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Energy-related approach for reduction of CO_2 emissions: A critical strategy on the port-to-ship pathway

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ABSTRACT

The maritime sector has been searching for efficient solutions to change energy consumptions patterns of ports and ships to ensure sustainable operation and to reduce CO_2 emissions to support sustainable transport in line with International Maritime Organization (IMO) policy guidelines. Therefore, pursuing smart strategies by utilizing renewable energy sources, clean fuels, smart grid, as well as measures of efficient-energy use are beneficial towards attaining the core goals of the IMO, specifically CO_2 emission reduction in the future. In this review work, the main methods and criteria for monitoring CO_2 emission from ports and ships are meticulously presented. Advanced renewable energy technologies connected with sources such as solar, wind, tidal, wave, and alternative fuels and their application in ports to reduce CO_2 are thoroughly examined. In addition, energy-saving techniques and strategies for alternative power and fuels in ships are comprehensively evaluated. The key finding is that port-to-ship interactions such as using zero-emission energy sources or nearly zero-emission approaches could offer significant benefits for CO_2 emission reduction. Finally, it is recommended that smart approaches associated with efficient and clean energy use for the port-to-ship pathways to generate net zero-CO_2 emissions for the maritime shipping sector need further urgent investigation.

1. Introduction

International shipping, especially maritime freight transport, is a major driving force of global trade. Indeed, a significant bulk of international trading, by both volume (80%) and value (70%), is conducted by means of ocean transport (D., 2016). Given the fact that shipping accounts for a substantial portion of global greenhouse gas (GHG) emissions, particularly CO_2, the continued growth in international trading and ocean shipping activity also anticipated the rise of CO_2 globally in the future. Based on historical data, there are an average annual growth rate of 5.9% in global trade between 1950 and 2004 (Hummels, 2007; D., 2017). In fact, the global shipping industry was responsible for the emissions of 950 million tons of CO_2 (Smith et al., 2015). This study also reported on the specific fuel consumption and its respective CO_2 emissions according to the available vessel types during the same year as shown in Fig. 1.

Based on the results obtained from the performed qualitative analysis, the worst offenders in terms of CO_2 emissions and fuel consumption: container ships, bulk carriers, oil tankers, general cargo ships, and chemical tankers. According to the forecast made in the IMO Third GHG (Greenhouse Gas) Study in 2014 (Smith et al., 2015), CO_2 emissions from maritime shipping could be expected to increase anywhere between 50% and 250% based on the then emissions level under the business-as-usual scenario in which no significant mitigation actions are taken. Hence, the percentage of global CO_2 emissions coming from the

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Nomenclature

AER	Annual Efficiency Ratio
AGV	Automated guided vehicle
ARMG	Automated rail-mounted gantry
ASC	Automated stacking crane
CCS	Carbon capture and storage
CHE	Cargo-handling equipment
CHP	Combined heat and power
CO_2	Carbon dioxide
CNG	Compressed natural gas
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
E-RTG	Electric- Rubber tyred gantry
ESS	Energy storage systems
FC	Fuel cells
HFO	Heavy fuel oil
GHG	Greenhouse gas
IMO	International Maritime Organization
KPI	Key performance indicator
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MDO	Marine diesel oil
MEPC	Marine Environment Protection Committee
MW	Megawatt
NO_x	Nitrogen oxides
RE	Renewable energy
RMG	Rail-mounted gantry
RTG	Rubber tyred gantry
PM	Particulate matter
PV	Photovoltaic
QC	Quay crane
SC	Straddle carrier
SEEMP	Ship Energy Efficiency Management Plan
SOFC	Solid oxide fuel cell
STS	Shore-to-ship
YT	Yard truck
WPCI	World Ports Climate Initiative

global shipping industry could rise as a result of decarbonization from other major sources.

As GHG emissions, notably CO_2, have been proven to cause anthropogenic global warming, the rise in these emissions has serious consequences on the earth's ecological systems and human habitats. Such concerns over the future sustainability of the planet have prompted studies on environmental impact assessment and emissions reduction strategies in the field of maritime transport (Hoang and Pham, 2020). There have been several regulations issued and agreements signed to combat climate change and to contribute to the overall goal of limiting the rise of global average temperature to below 2 °C from pre-industrial levels (FCCC/CP, 2016). Related specifically to maritime transport, regulations concerning GHG emissions reduction could be found in the regulations adopted at the 72nd meeting of the Marine Environment Protection Committee (MEPC) which set a path toward "at least" 50% reduction from the 2008 levels by the year 2050 and more optimistic goal of being fully decarbonized by the same time horizon, if feasible, as shown in Fig. 2. Bound by these rules, ship owners and operators are motivated to seek cost-effective solutions and practical technologies to implement as part of their effort to improve the ship's energy performance and meet the increasingly stringent emissions standards.

Fig. 2 implies that the role of ports and shipping fleet is fully realized as a promising opportunity for climate change mitigation, measures taken to reduce GHG emissions and improve energy efficiency from port and shipping activities are viewed as critical steps in transforming the industry toward a more green and sustainable future (Bjerkan and Seter, 2019; Lim et al., 2019; Bergqvist and Monios, 2019). In meeting this ambitious goal, concurrent initiatives to reduce GHG emission on both sides of the maritime operation (i.e., port and fleet; Joung et al., 2020), as well as land transportation to and from port destinations (Gonzalez Aregall et al., 2018). With the adoption of the Initial Strategy in 2018, the IMO has taken significant steps in charting a course toward a low-carbon future for the global shipping industry (IMO, 2018a; IMO, 2018b). The actions taken by port and ship operators and companies to implement low-carbon initiatives at the ship-port interface to lower GHG emissions from port and shipping activities. Moreover, a resolution was also taken up by the IMO as part of their effort to promote transparency and full cooperation between ports and the shipping fleet (IMO, 2019). Considering the sustained growth in the numbers of the global fleet and increased port activities in the short term, the corresponding

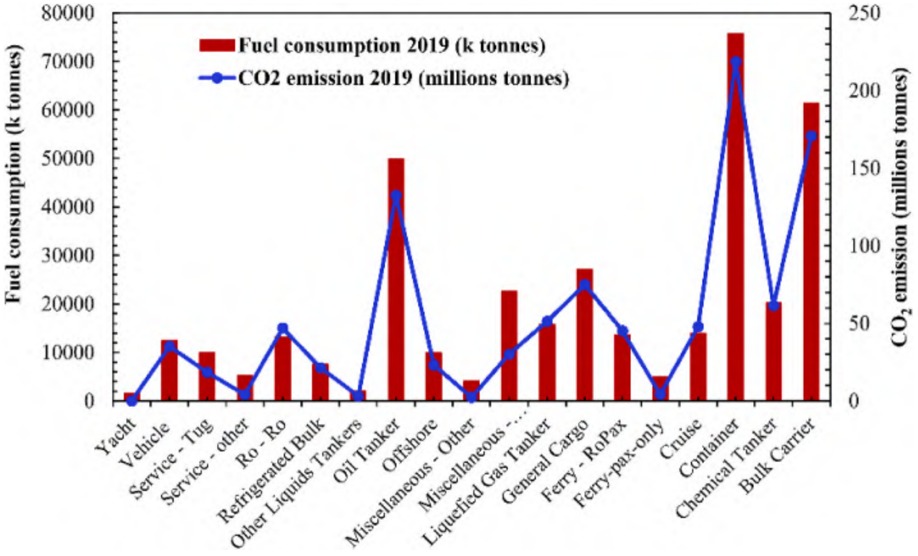

Fig. 1. Relationship between fuel consumption and CO_2 emissions for various ship types (Lion et al., 2020; UNCTAD, 2019).

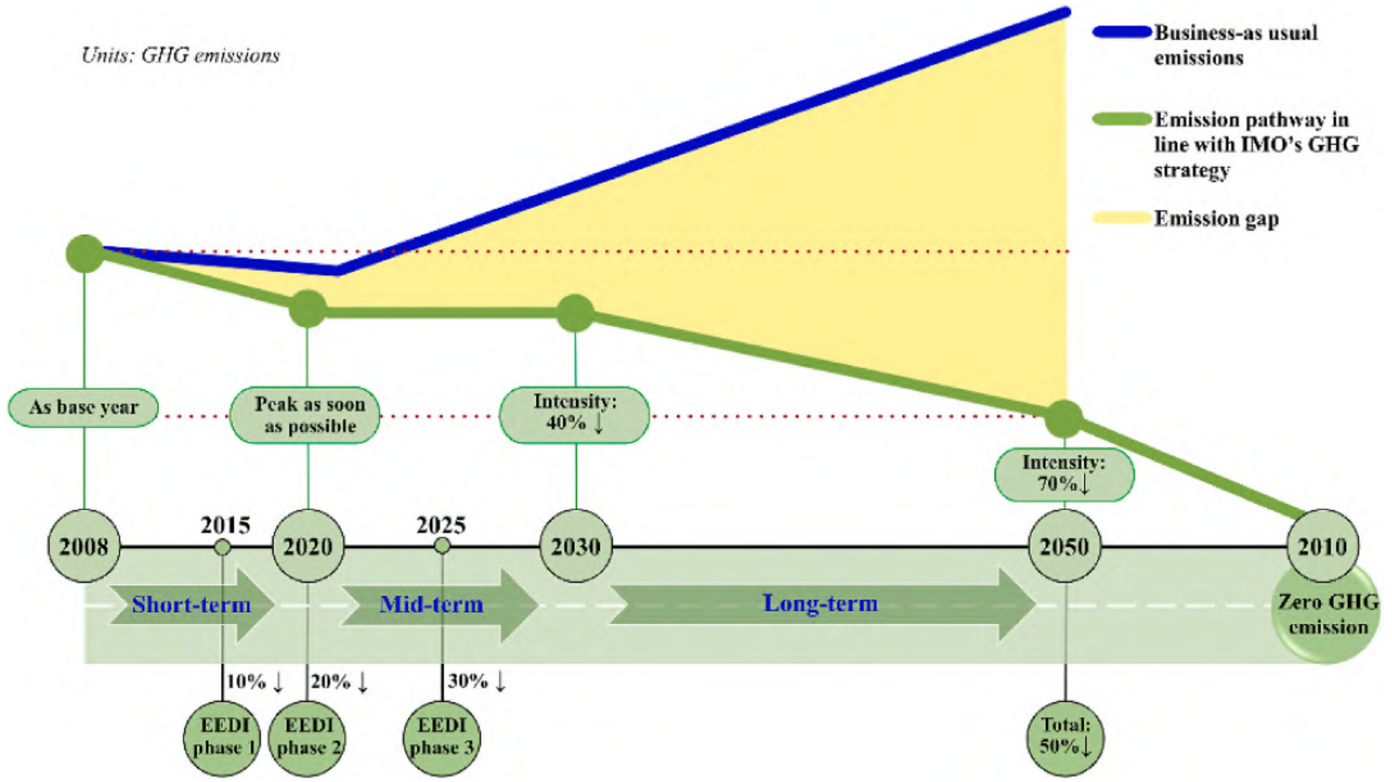

Fig. 2. A comparison of GHG emissions between business-as-usual emissions and orientated strategy of International Maritime Organization (IMO) (DNV, 2018).

rise in energy use of the global maritime shipping industry is likely to result in higher overall energy costs and a surge in emissions of GHG and air pollutants. Energy cost accounts for a large portion of overhead expenses borne by fleet owners and port operators, measures are taken to reduce energy demand. This is necessary in order to achieve cost-saving objectives. Furthermore, lowering GHG emissions from shipping and port activities also contribute to the effort to promote the industry's sustainability goals. As part of the energy-saving strategies, improving the energy efficiency of the existing operations can reduce the overall energy demand required to deliver the same level of services. On the other hand, sustainable sourcing of the energy supply from low-carbon energy resources, including distributed renewable energies and biofuels, makes up part of the overall GHG emissions reduction strategies. Along with advancing the operational efficiency of the global fleet and ports worldwide, improving energy efficiency and promoting the use of alternative renewable energy resources are critical elements in conceptualizing a "greener" and more sustainable future of port infrastructures and global fleet. Based on the posed targets for developing strategy of smart port and ship fleet, the efficiency and clean energy use is very important.

In recent years, there have been several studies on optimizing the technical parameters, design, operation of ships to reduce fossil fuel consumption, thus leading to a decrease in CO_2 emissions. Among these, some studies focused on ship hull optimization to reduce wave drag, while others indicated that the optimization of ship speed or begin-to-end operation route of ships could be an efficient solution to minimize fossil fuel consumption. Moreover, the reduction of lay times for loading and discharging in port could also be considered as an approach to decline CO_2 emissions. In general, the above-mentioned solutions target to go down fossil fuel consumption; however, those solutions appear not to be sustainable since they are still operated on the basis of fossil fuel. Due to this reason, large gaps still exist in the use of renewable energy sources for the ports and ship fleets, as well as the critical assessments for the potential of utilizing such renewable energy sources for the strategy of green maritime. Therefore, the aim of this paper is to provide a comprehensive overview of efficient and clean energy use as a smart approach for the reduction of CO_2 emission in the port-to-ship pathway.

This study contains 6 sections, in which Section 1 introduces the gaps of study to clarify the necessity of this current work. Section 2 presents methods for collecting and selecting data, while Section 3 summarizes the methods for monitoring CO_2 emission from ports and ships. Section 4 examines smart technologies and clean energy for CO_2 emission reduction in ports. Section 5 presents smart technologies and clean energy for ships with a primary focus on renewable energy systems-based propulsion of ships. Section 6 looks at the combination of the port-to-ship pathway for CO_2 emission reduction. Section 7 presents the primary conclusion as well as future scenarios for maritime areas towards zero or nearly-zero carbon footprints.

2. Methods for collecting and selecting data

A literature review relating to methods for reducing CO_2 emission from maritime activities (ports and ships) was presented in this work, and it is essential to know what studies have been already carried out in regards to the topic of current work and to offer researchers a perspective of what needs to examine and study further. To accomplish this, some keywords such as "clean energy", "renewable energy", "green energy", "clean port", "green port", "green shipping", "zero-CO_2 emission ships", "zero-CO_2 emission ports", "CO_2 emission in maritime activities" were searched in the databases such as Scopus, Web of Science, Google Scholar. In general, searching and collecting relevant data should be based on the three-step rule as follows:

(i) - A preliminary survey was conducted in data of Scopus, Web of Science, Google Scholar with the use of the aforementioned keywords;
(ii) - Classification criteria were posed to select and collect the most proper literature, in which four categories like clean energy for ships and ports, renewable energy for ships and ports, measures

for CO_2 reduction in the maritime industry, zero-emission ships and green ports were included.

(iii) - For each category, a more detailed and deeper search was performed on the basis of given specific keywords.

After using the filter for the collection and selection of data, there were a total of 982 references found to match the topics of this paper. However, there were 544 references eliminated since they were not directly related to the topic of this current work.

3. Methods for monitoring CO_2 emission from ports and ships

Despite the availability of cost-effective options that can be applied to lower CO_2 emissions on marine vessels, in reality, actions taken by ship owners and operators remain rather limited. According to IMO's estimation, various energy efficiency measures have the potential to reduce anywhere between 25% and 75% of the current CO_2 emissions from maritime shipping (Buhaug et al., 2009). Based on the assessments provided in previous studies, there is a high chance that the industry could achieve a minimum of 30% or greater in CO_2 emissions reduction at zero marginal cost by 2030 (Eide et al., 2011). Previous studies have asserted that a target of at least 50% emissions reduction would be possible at zero net cost by 2030 if low-cost energy savings were to be fully exploited (Hoffmann et al., 2012). Indeed, if all available energy efficiency and carbon mitigation measures are to be implemented, the projected growth in shipping activities could achieve a remarkable result, while the decrease of energy demands and zero-net reduction in CO_2 emissions could be seen.

In the current state of global shipping, the issue of controlling CO_2 emissions is not merely a technological, yet it is embedded with highly intricate and multifaceted policy elements. To reduce CO_2 emissions from ocean-going ships, the Energy Efficiency Design Index (EEDI) which applies only to new ships, and the Ship Energy Efficiency Management Plan (SEEMP) aim at compelling ship owners and operators in taking actions to reduce CO_2 emissions from their fleet (Bazari and Longva, 2011; Mellin and Rydhed, 2011). The main goal of the EEDI and ship energy efficiency management plan is to lower CO_2 emissions from maritime transport (Azetsu, 2016; Pham and Hoang, 2020). Therefore, both the vessel structural design and operations are subject to these stringent efficiency requirements (Pham et al., 2020). Once 50–80% of current CO_2 emissions are successfully reduced at a future point, it would compel the adoption of hydrogen (i.e., fuel cells) or biofuels as possible alternative forms of fuels in powering future marine vessels.

The current trend in CO_2 emissions reductions in the global shipping industry is driven mainly by the increasingly tighter international regulations and the advances in alternative fuel use. If EEDI sets performance standards for the design and construction of new ships, the SEEMP mainly focuses on addressing energy-saving opportunities on the operational level of both existing and new vessels above 400 GRT. In monitoring the compliance with SEEMP, the Energy Efficiency Operational Indicator (EEOI) has been developed by the IMO as an operational measure tool for the assessment of ship energy efficiency and CO_2 emissions. With the formulation of the EEOI, ship owners and operators now have access an indicator that can be used in the continuous and real-time monitoring of individual vessel operations. Despite the standard use of EEOI in the assessment of ship energy efficiency under the framework of SEEMP, popular opinion in the shipping industry has been controversial as the application of such indicator in comparing the performance between ships is deemed as flawed and inaccurate ("Brief for Eu Member States," 2013). One important aspect is for the energy efficiency metric to be as simple as possible, and another is for it to be verifiable in practice. Hence, a simpler factor, the Annual Efficiency Ratio (AER) measures the energy efficiency of ships in terms of GHG emissions per transport work, assuming a value for cargo, which is constant and based on the deadweight tonnage of the ship.

Regarding port operation, tracking the level of energy consumption and GHG emissions from port-related activities provide the best measurements on the carbon intensity of current operations as well as identifying opportunities for improved environmental performance and sustainability. Such topics have been the focus in previous studies on energy efficiency and emissions reductions of ports (Lam and Notteboom, 2014; Merk, 2013; Woo et al., 2018), ships (Christodoulou et al., 2019), and hinterland transport (Gonzalez Aregall et al., 2018). Prior to the implementation of any emissions reduction strategy, it is necessary to take stock of the carbon inventory as a first step in improving port sustainability (IAPH, 2018). Carbon inventory is a valuable tool in aiding the subsequent analysis and benchmarking of emissions from existing port operations (Pavlic et al., 2014; Van Duin and Geerlings, 2011). These provide the momentum for management boards and companies in reinventing their operation and heading toward a more sustainable future of ports worldwide. Notably, it is necessary for the identification and categorization of the main sources of energy consumption and corresponding scopes of emissions. Besides, emissions from ships arriving and departing from ports are also another potential source that needs to be accounted for (IMO, 2018a; IAPH, 2008). In reviewing the existing literature, several models and methodologies are commonly used in measuring the level of energy demand and analyzing GHG emissions from portside activities and ships docking at ports, including the World Ports Climate Initiative (WPCI) guide to calculate port's carbon footprint (Initiative, 2010), to measure carbon emissions from a container terminal (Sim, 2018; Yun et al., 2018), to control shipping emissions in ports (IAPH, 2018; Olaf Merk, 2014a,b; Zis et al., 2014), and to determine GHG emissions of marine diesel engines (Konstantzos et al., 2017; Saharidis and Konstantzos, 2018). Additionally, several studies also examined energy consumption in container terminals (Spengler and Wilmsmeier, 2018; Van Duin et al., 2017; Wilmsmeier and Spengler, 2016).

4. Smart technologies and clean energy for CO_2 emission reduction in ports

4.1. Energy-based criteria for evaluating the port sustainability

Port operations and logistics have significant energy demands. Given the current development and planned expansion of ports worldwide, a future increase in port energy consumption can be expected. In balancing between energy cost and port operational budget, options are available to reduce general consumption for smart port operations. Particularly, the application of on-site, distributed generation from renewable energy offer strategies for port operators to lower their CO_2 emissions and become energy independent (Rotterdam, 2016). As shown in Table 1, the main aspects of the port sustainability plan can include energy generation from alternative renewable resources, energy

Table 1
The trend of smart and clean energy in ports.

Smart energy in ports	Components	Ref
Energy consumption	Energy consumption by containers/fleet, offices, and companies, lighting, terminal equipment for container movement	(MedMaritime SMART PORT, 2016; Heilig and Voβ, 2017; Hamburg Port Authority, 2021)
Application of renewable energy	Wind, Solar, Biomass, Wave and tidal	(MedMaritime SMART PORT, 2016; Heilig and Voβ, 2017; Hamburg Port Authority, 2021; The Motorways of the Sea Digital Multi-Channel Platform, 2015)
Energy management	Monitoring, management, and optimization of energy use	(MedMaritime SMART PORT, 2016; Heilig and Voβ, 2017; Hamburg Port Authority, 2021)

efficiency improvements, and adopting and executing energy management systems.

In ports, there are two main groups of energy consumers (i.e., direct vs indirect users). The group of direct consumers includes sources of port activities that consume energy directly, such as indoor and outdoor lighting, office buildings, and various other facilities. Indirect energy consumers mainly exhibit seasonal consumption patterns that are highly dependent on the volume of port activities. Examples of indirect energy consumers are cranes, the internal fleet of the port, and refrigerated containers or reefers (PORT, 2016). Through different process improvement and retrofits/upgrades of equipment, port operators and management can realize the potential benefits from more efficient operations and lower energy costs which are resulted from optimized performance, better fuel efficiency, and reduced energy loss. As pointed out by previous research, while emissions from port operation only account for a small fraction of the total emissions from maritime trading (Acciaro and Wilmsmeier, 2015; Tzannatos, 2010), ports as a standalone industry contribute up to 3% of the total global GHG emissions annually (Misra et al., 2017a). Reducing local air pollution remains the top priority for port management boards and oftentimes lower GHG emissions are viewed as a nice extra benefit (Poulsen et al., 2018). When considering the mounting pressure on port authorities to reduce their carbon footprint and make changes toward more environmentally-friendly and sustainable operations (Poulsen et al., 2018), more attention is directed to searching for effective solutions in reducing GHG emissions, notably CO_2 (Du et al., 2018; Rosa-Santos et al., 2019). As port operations are tailored to meet these sustainability objectives, these various measures also contribute toward addressing other key issues concerning the port management companies and stakeholders, such as corporate social responsibility (Moon et al., 2018), compliance with special regulations (Puig et al., 2017), reduction of fossil fuel consumption (IAPH, 2018; Lee et al., 2015), maintenance of “green port” initiatives (Kang and Kim, 2017). Lastly, measures to improve energy efficiency and sustainable port operations through investment in smart micro-grids and low-carbon generation technologies were taken to ensure port operation continuity (Ramos et al., 2014), and saving on energy costs (Wilmsmeier and Spengler, 2016).

4.2. Smart and clean energy system in ports

4.2.1. Power system

4.2.1.1. Electrification. In current port operations, electrification is commonly found among major cargo-handling equipment (CHE), i.e. various crane types such as shore-to-ship (STS), rubber tyred gantry (RTG), and rail-mounted gantry (RMG; ALASALI et al., 2018; Interreg IVB North Sea Region Programme, 2012). Among these, CHE equipped with battery systems is often used (Dhupia et al., 2011). Despite many CHE currently runs on electricity, this category of equipment is one of the major sources of emissions from port activities (Liu and Gong, 2010; Li et al., 2019). Specifically, the total energy of CHE accounts for 80% consumed by container and 40% consumed by bulk terminal. Moreover, container terminals have a significant share in total port’s diesel consumption in several countries (e.g. 50% for Japanese terminals, 60% for Vietnamese terminals, 78% for the ports of Chile, and 88% for the ports of Nigeria) (Acciaro and Wilmsmeier, 2015). These systems require high initial capital expenditure for additional batteries suitable for swapping. Various types of vehicles used in port operations are ripe for electrification as they can be fully powered by the portable battery (such as stacking cranes, yard trucks, forklifts, rail movers, and electric automated guided vehicles (AGVs)) as exemplified by ports around the world, e.g., San Pedro Bay Port (Ports of Los Angeles and Long Beach, 2017), and container terminals in Port Kaohsiung of Taiwan (Yang and Lin, 2013). Examples of fully-electric RTGs equipped with batteries used for short-distance maneuvers have been demonstrated at the Port of Long Beach (Ports of Los Angeles and Long Beach, 2017). In contrast, the use of electric equipment for bulk handling of cargo is more limited due to their high power requirement. Even though it remains fairly difficult to install and operate fully electrified infrastructure, there have been successful applications of electrified-stationary buckets and electrified-conveyor belts used for handling the materials at Port of Long Beach and Los Angeles (CARB/EPA, 2015).

It is necessary to highlight the critical role in the electrification of CHE when considering the life-cycle emissions assessment of equipment and overall emissions reduction objective (Lirn et al., 2013). In a study by Kim et al. (2012), the authors performed a comparative life-cycle assessment between electric yard tractors and diesel engine-based yard tractors in Port of Los Angeles. It is typical to rely on the use of QCs and STS cranes to load and unload cargoes along the quayside of port container terminals (Wen et al., 2017). Depending on the yard layout and configuration (i.e., level of automation, area design, etc.), a wide range of equipment can be found operating in the container yard (Vo et al., 2004).

Equipment such as RMGs and RTGs are mainly used in stacking containers, while the horizontal handling of containers relies on YTs and AGVs. Besides, SCs and RSs are capable of performing both of the above functions (Carlo et al., 2014). With the recent introduction of highly automated equipment, the efficiency of port operations has significantly been improved along with a decrease in the reliance on manpower (Gharehgozli et al., 2016). One can find the use of automated QCs and RMGs in automated container ports. In automated terminals, particularly, operators often utilize QCs and RMGs. Automated guided vehicles, automated lift vehicles, intelligent autonomous vehicles for horizontal transport, while ASCs can be used for stacking operations. In Table 2, several alternative energy resources could be potential utilized to replace conventional fossil fuels in current port operations.

According to findings from recent research, the application of electromobility in ports can increase the overall energy efficiency and lower GHG emissions (Yang and Chang, 2013). As shown by trials at ports located in Copenhagen, Demark, and Malmö, Sweden, the use of electric vehicles has been found to reduce the level of energy consumption through automatic start/shutoff technologies coupled with the smart charging system (Verbeeck et al., 2014). Dhupia et al. (2011) have researched the development of optimal electric tugboats in harbor craft operations. Depending on the energy efficiency objectives, a wide range of technological improvement options is available for QCs and STS cranes, in which a significant amount of energy recovered from the operation of QCs can be stored and consumed at a later time (Nan Zhao et al., 2014). RTG is a commonly used handling equipment for stacking containers in the port yard due to its high flexibility and productivity. Bus bar, touch wire, and cable reel systems are examples of electrical equipment that can be used in the electrification of RTGs (Yang and Chang, 2013).

Compared to conventional RTG models, E-RTGs offer better energy efficiency and lower CO_2 emissions that can benefit from the ability to switch between being powered by the electric grid or a diesel engine. A summary of results from an economic and environmental analysis that compares the performance of conventional RTGs and E-RTGs is provided in Table 3. Based on these results, an 86.6% and 67% reduction in energy costs and GHG were achieved from E-RTGs compared to diesel-fueled conventional RTGs (GREENCRANES, 2012). Furthermore, the electrification of RTGs should be the focus of large-scale studies on the operational performance of container terminals. System optimization of phase in/out schedules for RTG replacement is also subject to resource constraint (Peng et al., 2016). Lastly, the integration of active front-end rectifiers to RTGs should be considered (Pietrosanti et al., 2016a; Papaioannou et al., 2017).

According to Yang and Chang (2013), there are around 86.6% of energy-savings and a decrease of 60–80% for CO_2 emissions recorded for an RTG cable reel. Moreover, the regenerative braking of RTG can save the energy consumption up to 60% (FAHDI et al., 2019). Additionally,

Table 2
Various energy sources for in-port equipment (Wilmsmeier and Spengler, 2016).

Energy sources	AGV (Automated guided vehicle)	ASC (Automated stacking crane)	RMG (Rail-mounted gantry crane)	RS (Reach stacker)	RTG (Rubber-tired gantry crane)	SC (Straddle carrier)	QC (Quay crane)	YT (Yard truck)
Diesel	x			x	x	x	x	x
LNG				x	x	x		x
Hydrogen								x
Electricity	x	x	x	x	x	x	x	x

Table 3
Comparison between RGT and E-RGT (Yang and Lin, 2013; Yang and Chang, 2013).

RGT types	Energy consumption	Energy cost	Total energy cost/year	GHG emission/container (kg)	Total GHG emission, (tons/year)
RTG	2.21 L	24.16	≈64 million	5.96	7,15
E-RTG	3.02 kW h	2.38	≈8.6 million	1.92	2,3

up to 30% of energy can be saved from claiming regenerative energy as a result of crane electrification (Davarzani et al., 2016). Besides, an additional 10% of energy is further saved by the application of battery-AGVs (Schmidt et al., 2015). The application of electric RTGs was the main subject of research in the Port of Tanjung Pelepas, Malaysia (Jonathan and Kader, 2018). In comparison, RMGs and ARMGs both have lower emissions than RTGs because the formers are powered primarily by electricity (Lazic, 2006). The different comparisons on varying levels of energy demand required by RTG, E-RTG, RMG, and ARMG (automated rail-mounted gantry) were provided (Yang and Lin, 2013; Y.-C. Yang, 2017). Among these, RTG ranks on top of the list for the highest level of energy consumption, while E-RTG has the lowest level of consumption. The order from the lowest to the highest is as follows: E-RTG < ARMG < RMG < RTG.

4.2.1.2. Hybridization. There are a variety of hybrid options for port equipment, including fuel-electric hybrids and plug-in hybrids, as well as diesel-hydraulic hybrids in which the motor and wheel motion are powered by hydraulic action (CARB/EPA, 2015). In a hybrid powertrain that is equipped with flywheels and ultracapacitors as the main energy storage device and main source of power, the improved configuration has the potential to save up to 330 kW in peak demand (Nan Zhao et al., 2014). Among the major pieces of equipment found in container terminals, cranes are good candidates for electric hybrid retrofits. As such equipment is powered by electricity, there is a potential for taking advantage of the energy produced from regenerative braking that can be fed back onto the grid as found in the examples of RMGs in the Port of Vancouver (APEC, 2014). According to Tran (2012) and Zhao et al. (Nan Zhao et al., 2014), around 1211 kW in peak demand has been recorded for a QC which could be reduced by as much as 72.7%. In another study, the use of ultracapacitors and supercapacitors can decrease peak demand from 1500 kW to 150 kW for energy storage and a bidirectional converter (Parise and Honorati, 2015). Similarly, there is also an opportunity to lower QC energy consumption with the utilization of the new spreader tandem twin lift (G Parise et al., 2016). Analyzing the use of hybrid RTGs, Wei et al. (2019) found that such an application could deliver up to 70% in energy saving. The following ports, including Port of Los Angeles, Spanish, Shenzhen, Tianjin, and Vancouver, all hybrid-electric RTGs have been used. Other examples include the use of hybrid reach stackers and hybrid hydraulic systems for bulk handling-equipment at the Port of Helsingborg and Port of Long Beach and Los Angeles, respectively equipment (Ports of Los Angeles and Long Beach, 2017), (Peng et al., 2016), (Fung et al., 2014).

Common energy storage devices, including supercapacitors (Kim and Sul, 2006), (Antonelli et al., 2017), batteries (Niu et al., 2016), and flywheels (GREENCRANES, 2012; Flynn et al., 2008; Tan and Yap, 2017) enable the storing of potential energy that can be consumed at a later time. In the context of port operations, this amount of stored energy is often used in hoisting and moving cargo. In the study of Flynn et al. (2008), the authors examined the configuration of a flywheel structure accompanied by an undersized diesel-generator as a means of energy storage for an RTG, as a result, up to 35% in energy saving was achieved. Furthermore, other added benefits, including an extended lifetime of generators, lower noise level, and quicker system response time, were observed. Besides, it has been shown that equipping supercapacitors with a generation source (e.g., diesel-powered generator) could lower energy demand by as much as 35% (Kim and Sul, 2006). In another study, the use of a flywheel in RTGs decreased 38% of initial energy consumption, as part of a power management system exhibiting stochastic loads and random duration (Pietrosanti et al., 2016b). Besides, a power management system was demonstrated for RTGs with the following main components (1)-a primary converter with a diesel engine, generator, and power converter, (2)-an energy storage system, and (3)-electric drives. The experimental result showed between 20% and 60% fuel reduction given the choice of hybridization models (Antonelli et al., 2017). In a study reported by Zhao et al. (2016), an example of a hybrid powertrain system was demonstrated for RTGs that resembled QCs. Lastly, a potential option includes the retrofit of RTGs with a smaller diesel generator consisting of a diesel engine and an electric generator (GREENCRANES, 2012). With recent advances, SCs have been converted to hybrid models equipping with a diesel-electric generator or an energy storage system which could achieve a fuel efficiency of up to 27.1% (Hangga and Shinoda, 2015). For hybrid SC models, there are different levels of energy consumption associated with traveling, hoisting, and lowering motion, at 52%, 31%, and 11%, respectively. Results from a sensitivity analysis have revealed the positive impact that hybridization has on the equipment's performance efficiency, travel distances, laden weight vs empty weight traveling (Hangga and Shinoda, 2015). Hence, retrofitted AGVs have achieved greater efficiency, reliability, and safety (Bechtsis et al., 2017). Similar to other port equipment, AGVs can be powered either by diesel fuels, electricity, or hybrid.

4.2.2. *Energy storage systems (ESSs)*

The application of energy storage systems (ESSs) as the main optimization method for the production and consumption of electricity has gained significant attention because of its role in lowering GHG emissions along with energy costs. Furthermore, ESSs allow for the integration and balancing so the surplus energy could be efficiently stored and fed back onto the grid (Kotrikla et al., 2017; Papaioannou et al., 2017). Commonly found ESS technologies include batteries, supercapacitors, and flywheels (Ahamad et al., 2019; PIANC, 2019a).

In the context of CHE, the lifting motion of containers accounts for the largest portion of the energy consumed by CHE. On the other hand, the energy consumed by lowering and braking actions is often wasted unless it was being captured (Antonelli et al., 2017). Hence, the potential energy savings from recaptured wasted energy from utilizing ESS in mobile CHE is as attractive as the anticipated environmental benefits. The utilization of ESSs has several important benefits including the ability to capture regenerative energy captured from braking motion and optimize combustion energy drive. In cases where electrification of CHE is not practical, the deployment of ESSs has the potential to save up to 20–50% of total fuel consumption (PIANC, 2019a). Examples of ESS deployment in CHE can be found in the following studies on STS crane supercapacitor (G. Parise et al., 2015a,b) and flywheels (Giuseppe Parise et al., 2016a), and RTG crane flywheels (Papaioannou et al., 2017), supercapacitor (Zhao et al., 2016), and batteries (Antonelli et al., 2017). Furthermore, the potential fuel saving from battery application in RTGs can reach up to 57% (Niu et al., 2016). Similarly, Tan and Yap (2017) found that over 30% reduction in the level of energy consumption was achieved with the installation of a flywheel structure. The principal scheme of RTG integrated with ESS is illustrated in Fig. 3.

4.2.3. Renewable energy in ports

Immense energy-saving opportunities exist in port operations. Energy generated from renewable energy (RE) resources, such as wind and solar, has the potential to supply part or all of the current energy demand from ports. These potential sources include large off-shore wind turbines or on-shore turbines located in the terminal area supplying electricity in powering cranes and forklifts, small vertical wind turbines installed on buildings to satisfy the energy demand of offices, garage facilities, and electric vehicles, solar photovoltaic (PV) installed on rooftops of buildings to meet the energy demand of offices, garage facilities, and electric vehicles, biodiesel supplying fuel to the internal fleet, and marine technologies utilizing wave and tidal energy to generate electricity in powering electric cranes and forklifts (PORT, 2016).

The focus on utilizing RE to enhance the sustainability aspect of port operations has significantly grown in recent years (Ramos et al., 2014). In cases where on-site generation is not feasible, port authorities have the option to purchase electricity produced from renewable energy resources through the RE Purchase Initiative as part of their sustainable strategies (IAPH, 2008). Ports can also explore opportunities for RE investment by forming shared agreements with other organizations and companies. Fig. 4 shows the trend of utilizing RE in port to reduce CO_2 emissions. In this aspect, a study was conducted by Hentschel et al. (2018) to examine the opportunities of RE cooperatives in the case of the Port of Rotterdam. Another example is the EU E-harbor project which examines the implementation of RE in EU ports (Delnooz et al., 2012).

Similarly, a report published by PIANC provides a detailed discussion on the applicability of RE technologies and their potential application in port (PIANC, 2019a). It has been observed that the integration of multiple RE supplies and resources can yield a large potential for energy savings and CO_2 emissions reduction. In their study, Fahdi et al. (FAHDI et al., 2019) provided a comparison of different case studies of RE utilization among Asian ports. The authors found around 12–84% in saving the energy consumption and 2.7–80% in a decrease of CO_2 emissions. In the studies conducted by Rijsenbrij et al. (Rijsenbrij and Wieschemann, 2011) and Acciaro et al. (2014a), the integral role that renewable energy plays in enhancing the sustainability of ports was reported. From this perspective, “the percentage of energy from renewable resource” can be used as an indicator or KPI in evaluating the green and sustainable operations of ports (Acciaro et al., 2014b; STP, 2015; Buiza et al., 2016).

For wind energy, the installation of large wind turbines is often limited to off-shore wind farms due to its space requirement (Chen et al., 2021). The case studies of wind energy project include the Ports of NYNJ, Long Beach, San Diego, San Francisco, Hamburg, Baltimore, and Zeebrugge, as well as notable large capacity wind energy projects such as Rotterdam port (200 MW), Amsterdam port (28.2 MW), and Antwerp port (45 MW) (Efforts, 2014). In the case of off-shore wind energy, the combined capacity of the generators often exceeds the port grid’s capacity to safely handle the surge of electricity flow. Hence, port authorities have found a solution to engage in power purchase agreements

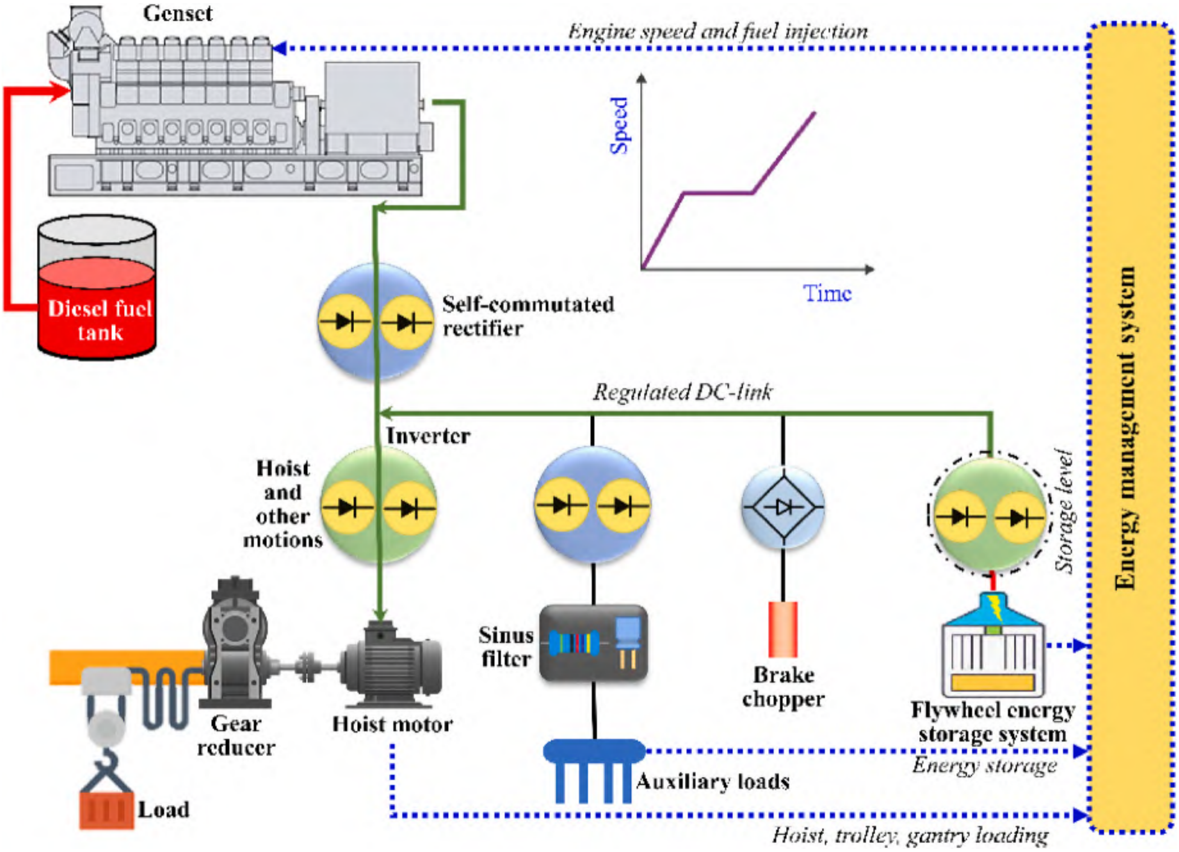

Fig. 3. Scheme of hybridized energy flow of RTG integrated with ESS (Siemens, 2008).

Fig. 4. Use of renewable energy in ports, (a) – Solar PV utilization in Ports of Stockholm (Persson and Olofsson, 2017); **(b) – Use of wind turbine in Port of Rotterdam** (TSCNET Services, 2017)**; (c) – Electric cranes in Port of Vancouver** (Greenport, 2020)**; (d) - Utilization of wave energy at port** (Greenport, 2016).

with wind farm developers to purchase a portion of its generated capacity (PIANC, 2019a). Li et al. (2019) conducted an optimization study on the suitability of offshore-wind generation and storage for container terminals.

Ocean energy is generated by ocean currents from a combination of temperature, wind, and salinity (Efforts, 2014). Tidal energy has bright potential due to the predictability of tidal motions even not yet widely used. High investment costs and low reliability are the key obstacles in tidal energy application. Several studies have focused on case studies of tidal energy applications among different ports around the world, e.g., the port of Avilés, Spain (Espina-Valdés et al., 2019), Port of Ribadeo, Spain (Ramos et al., 2014), and near Port of New Jersey, US (Tang et al., 2014). Similarly, studies focusing on wave energy can be found among the following examples, e.g. Port of Anzali, Iran (Hadadpour et al., 2014), Italian ports (Arena et al., 2018), and Port of Leixões, Portugal (Rosa-Santos et al., 2019). As recommended by Cascajo et al. (2019) and Li et al. (Li et al., 2018), a feasibility study should be performed before investing in either tidal energy or wave energy as a source of power supply for ports. Moreover, Vicinanza et al. (2019) reviewed the current state of innovation of wave energy and related conversion technology situated in harbor breakwaters.

Solar energy production can come in the form of electricity generation through solar photovoltaic or solar water heating. Solar PV applications can be off-grid for navigational signals, buoys, and remote beacons. Solar PV systems are built on an empty piece of land or mount on top of building rooftops. For ports of Venice, West Sacramento (Vincent, 2014), and Rijeka (Boile et al., 2016), rooftop solar PV shave been placed on cruise terminals, warehouses, and other types of storage facilities. Other port locations around the world have also utilized energy generated from solar PVs, including the ports located in Amsterdam, Felixstowe, Antwerp, Tokyo, Genoa, and San Diego (Acciaro et al., 2014a). Simulation studies have also been conducted on the benefits gained from solar water heating applications in ports, e.g., Ukrainian ports (combined with wind turbines) (Yarova et al., 2017), Port of Damietta-Egypt (El-Amary et al., 2018), and other Egyptian ports (Balbaa et al., 2019). In their research, Kotrikla et al. (2017) have shown that a significant amount of CO_2 emissions could be eliminated by utilizing solar PV and wind turbines in the onshore power supply. Lam et al. (2018) also highlighted the key role of solar photovoltaic in achieving a low-carbon footprint in port operations.

Furthermore, solar energy application in the form of solar water heating is a reliable energy source for hot water and heating. The use of rooftop solar water heating panels could help to reduce heating costs in buildings (Delnooz et al., 2012). As recommended in the study of Bergholz et al. (Bergholz, 2014), solar photovoltaic panels could be installed on top of as a main source of power for refrigerated shipping containers and other electrified equipment. There is also an additional advantage in covering such an area when considering the fact that the installed solar panels would create a shade shielding the containers from the sun. Hence, the cooler exterior temperature would help to lower the amount of electricity to power these refrigerated containers. In a study by Misra et al. (2017b), the authors evaluated the utilization of solar PV and wind turbines in the Port of Chennai through an economic analysis of solar PV systems based on the number of clear sky days, capacity utilization factor, and total available photovoltaic area. In another case, solar PV panels have been installed on warehouse rooftop at the Jurong Port of Singapore that has been able to generate 12 million kW/h annual energy capacity (JP, 2016). Similarly, warehouse rooftop solar photovoltaic systems at the Port of Hamburg have an expected annual generation capacity of 500 MWh (Acciaro et al., 2014a).

The use of alternative sources of cleaner fuels, such as biofuels, Liquified Natural Gas (LNG), dual-fuel LNG, hydrogen fuel cells in powering port equipment, buildings, and other operations provides effective solutions in lowering the potential emissions of air pollutants and GHG. There are several examples of LNG applications in ports around the world. The Port of Long Beach first tested the use of LNG in port equipment in 2008 (PLB, 2008). In Europe, several ports have utilized equipment as that is powered by LNG as a standalone or in combination with another fuel, e.g., LNG fuel-based terminal tractors, LNG, or dual-fuel RTGs, and LNG dual-fuel RSs (GREENCRANES, 2012). Among the above applications, up to 16% reduction in CO_2 emissions has been observed in LNG-based terminal tractors, while there has been a slight decrease in NO_x emissions. Compared to fossil fuels, the implementation of LNG has the potential to achieve as much as 25% of the current CO_2 emissions from port operations. The decision to select the optimal number of terminal tractors to be converted to LNG depends on the fuel prices in each country (GREENCRANES, 2012).

Also funded by the EU, the SEA terminals project has enabled the implementation of hybrid and LNG dual-fuel RTGs prototypes (SEA2014). The Port of Valencia has utilized LNG-fueled engines as part of the Green Effort project (Froese Jens, Toter Svenja, 2014). With the anticipated growth in the use of LNG as a potential alternative fuel in ships and port equipment, port authorities are required to pay additional attention to the availability of LNG fuel, as well as access to the reliable supply network and maintenance of bunkering infrastructure and storage facilities (Acciaro et al., 2014a; SEA, 2014). For other biofuel types, the Port of Rotterdam has attempted at using a biofuel mix that contains biofuel and regular diesel at a 30:70 vol ratio (Geerlings and Van Duin, 2011). Given the fact that 4.8 million tons of biofuels have been transported through the Port of Rotterdam in 2016 making it the top import and export hub of such fuels. Considering this fact, harbor wastes could be utilized as inputs for biofuel production (Misra et al., 2017b). The utilization of LNG and CNG/biomethane was found to be highly suitable for maritime aiming to ensure cleaner air and more sustainable shipping. Depending on the ship/vessel type, CNG/biomethane could be used for ship/vessel sailing a fixed route in urban ports, in which ferries could be connected with other transportation means through fixed renewable-fuel refueling points as shown in Fig. 5.

Obviously, there will be many benefits to the environment and the human living in the port cities as switching to alternative fuels as well as the commercial interest for ports. The fact shows that the total cost of ownership for the case of using CNG/biomethane or LNG as fuel could be comparable to that of diesel fuel for certain ship types. Furthermore, if ships and local traffic are simultaneously supplied with CNG/biomethane, the capital costs for its infrastructure are reported to remarkably reduce because not only the local port but also ferry/taxi companies could operate the same CNG/biomethane infrastructure (Pitpoint clean fuels, 2021).

Although hydrogen fuel cell remains a relatively new development in terms of its application as an energy source for port equipment, some notable case studies can be referenced. In Germany, the Port of Hamburg and the Port of Bremerhaven have tested the use of hydrogen fuel produced from renewable sources. While the former case utilized hydrogen fuel cells in forklifts, engines of SCs were the main subject of the hydrogen fuel cell engine conversion in the latter case (Tatiana, 2012). As discussed in (Froese Jens, Toter Svenja, 2014), hydrogen fuel cells were applied in powering tugboat engines via a static hydrogen injection system. On the other hand, the potential of hydrogen fuel cells was tested in a combination of hydrogen as a clean source of energy in a wide range of applications for port equipment at the Ports of Los Angeles and Long Beach (PLA, 2016). In a recent study of Sadek et al. (Sadek and Elgohary, 2020), they have found that the combination of offshore wind turbine and fuel cells for the case of Alexandria Port in Egypt has reduced CO_2 emissions by 80,441 tons/per. Despite its large potential, the key obstacles facing widespread utilization of hydrogen fuel remain, such as reliable supply, technology maturity level, and less competitive return of investment compared to the other fuel options in terms of costs.

In addition to the above-mentioned RE sources, co-generation plants or combined heat and power (CHP) hold a large potential in improving the energy efficiency of ports as discussed in (Giuseppe Parise et al., 2016b; Siemens, 2017). CHP is operated in a sufficient manner that captures and reuses the waste heat produced in the process of power

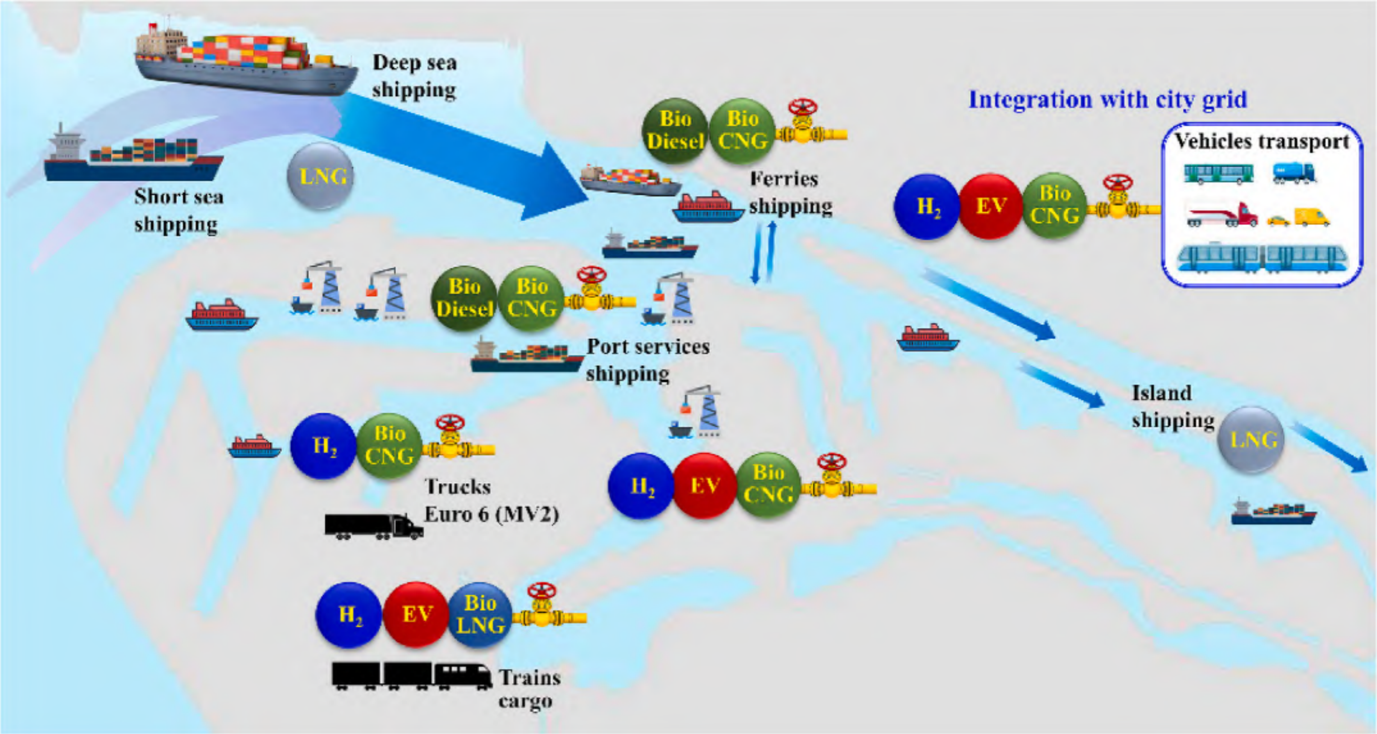

Fig. 5. Clean-fuel infrastructure in the port (Pitpoint clean fuels, 2021).

generation. A previous study provides a detailed analysis of CHP and its waste heat recovery mechanism (HPA2015). Funded by the European Union, the Green Efforts projects have advocated for the potential of (1) external supply of regenerative energy and (2) on-site renewable energy generation for ports (Froese Jens, Toter Svenja, 2014). In the former case, a power purchase agreement can be formed between the port authority and the power supplier. The supplied power can then be resold to individuals or groups of consumers in areas neighboring the ports. Hence, it would increase the ability of small consumers to gain access to energy produced from renewable sources. Due to the difference between the underground and ambient air temperature, geothermal energy can be used for heating and cooling buildings and other types of facilities in the port. Besides, the heat energy drawn from deep inside the Earth can be used to produce steam for feeding electric generators. Examples of near-surface geothermal energy can be found among ports in the EU (Efforts, 2014), Antwerp and Hamburg ports (Acciaro et al., 2014a), Rotterdam ports (Port of Rotterdam, 2017).

Several approaches to introduce renewable energy resources into existing port operations were discussed. Particularly, Acciaro et al. (2014a) suggested the reasons for adopting smart energy systems in ports as a part of the overall energy efficiency and sustainability objectives by comparing two different case studies involving ports that have adopted smart energy management system practices. In another similar review (Giuseppe Parise et al., 2016b), strategies in deploying and integrating smart grids and microgrids in the overall energy management system of ports have been presented. In their analysis, the authors also provide key recommendations for port management boards and stakeholders to incorporate key information in their energy management plan and decision-making to optimize the benefits received by the port and surrounding communities. Based on the statistical techno-economic analysis, several studies have set out to examine the potential effects of integrating renewable energy resources and energy storage technologies in the energy networks (Hoang et al., 2021; Vakili et al., 2022), this could enable to exchange of power between marine vessels and the grid potentially.

Specifically, Lamberti et al. (Arasto et al., 2012) were able to confirm the economic values gained from selling electricity generated from distributed renewable energy generation to the grid, while providing potential savings to cover capital and operation costs. The idea of building future ports into energy hubs using smart energy systems was discussed in Prousalidis et al. (2017). This concept is based on the assumption that cold ironing or shore-to-ship power process can be implemented to supply shoreside electrical power to ships at berth. In their study, Ramos et al. (2014) reviewed the potential application of a tidal farm in supplying the power needed for port activities. The authors performed the analysis using a 3D hydrodynamic model with 25 turbines in assessing the power capabilities in meeting the local energy demand. However, there are several obstacles as pointed out in the article concerning primarily the site selection of the tidal farm. Similarly, (Alvarez et al., 2013) also utilized a techno-economic analysis in reviewing the potential of tidal energy application to meet the energy demands for ports and local communities. The authors asserted the potential of tidal energy as a viable option in terms of cost and sustainability perspective. Particularly, a detailed review was provided on possible designs of a tidal turbine generator based on both technological and economic feasibility. In another study, a microgrid model was proposed by Ramos et al. (Misra et al., 2017b) in supplying the main energy demand of ports. They identified that the option of installing a 5 MW of solar PV and a 6.5 MW wind turbine was sufficient in meeting the existing level of energy demand. In another example, Manolis et al. (2017) provided a detailed analysis of implementing a distributed demand response strategy for voltage enhancement in port energy distribution networks via multi-agent systems. Other studies have also suggested the use of different statistical methods in optimizing solar and biomass energy supply among different port locations (Balbaa and El-Amary, 2017). According to these reviews, up to 50% of power demand optimization can be met by the integration of generation capabilities from local renewable energy sources. The utilization of RE in ports as a potential source of an alternative clean source of energy has gained considerable attention due to its power capabilities. In general, different RE technologies along with their main characteristics are listed in Table 4.

Table 4
Major characteristics and applicability of renewable energy systems in ports.

Technologies	Advantages	Disadvantages	Capacity	Ref
Energy storage systems	High reliability and stability; incorporative automation; easy electrification	High investment cost; low lifetime	–	Sifakis and Tsoutsos (2020)
Wind-based energy generation including onshore and offshore	High energy efficiency; high efficiency in unallocated space	High initial capital; low lifetime; easy degradation; suitability for large ports	2–6 MW	(Kotrikla et al., 2017; Yarova et al., 2017; Spiropoulou et al., 2015) (Weiss et al., 2018; Liang Li et al., 2018a, b; Christoforaki and Tsoutsos, 2017) (Blažauskas et al., 2015; H. Li et al., 2020; Díaz and Guedes Soares, 2020) PIANC (2019b)
Solar-based energy generation	High energy efficiency; low initial capital; mature and high-expertise technologies	Low lifetime; frequent repair and maintenance	1–50 MW for on-ground; 2–100 MW for rooftop	(Interreg IVB North Sea Region Programme, 2012; Balbaa et al., 2019; PIANC, 2019b) (Mitzinneck and Besharov, 2019; Augustine and McGavisk, 2016; Xiao et al., 2020)
Ocean-based energy generation	High energy efficiency and acceptance; multi-application; non-impact on landmark	High initial capital; only suitable for large ports; uncompleted technologies; low reliability; potential for harming the stability of the ecosystem	1.5–250 MW for wave energy; 50–750 kW for tidal energy	(Melikoglu, 2018; Espina-Valdés et al., 2019; Tang et al., 2014; PIANC, 2019b; Hiranandani, 2014)
Geothermal energy generation	High energy efficiency and acceptance; multi-applications	High initial capital; difficulty in low geothermal potential; low-expertise technologies	–	(Acciaro et al., 2014a; Sifakis and Tsoutsos, 2020)
Alternative fuels	Low cost; multi-application; non-impact on landmark; circular economy in the case of utilizing the waste	High initial capital; low-expertise technologies	–	(Hanssen et al., 2014; Siemens AG, 2017; Uche-Soria and Rodríguez-Monroy, 2019; Dvarionienė et al., 2013)

4.2.4. *Efficient strategies of energy/fuel use*

The use of automated mooring systems is considered a potential strategy in reducing the level of energy consumption in ports (Gibbs et al., 2014; Misra et al., 2017a). Particularly, such a system allows for the easy mooring of ships via vacuum and they can be fastened to berth with a simplified set of maneuvers, which results in lower levels of energy demand from ships. Other types of advanced technologies, such as start-stop engines, can be utilized in diesel-powered equipment that could deliver approximately a 10–15% reduction in fuel consumption (Froese Jens, Toter Svenja, 2014). Besides, the methods in leveraging the reactive power consumed by electric equipment have been explored for port energy management (Froese Jens, Toter Svenja, 2014). In future scenarios, there is also an opportunity for carbon capture and storage technology to be deployed in port operation to eliminated the amount of CO_2 that is emitted into the atmosphere (Acciaro et al., 2014a). In the case of the Port of Rotterdam, several approaches including the use of heat exchangers, water treatment technologies, and degassing installations are taken to achieving the desired heat and energy-saving (Hollen et al., 2015). Efficient use of resources and waste management strategy are important aspects to consider as part of port energy efficiency strategies (Acciaro et al., 2014a).

Lighting, among other activities, is another significant source of energy consumed in ports which accounts for between 3 and 5% of the total energy consumption (Acciaro et al., 2014a). There are several applicable lighting solutions to improve its energy efficiency, including converting high-pressure sodium lamps to energy-efficient light-emitting diodes (LED) lamps, using mast lighting for outdoor terminal (Claudius C, 2012). Particularly, an electricity cost saving of over 300, 000 euros has been realized by adopting the above recommendations by the ECT Delta terminal in the Netherlands (Van Duin et al., 2017). Besides LED, the improvements on lighting levels and design of armatures are important aspects in helping to reduce current energy demand for lighting (Rijsenbrij and Wieschemann, 2011). In a recent study, Buiza et al. (2016) provided a detailed analysis of smart energy system applications in ports using examples of ports in the Mediterranean region. The above assessment was conducted taking into account the implications of current port operations on the energy and environmental dimension. The study was able to highlight the important role of smart energy systems in managing port activities, improving energy efficiency, and reducing carbon emissions through the integration of renewable energy resources. In a project of SEA TERMINALS aiming to develop the port industry towards low-CO_2 emissions, they have indicated that the use of alternative fuels/renewable energy integrated with smart energy management could create considerable positive effects on the reduction of both GHG emissions and energy consumption. SEA TERMINALS was really examined in the ports of Valencia and Livorno with a comprehensively integrated prototype set based on low-CO2 emission technologies (shown in Fig. 6) (Fundacion Valencia port, 2015).

5. Smart technologies and clean energy for ships

Currently, ship propulsion systems on commercial vessels are mainly powered by diesel engines, steam, or gas turbines with diesel engines make up the majority of the available fleet (Pham and Hoang, 2019). Reducing the reliance of marine vessels on fossil fuels is part of the strategies to attain a more sustainable and low-carbon future for the global shipping industry. This is achieved via introducing alternative and cleaner fuel options in powering ships (Pham et al., 2020). Therefore, the potential applications of alternative fuels (e.g., LNG, biofuels, hydrogen, and ammonia) and advanced non-carbon emission systems in ship propulsion systems have gathered significant attention from researchers, as these potential low-carbon fuels are being tested on both laboratory and pilot scales.

5.1. *Alternative fuels*

Heavy fuel oil (HFO) has been used primarily by the shipping industry due to its cost advantage compared to other cleaner fuels (Buhaug et al., 2009; Buhaug et al., 2008). However, there is a high sulfur content of 2.5% in HFO, while diesel fuels typically contain up to 0.5% of sulfur. Hence, replacing conventional marine fuels with those containing lower sulfur content (<0.1%) will lead to lower emissions of air pollutants and GHG. According to IMO, the switch from HFO to marine diesel or gaseous fuels could lower CO_2 emissions by as much as 4–5% per

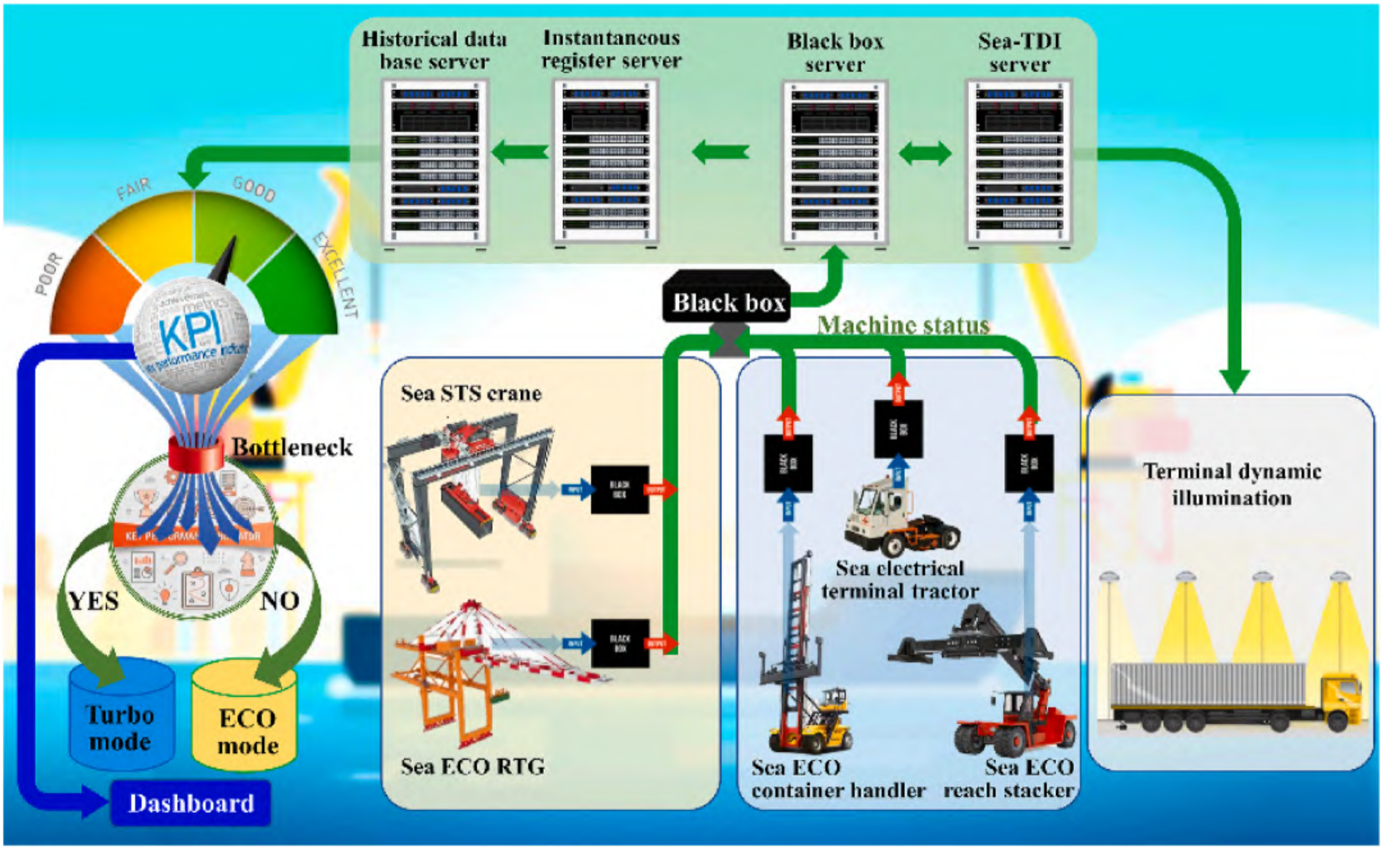

Fig. 6. Integration between smart/energy-efficient technologies with smart energy management (Fundacion Valencia port, 2015).

tonnage of fuel consumed (IMO, 2010). Detailed comparison of the carbon content and emissions characteristics for various fuel types could be found in reference (IMO MEPC.1/Circ.681, 2009).

LNG is a potentially attractive fuel for the shipping industry due to its low-carbon content. Compared to HFO and diesel, natural gas is a cleaner-burning fuel due to its lower emissions of SOx, NOx, and PMs (IMO, 2009a,b). On the path toward achieving a low-carbon future for the shipping industry, LNG plays a significant role in advancing the decarbonization effort due to its high energy density relative to other hydrocarbons or alcoholic-based fuels. In theory, LNG emits 20–25% less in carbon dioxide compared to other heavier fuel oils traditionally used on marine vessels. However, due to the potential of some methane slip, the actual CO_2 emissions reduction that LNG could achieve is approximately 12–20% (Fernández et al., 2017; Ushakov et al., 2019; Hwang et al., 2019). A move from using diesel fuel to dual-fuel such as LNG/diesel in powering a ship's main engine has the potential to reduce CO_2 emissions up to as much as 10% (Banawan et al., 2010). Performing a statistical analysis on the conversion of a two-stroke diesel engine from using HFO to LNG, researchers observed a reduction in average CO_2 by 811% and 96%, respectively (Elgohary et al., 2015). In a study by Anderson et al. (2015), the authors analyzed the emissions characteristics of an LNG-powered ship with four dual-fuel engines of 30,400 kW at different loads. CO_2 emissions for LNG were recorded to be lower than those of marine fuel oils. However, the combustion of LNG resulted in higher CO and HC emissions. Similar results were observed by Li et al. (J. Li et al., 2015) in a high-speed marine dual-fuel diesel engine. Not only LNG exhibits positive environmental effects due to its lower CO_2 emissions, but it also demonstrates an important cost advantage (Banawan et al., 2010; Ammar, 2019). For spark-ignition gas engines and dual-fuel engines, methane slip remains a major obstacle when operating at low engine loads (Ushakov et al., 2019). Several limitations currently prevent the wider adoption of LNG as a primarily marine fuel, such as access to LNG supply, availability of storage infrastructure, uncertainty related to operational risk, and regulation (Schinas and Butler, 2016). The additional design adjustment to accommodate the LNG storage tank and the power station is likely to increase ship operational cost (Burel et al., 2013). Given the insufficient technical and safety standards related to storage capabilities, the use of LNG on commercial ships remains quite limited (Kumar et al., 2011). However, researchers believe in the future growth of LNG applications when considering the technological advances related to its production, transportation, and storage (Thomson et al., 2015). LNG plays an integral part in the transition toward a decarbonized future for the global shipping industry (IMO, 2016; DNV, 2019).

Biofuel use is a climate-friendly option in terms of CO_2 reduction compared to conventional fossil fuels (Gaurav et al., 2017). The application of biofuels, including bioethanol and biodiesel, have immense potential for the shipping industry (Righi et al., 2011; Bengtsson et al., 2012). Biofuels have several important advantages over other alternative fuels such as hydrogen when taking into account the availability and diversity of raw materials for biofuel production, simplicity in handling and storage, reduced emissions, and high energy density (Ölçer et al., 2021). Apart from ethanol, methanol is another popular form of alcoholic fuel (Imran et al., 2013). On an industrial scale, methanol can be produced from natural gas or obtained through the gasification of biomass. Methanol, particularly bio-methanol, is considered a cleaner and more sustainable fuel for the shipping industry due to its low emissions of CO_2 and other air pollutants. When comparing HFO or marine gas oil, the combustion of methanol as the primary fuel used in powering marine vessels emits lower amounts of both CO_2 and other common air pollutants (Gilbert et al., 2018; DNV GL, 2016). In assessing the potential application of methanol/ethanol as alternative fuels for marine vessels, an evaluation has been conducted by the European Maritime Safety Agency on the benefits and challenges of these resources in terms of the technical, operational, and economic factors, supply availability, environmental impacts, and safety regulations (Ellis and Tanneberger, 2015). There are 13 methanol-powered ships are currently in operation worldwide (*Technology and Applications of Autonomous Underwater Vehicles*, 2002). The MS Stena Germanica is the world's first major marine vessel to run on recycled methanol since its conversion in 2015. The move to ethanol has resulted in a 25% reduction in CO_2 emissions meeting the standards set by the latest ECA regulations for the ship's route in the Baltic Sea (Bioenergy, 2016). Given the growth in global production of alcoholic fuels from renewable resources, the application of bio-ethanol and bio-methanol in the shipping industry has significant potential. Nevertheless, because methanol' energy density is lower compared to fossil fuels, larger storage space would be needed. Besides, the development of methanol-diesel dual-fuel engines is still very much underway (Imran et al., 2013; Balamurugan and Nalini, 2014). Despite the potential positive environmental effects, both methanol and ethanol still face considerable obstacles in their application onboard marine vessels due to the lack of adequate safety instructions, operational experience, and capable infrastructure to satisfy the bunkering need (Svanberg et al., 2018).

Hydrogen is considered a clean fuel due to its near-zero-emissions (e.g., CO_2, SO_2, PMs, etc.) during combustion. Hence, hydrogen has the potential to replace conventional fossil fuels as a cleaner alternative fuel. Hydrogen fuel is suitable for compression-ignition engines and spark-ignition engines, as well as gas turbines and boilers (Bui et al., 2020). Among these types of engines, spark-ignition engines can better accommodate the hydrogen fuel because its auto-ignition temperature is very high (around 585 °C) (Mohammadi et al., 2007; Roy et al., 2011). Given the current development of hydrogen fuel technology, it is more prevalent to find hydrogen-fueled engines operating under dual-fuel mode in which hydrogen is added as a supplementary component during the combustion of another hydrocarbon fuel (diesel, LNG, biodiesel, etc.) (Köse and Ciniviz, 2013; Saravanan and Nagarajan, 2008; Zhou et al., 2014). In the shipping industry, hydrogen has been the subject of research into suitable vessel engine models to take advantage of the fuel's higher power density and lower emissions. Taking into account the life cycle assessment, hydrogen fuel used in marine transport, even as a fuel in a dual-fuel engine combining another fossil fuel, has the potential to reduce up to 40% of CO_2 emissions per unit of transport work (Bicer and Dincer, 2018a).

Considering the availability of generation sources and low emissions potential, hydrogen has a critical role in the application as an alternative fuel for the transportation industry (Murugesan et al., 2021). Despite the current limitations (e.g., low volumetric-energy density compared to conventional fossil fuels, lack of adequate storage infrastructure), advances made on the technological front is likely to overcome these obstacles in the short term. Furthermore, there are important factors (e.g., technical feasibility, scalability, and cost-effectiveness, storage, transportation, and distribution (Salvi and Subramanian, 2015; Barreto et al., 2003)) that influence the sustainable development of the in-future hydrogen economy. Although hydrogen has been widely received in the fuel cell (Bui et al., 2021), the applicability of marine engines fueled with hydrogen to reality is rare. Wärtsilä engine manufacture has experimented on spark-ignited engines running on hydrogen and LNG in two modes including dual fuel and single fuel. They found that the existing dual-fuel marine engines could only work with blends of maximum 25% hydrogen without any modifications (Fathom.world, 2019). However, the engine modification is compulsory for the hydrogen proportions more than 25%. Up to now, CMB's passenger boat Hydroville has been known as the world's first sea-going vessel equipped with engines fueled with dual fuel of diesel and hydrogen. More interestingly, HyMethShip have developed a method to use of hydrogen and production of methanol for ships by storing only CO_2 and methanol onboard aiming to eliminate the challenge associated with storing hydrogen (HyMethShip, 2019). The fact shows that the storage of hydrogen, even with liquefied hydrogen, the tank capacity for liquefied hydrogen is also twice higher than that for LNG. Therefore, this disadvantage for hydrogen marine engine could be overcome with the methanol-based engine technology (shown in Fig. 7).

Ammonia is non-carbon fuel that can be used as either standalone or with another fuel for combustion engines. Several fuels such as diesel (Reiter and Kong, 2008; Reiter and Kong, 2011), hydrogen (Westlye et al., 2013; Valera-Medina et al., 2017; Boretti, 2012), or methanol (Rehbein et al., 2019) can be combined with ammonia to form potential fuel mixtures for combustion engines. When being used in direct internal combustion engines, ammonia combustion could achieve up to 44% of system efficiency (Zamfirescu and Dincer, 2008). Additionally, ammonia can be employed as a potential feedstock for hydrogen production (Zamfirescu and Dincer, 2009; Giddey et al., 2017). There are several key advantages of ammonia over hydrogen fuel, including reduced cost per unit of stored energy and higher volumetric-energy density. Furthermore, the production, handling, and distribution of ammonia are also much more simplified due to the well-developed infrastructure. These characteristics have made ammonia an attractive energy carrier as well as a competitive candidate over other alternative fuels such as hydrogen (Klerke et al., 2008; Lan et al., 2012). Recently, the use of ammonia has been proposed as an alternative fuel for marine vessels (GL, 2019; OECD, 2018; Klüssmann, J.N.; Ekknud, L.R.; Ivarsson, A.; Schramm, 2019; Maritime Knowledge Centre, 2017; Netherlands, 2017; Lloyd's Register and UMAS, 2018). Considering its characteristics as a zero-carbon fuel, ammonia has immense potential in reducing carbon emissions and charting a more sustainable path for the global shipping industry.

Currently, the employment of LPG as an alternative fuel for an internal combustion engine is of widespread interest, although LPG has not had any noticeable contribution to the segment of the marine market and the shipping sector, even with small recreational/commercial vessels equipped with outboard or inboard engines (Hoang and Pham, 2018). The majority of diesel engines are still using LNG and CNG as alternative fuels (Ashok et al., 2015). Nonetheless, LPG starts getting some attention since the 2020 IMO mandate was issued. The LPG utilization for marine engines fueled with mono fuel found that CO_2 emission was reduced by about 10–20%. In the case of dual-fuel marine engines, a small quantity of diesel fuel is for initiating the ignition, followed by LPG combustion (Kjartansson, 2012). It was reported that up to 97% LPG and 3% diesel could be used for marine engines, leading to low CO_2 emissions. Indeed, dual-fuel diesel engines are believed to be more efficient because of their high performance and reliability in comparison with diesel engines working with only diesel fuel. In a recent report, Wärtsilä and MAN have conducted their study to use LPG for tri-fuel engines, which are running on diesel fuel, LPG, and LNG. The first experiment was implemented on a 7300 TEU container ship by Wärtsilä. Although such experiments are only initial, the use of LPG could be a potential approach to reduce CO_2 emission (The WLPGA, 2017). More interestingly, MAN B&W engine manufacture has proposed a scheme for the use of both LPG and ammonia for the marine engine to reduce CO2 emissions (Michael Petersen and Eastern, 2019). They reported that there would be a minor modification for the LPG system for the application of ammonia as shown in Fig. 8.

Considering the supply chain, the level of emissions depends on the variety of feedstock and process. For example, natural gas-derived methanol has shown a life cycle of GHG emissions shows an approximately 10% higher than those of HFO and marine diesel oil (MDO) (Fig. 9). These characteristics are determined by the natural gas supply chain, gas reforming, and methanol synthesis process. If methanol is derived from recycled sources of CO_2, combined with renewable hydrogen, special consideration should be paid in terms of carbon accounting to avoid the inappropriate discount of such emissions. Compared to liquid fossil fuels and LNG, methanol is more costly, as a marine fuel requires additional regulatory and market incentives to promote its wider adoption. From a life-cycle assessment, biofuels are considered carbon-neutral because the amount of CO_2 released during

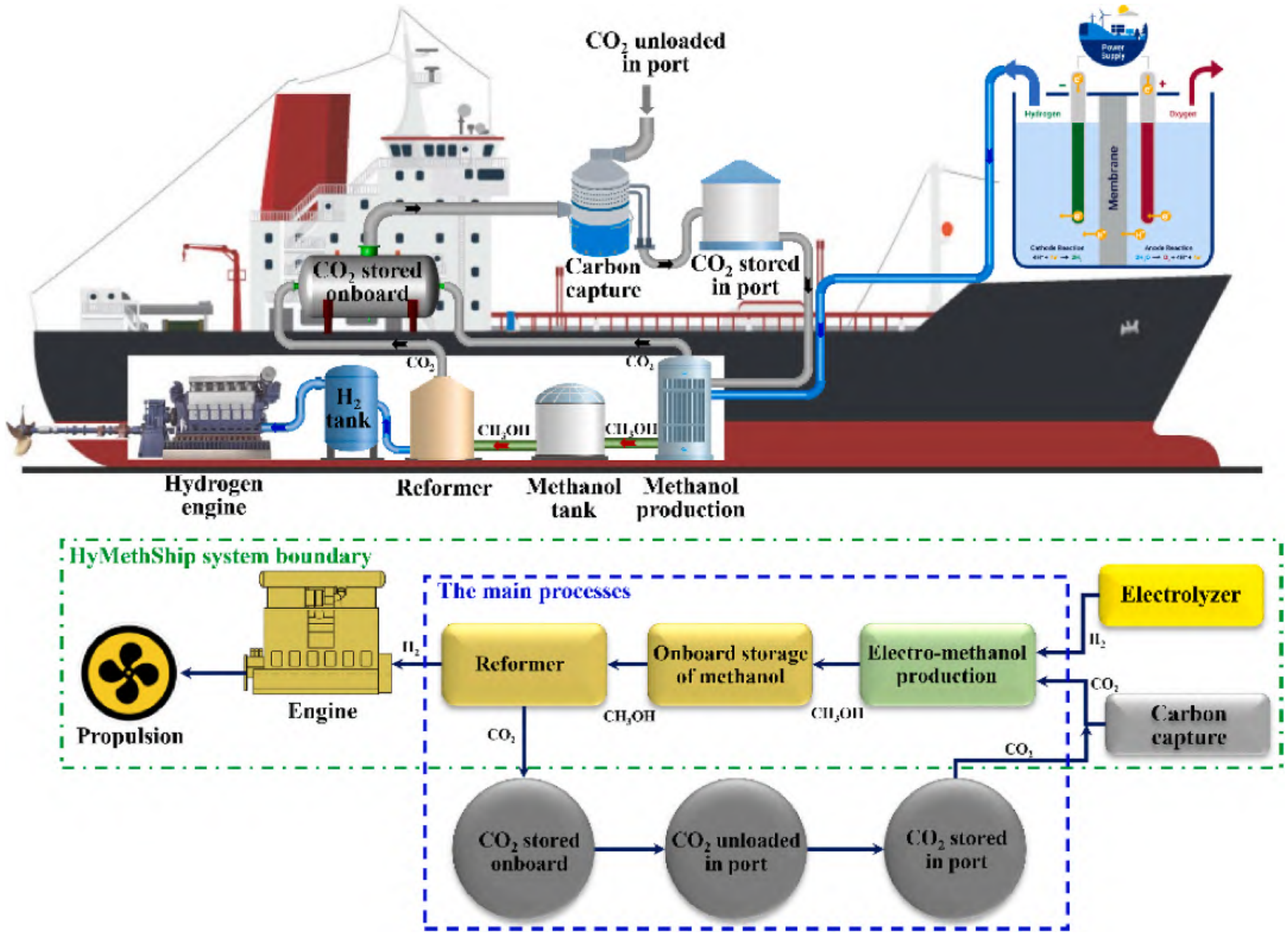

Fig. 7. HyMethShip with the engine running on hydrogen and integrated by methanol production system (HyMethShip, 2019).

combustion equals that captured by photosynthesis during plant growth (Bengtsson et al., 2014).

Thus, the application of biofuel in the shipping industry yields more advantages in terms of lower CO_2 emissions compared to fossil fuels. In theory, the consumption of biofuels produces net zero CO_2 emissions for the reason previously stated (Hoang et al., 2022; Kaya et al., 2019). However, the overall GHG audit can fluctuate between negative and positive values relative to fossil fuels when taking into account the production conditions of the power plant from a life cycle perspective (Anh, 2021). This particularly true when the amount of energy consumed for biofuel production is greater than the amount of energy released during its combustion (Hoang et al., 2020). Hence, it has called for a more environmentally-sustainable production process for biofuel (Petzold et al., 2011; Singh et al., 2014). As shown in Fig. 9, next-generation biofuels produce less GHG emissions compared to traditional biofuels. In general, the use of alternative fuels for ships could significantly reduce CO_2 emissions compared to fossil fuel.

5.2. Carbon capture and storage

With more attention being paid toward technological solutions for a decarbonized world, identifying appropriate methods to handle the amount of CO_2 released upon the combustion of fuels is as important as investing in the development of alternative low-carbon fuels. Carbon capture and storage (CCS) refers to a set of different technologies that aim to prevent CO_2 produced by power stations and factories from reaching the atmosphere (Seo et al., 2017). Several approaches can be applied to capture carbon emissions from power stations and industrial plants, including chemical or physical absorption/adsorption, membrane separation, and novel cryogenic liquefaction (Metz et al., 2005). After being captured, CO_2 is then transported mainly via pipelines or contained in storage tanks carried by ships to designated storage sites (Tan et al., 2016), (Xu et al., 2012). In the context of commercial shipping, CCS offers some opportunities for CO_2 emissions mitigation (Zhou and Wang, 2014). However, there are still technical challenges that overshadow the ability to implement CCS onboard marine vessels, e.g., higher levels of fuel consumption, additional space requirement to accommodate the new CCS system. Previous studies have pointed out the use of chemical absorption and membrane separation technology as potential candidates to capture CO_2 emissions emitted from ships.

It is estimated that up to 70% of current CO_2 emissions from shipping could be reduced with the deployment of CCS technologies (IMO, 2011; Balcombe et al., 2019). There are only a small number of available studies that have examined the feasibility of implementing integrated carbon capture systems onboard ships. The majority of these works rely on post-combustion capture technologies. A concept draft for designing an onboard carbon capture system equipped with liquefaction and temporary storage was proposed by the Process System Engineering group and Det Norske Veritas. The researchers have estimated the potential of the proposed system in reducing up to 65% of CO_2 emissions (DNV, 2013). Zhou and Wang (2014) proposed a solidification method for on-board CO_2 storage in the process of isolating the carbon emissions from the exhaust gases. The above strategy is useful considering the constant motion of ships during their journey at sea which can be

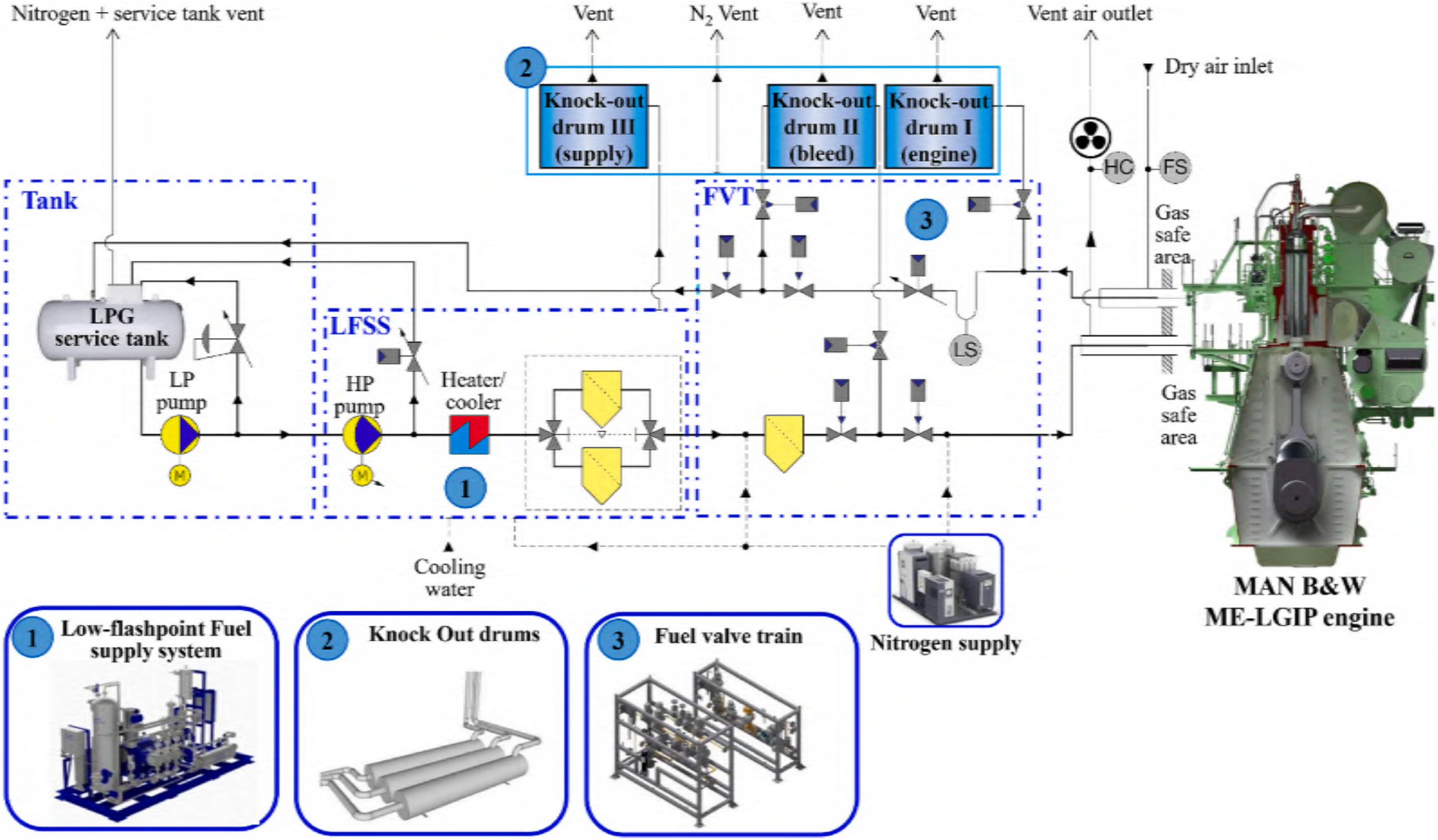

Fig. 8. Scheme of LPG and ammonia system for marine engine suggested by MAN B&W (Michael Petersen and Eastern, 2019).

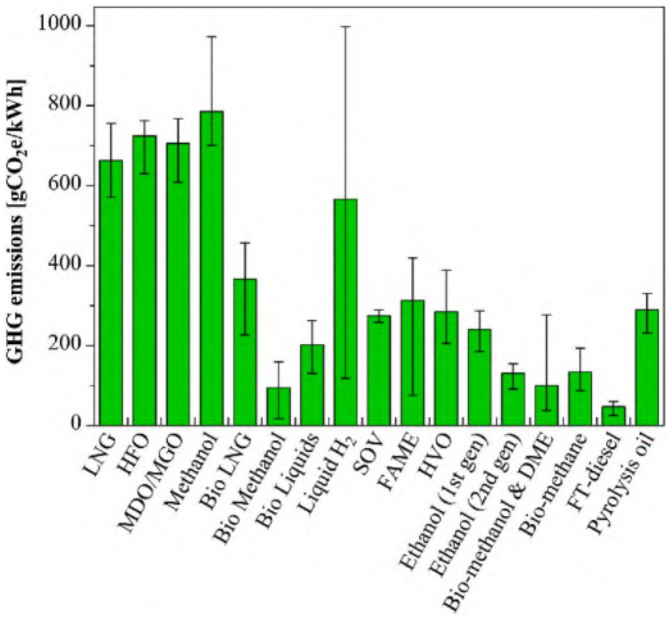

Fig. 9. GHG emission data from various biofuels compared to fossil fuel (Gilbert et al., 2018; Svanberg et al., 2018; Balcombe et al., 2019; Union, 2009; Lowell et al., 2013; DNV, 2016; Bengtsson et al., 2011; Ohashi, 2015; Cofala et al., 2007; Hsieh and Felby, 2017; Stephenson and MacKay, 2014; Florentinus et al., 2012).

considered a limiting factor for the application of CCS. In the aforementioned process, gaseous CO_2 is converted into sodium carbonate in the presence of added sodium hydroxide. This solid compound is treated with quicklime in solution to form calcium carbonate which can be easily and safely stored onboard while en-route to the destination. On the other hand, a solvent-based post-combustion carbon capture process was proposed by Luo et al. (Luo and Wang, 2017) that can be integrated onboard cargo ship to capture CO_2 released from the combustion of fuels. The authors found a potential capture level of 70% was feasible with the integration of the post-combustion carbon capture process in the ship's existing energy system. Furthermore, the availability of an extra gas turbine can increase the capture level up to 90%.

In another study, Van den Akker (van den Akker, 2017) performed a carbon capture experiment onboard an LNG-powered vessel in which 6 m was added to the length of the vessel to accommodate the installed CCS system. In a recent technology, the Japanese shipyard and engineering group (Lipsith, 2019) has developed a project to remove CO_2 by the approach of carbon capture, in which the onboard plant for capturing CO_2 includes towers for cooling the exhaust, absorbing CO_2, treating the exhaust, and regenerating the CO_2 (Fig. 10). Furthermore, the suggested CO_2 capture system also has facilities for liquefying and storing CO_2. However, they have reported that both the return on investment and technology have been considered as the great challenges posing for the decarbonization progress in the maritime area. Besides, the carbon capture was found to be not totally effective because its capture rate was approximately 86%. Nonetheless, the integration between the CO_2 capture and its subsequent reduction by hydrogen to produce methane/methanol fuel, was the most feasible route for large ships compared to electrical propulsion, nuclear power, and renewable energy. Besides the above-referenced studies, no other literatures on this topic are reported. Given this status, additional investigation is warranted to fill the knowledge gap in understanding the effects of capture system integration on marine vessels.

5.3. Alternative power sources

5.3.1. Wind

Against the backdrop of the 21st century's increasingly stringent standards for energy efficiency and GHG emissions, the topic of wind-assisted propulsion once again has become a popular choice for reducing carbon emissions from ships. The current development of wind-assisted propulsion comprises both conventional and modern sail technologies, including Flettner rotors, kites or spinnakers, soft sails, wing sails, and wind turbines (Carlton et al., 2013). Even though these sails are not capable of providing total propulsion power for modern merchant ships, they can generate additional propulsion thrust, especially during high seas (Staffell and Pfenninger, 2016), that allows for fuel-saving while sustaining the vessel's full speed (ITF OECD, 2018; Hirdaris and Cheng, 2012). Wind-assisted propulsion has been observed to be more effective under slow-speed conditions (e.g., less than 16 knots) (Smith et al., 2013) and on smaller-sized vessels (e.g., 3000–10,000 tons) (Smith et al., 2016), which make up about one-fifth of the global cargo fleet. Depending on the ship class, design compatibility might differ to avoid potential obstruction and conflict with the cargo handling process (Carlton et al., 2013; Traut et al., 2014). Based on the results from statistical and modeling analyses, between 15% and 25% of the current thrust power provided by the existing ship's propeller systems could be replaced by wing sails. Hence, the potential reduction in fuel consumption would result in lower CO_2 emissions from ship operations (OECD, 2018; Balcombe et al., 2019; Halim et al., 2018; Viola et al., 2015), (Q. Li et al., 2015). Among the commercialized products, SkySails propulsion system is one of few success stories which makes up of a towing kite attached to a rope propelling the ship forward under prevailing winds. According to its manufacturers, the SkySails system is stated to reduce up to 50% of fuel consumption from ships under optimal weather conditions and between 10 and 15% reduction on average in annual fuel consumption (GmbH, 2019). In another example, the Enercon E-Ship 1 is a testimony for the successful application of the Flettner Rotor-Sail system on a cargo ship. On its first sea trial between Emden, Germany, and Portugal, it was claimed to save up to 22.9% in fuel consumption. In the case of a Ro-Ro carrier equipped with two rotors, 5% of fuel savings on an annual basis was recorded for the M/V Estraden (Lu and Ringsberg, 2019).

Besides the examples of wind-assisted propulsion systems mentioned above, there are also opportunities for on-board mounted wind turbine generators (Eyring et al., 2005). According to recent publications, there is a wide range of potential fuel savings gained from different sail technologies, including 2–24% for a single Flettner rotor, 1–32% for a towing kite (Traut et al., 2014), up to 25% for a foldable eConowind's sail unit (IWSA, 2018). At lower sailing speeds, estimated fuel savings from wind-assisted propulsion can vary between 10 and 60% (Smith et al., 2013). Even though there are only a handful number of cases in which companies have tested the effectiveness of integrated sail technologies into existing merchant vessels (FathomShipping, 2012), the future of such application remains uncertain due to its relatively nascent development (Carlton et al., 2013). Compared with other types of wind-assisted propulsion systems, on-board wind-turbine systems have yielded lower fuel savings. Hence, their potential application remains quite narrow (Delft, 2016). Given the dearth of information and reliable financial data on the application and operation of wind-assisted propulsion on marine vessels, it is challenging in providing full cost analysis on the utilization of such systems (Rehmatulla et al., 2017). Overall, opportunities for commercialization and future uptake of various wind-assisted propulsion systems are limited by the high initial financial commitment, complex operational and control procedures, and the stochastic nature of wind energy. Coupled with the fact that fossil fuels remain relatively inexpensive and a slow-growth experienced by shipping sector, investors are still shunning research and development of wind-assisted propulsion technologies. Future investigations on this subject should focus on wind energy application on marine vessels along

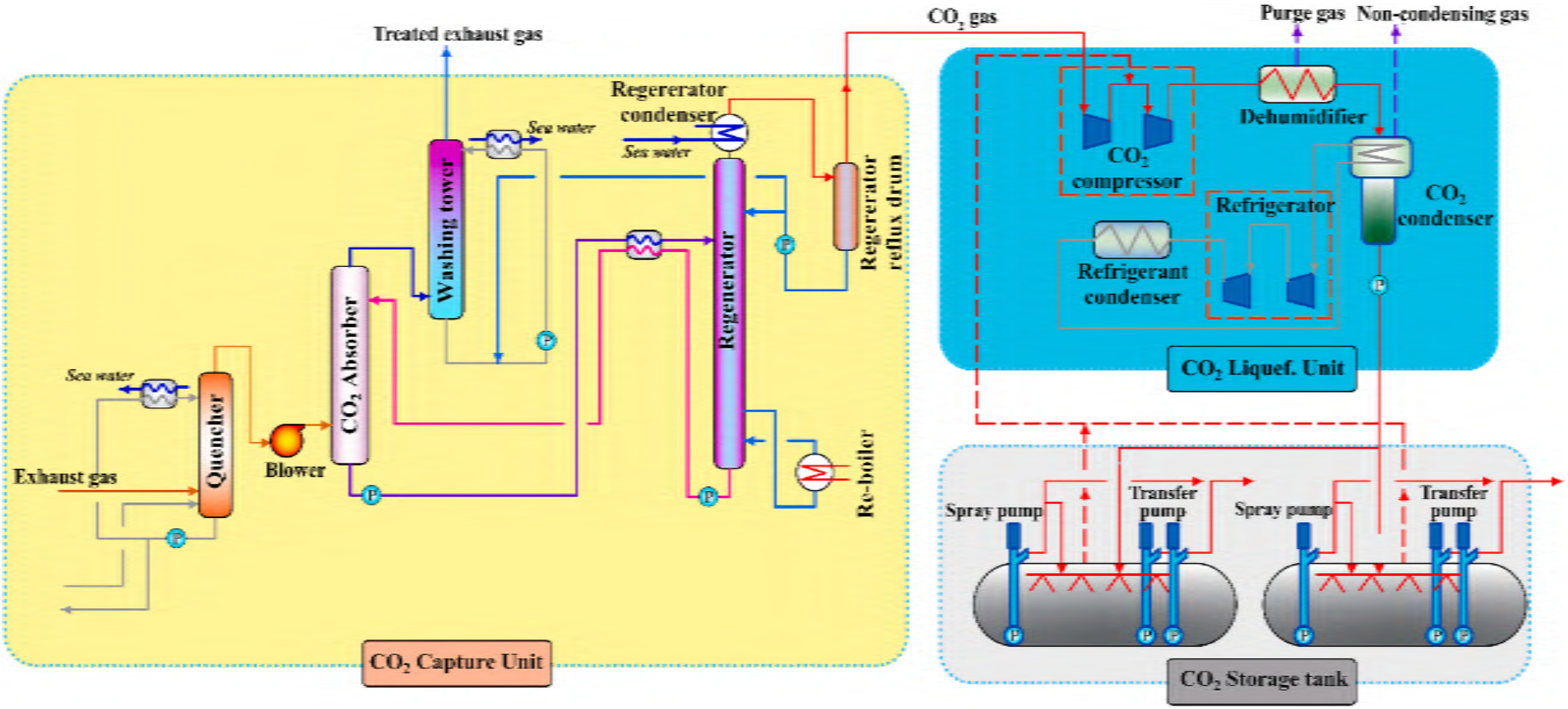

Fig. 10. CO$_2$ capture technology in the ship (Lipsith, 2019).

specific shipping lanes and optimization of sail types and configurations, as well as the automated control systems.

5.3.2. Solar

Solar PV systems have been installed on ship upper decks as a way to provide additional power to the ship's electrical equipment. The use of solar energy on merchant ships has been shown to contribute toward lowering fuel costs and CO_2 emissions (Glykas et al., 2010; Liu et al., 2019). Due to several constraints (e.g., low and uneven solar irradiance, lack of adequate space for mounted PV systems), the amount of energy generated from solar PV systems onboard vessels have generally been on the low side and fallen short of meeting the energy required for ship propulsion. Considering this unfortunate fact, the idea of full solar-powered cargo ships is simply impractical. However, solar PV systems are still capable of generating additional energy in powering auxiliary functions of cargo ships and the main operations of smaller boats.

There are several examples of integrated hybrid solar and wind systems onboard shipping carriers, including automated kite sails from SkySails, a 3000-ton 'zero-emission' cargo vessel from B9 Shipping, the UT Wind Challenger hybrid freighter equipped with nine solar sails (FathomShipping, 2012), the EMP Aquarius (Global, 2018) and the Nichioh Maru (OECD, 2018). Among these, the power generated from solar PV systems is only enough to power auxiliary demands (Carlton et al., 2013; Pfenninger and Staffell, 2016). Several studies have reported between 0.2% and 12% in terms of solar energy generation on marine vessels as the potential method for CO_2 reduction (Bouman et al., 2017). A solar-wind hybrid system from an integration with wind-assisted propulsion technologies could achieve 10–40% in fuel-saving (FathomShipping, 2012). However, additional empirical data is needed to confirm these claims and the potential cost-effectiveness of these systems. Recently, Karatuğ et al. (Karatuğ and Durmuşoğlu, 2020) have proposed an innovative solution to the configuration problem of solar arrays onboard a Ro-Ro marine vessel. In their study, the authors tested the proposed system design for a vessel traveling between Pendik, Turkey, and Trieste, Italy, and assessed its theoretical performance (Fig. 11). Based on the applicable methodology, the authors recorded a 7.76% improvement in the vessel's energy efficiency, while the solar PV system was able to generate enough power to displace 7.38% of the fossil fuel requirement. This equals to 232.393 tons of CO_2 saved from being emitted into the atmosphere. However, the solar PV generates direct current, while the majority of onboard electrical equipment on the load side uses alternating current. The inherent incompatibility combined with the high variability of solar power

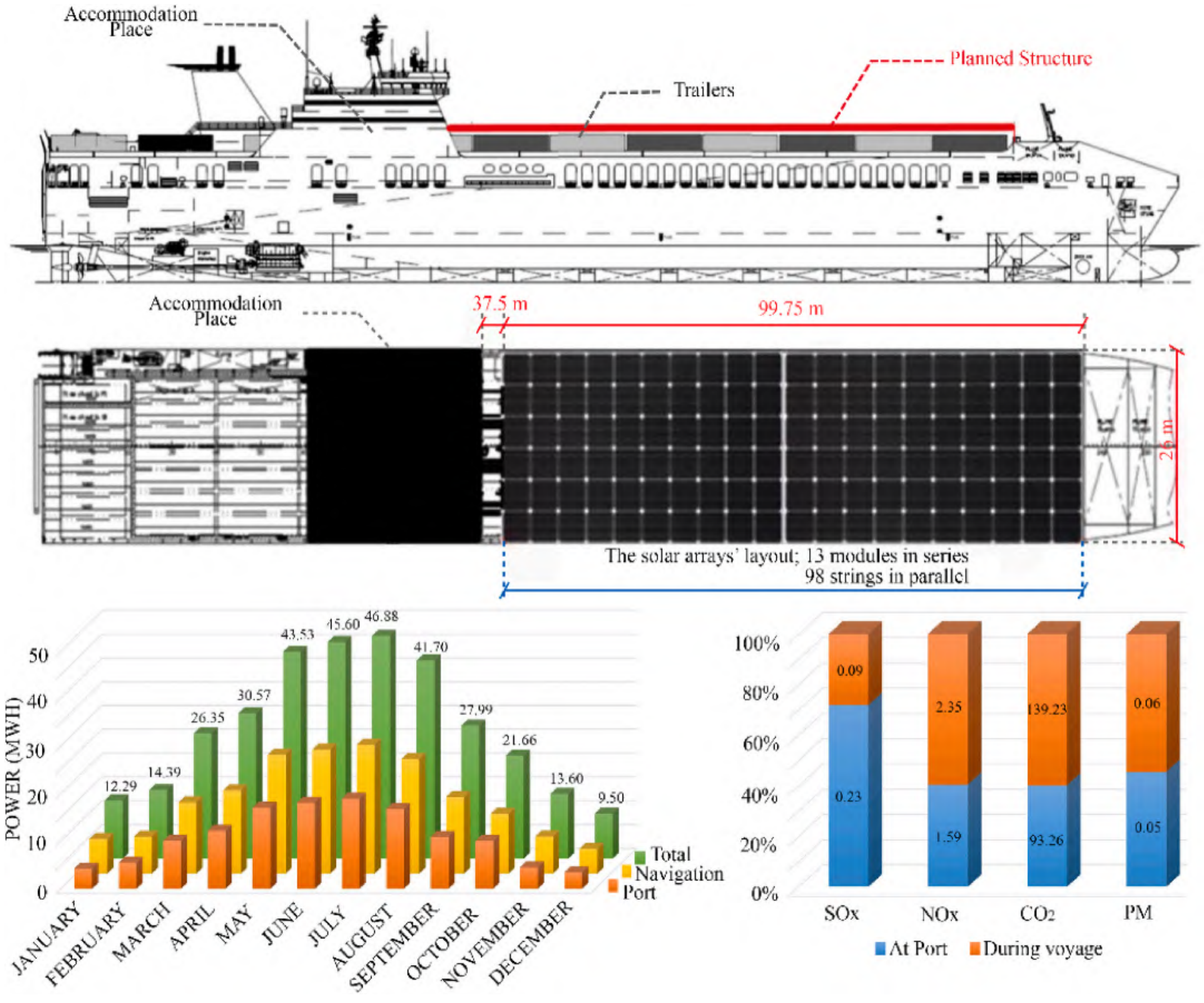

Fig. 11. Location of the solar array on the ship, achieved power, and reduced level of CO_2 emission (Karatuğ and Durmuşoğlu, 2020).

generation with time and location, has motivated the need for the development of capable energy management systems and research into energy optimization and management strategies (Tang et al., 2018a).

The safe measures while applying photovoltaic panels in producing electricity for the ships in their voyage should be considered because the intensity of solar radiation tends to differ when ships sails through different sea area. Indeed, the diverse uncertainties from renewable sources and onboard power loads should be solved by using a robust coordination measure aiming to guarantee a safe and reliable voyage. Therefore, the development of integrated energy systems that could have the capacity in capturing and storing energy is one of the critical strategies to target zero-emission from ships. For example, Li et al. (Z. Li et al., 2020) proposed a hybrid AC/DC MES microgrid structure (including the combined cooling heat and power unit, heterogeneous energy storage (battery storage and thermal storage), photovoltaic system, power-to-thermal conversion unit, diesel generators, bidirectional converter) with the flexible voyage and thermal loads by employing the two-stage robust optimization method. As reported in previous works, the combined cooling heat and power could be operated by utilizing natural gas with safe, convenient, and renewable (Hansen and Wendt, 2015; Li and Xu, 2018). The generated waste heat from the electricity production of the combined cooling heat and power unit could be recovered to generate thermal energy for the heating/cooling demand (Y. Chen et al., 2019; Zhang et al., 2019). Besides, thermal storage and power-to-thermal conversion unit could be used to enhance the dispatch flexibility of the system through the storage, release, or conversion of energy forms (Li and Xu, 2019), while power and thermal energy could be simultaneously produced by the photovoltaic system and the combined cooling heat and power unit. In this integrated system, diesel generators were used to produce electricity using diesel fuel, and battery storage was primarily employed to avoid the frequent start-up of the diesel generators as well as it could provide backup for power system (Othman et al., 2018a; Othman et al., 2018b).

Wind and solar energy are renewable energy resources with a high degree of intermittency, in which weather plays a crucial factor in the performance of wind and solar systems. Besides, there are also other variables including geographical location, season, and the efficiency of solar panels (Salem and Seddiek, 2016; Teeter and Cleary, 2014). Despite the large potential and key advantages of solar power application in the shipping industry, there are still major obstacles that need to be addressed. Additional improvements related to system efficiency, potentially diminishing performance due to weather-related factors, and inadequate energy management capability is highly warranted to ensure the continued development of solar energy applications in this sector (Glykas et al., 2010).

5.3.3. *Fuel cells*

Currently, a broad majority of ships have been employing diesel engine-driven generators for electricity production, in which there is a conversion of chemical energy into electricity through a thermal-mechanical process. On the contrary, electricity in the fuel cells (FC) is found to be directly produced from chemical energy without a thermal-mechanical process (Inal and Deniz, 2020), indicating that this energy conversion has omitted the indirect route through a thermal-mechanical process in engines (Tronstad et al., 2017). Therefore, a significant reduction of CO_2, NO_x, and PM emissions could be seen for FCs although FCs could achieve efficiencies as high as the use of diesel engines (Van Biert et al., 2016).

A recent study has demonstrated the outstanding performance over conventional internal combustion engines when combining the high-efficient electric propulsion system with close to 95% energy efficiency with ~45% efficient fuel cells (C, 2017). Another important positive characteristic of fuel cells is the smooth and seamless operation without the concern over potential noise or vibration that could negatively impact the marine ecosystems (Sapra et al., 2021). Furthermore, to generate the same amount of power output, a diesel generator and a micro gas turbine would consume 44% more fuel than what is required in a typical fuel cell (Welaya et al., 2011). Similar to batteries, the main characteristics of FCs are modular nature. Moreover, the single cell's intrinsic performance in FCs was found to be similar to that of a large stack (Sapra et al., 2021; Wachsman and Lee, 2011), leading to the produced power that could be distributed to the ships without any effects on the increase in the fuel consumption, a reduction of transport losses and the improvement of redundancy. Besides, good characteristics for the part-load of FC systems were reported because the increase in mechanical losses was found to have only an impact on the auxiliary components' parasitic loads. It also caused a decrease in electrochemical losses (Ahn et al., 2019; Payne et al., 2009; Xing et al., 2021). For this reason, the FC systems are believed to offer great potential for maritime application. Indeed, the classification of FC and their applicability for ships are summarized in Table 5.

Initial applications of fuel cells among submarines and autonomous underwater vehicles were first found in the twentieth century. More recently, pilot-scale demonstrations of fuel cell applications for commercial types of marine vessels have been developed, e.g., METHAPU, ZemShip, FellowSHIP, and E4Ships (De-Troya et al., 2016), in which passenger ship (ZemShip) equipped the commercial FC system is illustrated in Fig. 12a (Pospiech P, 2014). These projects have been trialed on small to medium-size vessels due to the insufficient amount of power that fuel cells can generate to propel large cargo ships. In the case that these large cargo ships are at berth, one study has shown fuel cells is a capable power source for cold-ironing (Pratt and Harris, 2013). Currently, examples of commercial ships that are equipped with fuel cell systems remain scarce. Specifically, only 23 marine fuel cell projects at various stages of development were identified by DNV GL in 2017 (Tronstad et al., 2017). The Viking Lady was the first commercial ship to debut fuel cell technology as a supplementary source of propulsion power to the main diesel engine running on LNG. In this case, the particular fuel cell system could be supplied with either hydrogen or methanol (with appropriate reconfiguration) and could reduce up to 20% of the ship's CO_2 emissions (Ovrum, 2012; Technology, 2010).

Proton exchange membrane fuel cells, alkaline fuel cells, and direct methanol fuel cells, molten carbonate fuel cells and solid oxide fuel cells are preferable alternatives for marine applications with higher power demands (Dimopoulos et al., 2016). As a clean source of energy, hydrogen fuel cells produce no CO_2 emissions and no air pollutants (Staffell et al., 2019). Even though hydrogen fuel cells emit no CO_2 emissions in the production of electricity through an electrochemical conversion process, potential emissions associated with the hydrogen supply chain should be carefully analyzed (Andrews and Shabani, 2012). Depending on the source of hydrogen production, the carbon footprint might vary (Speirs et al., 2018; Balcombe et al., 2018). As shown in Fig. 9a, the amounts of CO_2 emissions vary significantly among the three different applications of hydrogen fuel cells, ranging between 113 and 997 gCO_2eq/kWh. On the other hand, hydrogen fuels are still relatively more expensive compared to conventional fossil fuels (Raucci et al., 2015). Researchers have pointed at the potential for the prices of hydrogen to become more competitive with the falling cost of electrolyzers (Schmidt et al., 2017a). As part of the cost reduction strategy, hydrogen fuels could be used for certain point-to-point routes between major ports with capable infrastructures or in a small geographic area (Farrell et al., 2003). However, given the large power demand required by major classes of marine vessels, fuel cell technologies are not currently capable of displacing conventional multi-main engines in ships (Vogler and Wursig, 2011). In order to integrate renewable energy sources into the ship propulsion system aiming to enhance the energy efficiency and reduce CO_2 emission, Evrin and Dincer (2019) have proposed a zero-CO_2 emission system including absorption cooling refrigeration, solar, wind-based turbines, SOFC-based fuel cells, a bottoming cycle, and a steam power plant for the power generation as shown in Fig. 12b. They reported that the overall energy of the suggested integration system was 41.53%.

Table 5
Operating characteristics of fuel cells for ship application (Tronstad et al., 2017; Van Biert et al., 2016; Xing et al., 2021; Ahmed and Dincer, 2011; McPhail et al., 2011; Kulkarni and Giddey, 2012; Office of Energy Efficiency & Renewable Energy, n.d.; Rosli et al., 2017; Baldi et al., 2020).

Types	Size	Cost	Lifetime	Working-temperature range, °C	Electric efficiency (%)	Power, kW	Disadvantages
AFC	Small	Low	Medium	60–200	50–60	<500	CO_2 poisoning
DMFC		Medium		75–120	20–30	<5	Methanol crossover
HT-PEMFC		Medium		160–220	50–60	–	CO + S poisoning
PEMFC		Low		65–85	50–60	<120	
MCFC	Large	High	Good	650–700	50–55	120–10,000	S poisoning; a long time for the start process
PAFC		Medium		140–200	40–55	100–400	CO + S poisoning
SOFC	Medium	High	Medium	500–1000	50–60	<10,000	S poisoning; a long time for the start process

In general, FC systems could offer a highly-efficient approach to produce the onboard electricity from various logistic fuels with nearly zero-CO_2 emission. Nonetheless, for the hydrogen-based FC system, total system volumes for hydrogen storage could be 1.5–5 times higher than that of other alternative logistic fuels in the case of sailing times >100 h. Moreover, FC systems working at high temperatures could obtain higher overall efficiency by utilizing hydrocarbon fuels in combination with bottoming cycles. Normally, ships operated by FC systems were reported to attain relatively low CO_2 emission and they appeared to be suitable for several-day mission ships. In the case that ships had a longer independent operation, they were suggested to use more dense logistic fuels combined with a less dense gaseous-fuel.

5.3.4. Nuclear

Modern application of nuclear power in marine propulsion has been limited to only warships and various types of navy vessels, including submarines and aircraft carriers, and icebreakers (Khlopkin and Zotov, 1997). Due to the large capital expenditure required for the initial investment and operational and maintenance costs, nuclear-powered ships have fallen short of their potential and failed to become profitable (Freire and De Andrade, 2015; Schøyen and Steger-Jensen, 2017). Among the key advantages, the operation of nuclear-powered cargo ships has less of an environmental impact due to the elimination of potential CO_2 emissions and air pollution. However, safety issues are among the top issues related to nuclear-powered marine propulsion and could impede the wider adoption of the technology in the shipping industry (Kontovas, 2014). Besides, the remaining obstacles related to the distribution, testing and monitoring of equipment and parts, nuclear fuel production and decommissioning could slow down its development without the introduction of capable solutions (Wang et al., 2013).

5.3.5. Electric propulsion systems

Similar to that found in a hydrogen fuel cell-powered propulsion system, a motor is a critical component in electric propulsion systems that are driven mainly by a device capable of storing electrical energy (Smith et al., 2014; Nguyen and Hoang, 2020). Currently, a proposal has been put forward by "Norwegian Electric Systems" in developing hybrid engines and electric propulsion systems (S, 2017). The company has tested the use of electric propulsion systems containing rechargeable lithium-ion batteries on two of its ferries. These vessels operate on designated-route with high emission standards set by the Norwegian Road Authorities (S, 2017). Even though no economic analysis has ever been performed on electric propulsion ships, battery costs are considered the primary cost driver for electric propulsion systems that is expected to decrease with advances in technology. Another important factor to consider is the cost of electricity or fuel used for charging the batteries (Schmidt et al., 2017b). As depicted in Fig. 13, contained within the shipboard microgrid of full-electric ships, lies an energy network (blue lines and arrows) and a communication network (green lines and arrows). Power is supplied by the generators and batteries via the energy networks to the propulsion and electrical system (Fang et al., 2019).

While the propulsion load is primarily responsible for propelling the ship, the remaining service load consists of a variety of onboard equipment, including radar and navigational systems, air conditioning, and other electrical devices. Options to integrate renewable energy are available as potential solutions to improve the energy efficiency of full-electric ships. In contrast to convention marine vessels which are propelled primarily by mechanical power produced by the prime motor, electric power is the only means of power in driving and operating full-electric ships. From this perspective, a full-electric ship can be conceptualized as a "mobile microgrid" (Lan et al., 2015; Wen et al., 2016). Even though the operation of full-electric ships is physically detached from the seaport, several logistical issues remain related to voyage scheduling of ship to ensure an accurate time of arrival (Zhen et al., 2016), navigation route optimization for safety or efficiency and others (Goel et al., 2015; Kano et al., 2015). While at berth, full-electric ships can be switched to the cold-ironing mode which allows for the down-time of the onboard generators. Hence, the shipboard microgrid effectively turns to a grid-connected microgrid.

Considering emissions reduction strategies, several studies have proposed different measures that can be applied to the ship propulsion system. According to these observations, the median estimate of the potential reduction achieved by the above-mentioned measures is rather on the low side. The wide range of emissions reduction potential also reflects the contrast in the performance of conventional engine systems and other hybrid models. Based on the above results, biofuels demonstrate the highest CO_2 emissions reduction potential. Nevertheless, such potential can be amplified by the synergetic and system-related effects resulted from the wide-scale adoption of biofuels. Differences in biofeedstock and calculation methods are the two main factors that affect the CO_2 reduction potentials of biofuels. However, variations in type, quality, and production process can yield different CO_2 emissions reduction of biofuel products. On the other hand, how the reduction potential is measured and calculated can also affect the final analysis. For example, plant-based biomass is considered carbon-neutral due to the absorption of CO_2 during plant growth. Hence, the amount of CO_2 released during the combustion of biofuel does not result in net positive emissions. Despite its promising potential, the conversion to LNG as the primary fuel for marine vessels remains controversial. Compared to other conventional fossil fuels, LNG which comprises mostly methane has a lower emissions potential during combustion. However, the issues of methane leakage from engines can exacerbate the problem given that methane is also a very potent GHG. Because LNG is a carbon-based fuel, CO_2 emissions will continue to occur as a result of its combustion. Taking into account the relatively long time that CO_2 stays in the atmosphere (Archer et al., 2009), the continued infrastructural investment and deployment of a non-renewable and carbon-based resource like LNG is likely to lead the industry down a high-carbon and less sustainable path that is inconsistent with the current global climate goals set out by the Paris Agreement (Gilbert et al., 2014). Alternatively, wind and solar are clean, renewable energy resources with different potential for application in the current industry. In terms of emissions reduction potential, wind energy prevails over solar power. The performance and cost-effectiveness of technologies, such as sails, kites, and solar PV cells that leverage these renewable energy resources depend on the type and design of the vessels. Given the surface area constraint on most ships, the utilization of deck-mounted solar PV panels is more effective in

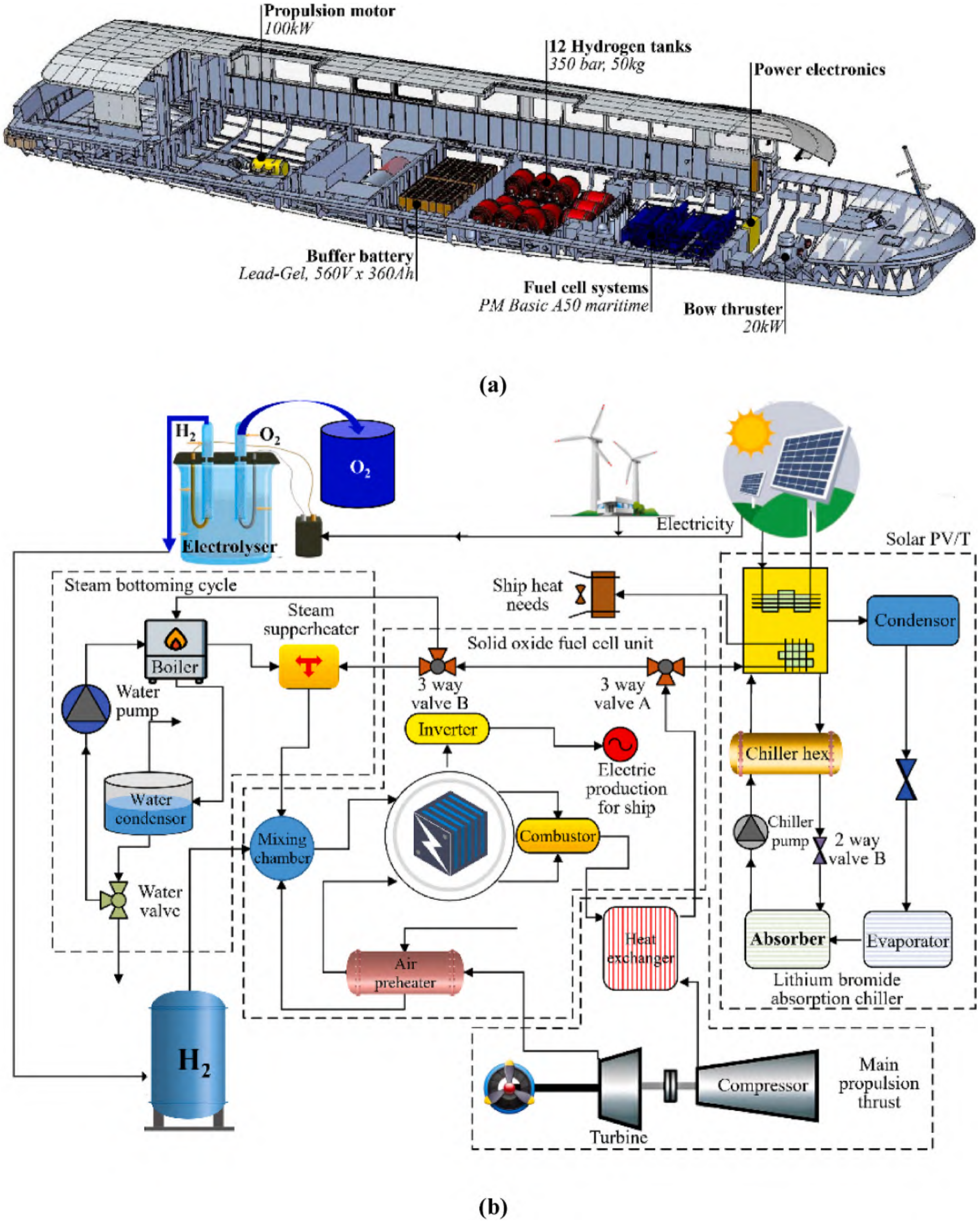

Fig. 12. (a) - Scheme of elements and layout of FC system in ZemShip (Pospiech P, 2014); **(b) – The present principle flow diagram of FC system with the integration of other renewable energy sources** (Evrin and Dincer, 2019).

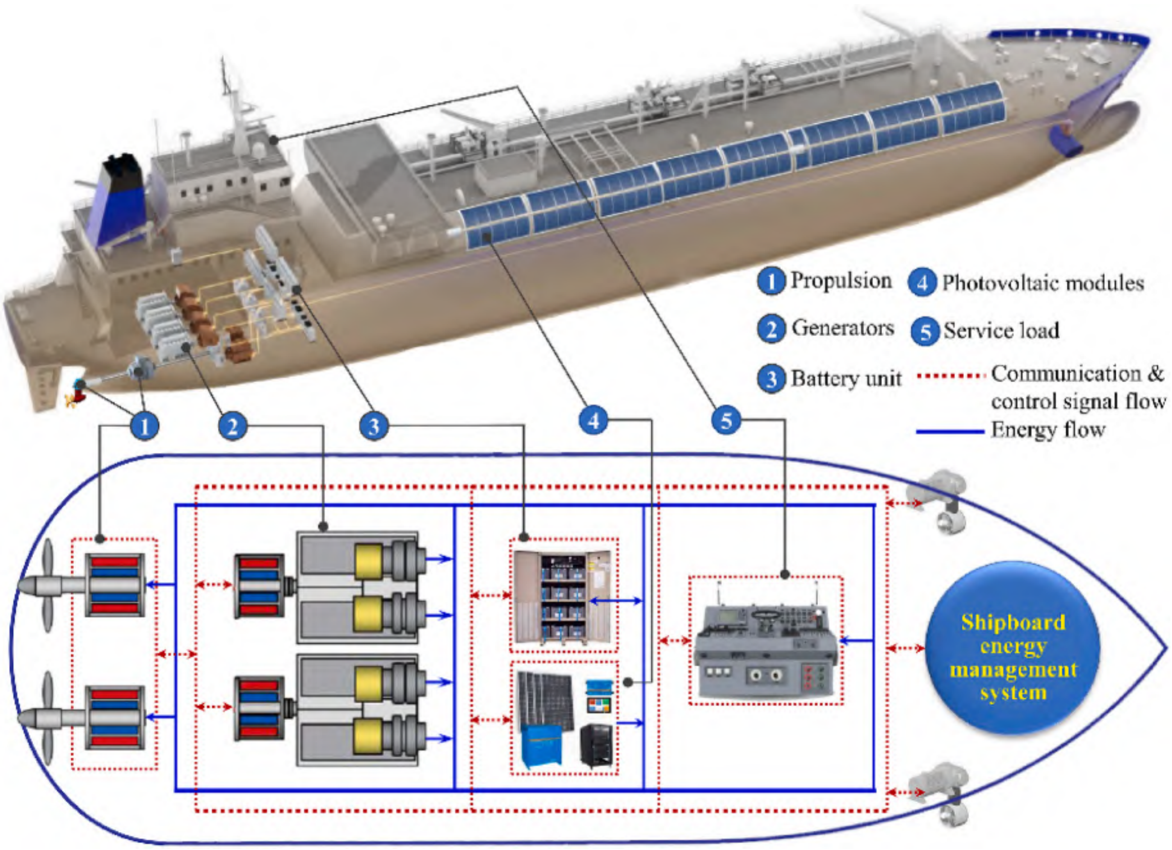

Fig. 13. Principle scheme of full-electric ships (Fang et al., 2019).

smaller-sized vessels traveling on routes with higher solar irradiance. Similarly, wind-assisted propulsion systems perform better on ships sailing with stronger prevailing winds. In terms of fuel cell application, little information could be found in the available literature. Despite its potential, the potential of supplying the bulk of energy for ship operation from fuel cells remains questionable. Deploying hybrid systems on marine vessels offer additional opportunities for efficiency improvement (e.g., equipping backup battery with existing combustion engines). In this case, the battery system can serve as a buffer to satisfy peak power demands and to improve the efficiency of combustion engines by displacing low power operations.

In general, modern ships could operate either with the hybrid system or fully on electricity, in which such ships usually require the battery energy storage systems that are charged by an onboard or in-harbor power system (Kumar et al., 2020). In this way, the electricity that is locally generated from renewables could have a balance between the load demand and power supply without increasing the power capacity. More importantly, the harbor grids could also supply surplus power for other purposes. Due to this reason, optimization of the size and location of battery energy storage systems is considered as the challenging task aiming to employ the battery energy storage system the most efficiently (Wong et al., 2019; Yang et al., 2018). Indeed, battery energy storage systems should have an appropriate size and proper thermal management strategy to satisfy the above-mentioned goals (Subramanian et al., 2021). With an appropriate size, battery energy storage systems could be located on ships or at certain substations, allowing the required power to be continuously supplied. Therefore, optimizing the size of battery energy storage systems should be further and more thoroughly studied to develop the electricity ship fleet in the future.

Compared to the estimated business-as-usual emissions, the different CO_2 emissions reduction potentials at the fleet level are provided in Table 6. For all alternative power sources except for nuclear power, emissions reductions can vary between 20% and 77%. The maximum reduction potential increases to 95% when including nuclear power as an alternative power source (Eide et al., 2013). In terms of projection, the longer the time frame is, the higher the emissions reduction potentials become. Particularly, the median reduction rates for 2020, 2030, and 2050 correspond to 35%, 39%, and 73%, respectively. Several studies have reached similar conclusions finding the highest emissions reduction potentials (58–77%) for 2050 or later (Eide et al., 2013; Lindstad, 2013). These results suggest the longer amount of time it takes to fully realize the potential of the adopted reduction measures. Not including the nuclear power scenario, the emissions reduction potentials for 2050 are consistent with the estimated figures provided in the Second IMO Study (Buhaug et al., 2009). It is noteworthy to point out the underlying assumptions used to arrive at the CO_2 emissions reduction estimates. Hence, these potentials are not only based on the adopted technical and operational measures, but also future growth scenarios for marine transportation. Emissions potential estimates can vary depending on the forecasted scenario. Particularly, the period up to 2030 observes an increase of 65% in emissions, while another scenario yields a maximum 34% reduction potential. The observation reflects the fact that it is unrealistic to obtain absolute emissions reduction figures given the continued increase in total marine transport volume without the introduction of solutions offering much larger and better-matched improvement potential.

6. Combination of the port-to-ship pathway for CO_2 emission reduction

Regarding the management of operational efficiency and emissions at the ship-port interface, measures are considered for the ports that ships are scheduled to arrive and allowed to moor, also known as ports of call. Studies have provided comparisons of shipping GHG emissions to

Table 6
Potential approaches for the efficient use of energy and the reduction of CO_2 emissions for ships.

Approaches	Classification	CO_2 emission reduction level	References
Power system	Hybrid system	2–45%	(Solem et al., 2015; Wärtsila, 2009; Lindstad et al., 2015; Sciberras et al., 2015b; Lindstad and Sandaas, 2016)
	Electricity	1–35%	(Balcombe et al., 2019; Nguyen et al., 2020; ITF OECD, 2018; DNV GL, 2017; Tillig et al., 2015; Solem et al., 2015)
	Nuclear	0–100%	(ITF OECD, 2018; DNV GL, 2017; Hirdaris et al., 2014)
	Waste heat recovery	1–20%	(ITF OECD, 2018; Hoang, 2018; Gilbert, 2014; Wärtsila, 2009; Deniz, 2015; Baldi and Gabrielii, 2015; de la Fuente et al., 2017; Zhu et al., 2020)
Alternative fuels	LNG	5–30%	(ITF OECD, 2018; El-Houjeiri et al., 2019; Sharafian et al., 2019; Lindstad et al., 2020; Lindstad and Rialland, 2020)
	Hydrogen	0–100%	(Bicer and Dincer, 2018a; ITF OECD, 2018; DNV GL, 2017; Pan et al., 2014; Bicer and Dincer, 2018b)
	Ammonia	0–100%	(ITF OECD, 2018; DNV GL, 2017; Bicer and Dincer, 2018b; Kim et al., 2020; Hansson et al., 2020; Schönborn, 2021)
	Biofuels	25–84%	(Bengtsson et al., 2014; Eide et al., 2013; Lindstad et al., 2015; Grahn et al., 2013; Brynolf et al., 2014a) (Gilbert, 2014; Brynolf et al., 2014b; Taljegard et al., 2014; ITF OECD, 2018; DNV GL, 2017)
Renewable energy	Wind	1–50%	(Psaraftis, 2016; Schmitz and Madlener, 2015; Lindstad et al., 2015)
	Solar	0.2–12%	(Karatuğ and Durmuşoğlu, 2020; Gilbert et al., 2014; Lindstad et al., 2015; Cotorcea et al., 2014; Qiu et al., 2015; Yuan et al., 2018)
	Fuel cells	2–75.8%	(Sapra et al., 2021; Lindstad et al., 2015; Ghenai et al., 2019; Wu and Bucknall, 2020; Villalba-Herreros et al., 2020; Klebanoff et al., 2017; İNAL and Deniz, 2021; Roh et al., 2019)

port emissions in Port of Barcelona (Villalba and Gemechu, 2011), 63–78% of port emissions in Port of Oslo (López-Aparicio et al., 2017), 61% in Port of Gothenburg, 66% in the Port of Osaka, 8% in the Port of Sydney, and 18% in the Port of Long Beach (Styhre et al., 2017), 53% of GHG emissions from ships in San Pedro Bay for ships at berth (SPBP, 2017). Therefore, the use of alternative power when ships docks at ports could be considered as one of the useful solutions to reduce CO2 emissions.

Alternative maritime power, which can be referred to as cold ironing, onshore power supply, shore-to-ship power supply, or shore-side electricity is a practice of supplying power from a shore-side source to ships at berth. Currently, it is an effective strategy in emissions control and pollution prevention (IMO, 2018a). The power generated from port mobile variable-frequency and variable-voltage sources can replace the use of onboard diesel generators. There are three main parts included in the alternative maritime power, namely onshore power supply system, shore-ship connecting system, and onboard power receiving system (as depicted in Fig. 14) (Mayur Agarwal, 2020). Once connected to the onshore power supply, a local port grid can supply the ship's power demands, while its main boilers and auxiliary engines can be switched off (J. Chen et al., 2019; Hall, 2010). According to Styhre et al. (2017), there is a large emissions reduction potential associated with the use of onshore power supply, however, the corresponding magnitude of saving depends significantly on the source of electricity (Sciberras et al., 2016). The reduction potential can be maximized when the supplied electrical power comes from renewable resources, such as a combination of wind or hydro or solar and wind energy (Winnes et al., 2015). In the case of San Pedro Bay Ports, the use of onshore power supply in powering harbor craft, which reduces up to 6% of GHG emissions, has been implemented. Specifically, port workers can charge hybrid tugboats into on-shore power while they are sitting at the berth or waiting on a station (Ports of Los Angeles and Long Beach, 2017). In another example, Port of Hamburg's operator has deployed an onshore power supply to charge battery-equipped AGVs and other mobility vehicles (Acciaro et al., 2014b). Particularly, the use of an onshore power supply in charging electric or hybrid harbor crafts and locomotives has been gaining considerable traction (ESPO, 2012).

To reduce potential carbon emissions and noise pollution from ships, most leading ports have provided access to shore-side facilities that are capable of supplying power to berthing vessels as. With available options in sourcing power from multiple sources of renewable energy such as hydro, wind, solar and nuclear, cold ironing is an integral part of achieving a low-carbon and more sustainable port operation (Sciberras et al., 2016). Possible generation sources of electricity provided from the grid can include renewables, LNG, or other forms of power (Zis et al., 2014; Sciberras et al., 2015a; Coppola et al., 2016a,b). The use of electricity can replace fuel consumption and reduce potential CO_2 emissions. Hence, the use of cold ironing offers greater benefits and savings to ports with higher average ship handling times (Zis et al., 2014). Applications of onshore power supply can be found in port terminals around the world, including Europe (e.g., Gothenburg (RoRo), CMP (Cruise), Antwerp (containers); the United States (e.g. ports of containers or containers/RoRo); and Asia (e.g. Osaka (RoRo), and Shanghai (containers)) (O Merk, 2014a,b), (Peng et al., 2019), (Tseng and Pilcher, 2015). Based on observations of UK ports, one study has shown the use of cold-ironing was responsible for 10% and 2% in CO_2 and SO_2 emissions reduction, respectively (Zis et al., 2014). The record has shown a significant amount of pollutant emissions, 94%–97%, was reduced upon its implementation (Corbett et al., 2007). Similarly, a study was carried out to analyze the potential CO_2 emissions reduction from the adoption of cold ironing at ports located in countries with major coastlines (Hall, 2010). The authors observed the sharpest drop in CO_2 emissions of 38% in the case of China. Among European ports, onshore power supply calling is enabled for 25 shipping lines and over 300 ships (Efforts, 2014). According to the WPCI, currently there are only 28 major ports worldwide that are using the onshore power supply in various specialized terminals which suggests a relatively low onshore power supply utilization rate (Bergqvist and Monios, 2019). The lower electricity consumption as a result of cold-ironing practice is the primary driver in achieving potential emissions reduction. For bulk freighters, the use of shoreline power supply outperforms onboard fuel consumption in terms of cost advantages, especially for ports located in countries with electricity prices well below \$0.19/kWh (Yiğit et al., 2016). The use of cold ironing is even more cost-effective for the operation of cruise ships while docking at ports because most passengers do remain on board and the ship's electrical load can be served by shoreline power supply through cold-ironing (Tseng and Pilcher, 2015; Ballini and Bozzo, 2015). Based on the referenced case studies, cold-ironing has the potential to reduce on average 29.3% of CO_2 emissions which is equal to 196.6 tons of CO_2. Furthermore, leveraging on shoreside power can help ship operators and port management to save up to 75% in terms of operational and energy costs (Yiğit et al., 2016). Depending on the local and regional regulations, emissions reduction potential can differ

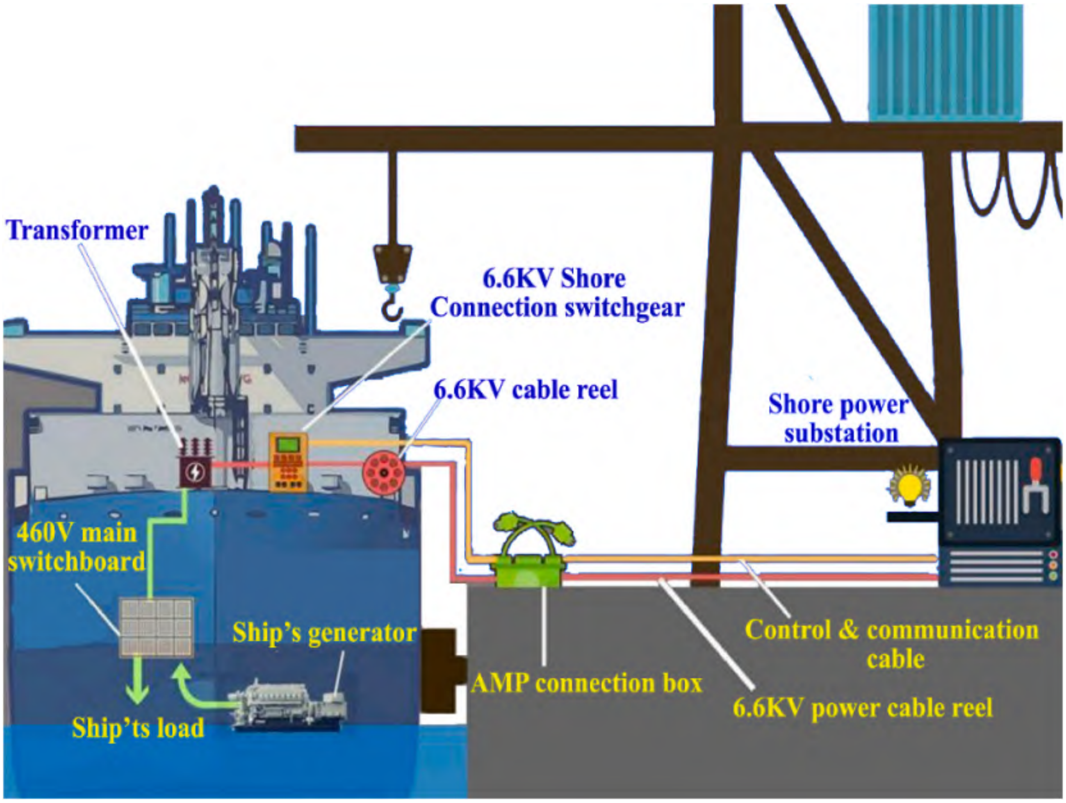

Fig. 14. Scheme of a shore-to-ship power supply system (Mayur Agarwal, 2020).

significantly resulting from the divergent policies and cost factors related to air pollution control. In general, the application of onshore power supply could significantly reduce CO_2 emission, the obtained data was given in Table 7.

Despite the benefits of cold-ironing, successful deployment of such technology remains quite difficult in practice (Tseng and Pilcher, 2015; Tsekouras and Kanellos, 2016). There are several technical barriers related to interface requirements including proper voltage and correct connection type, as well as other external factors related to the ability of the power utility to serve the port, and the grid integrity and security (Tseng and Pilcher, 2015). Before the start of cold-ironing deployment, port managers should perform various assessments on the power quality and the reliability of the local power system (Tsekouras and Kanellos, 2016). Particularly, an additional backup generator should be made available as the ship receiving power system is plugged into two sides to ensure a higher quality power supply (Tsekouras and Kanellos, 2016). The integration of smart electrical interfaces can enhance the performance and efficiency of cold-ironing (T. Coppola et al., 2016a,b). Additional investigations on the impacts of electric characteristics on cold-ironing could offer a greater understanding of maintaining good quality and reliable power supply for cold ironing (Sciberras et al., 2015a). Tang et al. (2018b) confirmed the potential cost saving of utilizing hybrid energy systems in managing multiple power sources (e.g., solar PV, battery, diesel, cold-ironing) on marine vessels up to 20% of savings from electricity costs. Even though the amount of fuel consumed by berthing ships only accounts for a small percentage of the total energy consumption throughout the lifetime of a vessel, there are still significant benefits gained from the practice of cold ironing. While achieving lower CO_2 emissions and air pollution, the downtime of ship's generators allows for the elimination of potential noise pollution from ships while berthing. There also positive impacts on the coastal marine habitats, as well as the physical and mental health of neighboring communities (Ballini and Bozzo, 2015). There is a strong need for established regulatory frameworks and financial incentives to overcome the large initial financial commitment for infrastructural investment. Furthermore, more streamlined ship operations can be developed to motivate ship operators and port management boards to start implementing cold ironing practices (Zis, 2019; Winkel et al., 2016).

In recent years, the smart grid has been using as a new concept aiming to harness the potential of renewable energy sources and reduces CO_2 (PIANC, 2019b). As reported, the smart grid provided an integrated platform for the port-grid/ship-grid/or port-to-ship grid including electric grid technologies and sensors (Giuseppe Parise et al., 2015a,b; Lam et al., 2017), battery technologies (Siemens, 2017), monitoring systems (Mondragon et al., 2015), control tools, and communication technologies (Yiğit et al., 2016). In a report of Siemens, they believed that the smart grid would replace the traditional grid to reduce CO_2 emission in the ports of the future generation (Siemens, 2017). Indeed, Yigit et al. (Yigit and Acarkan, 2018) explored the integration between the port with ships, they indicated that the smart grid infrastructure would offer remarkable benefits for the port-to-ship interactions. For the application of the smart grid to the port-to-ship interactions, it was also discussed in some EU project (Delnooz et al., 2012; Green Efforts, 2014). The scheme of the smart grid was suggested in the study of Fang et al. (2019) as shown in Fig. 15a. In another study, Tao et al. (2014) have indicated the potential and contribution of renewable energy sources to the smart grid, as shown in Fig. 15b, showing that the utilization of renewable energy sources could offer a significant benefits for reducing CO_2 emissions. However, it was reported that the utilization of the smart grid in ports have been facing challenges relating to communication infrastructure, cost, safe level, and legal implications (PIANC, 2019b). Therefore, the roadmap for the application of the smart grid in ports should be comprehensively studied.

7. Conclusions and future scenarios

Throughout this review article, an overall discussion on the different strategies to reduce CO_2 emissions from ships and ports has been

Table 7

CO_2 emissions reduction level as applying alternative power to ship.

Ports	Types of alternative power	CO_2 emissions reduction level	References
Kaohsiung, Taiwan	Cold-ironing	57.16%	Zis et al. (2014)
European port		40%	Sciberras et al. (2016)
Fort Lauderdale, US		9.4%	Hall (2010)
Oslo, Norway	Hydroelectric power	99.5%	Hall (2010)
France	Nuclear power	85.0%	
Port of Kaohsiung	Onshore power supply	57%	Chang and Wang (2012)
Ports of Antwerp and Genoa		50%	Acciaro et al. (2014b)
Port of Shenzhen		20%	(Y.C. Yang, 2017)
Aberdeen Port		4767 tons	Innes and Monios (2018)
Gothenburg Port		10% and 5% for RoRo-ferry and container vessels, respectively	Winnes et al. (2015)
Cartagena Port		10,000 tons/year	Gutierrez-Romero et al. (2019)
Various ports		50%	Krämer and Czermański (2020)
Oslo Port	Onshore power supply in combined with the reduced speed-zone	15%	(López-Aparicio et al., 2017)
Port of Ancona	Shore-to-ship power supply	87% (deduced from energy saving)	Colarossi and Principi (2020)
European ports	Shore-side electricity	3.7%	Stolz et al. (2021)
Port of Shanghai		50%	Dai et al. (2019)
Germany/France/UK/Norway		1296–1312 tons	Dai et al. (2020)
Port of Shanghai		34,000 tons	Wang et al. (2021)

provided through the careful examination of different low-carbon fuels, alternative clean renewable energy sources, as well as supporting regulatory framework. The authors have also offered several analyses and revealed important conclusions with regards to the potential and current obstacles in adopting a wide range of mitigation solutions in reducing CO_2 emissions from ship and port operations.

Through effective management and operational practices with the aim toward a low-carbon and sustainable shipping industry, potential energy and emissions reduction along with significant cost savings can be gained by ship operators and port authorities. Additional deployment of smart energy management systems, battery storage, energy conversion, and consumption monitoring can enhance potential energy savings. Apart from electrification as the main approach, ports and ship operators can consider integrating LNG, dual-fuel, and hydrogen fuel cell systems as alternative means of power generation.

Alternative fuels remain a major driving force in leading the shipping industry toward a low-carbon and sustainable path. As more commercial ships are converted from conventional HFO and MDO to cleaner and less carbon-intensive fuels, such as LNG, the potential in achieving significant CO_2 emissions can be realized. However, the risk of methane slip, which is the major component in LNG, reduces the overall CO_2 emissions reduction to 8–20% relative to the consumption of HFO and MDO. Biofuels are another potential source of alternative fuel that can be utilized onboard marine vessels. When combining with other fuels, biofuels become an attractive candidate due to their excellent commercial viability. Nevertheless, the wide range of different types of biofuels leads to high variability in emissions, costs, and applicability of these resources. Increase dependence on biofuels as the primary transportation fuel has a certain inherent degree of risk to the sustainability of the industry in the long run (i.e., feedstock supply and fuel prices). Besides, hydrogen and ammonia are two rising candidates that are anticipated to make headway in the future market for alternative marine fuels. Particularly, they can be proven highly cost-effective among niche markets such as inland, coastal and short sea shipping routes over long-distance journeys. Overall, only LNG is the one alternative fuel that is presently economically viable. Further investment in infrastructural improvements and adoption of supportive policy frameworks are needed to provide momentum for wider uptake of these alternative marine fuels in the global shipping industry.

The alternative marine fuels mentioned above indicated that renewable energy resources such as solar and wind offer important benefits in improving the efficiency in ship operation and propulsion allowing for potential fuel savings. Even though solar energy cannot fully replace the ship's main generators, it can be used to supply auxiliary power in certain ship models. Currently, nuclear power application on commercial vessels remains limited and can be expected to stay that way in the short term. However, the potential of such technology is still worthy of continued research into potential future applications despite the limited scope of research available on the subject.

Fuel cell technology provides an opportunity for decarbonization of the shipping industry given the zero-emissions characteristics of fuel cells. There is an urgent need for more thorough investigations on the technological advances, feasibility studies, and pilot demonstrations to fully explore the potential of fuel cell application on marine vessels. In the current stage of technological development and capability, researchers have advocated for the utilization of hybrid power systems and those that are specifically designed and optimized for selected ship models and shipping routes. These seem to be the most practical and cost-effective considering the current market conditions. The growth of energy storage technologies and design improvements of smaller-sized ships enables the future development of ship models that would be able to be powered mostly from alternative fuel sources. At the present, the nascent growth in the development of carbon capture storage technologies in maritime applications offer little potential without key research breakthrough and/or supporting policies.

For sustainable port operations, there are several opportunities for achieving port decarbonization, including electrification, hybridization, and alternative fuel measures. When these approaches are combined with the utilization of renewable energy, the potential benefits can be greatly enhanced. Currently, costs and difficulty in operation due to the complexity of the technology are the two main obstacles preventing the uptake of renewable energy in the maritime industry. With the introduction of supportive policy frameworks and appropriate financial incentive mechanisms, the adoption of renewable energy will be likely to trend upward. The availability of energy management systems has become a driving force in the performance and efficiency improvement of electrical and hybrid power systems while providing both regulation to the electrical demand and supply from the intermittent renewable resources and the electrical/hybrid power system on the consumer side.

Energy efficiency improvements not only can result in lower GHG emissions but also produce positive economic effects. Additional measures are available to improve the sustainability of port operations, such as enhancing the cooperation between the port authority and city government, green policies allowing for ports to leverage on financial incentives offered by the government to reduce the cost of investment in sustainable practices and efficiency improvements. In its position, ports hold a critical role as the kingpin in influencing the shipping and trucking behavior toward more environmentally and climate-friendly practices. In other words, as ports implement key energy efficiency measures, the potential spillover effect can start to make an imprint on

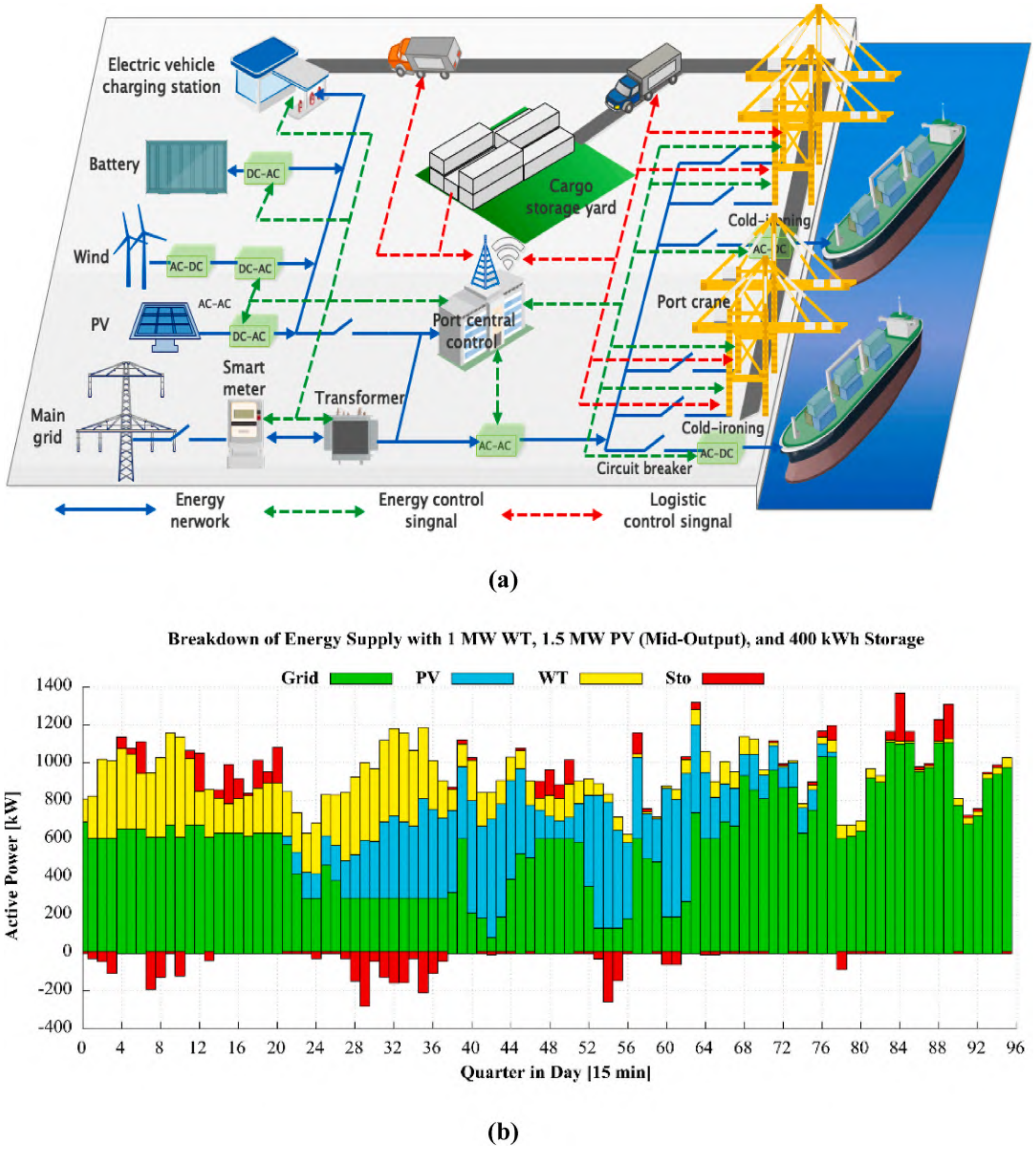

Fig. 15. (a) - Scheme of a smart grid system for the port-to-ship strategy (Fang et al., 2019); **(b) - Breakdown on the energy supply with the smart grid** (Tao et al., 2014).

the actors in the industry supply chain. Hence, the enhanced cooperation among key stakeholders, as well as different port authorities in the region, is essential for achieving a greater GHG emissions potential from the synergetic effects from such active collaboration. Furthermore, ports can also implement measures to improve energy distribution, design more effective power management plans, devise strategies to better handling of reefer containers, and invest in more renewable energy infrastructure. On-site distributed renewable generation can supply clean energy to be used for port equipment or sell to the utility grid. The future of next-generation ports depends on the successful implementation and deployment of smart microgrids. Besides, the availability of combined heat and power plants is viewed as potential carbon capture and storage facilities for port operations.

With the expected growth in demand for maritime shipping activities, a potential emissions cap would ensure the industry is on the right track toward a more sustainable future. An innovative cap-and-trade system could ensure the limit on the total carbon emissions while allowing for a certain degree of flexibility to achieve the individual requirements among the various actors in the industry. The additional revenue stream created from the auditing and trading process can provide a fund that supports climate progressive projects and initial investment for renewable energy infrastructure, and provide possible compensation for developing countries that are negative impacted by the emissions cap. More importantly, this funding is possible to incentivize the various emissions reduction and efficiency improvement measures. Well-defined regulations are needed to ensure the lowest risk for carbon spillage.

In the end, the combination of several elements, namely fuels, technology, and policy, is at the crux of the issue from both the short-term and long-term perspective. Energy efficiency, both technology and policy schemes, remains the most important measure in both scenarios, while the focus on the potential of nuclear, renewables, and hydrogen technologies is more appropriate to be placed in the longer timeframe. Eventually, underlying policy frameworks are urgently needed to provide the operating parameters for the continued decarbonization of the industry. Looking ahead to the fuOk, Ênture, additional energy-saving and emissions reduction strategies within the maritime transportation sector should continue to be promoted and researched for innovative ideas. As progress is being made on the technology side, windows of opportunities to optimize the energy efficiency and emissions reduction potential will sooner or later be fully realized.

CRediT authorship contribution statement

Anh Tuan Hoang: Conceptualization, Methodology, Writing – review & editing. **Aoife M. Foley:** Writing – review & editing. **Sandro Nižetić:** Methodology, Writing – review & editing. **Zuohua Huang:** Writing – review & editing. **Hwai Chyuan Ong:** Writing – review & editing. **Aykut I. Ölçer:** Writing – review & editing. **Van Viet Pham:** Drawing, Writing – review & editing. **Xuan Phuong Nguyen:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Acciaro, M., Wilmsmeier, G., 2015. Energy efficiency in maritime logistics chains. Res. Transport. Bus. Manag. 1–7.

Acciaro, M., Ghiara, H., Cusano, M.I., 2014a. Energy management in seaports: a new role for port authorities. Energy Pol. 71, 4–12.

Acciaro, M., Vanelslander, T., Sys, C., Ferrari, C., Roumboutsos, A., Giuliano, G., Lam, J. S.L., Kapros, S., 2014b. Environmental sustainability in seaports: a framework for successful innovation. Marit. Pol. Manag. 41, 480–500. https://doi.org/10.1080/03088839.2014.932926.

Agarwal, Mayur, 2020. What is alternate marine power (AMP) or cold ironing? [WWW Document]. URL. https://www.marineinsight.com/marine-electrical/what-is-alternate-marine-power-amp-or-cold-ironing/.

Ahamad, N.B.B., Su, C.L., Zhaoxia, X., Vasquez, J.C., Guerrero, J.M., Liao, C.H., 2019. Energy harvesting from harbor cranes with flywheel energy storage systems. IEEE Trans. Ind. Appl. https://doi.org/10.1109/TIA.2019.2910495.

Ahmed, M., Dincer, I., 2011. A review on methanol crossover in direct methanol fuel cells: challenges and achievements. Int. J. Energy Res. 35, 1213–1228.

Ahn, J., Noh, Y., Joung, T., Lim, Y., Kim, J., Seo, Y., Chang, D., 2019. Safety integrity level (SIL) determination for a maritime fuel cell system as electric propulsion in accordance with IEC 61511. Int. J. Hydrogen Energy 44, 3185–3194.

Alasali, F., Haben, S., Becerra, V., Holderbaum, W., 2018. Day-ahead industrial load forecasting for electric RTG cranes. J. Modern Power Syst. Clean Energy 6, 223–234. https://doi.org/10.1007/s40565-018-0394-4.

Alvarez, E.A., Manso, A.N., Gutiérrez-Trashorras, A.J., Francos, J.F., Secades, M.R., 2013. Obtaining renewable energy from tidal currents in the Aviles port: new services for citizens. In: Conference and Exhibition - 2013 International Conference on New Concepts in Smart Cities: Fostering Public and Private Alliances, SmartMILE. https://doi.org/10.1109/SmartMILE.2013.6708175, 2013.

Ammar, N.R., 2019. Environmental and cost-effectiveness comparison of dual fuel propulsion options for emissions reduction onboard lng carriers. Brodogradnja. https://doi.org/10.21278/brod70304.

Anderson, M., Salo, K., Fridell, E., 2015. Particle- and gaseous emissions from an LNG powered ship. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.5b02678.

Andrews, J., Shabani, B., 2012. Where does hydrogen fit in a sustainable energy economy?. In: Procedia Engineering https://doi.org/10.1016/j.proeng.2012.10.107.

Anh, T.H., 2021. Prediction of the density and viscosity of biodiesel and the influence of biodiesel properties on a diesel engine fuel supply system. J. Marine Engi. Technol. 20 (5), 299–311. https://doi.org/10.1080/20464177.2018.1532734.

Antonelli, M., Ceraolo, M., Desideri, U., Lutzemberger, G., Sani, L., 2017. Hybridization of rubber tired gantry (RTG) cranes. J. Energy Storage. https://doi.org/10.1016/j.est.2017.05.004.

APEC, 2014. Study on the Reduction of Energy Consumption and Prevention of Harmful Exhaust Emissions from International Shipping in the APEC Region. Asia-Pacific Economic Cooperation. APEC Transportation Working Group.

Arasto, A., Kujanpää, L., Mäkinen, T., Zwart, R.W.R., Kiel, J.H.A., Vehlow, J., 2012. Analysis and implications of challenges in achieving the targets of EU RES-E directive. Biomass Bioenergy. https://doi.org/10.1016/j.biombioe.2011.02.026.

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., Tokos, K., 2009. Atmospheric lifetime of fossil fuel carbon dioxide. Annu. Rev. Earth Planet Sci. https://doi.org/10.1146/annurev.earth.031208.100206.

Arena, F., Malara, G., Musolino, G., Rindone, C., Romolo, A., Vitetta, A., 2018. From green-energy to green-logistics: a pilot study in an Italian port area. In: Transportation Research Procedia. https://doi.org/10.1016/j.trpro.2018.09.013.

Ashok, B., Ashok, S.D., Kumar, C.R., 2015. LPG diesel dual fuel engine–A critical review. Alex. Eng. J. 54, 105–126.

Augustine, P., McGavisk, E., 2016. The next big thing in renewable energy: shared solar. Electr. J. 29, 36–42. https://doi.org/10.1016/j.tej.2016.04.006.

Azetsu, A., 2016. Regulation of GHG emissions and trend of countermeasures. J. Japan Inst. Mar. Eng. 51, 50–53. https://doi.org/10.5988/jime.51.50.

Balamurugan, T., Nalini, R., 2014. Experimental investigation on performance, combustion and emission characteristics of four stroke diesel engine using diesel blended with alcohol as fuel. Energy. https://doi.org/10.1016/j.energy.2014.10.020.

Balbaa, A., El-Amary, N.H., 2017. Green energy seaport suggestion for sustainable development in Damietta Port, Egypt. WIT Trans. Ecol. Environ. https://doi.org/10.2495/ECO170071.

Balbaa, A., Swief, R.A., El-Amary, N.H., 2019. Smart integration based on hybrid particle swarm optimization technique for carbon dioxide emission reduction in eco-ports. Sustainability. https://doi.org/10.3390/su11082218.

Balcombe, P., Speirs, J., Johnson, E., Martin, J., Brandon, N., Hawkes, A., 2018. The carbon credentials of hydrogen gas networks and supply chains. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2018.04.089.

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., Staffell, I., 2019. How to decarbonize international shipping: options for fuels, technologies and policies. Energy Convers. Manag. https://doi.org/10.1016/j.enconman.2018.12.080.

Baldi, F., Gabrielii, C., 2015. A feasibility analysis of waste heat recovery systems for marine applications. Energy 80, 654–665.

Baldi, F., Moret, S., Tammi, K., Maréchal, F., 2020. The role of solid oxide fuel cells in future ship energy systems. Energy 194, 116811.

Ballini, F., Bozzo, R., 2015. Air pollution from ships in ports: the socio-economic benefit of cold-ironing technology. Research in Transportation Business and Management. https://doi.org/10.1016/j.rtbm.2015.10.007.

Banawan, A.A., El Gohary, M.M., Sadek, I.S., 2010. Environmental and economical benefits of changing from marine diesel oil to natural-gas fuel for short-voyage high-power passenger ships. In: Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment. https://doi.org/10.1243/14750902JEME181.

Barreto, L., Makihira, A., Riahi, K., 2003. The hydrogen economy in the 21st century: a sustainable development scenario. Int. J. Hydrogen Energy. https://doi.org/10.1016/S0360-3199(02)00074-5.

Bazari, Z., Longva, T., 2011. Assessment of IMO Mandated Energy Efficiency Measures for International Shipping. Lloyd's Register.

Ports of Los Angeles, Beach, Long, 2017. San Pedro Bay Ports Approve Bold New Clean Air Strategies [WWW Document]. Clean Air Action Plan.

Bechtsis, D., Tsolakis, N., Vlachos, D., Iakovou, E., 2017. Sustainable supply chain management in the digitalization era: the impact of Automated Guided Vehicles. J. Clean. Prod. 142, 3970–3984.

Bengtsson, S., Andersson, K., Fridell, E., 2011. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. Proc. IME M J. Eng. Marit. Environ. 225, 97–110.

Bengtsson, S., Fridell, E., Andersson, K., 2012. Environmental assessment of two pathways towards the use of biofuels in shipping. Energy Pol. https://doi.org/10.1016/j.enpol.2012.02.030.

Bengtsson, S.K., Fridell, E., Andersson, K.E., 2014. Fuels for short sea shipping: a comparative assessment with focus on environmental impact. Proc. IME M J. Eng. Marit. Environ. https://doi.org/10.1177/1475090213480349.

Bergholz, W., 2014. Reduction of the CO2 Footprints of Container Terminals by Photovoltaics, Green Efforts Project Technical Report 2014.

Bergqvist, R., Monios, J., 2019. Green ports in theory and practice. In: Green Ports. Elsevier, pp. 1–17.

Bicer, Y., Dincer, I., 2018a. Clean fuel options with hydrogen for sea transportation: a life cycle approach. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2017.10.157.

Bicer, Y., Dincer, I., 2018b. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: a comparative evaluation. Int. J. Hydrogen Energy 43, 4583–4596.

Bioenergy, E., 2016. Biofuels in Shipping – Potential of Biodiesel, Biomethane, Methanol and SOFC Technology for Ships.

Bjerkan, K.Y., Seter, H., 2019. Reviewing tools and technologies for sustainable ports: does research enable decision making in ports? Transport. Res. Transport Environ. 72, 243–260. https://doi.org/10.1016/j.trd.2019.05.003.

Blažauskas, N., Grigelis, A., Gelumbauskaitė, L.Ž., Gulbinskas, S., Suzdalev, S., Ferrarin, C., 2015. Towards sustainable use of marine resources in the south-eastern Baltic Sea (Lithuania): a review. Baltica 28, 179–188. https://doi.org/10.5200/baltica.2015.28.15.

Boile, M., Theofanis, S., Sdoukopoulos, E., Plytas, N., 2016. Developing a port energy management plan: issues, challenges, and prospects. Transport. Res. Rec. 2549, 19–28. https://doi.org/10.3141/2549-03.

Boretti, A.A., 2012. Novel heavy duty engine concept for operation dual fuel H 2-NH3. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2012.01.091.

Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. Transport. Res. Transport Environ. 52, 408–421. https://doi.org/10.1016/j.trd.2017.03.022.

Brief for Eu Member States, 2013, 1–9.

Brynolf, S., Fridell, E., Andersson, K., 2014a. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.

Brynolf, S., Magnusson, M., Fridell, E., Andersson, K., 2014b. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transport. Res. Transport Environ. 28, 6–18.

Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Mjelde, A., 2008. Updated Study on Greenhouse Gas Emissions from Ships: Phase I Report, vol. 1. International Maritime Organization (IMO), London, UK.

Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W.-Q., Yoshida, K., 2009. Second IMO Greenhouse Gas Study 2009. International Maritime Organization (IMO).

Bui, V.G., Tran, V.N., Hoang, A.T., Bui, T.M.T., Vo, A.V., 2020. A simulation study on a port-injection SI engine fueled with hydroxy-enriched biogas. Energy Sources, Part A: recovery, Utilization and Environmental Effects. https://doi.org/10.1080/15567036.2020.1804487.

Bui, V.G., Bui, T.M.T., Hoang, A.T., Nižetić, S., Sakthivel, R., Engel, D., Hadiyanto, H., 2021. Energy storage onboard zero-emission two-wheelers: challenges and technical solutions. Sustain. Energy Technol. Assessments 47, 101435. https://doi.org/10.1016/j.seta.2021.101435.

Buiza, G., Cepolina, S., Dobrijevic, A., Del Mar Cerbápn, M., Djordjevic, O., González, C., 2016. Current situation of the Mediterranean container ports regarding the operational, energy and environment areas. In: Proceedings of 2015 International Conference on Industrial Engineering and Systems Management. IEEE IESM 2015. https://doi.org/10.1109/IESM.2015.7380209.

Burel, F., Taccani, R., Zuliani, N., 2013. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy. https://doi.org/10.1016/j.energy.2013.05.002.

C, M., 2017. Emission-Free Hydrogen for Shipping. Ship-technology.Com. Marine Hydrogen and Fuel Cell Association (MHFCA).

CARB/EPA, 2015. TECHNOLOGY ASSESSMENT: MOBILE CARGO HANDLING EQUIPMENT. California Air Resources Board & Environmental Protection Agency, USA.

Carlo, H.J., Vis, I.F.A., Roodbergen, K.J., 2014. Transport operations in container terminals: literature overview, trends, research directions and classification scheme. Eur. J. Oper. Res. 236, 1–13. https://doi.org/10.1016/j.ejor.2013.11.023.

Carlton, J., Aldwinkle, J., Anderson, J., 2013. Future Ship Powering Options: Exploring Alternative Methods of Ship Propulsion. Royal Academy of Engineering, London.

Cascajo, R., García, E., Quiles, E., Correcher, A., Morant, F., 2019. Integration of marine wave energy converters into seaports: a case study in the port of Valencia. Energies. https://doi.org/10.3390/en12050787.

Chang, C.C., Wang, C.M., 2012. Evaluating the effects of green port policy: case study of Kaohsiung harbor in Taiwan. Transport. Res. Transport Environ. https://doi.org/10.1016/j.trd.2011.11.006.

Chen, J., Zheng, T., Garg, A., Xu, L., Li, S., Fei, Y., 2019. Alternative Maritime Power application as a green port strategy: barriers in China. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.12.177.

Chen, Y., Xu, Y., Li, Z., Feng, X., 2019. Optimally coordinated dispatch of combined-heat-and-electrical network with demand response. IET Gener., Transm. Distrib. 13, 2216–2225.

Chen, W.-H., Wang, J.-S., Chang, M.-H., Mutuku, J.K., Hoang, A.T., 2021. Efficiency improvement of a vertical-axis wind turbine using a deflector optimized by Taguchi approach with modified additive method. Energy Convers. Manag. 245, 114609. https://doi.org/10.1016/j.enconman.2021.114609.

Christodoulou, A., Gonzalez-Aregall, M., Linde, T., Vierth, I., Cullinane, K., 2019. Targeting the reduction of shipping emissions to air. Maritime Bus. Rev. 4, 16–30. https://doi.org/10.1108/MABR-08-2018-0030.

Christoforaki, M., Tsoutsos, T., 2017. Sustainable siting of an offshore wind park a case in Chania, Crete. Renew. Energy 109, 624–633. https://doi.org/10.1016/j.renene.2017.03.063.

Claudius C, H.J., 2012. LED Technology for Container Terminals, Green Efforts Project Technical Report 2012.

Cofala, J., Amann, M., Heyes, C., Wagner, F., Klimont, Z., Posch, M., Schöpp, W., Tarasson, L., Whall, C., Stavrakaki, A., 2007. Analysis of Policy Measures to Reduce Ship Emissions in the Context of the Revision of the National Emissions Ceilings Directive.

Colarossi, D., Principi, P., 2020. Technical analysis and economic evaluation of a complex shore-to-ship power supply system. Appl. Therm. Eng. 181, 115988.

Coppola, T., Fantauzzi, M., Lauria, D., Pisani, C., Quaranta, F., 2016a. A sustainable electrical interface to mitigate emissions due to power supply in ports. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2015.10.107.

Coppola, T., Fantauzzi, M., Miranda, S., Quaranta, F., 2016b. Cost/benefit analysis of alternative systems for feeding electric energy to ships in port from ashore. In: 2016 AEIT International Annual Conference (AEIT). IEEE, pp. 1–7.

Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V., Lauer, A., 2007. Mortality from ship emissions: a global assessment. Environmental Science and Technology. https://doi.org/10.1021/es071686z.

Cotorcea, A., Ozkaynak, S., Nicolae, F., Ristea, M., 2014. Present and future of renewable energy sources onboard ships. case study: solar-thermal systems. Sci. Bull. " Mircea cel Batran" Naval Acad. 17, 35.

D, U.N.C.T.A., 2016. DEVELOPMENT, REVIEW of MARITIME TRANSPORT 2016. Place of Publication Not Identified. UNITED NATIONS, Geneva.

D, U.N.C.T.A., 2017. United Nations Conference on Trade and Development, Review of Maritime Transport 2017". Place of publication not identified, Geneva, 2017.

Dai, L., Hu, H., Wang, Z., Shi, Y., Ding, W., 2019. An environmental and techno-economic analysis of shore side electricity. Transport. Res. Transport Environ. 75, 223–235.

Dai, L., Hu, H., Wang, Z., 2020. Is Shore Side Electricity greener? An environmental analysis and policy implications. Energy Pol. 137, 111144.

Davarzani, H., Fahimnia, B., Bell, M., Sarkis, J., 2016. Greening ports and maritime logistics: a review. Transport. Res. Transport Environ. 48, 473–487.

de la Fuente, S.S., Roberge, D., Greig, A.R., 2017. Safety and CO2 emissions: implications of using organic fluids in a ship's waste heat recovery system. Mar. Pol. 75, 191–203.

De-Troya, J.J., Álvarez, C., Fernández-Garrido, C., Carral, L., 2016. Analysing the possibilities of using fuel cells in ships. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2015.11.145.

Delft, C.E., 2016. Study on the Analysis of Market Potentials and Market Barriers for Wind Propulsion Technologies for Ships.

Delnooz, A., Six, D., Kessels, K., Hommelberg, M.P.F., 2012. e-Harbours: identification and analysis of barriers for Virtual Power Plants in harbour regions. In: 2012 9th International Conference on the European Energy Market, pp. 1–6. https://doi.org/10.1109/EEM.2012.6254682.

Deniz, C., 2015. Thermodynamic and environmental analysis of low-grade waste heat recovery system for a ship power plant. Int. J. Energy Sci. 5, 23–34.

Dhupia, J., Adnanes, A.K., Lee, K.M., Kennedy, L., 2011. Electrification of port and port operations. In: Proceedings of MTEC2011.

Díaz, H., Guedes Soares, C., 2020. An integrated GIS approach for site selection of floating offshore wind farms in the Atlantic continental European coastline. Renew. Sustain. Energy Rev. 134, 110328. https://doi.org/10.1016/j.rser.2020.110328.

Dimopoulos, G.G., Stefanatos, I.C., Kakalis, N.M.P., 2016. Exergy Analysis and Optimisation of a Marine Molten Carbonate Fuel Cell System in Simple and Combined Cycle Configuration. Energy Conversion and Management. https://doi.org/10.1016/j.enconman.2015.09.007.

DNV, P., 2013. News - Press Releases - DNV-PSE CCS Report. Delft University of Technology.

DNV, 2016. Methanol as Marine Fuel: Environmental Benifits, Technology Readiness, and Economic Feasibility. IMO.

DNV, G.L., 2016. Methanol as Marine Fuel: Environmental Benifits, Technology Readiness, and Economic Feasibility. IMO.

DNV, G.L., 2017. Low Carbon Shipping towards 2050 [WWW Document]. URL. https://www.dnvgl.com/publications/low-carbon-shipping-towards-2050-93579.

DNV, G.L., 2018. Maritime Forecast to 2050. Energy Transition Outlook 2018.

DNV, G., 2019. LNG as Ship Fuel [WWW Document].

Du, K., Monios, J., Wang, Y., 2018. Green port strategies in China. In: Green Ports: Inland and Seaside Sustainable Transportation Strategies. https://doi.org/10.1016/B978-0-12-814054-3.00011-6.

Dvarionienė, J., Zobėlaitė-Noreikienė, G., Kruopienė, J., Stasiškienė, Ž., 2013. Application of the life-cycle assessment method for pollution prevention in klaipėda sea port, Lithuania. J. Coast Res. 290, 1083–1091. https://doi.org/10.2112/JCOASTRES-D-11-00167.1.

Efforts, G., 2014. Green and effective operations at terminals and in ports -deliverable 12.1- recommendations manual for terminals. European Commission.

Eide, M.S., Longva, T., Hoffmann, P., Endresen, Ø., Dalsøren, S.B., 2011. Future cost scenarios for reduction of ship CO 2 emissions. Marit. Pol. Manag. 38, 11–37. https://doi.org/10.1080/03088839.2010.533711.

Eide, M.S., Chryssakis, C., Endresen, Ø., 2013. CO2 abatement potential towards 2050 for shipping, including alternative fuels. Carbon Manag. https://doi.org/10.4155/cmt.13.27.

El-Amary, N.H., Balbaa, A., Swief, R.A., Abdel-Salam, T.S., 2018. A Reconfigured Whale Optimization Technique (RWOT) for renewable electrical energy optimal scheduling impact on sustainable development applied to Damietta seaport, Egypt. Energies. https://doi.org/10.3390/en11030535.

Elgohary, M.M., Seddiek, I.S., Salem, A.M., 2015. Overview of alternative fuels with emphasis on the potential of liquefied natural gas as future marine fuel. Proc. IME M J. Eng. Marit. Environ. https://doi.org/10.1177/1475090214522778.

Ellis, J., Tanneberger, K., 2015. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. Eur. Marit. Saf. Agency.

El-Houjeiri, H., Monfort, J., Bouchard, J., Przesmitzki, S., 2019. Life cycle assessment of greenhouse gas emissions from marine fuels: a case study of Saudi crude oil versus natural gas in different global regions. J. Ind. Ecol. 23, 374–388.

Espina-Valdés, R., Álvarez Álvarez, E., García-Maribona, J., Trashorras, A.J.G., González-Caballín, J.M., 2019. Tidal current energy potential assessment in the Avilés Port using a three-dimensional CFD method. Clean Technol. Environ. Policy. https://doi.org/10.1007/s10098-019-01711-2.

ESPO, 2012. ESPO Green Guide: towards Excellence in Port Environmental Management and Sustainability.

Evrin, R.A., Dincer, I., 2019. Thermodynamic analysis and assessment of an integrated hydrogen fuel cell system for ships. Int. J. Hydrogen Energy 44, 6919–6928.

Eyring, V., Köhler, H.W., Lauer, A., Lemper, B., 2005. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. Journal of Geophysical Research D: Atmospheres. https://doi.org/10.1029/2004JD005620.

Fahdi, S., Elkhechafi, M., Hachimi, H., 2019. Green port in blue ocean: optimization of energy in asian ports. In: 2019 5th International Conference on Optimization and Applications (ICOA). IEEE, pp. 1–4. https://doi.org/10.1109/ICOA.2019.8727615.

Fang, S., Wang, Y., Gou, B., Xu, Y., 2019. Toward future green maritime transportation: an overview of seaport microgrids and all-electric ships. IEEE Trans. Veh. Technol. 69, 207–219.

Farrell, A.E., Keith, D.W., Corbett, J., 2003. A strategy for introducing hydrogen into transportation. Energy Pol. https://doi.org/10.1016/S0301-4215(02)00195-7.

FathomShipping, 2012. Could Wind Power Return to Commercial Shipping?.

Fathom.world, 2019. Is Methanation the Future of Ship Fuel? [WWW Document].

FCCC/CP, 2016. Report of the Conference of the Parties on its Twenty First Session, Held in Paris from 30 November to 13 December 2015.

Fernández, I.A., Gómez, M.R., Gómez, J.R., Insua, Á.B., 2017. Review of propulsion systems on LNG carriers. Renew. Sustain. Energy Rev. 67, 1395–1411. https://doi.org/10.1016/j.rser.2016.09.095.

Florentinus, A., Hamelinck, C., Van den Bos, A., Winkel, R., Cuijpers, M., 2012. Potential of Biofuels for Shipping. Final Report.

Flynn, M.M., McMullen, P., Solis, O., 2008. Saving energy using flywheels. IEEE Ind. Appl. Mag. 14, 69–76.

Freire, L.O., De Andrade, D.A., 2015. Historic Survey on Nuclear Merchant Ships. Nuclear Engineering and Design. https://doi.org/10.1016/j.nucengdes.2015.07.031.

Fundacion Valencia port, 2015. SEA TERMINALS – SMART, ENERGY EFFICIENCY and ADAPTIVE PORT TERMINALS [WWW Document].

Fung, F., Zhu, Z., Becque, R., Finamore, B., 2014. Prevention and Control of Shipping and Port Air Emissions in china. NRDC White Paper.

Gaurav, N., Sivasankari, S., Kiran, G.S., Ninawe, A., Selvin, J., 2017. Utilization of bioresources for sustainable biofuels: a review. Renewable and sustainable energy reviews. https://doi.org/10.1016/j.rser.2017.01.070.

Geerlings, H., Van Duin, R., 2011. A new method for assessing CO2-emissions from container terminals: a promising approach applied in Rotterdam. J. Clean. Prod. 19, 657–666.

Gharehgozli, A.H., Roy, D., De Koster, R., 2016. Sea container terminals: new technologies and OR models. Marit. Econ. Logist. 18, 103–140.

Ghenai, C., Bettayeb, M., Brdjanin, B., Hamid, A.K., 2019. Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ship: a case study in Stockholm, Sweden. Case Stud. Therm. Eng. 14, 100497.

Gibbs, D., Rigot-Muller, P., Mangan, J., Lalwani, C., 2014. The role of sea ports in end-to-end maritime transport chain emissions. Energy Pol. 64, 337–348.

Giddey, S., Badwal, S.P.S., Munnings, C., Dolan, M., 2017. Ammonia as a renewable energy transportation media. ACS Sustain. Chem. Eng. https://doi.org/10.1021/acssuschemeng.7b02219.

Gilbert, P., 2014. From reductionism to systems thinking: how the shipping sector can address sulphur regulation and tackle climate change. Mar. Pol. 43, 376–378.

Gilbert, P., Bows-Larkin, A., Mander, S., Walsh, C., 2014. Technologies for the High Seas: Meeting the Climate Challenge. Carbon Management. https://doi.org/10.1080/17583004.2015.1013676.

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., Murphy, A., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.10.165.

GL, D., 2019. Comparison of Alternative Marine Fuels. DNV GL AS Maritime, Høvik, Norway.

Global, V., 2018. Eco Marine Power and Teramoto Iron Works Sign Patent License Agreement for Energy-Saving Propulsion Solutions.

Glykas, A., Papaioannou, G., Perissakis, S., 2010. Application and cost-benefit analysis of solar hybrid power installation on merchant marine vessels. Ocean Eng. https://doi.org/10.1016/j.oceaneng.2010.01.019.

GmbH, S., 2019. SkySails Propulsion System: Turn Wind into Profit. SkySails Product Brochure [WWW Document].

Goel, V., Slusky, M., Van Hoeve, W.J., Furman, K.C., Shao, Y., 2015. Constraint programming for LNG ship scheduling and inventory management. Eur. J. Oper. Res. https://doi.org/10.1016/j.ejor.2014.09.048.

Gonzalez Aregall, M., Bergqvist, R., Monios, J., 2018. A global review of the hinterland dimension of green port strategies. Transport. Res. Transport Environ. 59, 23–34. https://doi.org/10.1016/j.trd.2017.12.013.

Grahn, M., Taljegård, M., Bengtsson, S., Andersson, K., Johnson, H., 2013. Cost-effective choices of marine fuels under stringent carbon dioxide targets. In: Proceedings of 3rd International Conference on Technologies, Operations, Logistics and Modelling in Low Carbon Shipping. University College London.

Green Efforts, 2014. Green and Effective Operations at Terminals and in Ports -deliverable 12.1- Recommendations Manual for Terminals. European Commission.

GREENCRANES, 2012. Green Technologies and Eco-Efficient Alternatives for Cranes and Operations at Port Container Terminals, GREENCRANES Project. Technical report october. 2012.

Greenport, 2016. Wave Energy at Port [WWW Document].

Greenport, 2020. Electric Cranes Increase Smart Capability [WWW Document].

Gutierrez-Romero, J.E., Esteve-Pérez, J., Zamora, B., 2019. Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth. Appl. Energy 255, 113883.

Hadadpour, S., Etemad-Shahidi, A., Jabbari, E., Kamranzad, B., 2014. Wave energy and hot spots in Anzali port. Energy. https://doi.org/10.1016/j.energy.2014.07.018.

Halim, R.A., Kirstein, L., Merk, O., Martinez, L.M., 2018. Decarbonization pathways for international maritime transport: a model-based policy impact assessment. Sustainability (Switzerland). https://doi.org/10.3390/su10072243.

Hall, W.J., 2010. Assessment of CO2 and priority pollutant reduction by installation of shoreside power. Resour. Conserv. Recycl. 54, 462–467.

Hamburg Port Authority, 2021. SMARTPORT – THE INTELLIGENT PORT [WWW Document].

Hangga, P., Shinoda, T., 2015. Motion-based energy analysis methodology for hybrid straddle carrier towards eco-friendly container handling system. J. Eastern Asia Soc. Transport. Stud. 11, 2412–2431.

Hansen, J.F., Wendt, F., 2015. History and state of the art in commercial electric ship propulsion, integrated power systems, and future trends. Proc. IEEE. https://doi.org/10.1109/JPROC.2015.2458990.

Hanssen, L., de Vriend, H., Gremmen, B., 2014. The role of biosolar technologies in future energy supply making scenarios for The Netherlands: energy port and energy farm. Futures 63, 112–122. https://doi.org/10.1016/j.futures.2014.05.008.

Hansson, J., Brynolf, S., Fridell, E., Lehtveer, M., 2020. The potential role of ammonia as marine fuel—based on energy systems modeling and multi-criteria decision analysis. Sustainability 12, 3265.

Heilig, L., Voß, S., 2017. SMART PORT LOGISTICS OPPORTUNITIES and CHALLENGES for TRANSITIONING to SMARTER PORT OPERATIONS. Hamburg, Germany.

Hentschel, M., Ketter, W., Collins, J., 2018. Renewable Energy Cooperatives: Facilitating the Energy Transition at the Port of Rotterdam. Energy Policy. https://doi.org/10.1016/j.enpol.2018.06.014.

Hiranandani, V., 2014. Sustainable development in seaports: a multi-case study. WMU J. Maritime Affairs 13, 127–172. https://doi.org/10.1007/s13437-013-0040-y.

Hirdaris, S.E., Cheng, F., 2012. The role of technology in green ship design. In: 11th International Marine Design Conference.

Hirdaris, S.E., Cheng, Y.F., Shallcross, P., Bonafoux, J., Carlson, D., Prince, B., Sarris, G. A., 2014. Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion. Ocean Eng. 79, 101–130.

Hoang, A.T., 2018. Waste heat recovery from diesel engines based on Organic Rankine Cycle. Appl. Energy 231, 138–166.

Hoang, A.T., Pham, V.V., 2018. A review on fuels used for marine diesel engines. J. Mech. Eng. Res. Dev. 41, 22–32. https://doi.org/10.26480/jmerd.04.2018.22.32.

Hoang, A.T., Pham, V.V., 2020. A study on a solution to reduce emissions by using hydrogen as an alternative fuel for a diesel engine integrated exhaust gas recirculation. In: AIP Conference Proceedings. AIP Publishing LLC, p. 20035.

Hoang, A.T., Tabatabaei, M., Aghbashlo, M., Carlucci, A.P., Ölçer, A.I., Le, A.T., Ghassemi, A., 2020. Rice bran oil-based biodiesel as a promising renewable fuel alternative to petrodiesel: a review. Renew. Sustain. Energy Rev. 135, 110204. https://doi.org/10.1016/j.rser.2020.110204.

Hoang, A.T., Pham, V.V., Nguyen, X.P., 2021. Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process. J. Clean. Prod. 305, 127161. https://doi.org/10.1016/j.jclepro.2021.127161.

Hoang, A.T., Tran, V.D., Dong, V.H., Le, A.T., 2022. An experimental analysis on physical properties and spray characteristics of an ultrasound-assisted emulsion of ultra-low-sulphur diesel and Jatropha-based biodiesel. J. Marine Engi. Technol. 21 (2), 73–81. https://doi.org/10.1080/20464177.2019.1595355.

Hoffmann, P.N., Eide, M.S., Endresen, Ø., 2012. Effect of proposed CO 2 emission reduction scenarios on capital expenditure. Marit. Pol. Manag. 39, 443–460. https://doi.org/10.1080/03088839.2012.690081.

Hollen, R.M.A., Van Den Bosch, F.A.J., Volberda, H.W., 2015. Strategic levers of port authorities for industrial ecosystem development. Marit. Econ. Logist. 17, 79–96.

HPA, 2015. Energy Cooperation, Port of Hamburg Technical Report August 2015.

Hsieh, C.C., Felby, C., 2017. Biofuels for the Marine Shipping Sector-An Overview and Analysis of Sector Infrastructure. fuel technologies and regulations IEA Bioenergy.

Hummels, D., 2007. Transportation costs and international trade in the Second era of globalization. J. Econ. Perspect. 21, 131–154. https://doi.org/10.1257/jep.21.3.131.

Hwang, S., Jeong, B., Jung, K., Kim, M., Zhou, P., 2019. Life cycle assessment of lng fueled vessel in domestic services. J. Mar. Sci. Eng. https://doi.org/10.3390/jmse7100359.

HyMethShip, 2019. Hydrogen in Combustion Engines.

IAPH, 2008. IAPH Tool Box for Greenhouse Gasses. International Association of Ports & Harbours.

IAPH, G.-U.-I.G.P., 2018. Port Emissions Toolkit Guide No.1: Assessment of Port Emissions. GloMEEP Project Coordination Unit International Maritime Organization.

IMO, 2009a. The WMD World Maritime Day 2009, Proceedings, Climate Change: A Challenge for IMO Too. International Maritime Organization Background, pp. 21–25.

IMO MEPC.1/Circ.681, 2009b. Interim Guıdelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships. London.

IMO, 2010. MEPC 61/5/16, Reduction of GHG Emissions from Ships, Further Details on the United States Proposal to Reduce Greenhouse Gas Emissions from International Shipping, London.

IMO, 2011. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures. MEPC 62/INF.7, Submitted by the Institute of Marine Engineering, Science and Technology.

IMO, 2016. Studies on the Feasibility and Use of Lng as a Fuel for Shipping, Studies on the Feasibility and Use of LNG as a Fuel for Shipping.

IMO, 2018a. Port Emission Toolkit Guide no.2: Development of Port Emission Reduction Strategies. GloMeep project coordination unit and the International Maritime Organization, London: UK.

IMO, 2018b. MEPC/72/17/ADD.1. Resolution MEPC.304(72): Initial IMO Strategy on Reduction of GHG Emissions from Ships. International Maritime Organization, London: UK.

IMO, 2019. MEPC/74/18/ADD.1. Resolution MEPC.323(74): Invitation to Member States to Encourage Voluntary Cooperation between the Port and Shipping Sectors to Contribute to Reducing GHG Emissions from Ships. International Maritime Organization, London, UK.

Imran, A., Varman, M., Masjuki, H.H., Kalam, M.A., 2013. Review on alcohol fumigation on diesel engine: a viable alternative dual fuel technology for satisfactory engine performance and reduction of environment concerning emission. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.05.070.

Inal, O.B., Deniz, C., 2020. Assessment of fuel cell types for ships: based on multi-criteria decision analysis. J. Clean. Prod. 265, 121734.

İnal, Ö.B., Deniz, C., 2021. Emission analysis of LNG fuelled molten carbonate fuel cell system for a chemical tanker ship: a case study. Mar. Sci. Technol. Bull. 10, 118–133.

Initiative, W.P.C., 2010. Carbon Footprinting for Ports: Guidance Document. Carbon Footprinting Working Group.

Innes, A., Monios, J., 2018. Identifying the unique challenges of installing cold ironing at small and medium ports–The case of Aberdeen. Transport. Res. Transport Environ. 62, 298–313.

Interreg IVB North Sea Region Programme, 2012. Innovative Green Solutions for E-Harbours towards Sustainable , Clean and Energetic Innovative Harbour Cities in the North Sea Region.

ITF OECD, 2018. Decarbonising maritime transport by 2035 [WWW Document]. URL. https://www.itf-oecd.org/decarbonising-maritime-transport-2035.

IWSA, 2018. IWSA Member – eConowind BV. The International Windship Association.

Jens, Froese, Toter Svenja, E.I., 2014. Green and Effective Operations at Terminals and in Ports, Green Efforts Project Technical Report 2014.

Jonathan, Y.C.E., Kader, S.B.A., 2018. Prospect of emission reduction standard for sustainable port equipment electrification. Int. J. Eng. 31 https://doi.org/10.5829/ije.2018.31.08b.25.

Joung, T.-H., Kang, S.-G., Lee, J.-K., Ahn, J., 2020. The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. J. Int. Maritime Saf. Environ. Affairs Ship. 4, 1–7.

JP, 2016. http://www.jp.com.sg/about-us/awards-and-milestones/.

Kang, D., Kim, S., 2017. Conceptual model development of sustainability practices: the case of port operations for collaboration and governance. Sustainability 9, 2333. https://doi.org/10.3390/su9122333.

Kano, T., Seta, T., Sato, K., 2015. Eco-shipping project for Japanese coastal vessels—verification project for CO2 emission reductions with ship-scheduling/voyage-planning system. Towards Green Marine Technol. Transport 175.

Karatuğ, Ç., Durmuşoğlu, Y., 2020. Design of a solar photovoltaic system for a Ro-Ro ship and estimation of performance analysis: a case study. Sol. Energy. https://doi.org/10.1016/j.solener.2020.07.037.

Kaya, Y., Yamaguchi, M., Geden, O., 2019. Towards net zero CO2 emissions without relying on massive carbon dioxide removal. Sustain. Sci. 14, 1739–1743.

Khlopkin, N.S., Zotov, A.P., 1997. Merchant marine nuclear-powered vessels. Nucl. Eng. Des. https://doi.org/10.1016/s0029-5493(97)00109-x.

Kim, S.M., Sul, S.K., 2006. Control of rubber tyred gantry crane with energy storage based on supercapacitor bank. IEEE Trans. Power Electron. https://doi.org/10.1109/TPEL.2006.880260.

Kim, J., Rahimi, M., Newell, J., 2012. Life-cycle emissions from port electrification: a case study of cargo handling tractors at the port of Los Angeles. Int. J. Sustain. Transport. 6, 321–337. https://doi.org/10.1080/15568318.2011.606353.

Kim, K., Roh, G., Kim, W., Chun, K., 2020. A preliminary study on an alternative ship propulsion system fueled by ammonia: environmental and economic assessments. J. Mar. Sci. Eng. 8, 183.

Kjartansson, S., 2012. A Feasibility Study on LPG as Marine Fuel.

Klebanoff, L.E., Pratt, J.W., Leffers, C.M., Sonerholm, K.T., Escher, T., Burgard, J., Ghosh, S., 2017. Comparison of the greenhouse gas and criteria pollutant emissions from the SF-BREEZE high-speed fuel-cell ferry with a diesel ferry. Transport. Res. Transport Environ. 54, 250–268.

Klerke, A., Christensen, C.H., Nørskov, J.K., Vegge, T., 2008. Ammonia for hydrogen storage: challenges and opportunities. J. Mater. Chem. https://doi.org/10.1039/b720020j.

Klüssmann, J.N., Ekknud, L.R., Ivarsson, A., Schramm, J., 2019. The Potential for Ammonia as a Transportation Fuel—A Literature Review. The Technical University of Denmark (DTU), Lyngby, Denmark.

Konstantzos, G.E., Saharidis, G.K.D., Loizidou, M., 2017. Development of a model for assessing Greenhouse Gas (GHG) emissions from terminal and drayage operations. Oper. Res. 17, 807–819. https://doi.org/10.1007/s12351-016-0242-0.

Kontovas, C.A., 2014. The green ship routing and scheduling problem (GSRSP): a conceptual approach. Transport. Res. Transport Environ. 31, 61–69.

Köse, H., Ciniviz, M., 2013. An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. Fuel Process. Technol. https://doi.org/10.1016/j.fuproc.2013.03.023.

Kotrikla, A.M., Lilas, T., Nikitakos, N., 2017. Abatement of air pollution at an aegean island port utilizing shore side electricity and renewable energy. Mar. Pol. https://doi.org/10.1016/j.marpol.2016.01.026.

Krämer, I., Czermański, E., 2020. Onshore power one option to reduce air emissions in ports. In: Sustainability Management Forum| NachhaltigkeitsManagementForum. Springer, pp. 13–20.

Kulkarni, A., Giddey, S., 2012. Materials issues and recent developments in molten carbonate fuel cells. J. Solid State Electrochem. 16, 3123–3146.

Kumar, S., Kwon, H.-T., Choi, K.-H., Lim, W., Cho, J.H., Tak, K., Moon, I., 2011. LNG: an eco-friendly cryogenic fuel for sustainable development. Appl. Energy 88, 4264–4273.

Kumar, J., Parthasarathy, C., Västi, M., Laaksonen, H., Shafie-Khah, M., Kauhaniemi, K., 2020. Sizing and allocation of battery energy storage systems in Åland Islands for large-scale integration of renewables and electric ferry charging stations. Energies 13, 317.

Lam, J.S.L., Notteboom, T., 2014. The greening of ports: a comparison of port management tools used by leading ports in Asia and Europe. Transport Rev. 34, 169–189. https://doi.org/10.1080/01441647.2014.891162.

Lam, J.S.L., Ko, M.J., Sim, J.R., Tee, Y., 2017. Feasibility of implementing energy management system in ports. In: 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). IEEE, pp. 1621–1625.

Lam, J.S.L., Ko, M.J., Sim, J.R., Tee, Y., 2018. Feasibility of implementing energy management system in ports. In: IEEE International Conference on Industrial Engineering and Engineering Management. https://doi.org/10.1109/IEEM.2017.8290167.

Lan, R., Irvine, J.T.S., Tao, S., 2012. Ammonia and related chemicals as potential indirect hydrogen storage materials. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2011.10.004.

Lan, H., Wen, S., Hong, Y.Y., Yu, D.C., Zhang, L., 2015. Optimal sizing of hybrid PV/diesel/battery in ship power system. Appl. Energy 158, 26–34. https://doi.org/10.1016/j.apenergy.2015.08.031.

Lazic, M.B., 2006. Is the semi-automated or automated rail mounted gantry operation a green terminal? Am. Assoc. Port Author.

Lee, B.K., Low, J.M.W., Kim, K.H., 2015. Comparative evaluation of resource cycle strategies on operating and environmental impact in container terminals. Transport. Res. Transport Environ. 41, 118–135. https://doi.org/10.1016/j.trd.2015.09.014.

Li, Z., Xu, Y., 2018. Optimal coordinated energy dispatch of a multi-energy microgrid in grid-connected and islanded modes. Appl. Energy 210, 974–986.

Li, Z., Xu, Y., 2019. Temporally-coordinated optimal operation of a multi-energy microgrid under diverse uncertainties. Appl. Energy 240, 719–729.

Li, J., Wu, B., Mao, G., 2015. Research on the performance and emission characteristics of the LNG-diesel marine engine. J. Nat. Gas Sci. Eng. https://doi.org/10.1016/j.jngse.2015.09.036.

Li, Q., Nihei, Y., Nakashima, T., Ikeda, Y., 2015. A study on the performance of cascade hard sails and sail-equipped vessels. Ocean Eng. https://doi.org/10.1016/j.oceaneng.2015.02.005.

Li, L., Liu, Y., Yuan, Z., Gao, Y., 2018a. Wind field effect on the power generation and aerodynamic performance of offshore floating wind turbines. Energy 157, 379–390. https://doi.org/10.1016/j.energy.2018.05.183.

Li, L., Zhu, J., Ye, G., Feng, X., 2018b. Development of green ports with the consideration of coastal wave energy. Sustainability (Switzerland). https://doi.org/10.3390/su10114270.

Li, X., Peng, Y., Wang, W., Huang, J., Liu, H., Song, X., Bing, X., 2019. A method for optimizing installation capacity and operation strategy of a hybrid renewable energy system with offshore wind energy for a green container terminal. Ocean Eng. 186, 106125. https://doi.org/10.1016/j.oceaneng.2019.106125.

Li, H., Guedes Soares, C., Huang, H.-Z., 2020. Reliability analysis of a floating offshore wind turbine using Bayesian Networks. Ocean Eng. 217, 107827. https://doi.org/10.1016/j.oceaneng.2020.107827.

Li, Z., Xu, Y., Fang, S., Zheng, X., Feng, X., 2020. Robust coordination of a hybrid AC/DC multi-energy ship microgrid with flexible voyage and thermal loads. IEEE Trans. Smart Grid 11, 2782–2793.

Lim, S., Pettit, S., Abouarghoub, W., Beresford, A., 2019. Port sustainability and performance: a systematic literature review. Transport. Res. Transport Environ. 72, 47–64. https://doi.org/10.1016/j.trd.2019.04.009.

Lindstad, H., 2013. Strategies and Measures for Reducing Maritime CO_2 Emissions.

Lindstad, E., Rialland, A., 2020. LNG and cruise ships, an easy way to Fulfil regulations—versus the need for reducing GHG emissions. Sustainability 12, 2080.

Lindstad, H.E., Sandaas, I., 2016. Emission and fuel reduction for offshore support vessels through hybrid technology. J. Ship Prod. Des. 32, 195–205.

Lindstad, H., Verbeek, R., Blok, M., van Zyl, S., Hübscher, A., Kramer, H., Purwanto, J., Ivanova, O., Boonman, H., 2015. GHG Emission Reduction Potential of EU-Related Maritime Transport and on its Impacts. European Commission, CLIMA. B.

Lindstad, E., Eskeland, G.S., Rialland, A., Valland, A., 2020. Decarbonizing maritime transport: the importance of engine technology and regulations for LNG to serve as a transition fuel. Sustainability 12, 8793.

Lion, S., Vlaskos, I., Taccani, R., 2020. A review of emissions reduction technologies for low and medium speed marine Diesel engines and their potential for waste heat recovery. Energy Convers. Manag. 207, 112553.

Lipsith, G., 2019. Is Methanation the Future of Ship Fuel? [WWW Document].

Lirn, T., Jim Wu, Y., Chen, Y.J., 2013. Green performance criteria for sustainable ports in Asia. Int. J. Phys. Distrib. Logist. Manag. 43, 427–451. https://doi.org/10.1108/IJPDLM-04-2012-0134.

Liu, C., Gong, B., 2010. Analysis of energy-saving measures in ports. In: 2010 Asia-Pacific Power and Energy Engineering Conference. IEEE, pp. 1–4. https://doi.org/10.1109/APPEEC.2010.5449395.

Liu, J., Song, R., Nasreen, S., Hoang, A.T., 2019. Analysis of the complementary property of solar energy and thermal power based on coupling model. Nat. Environ. Pollut. Technol. 18.

Lloyd's Register, UMAS, 2018. Zero-Emission Vessels 2030 . How Do We Get There? Lloyds Register.

López-Aparicio, S., Tønnesen, D., Thanh, T.N., Neilson, H., 2017. Shipping emissions in a nordic port: assessment of mitigation strategies. Transportation research Part D: transport and environment. https://doi.org/10.1016/j.trd.2017.04.021.

Lowell, D., Wang, H., Lutsey, N., 2013. Assessment of the Fuel Cycle Impact of Liquefied Natural Gas as Used in International Shipping. The International Council on Clean Transportation.

Lu, R., Ringsberg, J.W., 2019. Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology. Ships and Offshore Structures. https://doi.org/10.1080/17445302.2019.1612544.

Luo, X., Wang, M., 2017. Study of solvent-based carbon capture for cargo ships through process modelling and simulation. Appl. Energy. https://doi.org/10.1016/j.apenergy.2017.03.027.

Manolis, N., Ahmad, I., Fotios, K., Palensky, P., Gawlik, W., 2017. MAS based demand response application in port city using reefers. In: Communications in Computer and Information Science. https://doi.org/10.1007/978-3-319-60285-1_31.

T. Maritime Knowledge Centre, T., 2017. Framework CO2 Reduction in Shipping. Maritime Knowledge Centre, TNO and TU, Delft, The Netherlands.

McPhail, S.J., Aarva, A., Devianto, H., Bove, R., Moreno, A., 2011. SOFC and MCFC: commonalities and opportunities for integrated research. Int. J. Hydrogen Energy 36, 10337–10345.

MedMaritime SMART, P.O.R.T., 2016. Action Plan towards the Smart Port Concept in the Mediterranean Area.

Melikoglu, M., 2018. Current status and future of ocean energy sources: a global review. Ocean Eng. https://doi.org/10.1016/j.oceaneng.2017.11.045.

Mellin, A., Rydhed, H., 2011. Swedish ports' attitudes towards regulations of the shipping sector's emissions of CO 2. Marit. Pol. Manag. 38, 437–450. https://doi.org/10.1080/03088839.2011.588261.

Merk, O., 2013. The Competitiveness of Global Port-Cities: Synthesis Report. OECD Regional Development Working Papers.

Merk, O., 2014a. Shipping Emissions in Ports. The International Transport Forum's Discussion Paper.

Merk, O., 2014b. Shipping Emissions in Ports. International Transport Forum Discussion Papers.

Metz, B., Davidson, O., De Coninck, H., 2005. Carbon Dioxide Capture and Storage: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Misra, A., Panchabikesan, K., Gowrishankar, S.K., Ayyasamy, E., Ramalingam, V., 2017a. GHG emission accounting and mitigation strategies to reduce the carbon footprint in conventional port activities–a case of the Port of Chennai. Carbon Manag. 8, 45–56.

Misra, A., Venkataramani, G., Gowrishankar, S., Ayyasam, E., Ramalingam, V., 2017b. Renewable energy based smart microgrids—a pathway to green port development. Strat. Plann. Energy Environ. 37, 17–32.

Mitzinneck, B.C., Besharov, M.L., 2019. Managing value tensions in collective social entrepreneurship: the role of temporal, structural, and collaborative compromise. J. Bus. Ethics 159, 381–400. https://doi.org/10.1007/s10551-018-4048-2.

Mohammadi, A., Shioji, M., Nakai, Y., Ishikura, W., Tabo, E., 2007. Performance and combustion characteristics of a direct injection SI hydrogen engine. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2006.06.005.

Mondragon, A.E.C., Coronado, E.S., Mondragon, C.E.C., 2015. Defining a convergence network platform framework for smart grid and intelligent transport systems. Energy 89, 402–409.

Moon, D.S.H., Woo, J.K., Kim, T.G., 2018. Green ports and economic opportunities. In: Corporate Social Responsibility in the Maritime Industry. Springer, pp. 167–184.

Murugesan, P., Hoang, A.T., Venkatesan, E.P., Kumar, D.S., Balasubramanian, D., Le, A.T., 2021. Role of hydrogen in improving performance and emission characteristics of homogeneous charge compression ignition engine fueled with graphite oxide nanoparticle-added microalgae biodiesel/diesel blends. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2021.08.107.

Netherlands, C., 2017. Ship 2040: Pioneers of the Maritime Sector. MVO Nederland, Utrecht, the Netherlands.

Nguyen, X.P., Hoang, A.T., 2020. The flywheel energy storage system: an effective solution to accumulate renewable energy. In: 2020 6th International Conference on Advanced Computing and Communication Systems (ICACCS), pp. 1322–1328. https://doi.org/10.1109/ICACCS48705.2020.9074469.

Nguyen, H.P., Hoang, A.T., Nizetic, S., Nguyen, X.P., Le, A.T., Luong, C.N., Chu, V.D., Pham, V.V., 2020. The electric propulsion system as a green solution for management strategy of CO2 emission in ocean shipping: a comprehensive review. Int. Trans. Electr. Energy Syst., e12580 https://doi.org/10.1002/2050-7038.12580.

Niu, W., Huang, X., Yuan, F., Schofield, N., Xu, L., Chu, J., Gu, W., 2016. Sizing of energy system of a hybrid lithium battery RTG crane. IEEE Trans. Power Electron. 32, 7837–7844.

OECD, 2018. Decarbonising maritime transport. Pathways to zero-carbon shipping by 2035. Int. Transport For.

Office of energy efficiency & renewable energy, n.d. Fuel cells [WWW Document]. URL. https://www.energy.gov/eere/fuelcells/fuel-cells.

Ohashi, I., 2015. Dual-fuel marine engine (highly reliable environmentally friendly engine). YANMAR Tech. Rev.

Ölçer, A.I., Ong, H.C., Hoang, A.T., Nizetic, S., 2021. Synthesis pathway and combustion mechanism of a sustainable biofuel 2,5-Dimethylfuran: progress and prospective. Fuel 286, 119337. https://doi.org/10.1016/j.fuel.2020.119337.

Othman, M., Anvari-Moghaddam, A., Ahamad, N., Chun-Lien, S., Guerrero, J.M., 2018a. Scheduling of power generation in hybrid shipboard microgrids with energy storage systems. In: 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe). IEEE, pp. 1–6.

Othman, M., Su, C.-L., Anvari-Moghaddam, A., Guerrero, J.M., Kifune, H., Teng, J.-H., 2018b. Scheduling of power generations for energy saving in hybrid AC/DC shipboard microgrids. In: 2018 IEEE Industry Applications Society Annual Meeting (IAS). IEEE, pp. 1–7.

Ovrum, E., 2012. Shipping industry eyeing hydrogen fuel cells as possible pathway to emissions reduction; work by Germanischer Lloyd and DNV [WWW Document]. URL. https://www.greencarcongress.com/2012/09/h2shipping-20120907.html.

Pan, H., Pournazeri, S., Princevac, M., Miller, J.W., Mahalingam, S., Khan, M.Y., Jayaram, V., Welch, W.A., 2014. Effect of hydrogen addition on criteria and greenhouse gas emissions for a marine diesel engine. Int. J. Hydrogen Energy 39, 11336–11345.

Papaioannou, V., Pietrosanti, S., Holderbaum, W., Becerra, V.M., Mayer, R., 2017. Analysis of energy usage for RTG cranes. Energy 125, 337–344.

Parise, G., Honorati, A., 2014. Port cranes with energy balanced drive. In: 2014 AEIT Annual Conference - from Research to Industry: the Need for a More Effective Technology Transfer, AEIT. https://doi.org/10.1109/AEIT.2014.7002047, 2015.

Parise, G., Honorati, A., Parise, L., Martirano, L., 2015a. Near zero energy load systems: the special case of port cranes. In: 2015 IEEE/IAS 51st Industrial and Commercial Power Systems Technical Conference, I and CPS 2015. https://doi.org/10.1109/ICPS.2015.7266430.

Parise, G., Parise, L., Martirano, L., Chavdarian, P., Ben Su, C.-L., Ferrante, A., 2015b. Wise port and business energy management: port facilities, electrical power distribution. IEEE Trans. Ind. Appl. 52, 18–24.

Parise, G., Parise, L., Pepe, F.M., Ricci, S., Su, C.L., Chavdarian, P., 2016. Innovations in a container terminal area and electrical power distribution for the service continuity. In: 2016 IEEE/IAS 52nd Industrial and Commercial Power Systems Technical Conference (I&CPS). IEEE, pp. 1–6.

Parise, G., Parise, L., Malerba, A., Pepe, F.M., Honorati, A., Chavdarian, P. Ben, 2016a. Comprehensive peak-shaving solutions for port cranes. IEEE Trans. Ind. Appl. 53, 1799–1806.

Parise, G., Parise, L., Martirano, L., Chavdarian, P., Ben Su, C.L., Ferrante, A., 2016b. Wise port and business energy management: port facilities, electrical power distribution. In: IEEE Transactions on Industry Applications. https://doi.org/10.1109/TIA.2015.2461176.

Pavlic, B., Cepak, F., Sucic, B., Peckaj, M., Kandus, B., 2014. Sustainable port infrastructure, practical implementation of the green port concept. Therm. Sci. 18, 935–948. https://doi.org/10.2298/TSCI1403935P.

Payne, R., Love, J., Kah, M., 2009. Generating electricity at 60% electrical efficiency from 1-2 kWe SOFC products. ECS Trans. 25, 231.

Peng, Y., Wang, W., Song, X., Zhang, Q., 2016. Optimal allocation of resources for yard crane network management to minimize carbon dioxide emissions. J. Clean. Prod. 131, 649–658.

Peng, Y., Li, X., Wang, W., Wei, Z., Bing, X., Song, X., 2019. A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective. Ocean Coast Manag. https://doi.org/10.1016/j.ocecoaman.2018.10.007.

Persson, U., Olofsson, W., 2017. Ports of Stockholm Commits to Photovoltaic Systems.

Petersen, Michael, Eastern, A., 2019. LPG as Future Bunker Fuel.

Petzold, A., Lauer, P., Fritsche, U., Hasselbach, J., Lichtenstern, M., Schlager, H., Fleischer, F., 2011. Operation of marine diesel engines on biogenic fuels: modification of emissions and resulting climate effects. Environ. Sci. Technol. https://doi.org/10.1021/es2021439.

Pfenninger, S., Staffell, I., 2016. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy. https://doi.org/10.1016/j.energy.2016.08.060.

Pham, V.V., Hoang, A.T., 2019. Technological perspective for reducing emissions from marine engines. Int. J. Adv. Sci. Eng. Inf. Technol. 9, 1989–2000.

Pham, V.V., Hoang, A.T., 2020. Analyzing and selecting the typical propulsion systems for ocean supply vessels. In: 2020 6th International Conference on Advanced Computing and Communication Systems, ICACCS. https://doi.org/10.1109/ICACCS48705.2020.9074276, 2020.

Pham, V.V., Hoang, A.T., Do, H.C., 2020. Analysis and evaluation of database for the selection of propulsion systems for tankers. In: INTERNATIONAL CONFERENCE ON EMERGING APPLICATIONS IN MATERIAL SCIENCE AND TECHNOLOGY. https://doi.org/10.1063/5.0007655. ICEAMST 2020.

PIANC, 2019a. Renewables and Energy Efficiency for Maritime Ports - MarCom WG Report N° 159-2019. The World Association for Waterborne Transport Infrastructure. PIANC Maritime Navigation Commission, Brussels: Belguim.

PIANC, 2019b. Renewables and Energy Efficiency for Maritime Ports - MarCom WG Report N° 159-2019. The World Association for Waterborne Transport Infrastructure. Brussels, Belguim.

Pietrosanti, S., Harrison, I., Luque, A., Holderbaum, W., Becerra, V.M., 2016a. Net energy savings in Rubber Tyred Gantry cranes equipped with an active front end. In: 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC). IEEE, pp. 1–5.

Pietrosanti, S., Holderbaum, W., Becerra, V.M., 2016b. Optimal power management strategy for energy storage with stochastic loads. Energies. https://doi.org/10.3390/en9030175.

Pitpoint clean fuels, 2021. The Growing Role of Sustainability [WWW Document].

PLA, 2016. Hydrogen and Fuel Cells in the Ports Workshop Report, Port of Los Angeles Technical Report August 2016.

PLB, 2008. Liquefied Natural Gas (LNG) Yard Hostler Demonstration and Commercialization Project Final Report, Port of Long Beach Technical Report August 2008.

PORT, M.S., 2016. Action Plan towards the Smart Port Concept in the Mediterranean Area.

Port of Rotterdam, 2017. Port Authority to Explore Geothermal Options in Port Area [WWW Document].

Pospiech, P., 2014. FCS ALTSERWASSER - RIVERBOAT, HAMBURG [WWW Document].

Poulsen, R.T., Ponte, S., Sornn-Friese, H., 2018. Environmental upgrading in global value chains: the potential and limitations of ports in the greening of maritime transport. Geoforum 89, 83–95. https://doi.org/10.1016/j.geoforum.2018.01.011.

Pratt, J.W.J., Harris, A.P.A.A.P., 2013. Vessel Cold-Ironing Using a Barge Mounted PEM Fuel Cell : Project Scoping and Feasibility. Eere.Energy.Gov.

Prousalidis, J., Lyridis, D.V., Dallas, S., Papaleonidas, C., Mitrou, P., Vergetis, E., Vaimaki, E., Aggelopoulos, S., Kourmpelis, T., Georgiou, V., 2017. The ports as smart micro-grids: development perspectives. Proc. HAEE 12–16.

Psaraftis, H.N., 2016. Green maritime transportation: market based measures. In: Green Transportation Logistics. Springer, pp. 267–297.

Puig, M., Michail, A., Wooldridge, C., Darbra, R.M., 2017. Benchmark dynamics in the environmental performance of ports. Mar. Pollut. Bull. 121, 111–119. https://doi.org/10.1016/j.marpolbul.2017.05.021.

Qiu, Y., Yuan, C., Sun, Y., 2015. Review on the application and research progress of photovoltaics-ship power system. In: 2015 International Conference on Transportation Information and Safety (ICTIS). IEEE, pp. 523–527.

Ramos, V., Carballo, R., Álvarez, M., Sánchez, M., Iglesias, G., 2014. A port towards energy self-sufficiency using tidal stream power. Energy 71, 432–444. https://doi.org/10.1016/j.energy.2014.04.098.

Raucci, C., Calleya, J., Suarez de la Fuente, S., Pawling, R., 2015. Hydrogen on board ship: a first analysis of key parameters and implications. In: International Conference on Shipping in Changing Climates.

Rehbein, M.C., Meier, C., Eilts, P., Scholl, S., 2019. Mixtures of ammonia and organic solvents as alternative fuel for internal combustion engines. Energy Fuel. https://doi.org/10.1021/acs.energyfuels.9b01450.

Rehmatulla, N., Parker, S., Smith, T., Stulgis, V., 2017. Wind technologies: opportunities and barriers to a low carbon shipping industry. Mar. Pol. https://doi.org/10.1016/j.marpol.2015.12.021.

Reiter, A.J., Kong, S.C., 2008. Demonstration of compression-ignition engine combustion using ammonia in reducing greenhouse gas emissions. Energy Fuel. https://doi.org/10.1021/ef800140f.

Reiter, A.J., Kong, S.C., 2011. Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. Fuel. https://doi.org/10.1016/j.fuel.2010.07.055.

Righi, M., Klinger, C., Eyring, V., Hendricks, J., Lauer, A., Petzold, A., 2011. Climate impact of biofuels in shipping: global model studies of the aerosol indirect effect. Environ. Sci. Technol. https://doi.org/10.1021/es1036157.

Rijsenbrij, J.C., Wieschemann, A., 2011. Sustainable container terminals: a design approach. In: Handbook of Terminal Planning. Springer, pp. 61–82.

Roh, G., Kim, H., Jeon, H., Yoon, K., 2019. Fuel consumption and CO2 emission reductions of ships powered by a fuel-cell-based hybrid power source. J. Mar. Sci. Eng. 7, 230.

Rosa-Santos, P., Taveira-Pinto, F., Clemente, D., Cabral, T., Fiorentin, F., Belga, F., Morais, T., 2019. Experimental study of a hybrid wave energy converter integrated in a harbor breakwater. J. Mar. Sci. Eng. 7, 33. https://doi.org/10.3390/jmse7020033.

Rosli, R.E., Sulong, A.B., Daud, W.R.W., Zulkifley, M.A., Husaini, T., Rosli, M.I., Majlan, E.H., Haque, M.A., 2017. A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system. Int. J. Hydrogen Energy 42, 9293–9314.

Rotterdam, P. of, 2016. Smart Port [WWW Document].

Roy, M.M., Tomita, E., Kawahara, N., Harada, Y., Sakane, A., 2011. Comparison of performance and emissions of a supercharged dual-fuel engine fueled by hydrogen and hydrogen-containing gaseous fuels. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2011.03.070.

S, N.E., 2017. Another Ferry Contract for NES.

Sadek, I., Elgohary, M., 2020. Assessment of renewable energy supply for green ports with a case study. Environ. Sci. Pollut. Control Ser. 27, 5547–5558.

Saharidis, G.K.D., Konstantzos, G.E., 2018. Critical overview of emission calculation models in order to evaluate their potential use in estimation of Greenhouse Gas emissions from in port truck operations. J. Clean. Prod. 185, 1024–1031. https://doi.org/10.1016/j.jclepro.2018.02.036.

Salem, A.A., Seddiek, I.S., 2016. Techno-Economic Approach to Solar Energy Systems Onboard Marine Vehicles. Polish Maritime Research. https://doi.org/10.1515/pomr-2016-0033.

Salvi, B.L., Subramanian, K.A., 2015. Sustainable development of road transportation sector using hydrogen energy system. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2015.07.030.

Sapra, H., Stam, J., Reurings, J., van Biert, L., van Sluijs, W., de Vos, P., Visser, K., Vellayani, A.P., Hopman, H., 2021. Integration of solid oxide fuel cell and internal combustion engine for maritime applications. Appl. Energy 281, 115854.

Saravanan, N., Nagarajan, G., 2008. An experimental investigation of hydrogen-enriched air induction in a diesel engine system. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2007.12.065.

Schinas, O., Butler, M., 2016. Feasibility and commercial considerations of LNG-fueled ships. Ocean Eng. https://doi.org/10.1016/j.oceaneng.2016.04.031.

Schmidt, J., Meyer-Barlag, C., Eisel, M., Kolbe, L.M., Appelrath, H.-J., 2015. Using battery-electric AGVs in container terminals — assessing the potential and optimizing the economic viability. Res. Transport. Bus. Manag. 17, 99–111. https://doi.org/10.1016/j.rtbm.2015.09.002.

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., Few, S., 2017a. Future cost and performance of water electrolysis: an expert elicitation study. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2017.10.045.

Schmidt, O., Hawkes, A., Gambhir, A., Staffell, I., 2017b. The future cost of electrical energy storage based on experience rates. Nat. Energy. https://doi.org/10.1038/nenergy.2017.110.

Schmitz, M., Madlener, R., 2015. Economic viability of kite-based wind energy powerships with CAES or hydrogen storage. Energy Proc. 75, 704–715.

Schönborn, A., 2021. Aqueous solution of ammonia as marine fuel. Proc. IME M J. Eng. Marit. Environ. 235, 142–151.

Schøyen, H., Steger-Jensen, K., 2017. Nuclear propulsion in ocean merchant shipping: the role of historical experiments to gain insight into possible future applications. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.05.163.

Sciberras, E.A., Zahawi, B., Atkinson, D.J., 2015a. Electrical characteristics of cold ironing energy supply for berthed ships. Transport. Res. Transport Environ. 39, 31–43.

Sciberras, E.A., Zahawi, B., Atkinson, D.J., Juandó, A., 2015b. Electric auxiliary propulsion for improved fuel efficiency and reduced emissions. Proc. IME M J. Eng. Marit. Environ. 229, 36–44.

Sciberras, E.A., Zahawi, B., Atkinson, D.J., Juandó, A., Sarasquete, A., 2016. Cold Ironing and Onshore Generation for Airborne Emission Reductions in Ports. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment. https://doi.org/10.1177/1475090214532451.

SEA, S., 2014. Energy-Efficient and Adaptive Port Terminals. International congress on energy and the environment, Valencia port.

Seo, Y., Lee, S., yeob, Kim, J., Huh, C., Chang, D., 2017. Determination of optimal volume of temporary storage tanks in a ship-based carbon capture and storage (CCS) chain using life cycle cost (LCC) including unavailability cost. Int. J. Greenh. Gas Control. https://doi.org/10.1016/j.ijggc.2017.06.017.

Sharafian, A., Blomerus, P., Mérida, W., 2019. Natural gas as a ship fuel: assessment of greenhouse gas and air pollutant reduction potential. Energy Pol. 131, 332–346.

Siemens, A.G., 2008. Saving fuel using ECO-RTG hybrid drive system. In: Proceedings of the TOC Asia Conference.

Siemens, 2017. Innovative Power Distribution for Ports & Harbors Concept for Profitable and Safe Electric Power Distribution Technical Report 2017.

Siemens, A.G., 2017. Innovative Power Distribution for Ports and Harbors. Erlangen, Germany.

Sifakis, N., Tsoutsos, T., 2020. Planning zero-emissions ports through the nearly Zero Energy Port concept. J. Clean. Prod. 125448.

Sim, J., 2018. A carbon emission evaluation model for a container terminal. J. Clean. Prod. 186, 526–533. https://doi.org/10.1016/j.jclepro.2018.03.170.

Singh, B., Guldhe, A., Rawat, I., Bux, F., 2014. Towards a sustainable approach for development of biodiesel from plant and microalgae. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.067.

Smith, T., Newton, P., Winn, G., Grech La Rosa, A., 2013. Analysis techniques for evaluating the fuel savings associated with wind assistance. In: Low Carbon Shipping Conference.

Smith, T.W.P., Raucci, C., Sabio, N., Argyros, D., 2014. Global Marine Fuel Trends 2030.

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., Hoen, M.A., 2015. Third IMO Greenhouse Gas Study 2014, Executive Summary and Final Report. IMO.

Smith, T., Raucci, C., Hosseinloo, S.H., Rojon, I., Calleya, J., Fuente, S.D., La Wu, P., Palmer, K., 2016. CO2 Emissions from International Shipping: Possible Reduction Targets and Their Associated Pathways. UMAS - UCL Energy Institute.

Solem, S., Fagerholt, K., Erikstad, S.O., Patricksson, Ø., 2015. Optimization of diesel electric machinery system configuration in conceptual ship design. J. Mar. Sci. Technol. 20, 406–416.

SPBP, 2017. San Pedro Bay Ports Clean Air Action Plan Update. Port of Los Angeles and the Port of Long Beach.

Speirs, J., Balcombe, P., Johnson, E., Martin, J., Brandon, N., Hawkes, A., 2018. A greener gas grid: what are the options. Energy Pol. 118, 291–297.

Spengler, T., Wilmsmeier, G., 2018. Sustainable performance and benchmarking in container terminals-the energy dimension. In: Green Ports: Inland and Seaside Sustainable Transportation Strategies. https://doi.org/10.1016/B978-0-12-814054-3.00007-4.

Spiropoulou, I., Karamanis, D., Kehayias, G., 2015. Offshore wind farms development in relation to environmental protected areas. Sustain. Cities Soc. 14, 305–312. https://doi.org/10.1016/j.scs.2014.05.006.

Staffell, I., Pfenninger, S., 2016. Using bias-corrected reanalysis to simulate current and future wind power output. Energy. https://doi.org/10.1016/j.energy.2016.08.068.

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P.E., Ekins, P., Shah, N., Ward, K.R., 2019. The role of hydrogen and fuel cells in the global energy system. Energy Environ. Sci. https://doi.org/10.1039/c8ee01157e.

Stephenson, A.L., MacKay, D.J., 2014. Life Cycle Impacts of Biomass Electricity in 2020. Department of Energy and Climate Change Technical Report.

Stolz, B., Held, M., Georges, G., Boulouchos, K., 2021. The CO2 reduction potential of shore-side electricity in Europe. Appl. Energy 285, 116425.

STP, 2015. Smart, Energy Efficient and Adaptive Port Terminals (Sea Terminals), SEA TERMINALS Project Technical Report December 2015.

Styhre, L., Winnes, H., Black, J., Lee, J., Le-Griffin, H., 2017. Greenhouse gas emissions from ships in ports – case studies in four continents. Transportation Research Part D: transport and Environment. https://doi.org/10.1016/j.trd.2017.04.033.

Subramanian, M., Hoang, A.T., Kalidasan, B., Nižetić, S., Soloman, J.M., Balasubramanian, D., Subramaniyan, C., Thenmozhi, G., Metghalchi, H., Nguyen, X. P., 2021. A technical review on composite phase change material based secondary assisted battery thermal management system for electric vehicles. J. Clean. Prod. 322, 129079 https://doi.org/10.1016/j.jclepro.2021.129079.

Svanberg, M., Ellis, J., Lundgren, J., Landälv, I., 2018. Renewable methanol as a fuel for the shipping industry. Renew. Sustain. Energy Rev. 94, 1217–1228.

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., Johnson, H., 2014. Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model. Environ. Sci. Technol. 48, 12986–12993.

Tan, K.H., Yap, F.F., 2017. Reducing Fuel Consumption Using Flywheel Battery Technology for Rubber Tyred Gantry Cranes in Container Terminals.

Tan, Y., Nookuea, W., Li, H., Thorin, E., Yan, J., 2016. Property impacts on carbon capture and storage (CCS) processes: a review. Energy Convers. Manag. https://doi.org/10.1016/j.enconman.2016.03.079.

Tang, H.S., Qu, K., Chen, G.Q., Kraatz, S., Aboobaker, N., Jiang, C.B., 2014. Potential sites for tidal power generation: a thorough search at coast of New Jersey, USA. Renew. Sustain. Energy Rev. 39, 412–425.

Tang, R., Li, X., Lai, J., 2018a. A novel optimal energy-management strategy for a maritime hybrid energy system based on large-scale global optimization. Appl. Energy. https://doi.org/10.1016/j.apenergy.2018.06.092.

Tang, R., Wu, Z., Li, X., 2018b. Optimal operation of photovoltaic/battery/diesel/cold-ironing hybrid energy system for maritime application. Energy 162, 697–714.

Tao, L., Guo, H., Moser, J., Mueller, H., 2014. A roadmap towards smart grid enabled harbour terminals. In: CIRED Workshop-Rome. Citeseer, pp. 528–542.

Tatiana, E., 2012. Status Quo of Use of Hydrogen as Fuel in Port, Shipping and Transport Industrys, Green Efforts Project Technical Report 2012.

Technology, S., 2010. Viking Lady Offshore Supply Vessel.

Technology and Applications of Autonomous Underwater Vehicles, 2002. Technology and applications of autonomous underwater vehicles. https://doi.org/10.1201/9780203522301.

Teeter, J.L., Cleary, S.A., 2014. Decentralized Oceans: Sail-Solar Shipping for Sustainable Development in SIDS. Natural Resources Forum. https://doi.org/10.1111/1477-8947.12048.

The Motorways of the Sea Digital Multi-Channel Platform, 2015. Smart Port.

The WLPGA, 2017. LPG for Marine Engines, the Marine Alternative Fuel. Charles de Gaulle, France.

Thomson, H., Corbett, J.J., Winebrake, J.J., 2015. Natural gas as a marine fuel. Energy Pol. https://doi.org/10.1016/j.enpol.2015.08.027.

Tillig, F., Mao, W., Ringsberg, J., 2015. Systems Modelling for Energy-Efficient Shipping. Chalmers University of Technology.

Tran, T.K., 2012. Study of Electrical Usage and Demand at the Container Terminal. Deakin University.

Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., Wood, R., 2014. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Appl. Energy. https://doi.org/10.1016/j.apenergy.2013.07.026.

Tronstad, T., Åstrand, H.H., Haugom, G.P., Langfeldt, L., 2017. Study on the Use of Fuel Cells in Shipping, Report to European Maritime Safety Agency by DNV GL; DNV GL. Oslo, Norway.

TSCNET Services, 2017. Port of Rotterdam Joins Power Hub Consortium [WWW Document].

Tsekouras, G.J., Kanellos, F.D., 2016. Ship to shore connection - reliability analysis of ship power system. In: Proceedings - 2016 22nd International Conference on Electrical Machines, ICEM. https://doi.org/10.1109/ICELMACH.2016.7732944, 2016.

Tseng, P.H., Pilcher, N., 2015. A study of the potential of shore power for the port of Kaohsiung, Taiwan: to introduce or not to introduce? Research in Transportation Business and Management. https://doi.org/10.1016/j.rtbm.2015.09.001.

Tzannatos, E., 2010. Cost Assessment of Ship Emission Reduction Methods at Berth: the Case of the Port of Piraeus, Greece, vol. 37. Maritime Policy & Management, pp. 427–445. https://doi.org/10.1080/03088839.2010.486655.

Uche-Soria, M., Rodríguez-Monroy, C., 2019. Solutions to marine pollution in canary islands' ports: alternatives and optimization of energy management. Resources 8, 59. https://doi.org/10.3390/resources8020059.

UNCTAD, 2019. Review of maritime transport 2019. In: International Economic Integration. Oldenbourg Verlag, München. https://doi.org/10.1524/9783486599381.35.

Union, E., 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union 5, 2009.

Ushakov, S., Stenersen, D., Einang, P.M., 2019. Methane slip from gas fuelled ships: a comprehensive summary based on measurement data. J. Mar. Sci. Technol. https://doi.org/10.1007/s00773-018-00622-z.

Vakili, S., Ölçer, A.I., Schönborn, A., Ballini, F., Hoang, A.T., 2022. Energy-related clean and green framework for shipbuilding community towards zero-emissions: a strategic analysis from concept to case study. Int. J. Energy Res. https://doi.org/10.1002/er.7649.

Valera-Medina, A., Pugh, D.G., Marsh, P., Bulat, G., Bowen, P., 2017. Preliminary study on lean premixed combustion of ammonia-hydrogen for swirling gas turbine combustors. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2017.08.028.

Van Biert, L., Godjevac, M., Visser, K., Aravind, P.V., 2016. A review of fuel cell systems for maritime applications. J. Power Sources 327, 345–364.

van den Akker, J., 2017. Carbon Capture Onboard LNG-Fueled Vessels: A Feasibility Study.

Van Duin, J.H.R., Geerlings, H., 2011. Estimating CO 2 footprints of container terminal port-operations. Int. J. Sustain. Dev. Plann. 6, 459–473. https://doi.org/10.2495/SDP-V6-N4-459-473.

Van Duin, J.H.R., Geerlings, H., Froese, J., Negenborn, R.R., 2017. Towards a method for benchmarking energy consumption at terminals: in search of performance improvement in yard lighting. Int. J. Transport Dev. Integr. 1, 212–224.

Verbeeck, J., Kuijper, F., Wellbrock, P., Gray, D., Skog, D., Schreuder, J., Kooistra, S., 2014. The E-Harbours Journey: Point of Arrival; Smart Energy Networks in the North Sea Region.

Vicinanza, D., Lauro, E. Di, Contestabile, P., Gisonni, C., Lara, J.L., Losada, I.J., 2019. Review of innovative harbor breakwaters for wave-energy conversion. Journal of waterway, port, coastal, and ocean engineering. https://doi.org/10.1061/(asce)ww.1943-5460.0000519.

Villalba, G., Gemechu, E.D., 2011. Estimating GHG emissions of marine ports—the case of Barcelona. Energy Pol. 39, 1363–1368.

Villalba-Herreros, A., Gómez, M.R., Morán, J.L., Leo, T.J., 2020. Emissions and noise reduction on-board an oceanographic vessel thanks to the use of proton-exchange membrane fuel cells. Proc. IME M J. Eng. Marit. Environ. 234, 298–310.

Vincent, R., 2014. American Association of Port Authorities Environmental Improvement Award Application Stakeholder Awareness, Education and Involvement Category Environmental Initiatives at Seaports Worldwide: A Snapshot of Best Practices White Paper Port of Portland.

Viola, I.M., Sacher, M., Xu, J., Wang, F., 2015. A numerical method for the design of ships with wind-assisted propulsion. Ocean Eng. https://doi.org/10.1016/j.oceaneng.2015.06.009.

Vo, S., Stahlbock, R., Steenken, D., 2004. Container terminal operation and operations research - a classification and literature review. Spectrum 26, 3–49. https://doi.org/10.1007/s00291-003-0157-z.

Vogler, F., Wursig, G., 2011. Fuel cells in maritime applications challenges, chances and experiences. In: The 4th International Conference on Hydrogen Safety (ICHS).

Wachsman, E.D., Lee, K.T., 2011. Lowering the temperature of solid oxide fuel cells. Science 334, 935–939.

Wang, S., Meng, Q., Sun, Z., 2013. Container routing in liner shipping. Transportation research Part E: logistics and transportation review. https://doi.org/10.1016/j.tre.2012.06.009.

Wang, Y., Ding, W., Dai, L., Hu, H., Jing, D., 2021. How would government subsidize the port on shore side electricity usage improvement? J. Clean. Prod. 278, 123893.

Wärtsila, 2009. Boosting Energy Efficiency: Energyefficiency Catalogue [WWW Document]. Energy Efficiency Catalogue/Ship Power R&D. Wärtsila.

Wei, H.L., Gu, W., Chu, J.X., 2019. The dynamic power control technology for the high power lithium battery hybrid rubber-tired gantry (RTG) crane. IEEE Trans. Ind. Electron. https://doi.org/10.1109/TIE.2018.2816011.

Weiss, C.V.C., Guanche, R., Ondiviela, B., Castellanos, O.F., Juanes, J., 2018. Marine renewable energy potential: a global perspective for offshore wind and wave exploitation. Energy Convers. Manag. 177, 43–54. https://doi.org/10.1016/j.enconman.2018.09.059.

Welaya, Y.M.A., El Gohary, M.M., Ammar, N.R., 2011. A comparison between fuel cells and other alternatives for marine electric power generation. Int. J. Nav. Archit. Ocean Eng. https://doi.org/10.3744/JNAOE.2011.3.2.141.

Wen, S., Lan, H., Hong, Y.Y., Yu, D.C., Zhang, L., Cheng, P., 2016. Allocation of ESS by interval optimization method considering impact of ship swinging on hybrid PV/diesel ship power system. Appl. Energy 175, 158–167. https://doi.org/10.1016/j.apenergy.2016.05.003.

Wen, B., Jin, Q., Huang, H., Tandon, P., Zhu, Y., 2017. Life cycle assessment of Quayside Crane: a case study in China. J. Clean. Prod. 148, 1–11. https://doi.org/10.1016/j.jclepro.2017.01.146.

Westlye, F.R., Ivarsson, A., Schramm, J., 2013. Experimental investigation of nitrogen based emissions from an ammonia fueled SI-engine. Fuel. https://doi.org/10.1016/j.fuel.2013.03.055.

Wilmsmeier, G., Spengler, T., 2016. Energy Consumption and Container Terminal Efficiency.

Winkel, R., Weddige, U., Johnsen, D., Hoen, V., Papaefthimiou, S., 2016. Shore side electricity in Europe: potential and environmental benefits. Energy Pol. https://doi.org/10.1016/j.enpol.2015.07.013.

Winnes, H., Styhre, L., Fridell, E., 2015. Reducing GHG emissions from ships in port areas. Res. Transport. Bus. Manag. https://doi.org/10.1016/j.rtbm.2015.10.008.

Wong, L.A., Ramachandaramurthy, V.K., Taylor, P., Ekanayake, J.B., Walker, S.L., Padmanaban, S., 2019. Review on the optimal placement, sizing and control of an energy storage system in the distribution network. J. Energy Storage 21, 489–504.

Woo, J.-K., Moon, D.S.H., Lam, J.S.L., 2018. The impact of environmental policy on ports and the associated economic opportunities. Transport. Res. Pol. Pract. 110, 234–242.

Wu, P., Bucknall, R., 2020. Hybrid fuel cell and battery propulsion system modelling and multi-objective optimisation for a coastal ferry. Int. J. Hydrogen Energy 45, 3193–3208.

Xiao, Q., Cao, J., Zhang, Y., Li, L., Xu, T., Yuan, W., 2020. The application of solar-to-thermal conversion phase change material in novel solar water heating system. Sol. Energy 199, 484–490. https://doi.org/10.1016/j.solener.2020.02.054.

Xing, H., Stuart, C., Spence, S., Chen, H., 2021. Fuel cell power systems for maritime applications: progress and perspectives. Sustainability 13, 1213.

Xu, G., Li, L., Yang, Y., Tian, L., Liu, T., Zhang, K., 2012. A novel CO2 cryogenic liquefaction and separation system. Energy. https://doi.org/10.1016/j.energy.2012.02.048.

Yang, Y.-C., 2017. Operating strategies of CO2 reduction for a container terminal based on carbon footprint perspective. J. Clean. Prod. 141, 472–480.

Yang, Y.C., 2017. Operating strategies of CO2 reduction for a container terminal based on carbon footprint perspective. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.09.132.

Yang, Y.-C., Chang, W.-M., 2013. Impacts of electric rubber-tired gantries on green port performance. Res. Transport. Bus. Manag. 8, 67–76.

Yang, Y.-C., Lin, C.-L., 2013. Performance analysis of cargo-handling equipment from a green container terminal perspective. Transport. Res. Transport Environ. 23, 9–11.

Yang, Y., Bremner, S., Menictas, C., Kay, M., 2018. Battery energy storage system size determination in renewable energy systems: a review. Renew. Sustain. Energy Rev. 91, 109–125.

Yarova, N., Vorkunova, O., Khoteyeva, N., 2017. Economic assessment of the alternative energy sources implementation for port enterprises. Econ. Ann. XXI https://doi.org/10.21003/ea.V166-09.

Yigit, K., Acarkan, B., 2018. A new electrical energy management approach for ships using mixed energy sources to ensure sustainable port cities. Sustain. Cities Soc. 40, 126–135.

Yiğit, K., Kökkülünk, G., Parlak, A., Karakaş, A., 2016. Energy cost assessment of shoreside power supply considering the smart grid concept: a case study for a bulk carrier ship. Marit. Pol. Manag. 43, 469–482.

Yuan, Y., Wang, J., Yan, X., Li, Q., Long, T., 2018. A design and experimental investigation of a large-scale solar energy/diesel generator powered hybrid ship. Energy 165, 965–978.

Yun, P.E.N.G., Xiangda, L.I., Wenyuan, W.A.N.G., Ke, L.I.U., Chuan, L.I., 2018. A simulation-based research on carbon emission mitigation strategies for green container terminals. Ocean Eng. 163, 288–298. https://doi.org/10.1016/j.oceaneng.2018.05.054.

Zamfirescu, C., Dincer, I., 2008. Using ammonia as a sustainable fuel. J. Power Sources. https://doi.org/10.1016/j.jpowsour.2008.02.097.

Zamfirescu, C., Dincer, I., 2009. Ammonia as a green fuel and hydrogen source for vehicular applications. Fuel Process. Technol. https://doi.org/10.1016/j.fuproc.2009.02.004.

Zhang, C., Xu, Y., Dong, Z.Y., 2019. Robustly coordinated operation of a multi-energy micro-grid in grid-connected and islanded modes under uncertainties. IEEE Trans. Sustain. Energy 11, 640–651.

Zhao, Nan, Schofield, N., Niu, Wangqiang, Suntharalingam, P., Zhang, Yaozhou, 2014. Hybrid power-train for port crane energy recovery. In: 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific). IEEE, pp. 1–6. https://doi.org/10.1109/ITEC-AP.2014.6941043.

Zhao, N., Schofield, N., Niu, W., 2016. Energy storage system for a port crane hybrid power-train. IEEE Trans. Transport. Electrif. https://doi.org/10.1109/TTE.2016.2562360.

Zhen, L., Shen, T., Wang, S., Yu, S., 2016. Models on ship scheduling in transshipment hubs with considering bunker cost. Int. J. Prod. Econ. https://doi.org/10.1016/j.ijpe.2015.12.008.

Zhou, P., Wang, H., 2014. Carbon capture and storage - solidification and storage of carbon dioxide captured on ships. Ocean Eng. https://doi.org/10.1016/j.oceaneng.2014.09.006.

Zhou, J.H., Cheung, C.S., Leung, C.W., 2014. Combustion, performance, regulated and unregulated emissions of a diesel engine with hydrogen addition. Appl. Energy. https://doi.org/10.1016/j.apenergy.2014.03.089.

Zhu, S., Zhang, K., Deng, K., 2020. A review of waste heat recovery from the marine engine with highly efficient bottoming power cycles. Renew. Sustain. Energy Rev. 120, 109611.

Zis, T.P.V., 2019. Prospects of cold ironing as an emissions reduction option. Transport. Res. Pol. Pract. https://doi.org/10.1016/j.tra.2018.11.003.

Zis, T., North, R.J., Angeloudis, P., Ochieng, W.Y., Bell, M.G.H., 2014. Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. Marit. Econ. Logist. 16, 371–398.