	dwt/nt	14–20	2–28
	Coaster	1 FP or 1 CP	2 or 4-stroke	dwt/nt	13–16	< 12
RoRo cargo ship	-	1 CP or 2 CP	2 or 4-stroke	Lane meters (lm)	18–23	0.7–32
Passenger cargo ship		2 CP	2 or 4-stroke	Passengers/ lm	18–23	0.7–32
Passenger ship	Cruise Ship	2 CP	4-stroke	Passengers/ gt	20–23	0.8–97
	Ferry	2 CP	4-stroke	Passengers/ gt	16–23	0.8–68

[a] *FP* fixed pitch, *CP* controllable pitch, *DWT* deadweight tonnage, *TEU* twenty-foot unit, *GT* gross tonnage, lm lane meters
Source MAN Energy solutions (MAN Energy Solutions 2018) and data from ship-db.de (Hannemann 2024)

applications by 2030 (see KPI Fuel cell system lifetime) than for heavy duty vehicles (see KPI FC stack durability). Since maritime applications require high power (see Table 2), the fuel cell power rating is expected to increase from around 500 kW in 2020 to around 20 MW in 2030. Finally, topics related to the loading of platinum-group metals (PGM) and power density at cell level are also considered for the development of stacks for heavy duty vehicles.

BESS

BESS are rapidly evolving and being adopted for maritime applications. Table 6 summarizes the features of some products used for maritime applications according to specifications made public by their manufacturers.

Table 3 KPIs of diesel engines

KPI	Unit	Two-stroke diesel engines	Four-stroke diesel engines
Power range	kW	3200–82,440	1290–19,200
Specific power	W/kg	32–50	57–336
Power density	W/L	26–44	44–295
Specific fuel oil consumption at 75%	g/kWh HFO	151.5–175.5	174.4–202[a]
Specific gas consumption + specific pilot oil consumption (1.5%) at 75%	g/kWh methane + g/kWh HFO	(126.3 + 2.9)–(133.9 + 3.1)	N/A
Specific gas consumption + specific pilot oil consumption (5%) at 75%	g/kWh methanol + g/kWh HFO	(306.9 + 9.8)–(322.1 + 10.2)	N/A
Capital costs	$/kW	240–420 Korberg et al. (2021), Dotto and Satta (2023)	238–493 Talluri et al. (2016), Wärtsilä (2016), Korberg et al. (2021), Karvounis et al. (2022), Dotto and Satta (2023)

Based on the Marine Engine Program of MAN Energy Solutions (2024). Capital costs are taken from literature references

[a] Diesel generators for maritime applications typically consist of a four-stroke diesel engine which and an electrical generator assumed with an efficiency in the range 95–97%; therefore, the SFOC for diesel generators is the range 180–213 g/kWh$_{el}$

As a result of the highly dynamic market of BESS and their parallel development for massive markets like land transportation, their prices and particularly those of Li-ion-based BESS are decreasing rapidly due to technological progress, upscaling of production and economies of scale. Figure 7 shows predicted price trends for maritime batteries from the E-Ferry project. Industry sources report current prices ranging from 400 to 420 EUR/kWh in 2024. However, the prices vary depending on system scope and size. These prices are considerably higher than those for automotive applications, for which forecasts predict a price at around 80 USD/kWh (approx. 76 EUR/kWh) by 2026 and faster than original predictions to higher energy densities related with technological development and decreases in metal prices like lithium and cobalt, which contribute considerably to the cost of producing Li-ion batteries (GoldmanSachs 2024).

In general, KPIs for automotive applications are more developed and show the trends that the industry is moving toward. A summary of present and future KPIs for lithium-ion batteries is presented in Table 7.

Table 4 KPIs of fuel cells

KPI	Unit	LT-PEMFC	HT-PEMFC	SOFC
Operating temperature	°C	65–85	140–180	500–1000
Electrical efficiency	%LHV	40–60	40–50	50–65
Hydrogen purity	–	> 99.98% H_2	< 3% CO	< 20 ppm S
Cooling medium	–	Water mixture	Thermal oil	Air
Specific power	W/kg	125–750	25–150	20–80
Power density	W/L	50–400	10–100	10–40
Stack life time	Thousand hours	5–35	5–20	20–90
Start-up time (cold)	Cold	< 10 s	10–60 min	> 30 min
Load transients	Idle-rated power	< 10 s	< 5 min	< 60 min
Capital costs 2021 *(2030)*[*]	$/kW	1000–2500 (*60–600*)	3000–5000 (*150–1500*)	3500–8000 (*500–2000*)

[a] Future expected values italic under current values
Taken from van Biert and Visser (2022)

Table 5 KPIs and future targets for fuel cell technology for heavy duty vehicles and for maritime applications

	KPI	Unit	2020	2024	2030
Heavy duty vehicles	FC module CAPEX	EUR/kW	1500	< 480	< 100
	FC module availability	%	85%	95%	98%
	FC stack durability	Hours	15,000	20,000	30,000
	FC stack cost	EUR/kW	> 100	< 75	< 50
	Power density	W/cm^2	1 at 0.650 V	High TRL: 1.0 at 0.675 V Low TRL: 1.2 at 0.650 V	High TRL: 1.2 at 0.675 V Low TRL: 1.5 at 0.650 V
	PGM loading	g/kW	0.4	High TRL: 0.35 Low TRL: < 0.30	High TRL: 0.30 Low TRL: < 0.25
Maritime applications	FC power rating	MW	0.5	3	10
	Hydrogen bunkering rate	Ton H_2/h	0	2	20
	Fuel cell system lifetime	Hours	20,000	40,000	80,000
	PEMFC CAPEX	EUR/kW	2000	1500	1000

Based on Tables 16 and 17 of the Strategic Research Agenda 2021–2027 of the Clean Hydrogen Joint Undertaking (2022)

Table 6 KPIs of BESS for maritime applications Corvus Energy (2024b), Leclanché Energy Storage Solutions (2024)

KPI	Unit	Leclanché MRS-3/65	Leclanché MR-3/72	Corvus energy Orca ESS
Battery cell chemistry		G/NMC, 65 Ah	G/NMCA, 72 Ah	Li-ion NMC/ Graphite
Operating temperature		Charge: 0 to + 45 °C; Discharge: − 20 to + 55 °C		
Electrical efficiency		Typically, 85–90%, round	Typically, 85–90%, round	Typically, 85–90%, round
C-Rate discharge, peak, 20 s	C-Rate	4.6C	TBC	3C
C-Rate charge, peak, 20 s	C-Rate	2.8C	TBC	3C
C-Rate discharge, continuous	C-Rate	2.7C	2.4C	
C-Rate charge, continuous	C-Rate	1.8C	1.5C	
Cooling medium		Liquid cooled	Liquid cooled	
Specific energy (pack)	Wh/kg	152–157	N/A	77
Energy density (pack)	Wh/L	249–270	N/A	88
Specific energy (system)	Wh/kg	101	112	76
Energy density (system)	Wh/L	108	120	76
Life time	Cycles	7000 at 80%DoD 4000 at 100%DoD	6000 at 80%DoD	–

Alternative cell chemistries are under development. This implies developing new cathodes, anodes, electrolytes in lithium-based batteries or even substituting lithium completely for other elements like sodium (Cai et al. 2024), potassium (Xu et al. 2023), calcium (Stievano et al. 2021), magnesium (Dominko et al. 2020), or aluminum (Elia et al. 2021). Expected KPIs for some of these emerging battery technologies at cell level are currently collected on a regular basis by Batteries Europe (Batteries Europe 2023).

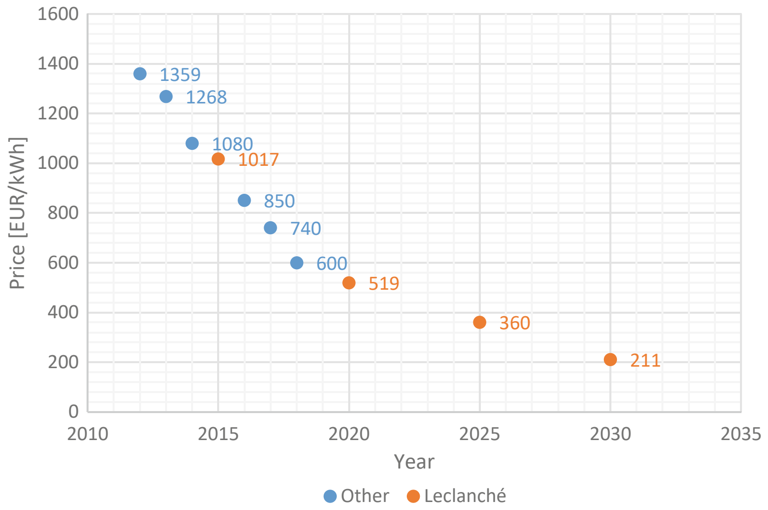

Fig. 7 Battery pack prices for maritime applications. Data gathered by Marstal Navigationsskole combined with estimated and realized prices from the company Leclanché. *Source* Own plot with data from Kortsari et al. (2022)

Table 7 KPIs for lithium-ion batteries

KPI	Unit	Level	2020	2030	2050
Gravimetric energy density	Wh/kg	Pack	90–180	190–2320	> 250
		Cell	160–260	275–320	> 350
Volumetric energy density	Wh/L	Pack	250–400	450–550	> 600
		Cell	450–730	750–900	> 1000
Gravimetric power density	W/kg (100–20% SOC)	Cell	340–500	800–1100	> 1200
Fast charging time	min (20–80% SOC, 25 °C)	–	~ 1000	~ 2000	> 3000
Battery lifetime to 80% end-of-life capacity for BEV	Cycles (25 °C)	–	15–30	10–15	< 10
Battery lifetime to 80% end-of-life capacity for stationary applications	Cycles (40–50 °C)	–	~ 1000	Up to 2000	2500–5000
Calendar life	Years (80% energy)	–	10	10–15	15–20
Cost targets	EUR/kWh	Cell	60–100	40–60	< 50
	EUR/kWh	Pack	90–140	65–110	40–70
Collection/take back rate	–	–	–	> 50%	> 90%
Recycling efficiency by weight	–	–	–	> 40%	> 90%
Economy of recycling	–	–	–	~ 150%	~ 50%

Taken from Armand et al. (2020)

4.3.3 Comparison of Different Power Generation and ESS Technologies

In the previous section, a few key indicators about the three key technologies were summarized. Combustion engines (diesel) as prime movers have a lower upfront cost compared to fuel cells, especially in its LT-PEMFC and SOFC variations. Batteries are not directly comparable because they are energy storage technologies and not a mechanical or electrical power generation technology. Nevertheless, as their prices are decreasing rapidly, they are becoming an option to store and provide power for automotive applications and further onboard ships (GoldmanSachs 2024).

Considering the specific fuel consumption of the diesel engines and the heating value of the fuels they can burn, their efficiency is in the range between 42 and 52%, depending on the size and type of engine. The addition of one electrical generator decreases the efficiency to around 46% in the best cases considering the production of electricity. This is lower than the efficiency of fuel cells which is in the best cases around 60%. Therefore, fuel cells promise a higher efficiency than the internal combustion engines, with the tradeoff so far of a higher upfront cost. Specific power and power density are relevant aspect for transportation equipment and those of fuel cells and diesel engines are comparable.

Scalability is still an issue for fuel cells. The power demands for ships can go up to two-digit MW, whereas currently the fuel cell modules offered in the market have rated power around hundreds of kW. Therefore, power upscaling is one of the KPIs for the upcoming years for fuel cells (see Table 7). Although in principle modularity allows to put several modules together to meet the power demands, in reality this becomes unpractical. Diesel engines as the incumbent technology come in power outputs, often with smaller power in their four-stroke variation and higher in the two-stroke.

The integration of these elements into hybrid power systems also requires a considerable amount of equipment for the control of the different devices, fault protection, voltage conversion, rectification, among others. This equipment is not mentioned here, but can certainly have considerable additional costs and conversion losses during the operation.

The following section will show an example of a hybrid hydrogen fuel cell battery electric ferry, encompassing the motivations, the specifications of the system and how this system compares to other alternatives in environmental and economic terms.

5 Case Study: Electric Propulsion Hybrid Power System Ferry Developed in the Project HySeas III

Building on previous sections, this section showcases an example vessel with an electrical propulsion system and hybrid power supply (see Sect. 4.1.4). The EU Horizon 2020 project HySeas III (Grant Agreement 769,417, 2018–2022) conceptualized this hybrid Hydrogen Fuel Cell and Battery Electric (HFCBE) passenger/car

(RoPax) ferry, for which approval in principle was granted by the end of the project (European Commission 2022).

5.1 Motivation for the Concept Development

The HySeas III project aimed at developing and testing a hybrid Hydrogen Fuel Cell and Battery Electric (HFCBE) RoPax ferry concept, with the final goal of creating the world's first sea-going hydrogen-powered vessel for the Orkney Islands in Scotland. The project built on the previous feasibility studies (HySeas I and HySeas II) and tested the effectiveness of hydrogen and fuel cells in seagoing vessels through testing a real size power system on land. The selection of the route and the operation site aimed also at the hydrogen availability and utilization in the Orkney Islands, a location where hydrogen infrastructure is already existing and has been installed by other parallel testing projects. The outcomes contributed to paving the way for future ship construction by conceptualizing the ferry and its hybrid propulsion and power system, designing and testing the power systems at real scale, conceptualizing the refueling infrastructure and conducting market-potential and sustainability assessments. A rendering of the concept developed in the project can be seen in Fig. 8, where the compressed hydrogen tanks can be seen over deck.

Fig. 8 Rendering of the HySeas III RoPax hydrogen fuel cell RoPax ferry concept. *Source* Gomez Trillos and Draheim (2022), created by Courtesy of ABL Group/Caledonian Maritime Assets Limited

Table 8 Ship general specifications

Ship Specification	Value	Unit
Route	Kirkwall-Shapinsay	–
Number of crossings per day	12	–
Operation speed	9.5	kn
Maximum speed	11.0	kn
Length overall	40	m
Breadth (moulded)	11.5	m
Depth (main deck)	2.5	m
Type of ferry	Double-ended	–
HGV	2	Units
Cars	16	Units
Deadweight	115	Ton
Lightship	315	Ton
Crew	4	Person

Source HySeas Preliminary General Arrangement Caledonian Maritime Assets Limited (2021)

5.2 Technology Neutral Requirements

The carrying capacity, number of crossings and speed were specified according to local transportation demands between the ports of Kirkwall and Shapinsay. Based on these specifications, a design was drafted and its corresponding power demands were estimated. Table 8 outlines the key specifications for the concept developed in the project.

An electrical propulsion with hybrid power supply including fuel cells and batteries was designed to meet the calculated power demand, based on the specifications. Key propulsion and power system specifications are summarized in Table 9. The fuel cell and battery capacity on board was estimated according to the operational profile of the ship and to meet the power requirements onboard, with margins for weather conditions, redundancy in case of failure and considering emergency operation with system limitations.

5.3 Operational Profile and Hybrid Power System Solution

The daily operation of the ship consists of 12 crossings between Kirkwall and Shapinsay, covering a distance of 4 nm (7.2 km) at a service speed of 9.5 kn (17.6 km/h), each crossing taking approximately 25 min. The loads considered for the propulsion design are depicted in Fig. 9, which indicates the highest loads at around 900 kW, and around 400 kW during steady crossing. When the ship is docked at port, the loads

Table 9 Propulsion and power system specifications Gomez Trillos and Draheim (2022)

Feature	Value	Unit	Note
Propulsion load	850	kW_{el}	Estimated
Hotel load	50	kW	Estimated
Maximum load	900	kW_{el}	Propulsion + Hotel load
Fuel cells	100 × 6 = 600	kW_{el}	Assumed as FCMove® 100 kW fuel cell of the company Ballard
Battery capacity	740	kWh	Charging overnight and from fuel cells during operation
Hydrogen consumption	~ 120	kg/day	Estimated
Hydrogen storage onboard	320	kg	Per design and according to fueling frequency specifications

are just under 200 kW, accounting for minimum operation of thrusters to maintain the position of the ship hotel loads.

To meet the power demands, various strategies with the specified hybrid power system comprised of fuel cells and batteries were analyzed. A strategy that maximizes the battery usage with overnight charging was deemed optimal and will be considered hereafter. This approach is exemplified in Fig. 10, where the fuel cells operate at around 45% of their rated power, near their optimal range (10–40%), minimizing therefore the specific hydrogen consumption per unit of electricity produced. The batteries absorb the demand peaks during acceleration and maneuvering, while negative values represent battery charging from the fuel cells when docked. During

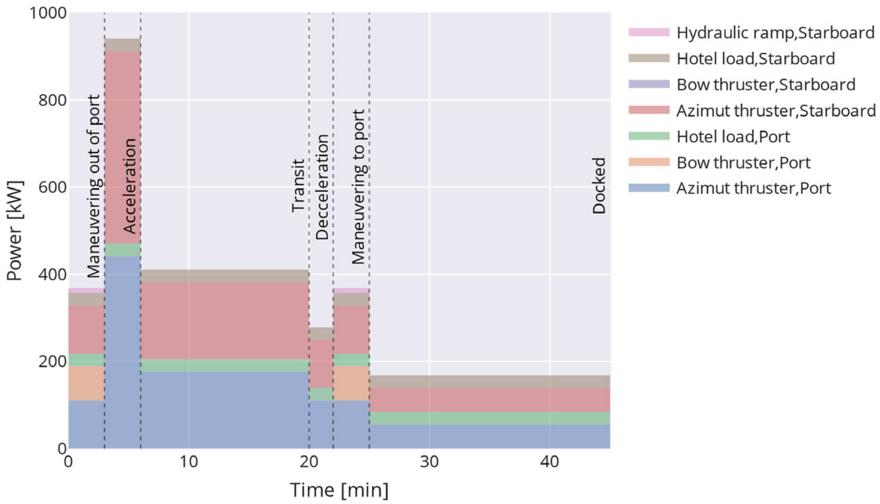

Fig. 9 Load profile as assumed for the HySeas III concept Gomez Trillos and Draheim (2022)

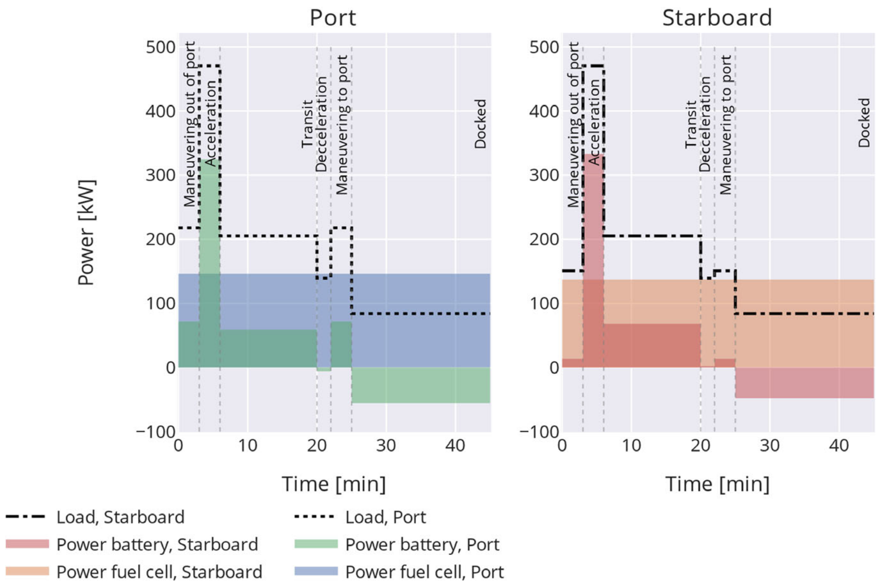

Fig. 10 Operational strategy using maximum battery and maintaining the operational point of the fuel cell in their highest efficiency Gomez Trillos and Draheim (2022)

each crossing, the net charge in the battery decreases slightly, so overnight charging is necessary to compensate for the net energy discharged during the entire day. In addition as shown in Fig. 10, the loads are divided into port and starboard sides more or less evenly and therefore reach around 450 kW for each side (Compare with Fig. 9). The total net power supply for each of the sides is shown in dotted black lines.

5.4 Sustainability: Environmental and Economic Assessments

Environmental and economic assessments of the HFCBE RoPax ferry were carried out and compared against other alternatives like Diesel Electric (DE), hybrid Diesel Battery Electric (DBE) and Battery Electric (BE), the latter based completely on batteries. The HFCBE, DBE and BE were considered as plug-in alternatives with charging overnight. Life cycle assessment (LCA) was used to assess the environmental impacts according to the ISO 14040/14044 standards and using the ILCD2.0—2018 impact assessment method. Construction, operation and end-of-life management were considered. The software Brightway2, its user interface ActivityBrowser and the database ecoinvent 3.7 were used to carry out the calculations (Wernet et al. 2016; Mutel 2017; Steubing et al. 2020). The economic assessment was

Table 10 Yearly energy carrier and fuel/electricity consumption of the different considered alternatives Gomez Trillos and Draheim (2022)

Energy carrier	Fuel/electricity consumption			
	HFCBE	DBE	DE	BE
Diesel (kg)	–	174,625	201,044	–
Hydrogen (kg)	49,988	–	–	–
Electricity (kWh)	146,482	146,482	–	1,095,368

carried out via Life Cycle Costing (LCC) by considering the construction costs, operation expenses, energy carriers, component replacement and end-of-life processing. The analysis built on data of fuel consumption calculations and energy flows for the operational phase of the ship. The functional unit for both LCA and LCC was 1 km of crossing over a 30-year ship lifetime. For the HFCBE alternative, hydrogen was assumed as produced in the UK and electricity from UK's grid was assumed for battery charging overnight. Some results of this work can be found in other documents (Trillos et al. 2021; Gomez Trillos and Draheim 2022; Kazemi Esfeh et al. 2022).

As the project focused on developing an innovative hybrid power system based on hydrogen fuel cells and Li-ion batteries, which impacts directly the energy carriers used by the ship and the emissions, the operational profile was therefore emphasized. A summary of the yearly energy carrier and electricity consumption according to the modelled considerations can be seen in Table 10. According to the estimations carried out in the project, the operation of the ship requires approximately 50 tons of hydrogen per year and it is additionally supported with the charging of around 146 MWh of electricity overnight from the grid for battery charging. For the diesel-based alternatives, around 174 tons of diesel are consumed by the hybrid DBE alternative and 201 tons are consumed by the DE alternative on a yearly basis. The latter had a higher fuel consumption because of not having the possibility of storing electricity onboard. Finally, the BE alternative consumes around 1095 MWh per year and no fuel, as this alternative is completely based on electricity charged from shore.

5.5 *Environmental Assessment*

The results of the GHG emissions per km of crossing are shown in Fig. 11. The operation phase has the higher share among the three considered phases and for all the alternatives. This increases from 76.3% for the HFCBE up to 96.1% for the DE alternative. Moreover, the construction has higher relative impact in the case of the HFCBE (22.9%) than in the case of the DE alternative (3.8%). The end-of-life was found to have a limited impact in the life cycle, although the data for the scrapping process was limited and scrapping on site was assumed for this phase.

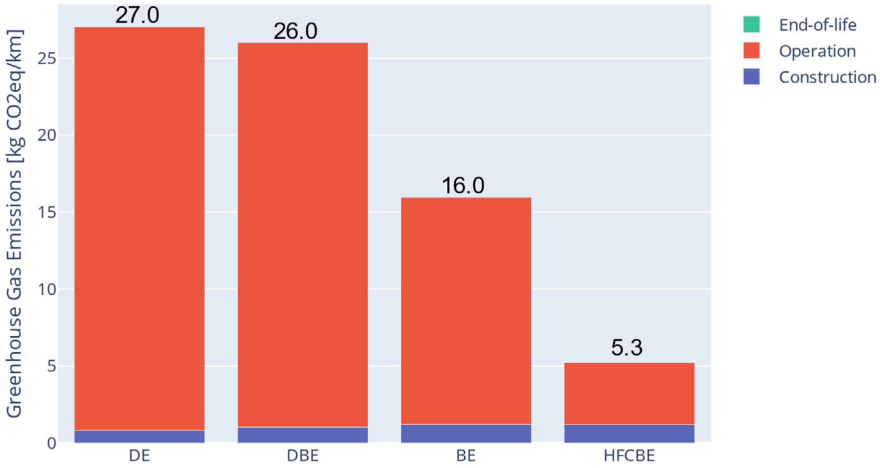

Fig. 11 Complete life cycle GHG emissions for the different alternatives considered for the analysis of the concept in the project HySeas III Gomez Trillos and Draheim (2022)

When comparing the impact per km of crossing, the DE alternative was found as the one with the highest GHG emissions with 27.0 kg CO_2eq/km. The hybrid DBE alternative achieve certain reductions with an impact of 26.0 kg CO_2eq/km mainly linked to the lower diesel fuel consumption but in turn with higher emissions for the construction of the ship due to the onboard batteries, despite considering replacement of the batteries during the lifetime, the impact of this was relatively minor in relation to the impacts of fuel combustion on board. Therefore, the DBE alternative achieves a reduction of the GHG emissions by approximately 3.7% compared to the DE alternative when all the life cycle is considered. The reduction achieves 5.0% when only the operation phase is considered. For the BE alternative, for which only electricity is considered for the operation, the reduction compared to the DE alternative is even higher. In this case, the impact per km of crossing reduces to 16.0 kg CO_2eq/km, therefore resulting a reduction of 40.7% compared to the DE alternative. Finally, the hybrid HFCBE alternative developed in HySeas III had estimated GHG emissions of 5.3 kg CO_2eq/km, thus a reduction of 80.4% compared to the DE alternative, considering the assumption that the hydrogen consumed by the power system onboard is produced via electrolysis with electricity sourced from wind power.

5.6 Economic Assessment

Table 11 summarizes the total life cycle costs as well as the life cycle costs per km estimated for the different alternatives. The HFCBE alternative is estimated to have costs per km and for the entire life cycle costs 51.1% higher than those of the DE alternative. The contribution of different cost items can be seen in Fig. 12. The main

Table 11 Life cycle costs and life cycle costs per km for the different alternatives Gomez Trillos and Draheim (2022)

Alternative	Life cycle cost (MEUR2021)	Life cycle cost per km (EUR2021/km)	Comparison with DE (%)
HFCBE	36.8	69.83	+ 51.1
BE	28.5	54.14	+ 17.2
DBE	25.3	48.06	+ 4.0
DE	24.3	46.21	–

contributor to the life cycle costs are the CAPEX of the ship shown in the plot under the item “ship construction”, which includes the metal work and ship equipment but excludes the power system of the ships. In the particular case of the HFCBE and BE alternatives, these costs are higher due to a higher construction costs assumed for these alternatives. Next to the CAPEX, the personnel costs for the operation of the ship also contribute a considerable share to the total life cycle costs and are the ones with the second highest share for the BE, DBE and DE alternatives. The personnel costs were assumed equal for all the alternatives. Following this, the costs of the fuels and electricity are the third contributor in all the cases, with a marked contribution in the case of the HFCBE alternative, for which the hydrogen costs are higher than the personnel costs. Interestingly, the power train and the replacements of batteries (and in the case of the HFCBE alternative fuel cells) contribute in lesser degree to the life cycle cost of the ship, being more relevant for the HFCBE alternative which includes both batteries and fuel cells.

5.7 Conclusions of the Case Study and Outlook

This chapter described the requirements necessary for the operation of a passenger/car ferry. Built on these specifications, a solution based on hybrid hydrogen fuel cell and battery power system was developed, considering the power demands according to estimations made in the project HySeas III. Following this, sustainability assessments were carried out, showing that the proposed solution allows to reduce the GHG emissions considering all the life cycle phases from 27.0 for a diesel electric alternative to 5.3 kgCO_2eq/km for the hybrid hydrogen fuel cell and battery alternative, therefore allowing a reduction of 80.4% of the GHG emissions per km. This result was obtained considering hydrogen produced via electrolysis fed with onshore wind electricity. Even some reductions estimated at 3.7% were obtained for a hybrid diesel electric alternative also assessed as comparison in the project. Nevertheless, the GHG reductions come along with higher expected life cycle costs, which were estimated as 51.1% higher than those of a diesel electric alternative due to the high CAPEX and hydrogen costs for operating the ship. In general, this study case shows that the hybrid power solutions for ships may provide environmental benefits in terms of the

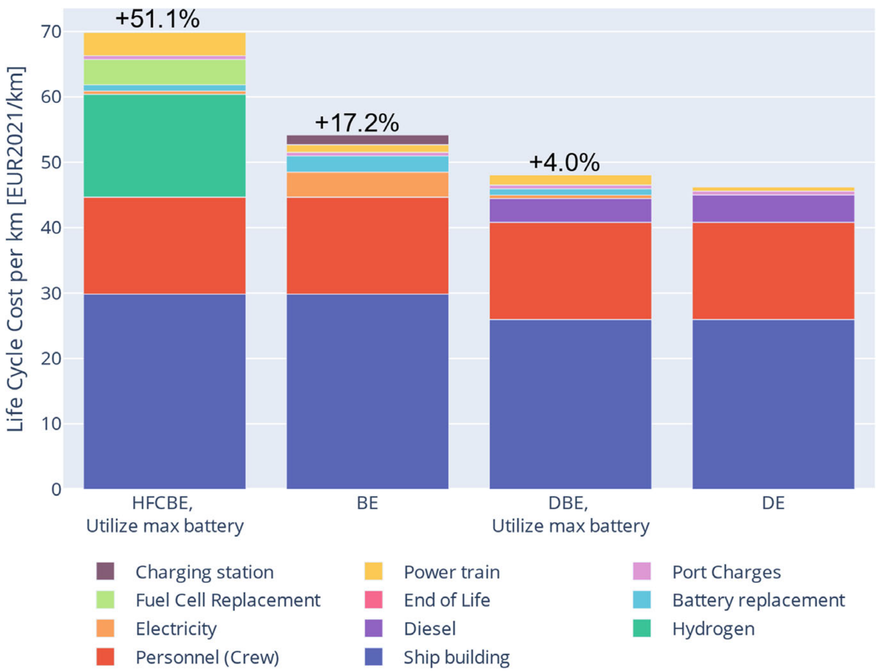

Fig. 12 Contribution of different cost items to the life cycle cost per km for the different alternatives considered in the study. Discount rate of 3.5% assumed Gomez Trillos and Draheim (2022)

reduction of potential GHG emissions. However, some tradeoffs between the reduction of GHG emissions and the upfront and operational costs exist, as the hybrid solutions were found to be more expensive than more traditional and non-hybrid solutions.

Although the construction of the HySeas III concept has not yet been realized, in this dynamic market, ships using fuel cells for their power systems have already been built in parallel projects. These include, for example, the MF Hydra in Norway, the MV Sea Change in the USA and the Suchetha ferry in India, which are already testing these technologies under operating conditions.

6 Conclusions

Waterborne transportation is under increasing pressure to minimize its contributions to climate change and pollution. The introduction of solutions for ships is a relevant part of the measures being taken in this direction, but other equipment at the port as well as the energy supply when ships are at berth are also seen as part of the solution.

To this end, hybrid solutions are already being considered, which have been discussed in detail in the previous chapters. For instance, for ports, the use of Rubber-Tire Gantry (RTG) Cranes has been presented, where hybridization makes it possible to store the energy used to lift containers, which would otherwise be dissipated during container descending. The fuel savings from these solutions are estimated to be in the range 30–60%. Hybrid tugs, ships used to assist other ships during maneuver, are also being considered as a solution to decrease pollution and GHG emissions at ports, already with some offers from commercial producers of these pieces of equipment in the market. Fuel savings of 20–28% have been described in the literature for hybrid tugs. Finally, drayage trucks carrying containers ashore within ports were also portraited as a means of transport where hybridization could also bring benefits such as reducing air pollution with the added possibility of reducing GHG emissions due to higher efficiency and the possibility of use green electricity from the grid.

Shore-side electricity (SSE) applications aim at the supply of electricity to ships while at berth were shown. Hybrid solutions in this regard were discussed and are promising, especially when the electricity supply at port is limited. Conventional solutions such as diesel generators, especially for large ships at berth, have a non-negligible share of total CO_2 emissions and air pollutants like NO_x, SO_x and $PM_{2.5}$. Alternative variants such as shore-side power supply, e.g., with renewable energies (OPS) via the local grid and the combination with storage on land (power banks), own port energy generators like fuel cells and the use of battery-electric ships (e.g., charging with the help of battery swapping) can reduce pollution and CO_2 emissions in the future and increase the resilience of the supply in the ports. If hybrid power systems onboard ships are increasingly adopted in the future and the energy stored on board is used for ship propulsion, other operational phases of the ships can also be impacted and additional benefits in terms of reduction of air pollution and GHG emissions are expected. Even if various SSE options are available, the lack of uniform standards, e.g., in the area of interchangeable batteries, eclectically operated ships and direct current charging in a maritime context are preventing implementation. In addition, the high costs of electricity and hydrogen and the associated propulsion systems compared to the low costs of MDO and HFO are also a deterrent to developing an infrastructure for SSE. However, an improved energy management system to absorb peak loads and use cheaper electricity at times of higher load could help to improve efficiency and reduce the ship's overall electricity costs.

Hybrid power and propulsion systems on ships were also highlighted in comparison to traditional mechanical propulsion systems. The current increasing trends of the adoption of hybrid power for ships based on battery energy storage systems were briefly explained. Current key performance indicators of the power demands for ships as well as the current performance of some key equipment like internal combustion engines, fuel cells and batteries were briefly described and compared. In addition, statistics of the hybridization of ships based on battery energy storage on board were shown, from which it can be concluded that Europe and Norway are the main locations where these solutions are being implemented. Moreover, car/passenger ferries are the main type of ship for which these systems are being adopted, hybrid and plug-in hybrid are the main ship types in terms of the number of active or ordered vessels, and the number of ships fitted with batteries is generally increasing.

Finally, the particular case of the project HySeas III was presented showing that the hybrid hydrogen fuel cell and battery electric concept allows a reduction of 80.4% of the GHG emissions during its entire life cycle compared to a diesel electric alternative. However, the HFCBE alternative was estimated with a life cycle cost of 69.83 EUR2021/km, exceeding by 51.1% that of a comparable diesel electric alternative. One prerequisite for this is that the hydrogen consumed by the ship is produced using wind power and assuming the average GHG emissions from the grid in the UK for the overnight electricity supply to charge the batteries onboard. Therefore, tradeoffs between the reduction of environmental impacts and the costs remain to be one of the barriers to overcome for these innovative hybrid power alternatives.

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