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REVIEW

Towards the application of renewable energy technologies in green ports: Technical and economic perspectives

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Abstract

With growing concerns over environmental degradation and climate change, the shipping industry is under increasing pressure to reduce its environmental impact. This has led to the development of green port initiatives in the field of maritime transport and logistics, which aim to promote sustainable practices and reduce the environmental footprint of ports and their operations. One of the key strategies for achieving this goal is the use of renewable energy technologies (RETs). This paper summarizes the potentials, challenges, and economic analysis of RETs applications in green ports, emphasizing those that require aquatic environments for operation, including floating photovoltaic systems, offshore wind turbines, and ocean energy. The paper investigates the concept of green ports and explores the feasibility of integrating RETs into these facilities. Also, the potential of the various RETs is presented in terms of technical and economic aspects and installed capacity. Additionally, due to high flexibility in electrical systems and compatibility with maritime transportation, the use of fuel cells in green ports has been discussed as a feasible solution for supplying power to ports (either as the primary or backup source). The findings of this study show that RETs can significantly contribute to achieving sustainable goals in the maritime industry and pave the way for the creation of more efficient and environmentally friendly ports.

1 | INTRODUCTION

The world is facing an imminent climate crisis due to the increase in greenhouse gas (GHG) emissions, which are primarily caused by the burning of fossil fuels. Ports are a vital part of the global transportation network, serving as a gateway for goods and passengers to travel across the world. They are crucial infrastructures for global trade and commerce and play a vital role in economic growth and development [1]. Ports have allocated about 80% of the global commerce volume and 70% of its economic value. There are over 2000 ports around the world that provide economic growth; however, they are also significant emitters of GHGs, with emissions from ships, cargo handling equipment, and other port-related activities contributing to air pollution and climate change [2, 3].

According to the International Maritime Organization (IMO) report, from 2012 to 2018, the GHG emissions from all forms of shipping - domestic, international, and fishing - have risen by 9.6%, from 977 million tonnes to 1,076 million tonnes. Specifically, in 2012, CO_2 emissions were 962 million tonnes, while in 2018, it increases by 9.3% (1,056 million tonnes) [4]. Figure 1 shows that 11% of GHG emission is related to the marine transportation sector. The target of IMO for 2050 is to decrease GHG emissions from international shipping by at least 50%, compared to 2008 levels [5]. To address this issue, green ports have emerged as a key initiative in the shipping industry that promote sustainable practices. Green ports are designed and operated to reduce environmental footprint by minimizing the use of fossil fuels, reducing emissions, and optimizing the use of energy and resources [6]. To achieve this goal, renewable energy technologies (RETs) can be integrated into ports to replace fossil fuel-based energy sources. RETs, such as solar, wind, and wave energy, have gained prominence in recent years due to their potential to provide a clean and sustainable source of energy. These technologies can reduce carbon emissions and

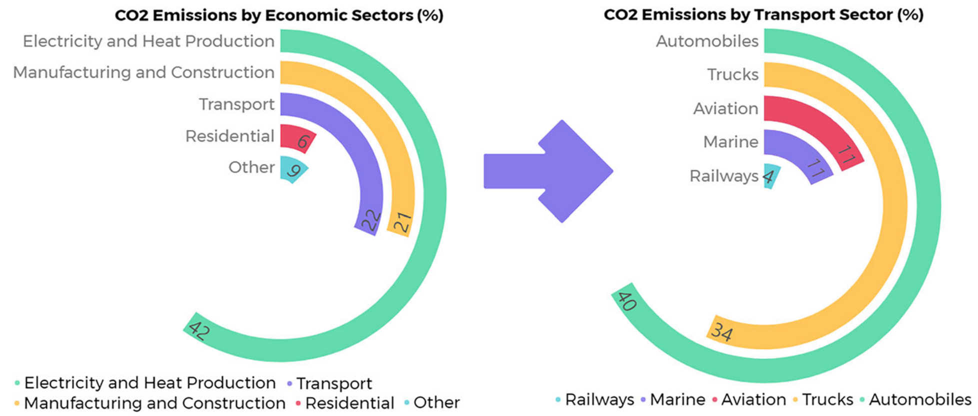

FIGURE 1 CO_2 emissions by economic sectors [8].

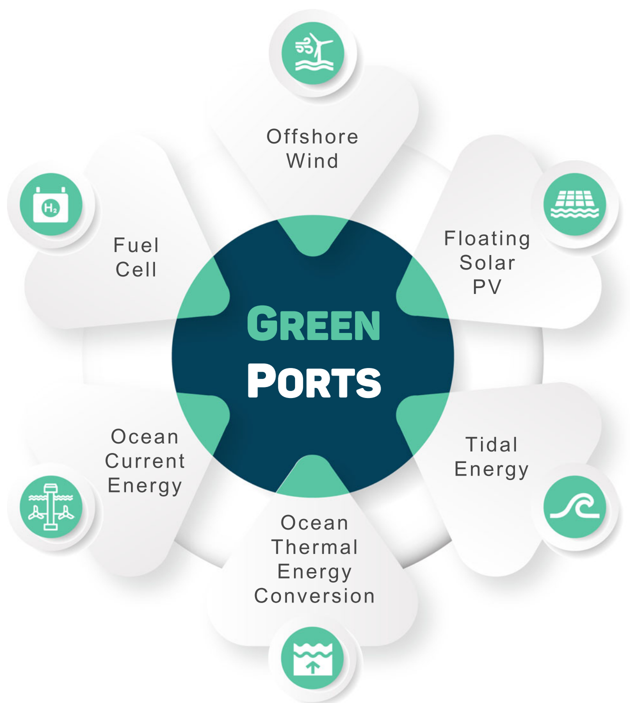

FIGURE 2 Various RETs in green ports.

improve air quality, making them ideal for use in green ports. Furthermore, RETs can provide energy security, reduce energy costs, and enhance the resilience of port operations [7].

In recent years, there has been a significant increase in the deployment of RETs in ports worldwide, with many port authorities and operators committing to achieving zero-emission goals. Many ports have implemented solar photovoltaic (PV) systems, wind turbines, and other RETs to reduce their carbon footprint and achieve sustainability goals. RETs have also been used to power electric vehicles and equipment, reducing emissions from port operations. Figure 2 shows the various RETs in green ports. However, implementing RETs in green ports poses several challenges, including high initial costs, limited space availability, and technical complexities. Additionally, the integration of RETs in ports requires careful planning and coordination between various stakeholders, including port authorities, operators, energy providers, and regulatory agencies.

This paper aims to summarize the application of RETs in green ports, highlighting the opportunities and challenges associated with their implementation. The paper explores the different types of RETs used in ports, their benefits, and the factors influencing their adoption. Additionally, this paper seeks to contribute to the knowledge base on RETs in green ports and inform future research in this area. The paper begins by providing a brief introduction to green ports and the role of RETs in achieving sustainability goals. Then, the various RETs that have been deployed in green ports, and their benefits and challenges are discussed. Moreover, an economic analysis is presented for various types of RET. Finally, the paper concludes by summarizing the key findings and discussing the prospects of RETs in green ports. By highlighting the potential of renewable energy technologies in reducing the environmental impact of port operations and achieving sustainability goals, the paper provides insights for port operators, policymakers, and researchers interested in promoting sustainable development in the maritime sector.

2 | GREEN PORTS

Ports are important gateways for international commerce. They also provide warehousing and packaging operations and are a hub for domestic transportation [9]. Therefore, ports can play a significant role in "green objectives". Ports are essential for the smooth functioning of global trade and commerce, providing a link between different countries and continents, enabling the exchange of goods and commodities, and supporting economic growth and development [10]. However, conventional port operations have significant environmental impacts, such as GHG emissions, water pollution, waste disposal, land occupation, and energy consumption [11]. With increased environmental awareness, the green port concept has emerged. For example, the Long Beach port adopted the green port policy in January 2005, establishing the basic framework for environment-friendly port operations [12].

Various definitions have been presented for the concept of "environmental ports", "green ports", or "environmentally friendly ports", where each one has specific features for these facilities. According to the definition presented in ref. [13], green ports are designed based on the balance between environmental effects and economic benefits. These ports are environmentally stable and their activities do not result in irreversible environmental changes. In the design of green ports, economic and environmental benefits should be considered simultaneously, with neither taking priority over the other. Accordingly, the construction of these ports entails a focus on environmental protection, sustainable resource development, and energy conservation. Overall, green ports refer to ports with approaches such as a healthy environment, reasonable use of resources, low energy consumption, reduction of pollutant emissions, efficient use of resources, and environmental protection [14].

Researchers have conducted various studies about the motivations, innovations, and challenges of green ports, building a strong foundation for green port approaches. In terms of motivations, economic and technological operations increase green port competitiveness. Such operations include the design of score contracts, changing business models, and improving green technologies [15]. Environmental and political factors might impose severe pressure on green ports; for example, water and noise pollution may require supervisory necessities [16]. Technology innovation at green ports includes several areas, i.e. basic, operational, and energy operations. In terms of basic operations, the environment should be considered in policies and planning infrastructures. Emission amount should be determined for supervising port activities, and environmental improvement and energy efficiency should be achieved through sustainable construction approaches [14].

GHG emission from marine transportation is one of the most significant issues for reducing the environmental impacts of transportation [17]. There are three main approaches to reducing marine GHG emissions:

(i) Technical measures: They include making the ship body more efficient, designing low-consumption engines, making the driving force more efficient, using alternative energy sources such as fuel cells, biofuel, and cold ironing (the process of connecting a docked ship to a shore-based electrical power source, allowing the ship to turn off its engines and reduce emissions while still receiving the necessary power for onboard operations [18, 19]),
(ii) Market-based measures: They include emission commerce and carbon tax plans, and
(iii) Operational measures: They include speed optimization, optimal routing, fleet planning improvement, and other logistics-based operations.

2.1 | Alternative energy resources at the ports

Renewable energy resources have become the main priority of countries to reduce dependency on conventional energy resources [7]. Ports, as an energy-consuming sector, are seeking alternative sources of energy. Various approaches have been proposed to develop an alternative energy source in ports. Some ports, such as Antwerp and Genoa, decided to use solar energy as an alternative energy source for their some loads. Various studies have been conducted on using alternative sources for ports and converting them into green ones. Ref. [7] discusses the prospect of transforming the Alexandria port in Egypt into an environment-friendly port considering the technical, logistical, and financial requirements. In ref. [20], a simple green port model is designed for several ports in Turkey, Europe, and the United States. For example, Amberley Port (Marport) in Istanbul, which is Turkey's first private container port, has implemented several approaches as long-term projects for environmental and occupational safety issues. The aim of ref. [11] is to reflect the status of green marketing in major ports of the world by their strategies, structures, and functions. The results show that more than half of the studied cases are actively engaged in green marketing. In ref. [21], a case study of Laem Chabang port in Thailand is used to determine the evaluation criteria of the green port and to set the environmental performance indicators.

2.2 | Environmental policies in green ports

The green ports approach has been known in European countries for many years ago. In 1994, the European Sea Ports Organization (ESPO) published the first version of the ESPO environmental performance code for ports. Its second edition was published in 2003 and the latest version was updated in 2012, which is called "ESPO Green Guide" [21]. Several ports in East Asia have green port certification, such as Shanghai, Hong Kong, Singapore, Tokyo, and Busan Ports. According to the ESPO and EcoPorts reports, there are over 30 significant environmental issues only in the port sector in Europe [22]. The priority of these issues changes over time, but some of them have maintained their importance, such as waste disposal in ports, noise pollution, and air quality. These negative environmental impacts in ports are tightly related to shipping activities in a port, port operations, and domestic transportation to/from ports. The long-term survival of ports and port cities necessitates reducing the negative environmental effects of ports. The ports must rid themselves of the negative impacts associated with their developments to achieve sustainable prospects. Numerous ports recognize the need to develop "green policies" supported by incentives to encourage ports to implement green practices.

The waste collection activity includes waste produced by residential, industrial, and port areas, which consist of all types of waste such as household waste, food waste, plastic, industrial waste, metals, and waste produced by factories. In ref. [23], an approach to choose the best route for port waste transfer is presented, aiming to create an efficient waste collection management that is both cost-effective and reduces carbon emissions. In ref. [24], a conceptual framework regarding the green concept is developed to support environmental sustainability, where air pollution and efficient use of energy indicators are used as required indicators for the green concept. According to a general evaluation, the potential of increasing energy efficiency of green ports is 17.6% and each port prevents the emission of 25.16 tons of CO_2 to the environment. Each policy tool for reducing GHG emission in ports imposes costs to the associated parties, particularly the ports themselves [22]. However, these tools might bring up economic growth for the region.

3 | APPLICATION OF RET IN GREEN PORTS

Two of the most important advantages of RETs are that they are relatively clean and can be used in a decentralized manner. While the former advantage is more widely known, the latter advantage is less considered. Decentralization has played an essential role in energy transmission [25]. The integration of renewable energies into other power sources of ports is a real necessity and of increasing importance.

Some RETs can supply electricity to ports due to their compatibility with aquatic environments. One of the wind energy system types is the offshore wind power plant, which includes a set of wind turbines that are installed on the sea. The wind speed in the sea is higher than on the coast or land. Consequently, in the same area, the generated electrical power of offshore wind turbines is more than the onshore ones. Another renewable technology compatible with ports is floating PV power plants. The PV panels used in these power plants are the same as those installed on the land, except that they are installed and fixed on a structure floating in the water. The first floating solar power plant was installed in 2007 in California, USA. Currently, 70 floating solar power plants in the world with a capacity of 93 MW are operating. Other types of clean technologies compatible with ports include small hydro systems, hydrogen energy, ocean thermal power, tidal power, wave energy, and ocean current power. Table 1 presents the programs for utilizing RETs in green ports across the world.

TABLE 1 Programs of utilizing RETs in green ports worldwide [26].

Port Name	Country	Implemented/ Planned RET
Port of North Sea	Belgium and The Netherlands	Photovoltaic
Port of Vienna	Austria	Hydrogen
Port of Solomon Islands	Solomon Islands	Photovoltaic
Port of London	United Kingdom	Hydrogen
Port of Amsterdam	The Netherlands	Hydrogen
Ports of Fiji	Fiji	Photovoltaic
Port of Colombo	Sri Lanka	Photovoltaic
Port of Gothenburg	Sweden	Hydrogen, biogas, hydrogenated vegetable oils, wind
Port of Yokohama	Japan	Hydrogen
Port of Los Angeles	United States	Hydrogen fuel cell, photovoltaic
Port of Rotterdam	The Netherlands	Wind energy
Ports of Auckland	New Zealand	Biofuel, hydrogen
Port of Marseille	France	Hydrogen fuel cell, photovoltaic
Port of Helsinki	Finland	Biofuel, photovoltaic
Port of Long Beach	United States	Hydrogen fuel cell, photovoltaic
Port of Antwerp	Belgium	Hydro turbine, photovoltaic
Ports of Niedersachsen	Germany	Hydrogen
Port of Batangas	Philippines	Photovoltaic
Ports of Associated British	United Kingdom	Photovoltaic, wind turbine
Ports of Gladstone	Australia	Tidal energy
Port of Valencia	Spain	Hydrogen fuel cells, photovoltaic
Ports of Tenerife	Spain	Photovoltaic, wind
Port of Kobe	Japan	Hydrogen
Ports of Auckland	New Zealand	Photovoltaic
Ports of Stockholm	Sweden	Photovoltaic, hydrogenated vegetable oils
Port of Qingdao	China	Hydrogen
Port of Helsinki	Finland	Wind power
Port of Hamburg	Germany	Photovoltaic
Port of Barcelona	Spain	Photovoltaic
Port of Antwerp	Belgium	Concentrated solar thermal
Port of Genoa	Italy	Solar, biomass, wind, geothermal energy

3.1 | Offshore wind energy

Offshore wind power has attracted significant attention due to its great potential for energy production, and it is developing quickly. Up to 2020, the total capacity of the offshore wind plant was 35.3 GW [27]. Britain (29%), China (28%), and Germany (22%) consist of more than 75% of the world's installed capacity of offshore wind power. 1.2 GW Hornsea Project One in Britain is the world's largest offshore wind farm [28]. Other projects are currently planned, including Dogger Bank in Britain with a capacity of 4.8 GW, and Changhua in Taiwan, with a capacity of 2.4 GW [29].

Without required improvement, the lack of proper port infrastructure challenges constructing the main components of wind energy technology and installing projects efficiently. This constraint may limit the participation of offshore wind energy in achieving clean energy and domestic economic growth; because,

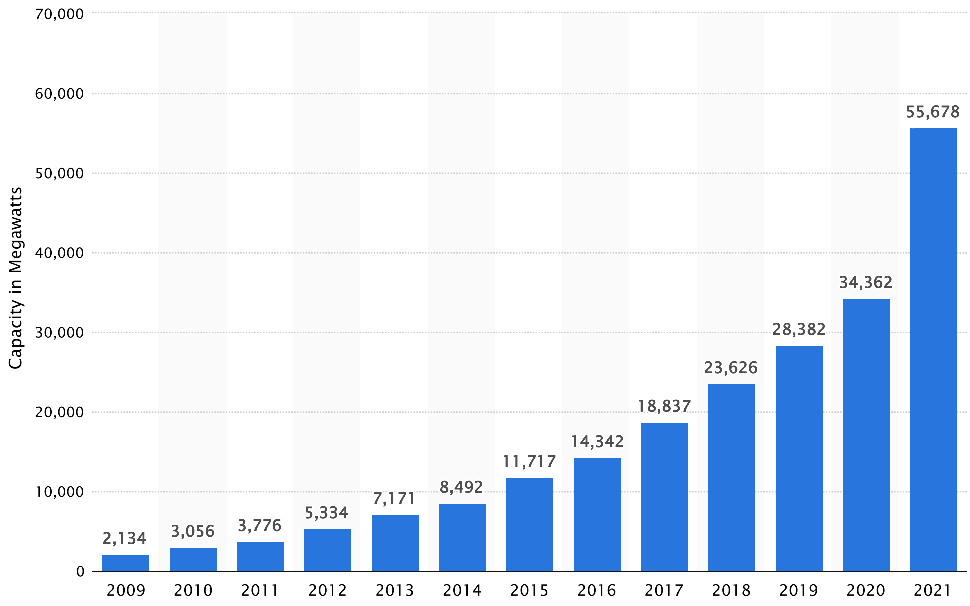

FIGURE 3 Cumulative offshore wind energy capacity worldwide [34].

if the projects are not implemented efficiently, they might be prolonged or cancelled.

The West Coast of the United States is increasing offshore wind energy activities, with the prospect of deploying commercial-scale floating offshore wind energy projects in California, Oregon, Hawaii, and elsewhere by the 2030s, and this industry is expected to expand worldwide by 2050 [30]. Other areas of the United States, such as the Gulf of Maine, the Central Atlantic Ocean, and the Gulf of Mexico, also have the potential to deploy offshore wind energy.

By increasing the deployment speed and decreasing the cost, these systems are expected to face growth in Mainland China and Northern Europe by 2050 [36]. The European Union (EU) has set specific targets for offshore wind capacity, with a goal of at least 60 GW installed capacity by 2030 and 300 GW by 2050. Additionally, it is estimated that the global offshore wind gross capacity will increase by approximately 190 GW by 2030 [35]. It shows the great potential for using offshore wind farms in green ports by reducing costs and increasing the efficiency of this technology.

3.1.1 | Installed capacity of offshore wind energy

By 2017, the worldwide installed capacity of offshore wind power was less than 20 GW, and in 2018, offshore wind energy accounted for only 0.3% of the global electricity supply. However, in 2018, 4.3 GW of electricity was generated over the prediction from overall offshore wind capacity [31]. In 2018, 50% of the electricity of Denmark was supplied by wind energy annually, where 15% was offshore. The average size of turbines installed in 2018, 2019, and 2020 was 6.8, 7.2, and 8.2 MW, respectively [32]. It is predicted that the shortage of special offshore wind turbine installation vessels, especially those that can install 10 MW turbines, will increase the demand for these vessels after 2022 [33]. Figure 3 shows the world's installed capacity of offshore wind energy from 2009 to 2021.

Wind energy has been identified by IHS Markit as well as the Global Wind Energy Council (GWEC) and the International Renewable Energy Agency (IREA) as one of the most rapidly growing RETs across the world. The overall generation capacity for both onshore and offshore wind powers has grown by approximately 75 times over the past two decades, increasing from 7.5 GW in 1997 to approximately 823 GW in 2021 [35].

3.1.2 | Economy of offshore wind energy

In 2010, the U.S. Energy Information Administration (EIA) announced that "offshore wind power is the most expensive energy generation technology for large-scale deployment in ports" [37]. In that year, the offshore wind plants had significant economic challenges compared to onshore ones and their employment cost was about 2.5 to 3 million € /MW [38]. By the end of 2011, 53 European offshore wind farms were operated in Belgium, Denmark, Finland, Germany, Ireland, Netherlands, Norway, Sweden, and Britain with an operated capacity of 3813 MW and installation capacity of 5603 MW [39]. € 8.5 billion ($11.4 billion) offshore wind farms were under construction in European waters in 2011. In 2012, Bloomberg estimated that offshore wind turbines cost € 161 ($208)/MWh [40]. The offshore wind energy cost reduced faster than expected. By 2016, four contracts were made with a lower cost than the lowest cost expected for 2050 [41]. In September 2017, several contracts were made in Britain for 57.50 pounds/MWh, which were cheaper and more competitive than gas energy [42].

The cost of installing offshore wind turbines in 2019 decreased by 30% and reached $78/MWh, which has decreased faster than other types of renewable energies [43]. The offshore wind power market plays a significant role in achieving the goal of renewable energy in most countries in the world. In September 2018, contracts were signed for Vineyard Wind located in Massachusetts, with a cost between $65 and $74/MWh [44]. The National Renewable Energy Laboratory (NREL) report states that the Levelized Cost Of Energy (LCOE) in 2021 is $78/MWh and $133/MWh for fixed-bottom and floating utility-scale offshore wind turbines, respectively [45]. According to the 2022 edition of the Offshore Wind Market Report, on average, the LCOE for commercial-scale fixed-bottom offshore wind projects in the United States experienced a 13% decrease to $84/MWh, encompassing a price range of $61/MWh to $116/MWh; more reduction to $60/MWh on average is estimated by 2030 [46]. By using the Forecasting Offshore wind Reductions in Cost of Energy (FORCE) model, it is estimated that LCOE could reduce to $53/MWh and $64/MWh in 2035 for fixed-bottom and floating offshore wind energy, respectively [47]. The offshore wind farm economy tends to install larger turbines; because the cost of installing and integrating into the electrical network per energy generation unit reduces. The offshore wind farms do not have the limitations of onshore systems for increasing the size of wind turbines, such as land availability or transportation requirements [48].

3.1.3 | Offshore wind turbines

Technically, fixed-foundation wind turbines are more robust in areas with a water depth of less than 50 m (160 ft.) and an average wind speed of 7 m/s (23 ft/s). Floating wind turbines in areas with water depths ranging from 50 to 1000 m (160 to 3280 ft) are robust. Different types of offshore wind turbines are as follows:

- Vertical axis wind turbines: Although most of the installed onshore wind turbines and all large-scale wind turbines have a horizontal axis, vertical axis wind turbines are more appropriate for use in marine facilities. Thanks to installation in the sea and their low center of gravity, these turbines can be constructed larger than horizontal axis turbines up to 20 MW capacity. As mentioned in the previous subsection, this can improve the economy of offshore wind plants [48].
- Floating wind turbines: For regions that are deeper than 60–80 m, the fixed-foundation wind turbines are not economical and they are technically impractical. Thus, floating wind turbines connected to the ocean bed are required. Blue H Technologies which was finally purchased by Seawind Ocean Technology, installed the first floating wind turbine in 2007. Hywind is the first full-scale floating wind turbine in the world that was installed in the North Sea near Norway in 2009. Hywind Scotland which was started in October 2017, is the first operational floating wind farm with a capacity of 30 MW [49].
- Fixed-foundation wind turbine: Almost all offshore wind farms that are currently active, except a few experimental projects, use fixed-foundation wind turbines. Fixed-foundation wind turbines have fixed foundations under the water, which are installed at shallow waters of 50–60 m (160–200 ft) depth. Various underwater structures include single-pillar, triple-pillar and jacketed, with different foundations on the sea bed, including single-pillar or multi-pillar, gravity foundation, and box foundation (Caisson) [50]. Depending on the water depth, these turbines need different types of foundations for stability.

3.2 | Floating solar plant

Solar PV systems are gaining attention due to their numerous advantages, including zero GHG emissions, an unlimited energy source, ease of accessibility, low maintenance requirements, and scalability from rooftop household systems to large power plants [51–54]. Additionally, advancements in solar panel technology and government subsidies further contribute to their appeal [55, 56]. The most common application for using solar energy is PV systems. PV modules are one of the most sustainable and environment-friendly technologies in the field of renewable energy [57]. Constructing PV systems needs a lot of land. There are large water areas in most regions of the world, in which PV systems can be installed to reduce the cost of land and electricity generation. Therefore, installing solar PV systems in accessible waters can become a logical option for harnessing solar energy and increasing the economic efficiency of solar projects. Floating solar power plants generate more electricity than ground and rooftop systems due to the cooling effect of water. Also, by casting a shadow on the water, they reduce the water evaporation and the growth of algae [58]. High-density polyethylene is used in the construction of floating solar systems, which is robust against UV rays and corrosion [59].

3.2.1 | Installed capacity of floating solar plants

The first 20 plants with a capacity of tens of kW were constructed between 2007 to 2013 [60]. After the first projects in 2006, the installed capacity for the floating solar plant by 2015 was only 10 MW. The Market for floating solar technology has grown since 2016. Ref. [61] states that the installed capacity of floating solar plants in 2018 is about 1.3 MW, with an estimation of about 3.7 GW for 2020 (Figure 4). In 2020, the worldwide utilization of floating solar panels reached 3 GW, in stark contrast to the land-based solar systems which exceeded 700 GW. If 10% of the hydropower reservoirs across the globe were covered with floating solar panels, an estimated 4,000 GW of solar capacity could be installed, which is equivalent to the electricity generation capacity of all operational fossil-fuel plants worldwide. A project in Batam, Indonesia, expected to be finalized by 2024, aims to generate 2.2 GW by implementing solar panels over 16 km^2 of water, effectively almost doubling the current global output [62]. In most countries like Iran, construction of floating PV plants has begun [63].

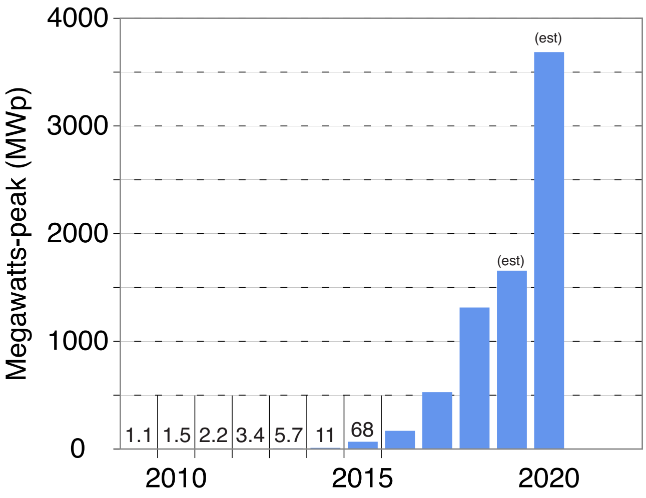

FIGURE 4 Installed capacity of floating solar plants [61].

3.2.2 | Economy of floating solar plants

Constructing floating solar plants requires different costs. Ref. [64] have reported that the employee cost for a ground solar plant is $40/h, while it increases to $60/h for floating ones. Considering that floating solar plants do not need land, these additional costs may be compensated. In ref. [65], a list of the construction cost of a floating solar plant is presented. This study estimates the cost of PV modules at $0.25/W, electrical components including cables and inverters at $0.12/W, galvanized steel at $2.20/kg, and the cost of heavy-duty polyethylene (HDPE) at $2.40/kg. The LCOE of the floating solar power plant in 2018 was € 53/MWh which is higher than ground-mounted plants ranging from 35 to 40 € /MWh [66]. According to the NREL report in 2021, the LCOE is $57/MWh without the Investment Tax Credit (ITC) and $38/MWh with the ITC for floating solar power plants while it is about $47/MWh without the ITC and $32/MWh with the ITC for ground-mounted solar power plants [67]. Ref. [68] states that the LCOE of floating solar systems may reach $34/MWh to $49/kWh depending on the location in Bangladesh.

3.3 | Ocean energy

Ocean energy refers to renewable energy that can be harnessed from the ocean's natural resources, including tides, waves, ocean currents, and thermal gradients. Various technologies are being developed to harness this energy, such as ocean thermal energy conversion (OTEC), and tidal and ocean current turbines. The potential of ocean energy as a clean and sustainable source of power is vast, as the ocean covers over 70% of the Earth's surface. The target of the EU for the installed capacity of ocean energy for 2030 and 2050 is at least 1 and 40 GW, respectively [36]. While ocean energy is still in the early stages of development, it holds great promise for meeting the world's growing energy needs while reducing carbon emissions and mitigating the impacts of climate change.

3.3.1 | Ocean thermal energy conversion

The OTEC generates energy based on the temperature difference between cold waters at the ocean depth and warm waters at the ocean surface. OTEC plants pump a lot of cold and warm sea water for electricity generation [69]. OTEC is a strong and clean energy resource that is environmentally sustainable and can provide large energy levels. In tropical regions, the temperature difference between the surface of the ocean and 1 km below the surface may reach 20°C. Using this temperature difference, steam can be produced at low pressure, and it can be used as the input for a steam turbine [70]. Experimental power plants are constructed in Hawaii (U.S.) and Japan with a net power output of up to 50 kW. Among ocean energy sources, OTEC is one of the continuously available renewable energy sources that can contribute to base load energy supply [71]. The OTEC resource potential is considered larger than other forms of ocean energy. Up to 88,000 TWh of electricity can be generated through OTEC without affecting the thermal structure of the ocean.

Various OTEC projects are being constructed or operated all over the world. For example, a 100 kW plant was started in Hawaii in August 2015 [72], a 10 MW plant at south costs of China to supply electricity for a purlieu in Hainan island, and a required budget was allocated to construct a 10.7 MW plant in Martinique islands.

Since OTEC systems have not yet been widely deployed and commercialized, their exact cost estimation is uncertain. A study by the University of Hawaii in 2010 states that the cost of electricity for OTEC is 94 ¢/kWh for a 1.4 MW plant, 44 ¢/kWh for a 10 MW plant, and 18 ¢/kWh for a 100 MW plant [73]. In 2015, a report by the ocean energy systems organization of the International Energy Agency (IEA) estimated about 20 ¢/kWh for 100 MW OTEC plants [74]. This technology is relatively expensive compared to other renewable energy sources; for example, a study in 2019 estimated the cost of unsubsidized electricity to be between 3.2 and 4.2 ¢/kWh for urban-scale solar PV and 2.8 to 5.4 ¢/kWh for wind power, which is lower than ocean thermal power [75]. Ref. [76] states that the LCOE of OTEC in 2018 is ranging from 0.03 to 0.76 $/kWh in different projects.

3.3.2 | Tidal energy

Sea waves that are generated by the wind blowing on the water surface, have a large power potential and can be used as a clean source for energy generation [70]. Tidal energy can meet annual energy needs. However, it has not been widely used yet. But with further study and development, it can be a reliable alternative to supply the required energy [77]. The first large-scale tidal plant is in Ranse, France that was operated in 1966. Electricity generated by marine technologies was about 16% in 2018, which increased by 13% in 2019 [78].

Most marine energy systems are comprised of turbines that operate by condensed air pressure. The air pressure is generated by wave fluctuation force or relative movement of underwater waves. The most important challenge for commercializing these systems is the harsh natural conditions of the ocean. To this end, it is important to notice that using these systems needs to predict waves condition. Today, artificial intelligence, particularly machine learning algorithms can provide an accurate prediction of waves to calculate the input and output of the system at different moments. In ref. [79], the wave energy is predicted using Bayesian machine learning. The prediction error of this machine for short-term wave prediction is up to 55.4%, which is 11.7% less than linear wave theory and certain machine learning methods. In ref. [80], tidal energy prediction is presented through the concept of machine learning and deep learning. Ref. [81] presents the concept of tidal energy prediction based on the combined machine learning algorithm. The efficiency of this method is confirmed by referring to the tidal data obtained in Zhejiang province, China, using the acoustic doppler current profiler (ADCP).

Compared to other marine energy sources, tidal energy which is the energy dissipated by tidal movements caused by the gravitational and centrifugal forces between the Earth, the Moon, and the Sun is very predictable in the long term [82]. The loss of tidal energy on Earth is about 3.5 TW. Considering that the global demand for electricity in 2010 was 2.7 TW and is expected to reach 3.6 TW in 2030, tidal energy has a significant potential to meet most of the world's electricity needs. Tidal energy can generate a lot of electricity. For example, the MeyGen tidal energy project began operations in 2018, and its first four turbines generated and delivered more than 35 GWh of electricity to the grid by the end of 2020 [83]. With the complete installation of 61 submerged turbines on the seabed, this power plant can generate up to 400 MW of energy from high-speed wave currents in the region. According to the International Energy Agency Technology Collaboration Programme for Ocean Energy Systems report in 2015, the LCOE for tidal energy is ranging from 130 to 280 $/MWh [84]. Ref. [85] states that the LCOE for this technology in 2021 is ranging from 225 to 943 $/MWh for various case studies.

Generating electricity from tidal energy has a high initial cost, which makes it unpopular among other renewable energy resources, although various research such as ref. [86] have shown that the public is willing to pay and support the research for the development of tidal power plants.

3.3.3 | Ocean current energy

Ocean currents exist in the deep waters of the oceans just as the wind flows in the Earth's atmosphere. The source of ocean currents might be the movement of water caused by tides [70]. The underwater topography in the straits between the islands and the mainland or in the shallow areas around the water sources plays a major role in increasing the speed of marine currents, which results in significant kinetic energy [87]. But unlike wind turbines, which can only withstand a certain speed and intensity of wind currents, marine current turbines can generate electricity in regions where there are strong marine currents.

Recently, marine current turbines with horizontal and vertical axis are developed. In refs. [88, 89], the recent achievements in the field of marine current turbines have been reported. In these studies, the latest information about large tidal turbine projects of more than 500 kW is given. The total global power for ocean currents is estimated to be about 5000 GW with a power density of up to 15 kW/m^2. The relatively constant energy density that can be extracted near the surface of the Florida Straits stream is about 1 kW/m^2 of the water current area.

Prototype marine energy technologies require significant cost reductions before they can compete with other forms of grid-compatible power generation technologies [90]. There are limited technology and project cost data for different types of marine energy technology, which makes it challenging to evaluate baseline costs and identify high-impact research and development (R&D) opportunities.

3.4 | Fuel cell

Using fuel cells is gaining great attention in green ports. Four main factors are important for using fuel cells in ports: (1) technology criteria such as power rating, life span, efficiency, and sensitivity to fuel impurities, (2) the cost of various types of fuel cells, (3) safety, and (4) the environmental issue and emissions.

Large amounts of green electricity are required for sustainable hydrogen production. Several projects are being conducted to realize this and there are still opportunities for other companies. In the North Sea port area, which currently generates 500 MW of solar and wind energy, thanks to the national high-voltage grid (380 kV) in Borssele and Ghent (Rodenhuize), hydrogen plants buy large amounts of electricity from these power plants [91]. Generating renewable hydrogen will not be sufficient for the large energy demand in the North Sea port and domestic areas. Importing is essential and the North Sea port is also suitable. The potential of hydrogen import through the North Sea port is estimated to be about 6 million tons annually by 2050 [91]. Hydrogen is imported in different ways, one of which is in the form of ammonia. Unlike hydrogen, ammonia can be stored in liquid form in tanks. It can be used as a source of energy and as a raw material for hydrogen production.

In ref. [92], the integration of cold ironing technology to reduce the emission of GHGs caused by the operation of auxiliary engines of berthed ships and to lay the groundwork for future regulations has been investigated. In this study, thirteen scenarios were conceptualized, simulated, and evaluated. For each scenario, the independence of the port in terms of energy supply is ensured by generating renewable energy and storing excess energy in a hydrogen storage system. This study proves that small ports can implement cold ironing technology and increase their energy efficiency through a renewable hydrogen system. Narvik port in the north of Norway requires a new boat that is both fast and non-polluting. This port along with eight partners of the project seeks a public budget to construct one of the first fast hydrogen ships. This boat will be equipped with TECO 2030 hydrogen fuel cells. It will replace one of the diesel ships of the port [93]. A part of the port of Alexandria, which has 67 berths and 20 terminals, is also dedicated to installing fuel cells [7]. Fuel cell units with a length of 60 m and a width of 12 m are located in this port. The area required for electrolysis is 141 m (length) by 2 m (width). In this system, 20 fuel cell units are used at a distance of 2.5 m and in 6 parts. 7 MW of produced electricity from 7 fuel cell units in this power plant is used for the unit's own electricity consumption, and the output of the other 13 units is given to the main control system. These 13 units can supply 65% of the port's electricity.

3.4.1 | Various applications of fuel cell in ports

The main application of fuel cells in ports and other goods transportation centers is electricity generation. Fuel cells can supply the main and backup powers and provide emergency electricity, auxiliary power units (APU), and battery charging depending on port requirements with different ratings [94]. In ref. [95], a fuel cell/battery hybrid direct current (DC) backup power system is presented for increasing the speed that is made of a new non-isolated three-port converter.

Fuel cell technology is a suitable option for deployment in microgrids due to its ability in following the load, islanded operation, grid-connected operation, and the black start of the power plant. Additionally, fuel cells are a stable, reliable, and clean source of energy. Considering these features, fuel cells have been deployed in several microgrids. For example, the University of California includes a 2.8 MW fuel cell powered by biogas [96]. Also, at Bridgeport University, a microgrid operates only with a 1.4 MW fuel cell with black start capability. This fuel cell is used to supply the university's thermal load. Using fixed fuel cells provides the necessary opportunity for the combined cooling, heat, and power (CCHP) through the produced heat to meet thermal needs, including heating or cooling buildings and warehouses, or the heat required for industrial processes. The technical potential for CCHP in ports is determined by the simultaneous demand for electricity and thermal energy including steam, hot water, cold water, industrial process heat, refrigeration, and dehumidification [97]. The economic justification for CCHP systems in ports is determined considering the current and future cost of fuel, water, and electricity, planned new constructions, or replacement of heating, ventilation, and air conditioning (HVAC) equipment, and the need for reliability and power quality.

Fuel cells can provide the required driving force for transportation with advantages similar to electricity like high efficiency and low emission (near zero) [98]. Proton exchange membrane fuel cells can provide the driving force required for road fuel cell electric vehicles. In ref. [99], a new driving system is designed for a heavy vehicle. Specifically, this is done to create bases to develop an industrial cargo vehicle with hydrogen fuel for use in real port operations. Los Angeles port and its partners have started 5 new electric vehicles with hydrogen fuel and two hydrogen fueling stations in a $82.5 million project in California.

3.4.2 | Economy of fuel cell

Economic analysis of fuel cells considering parameters like type and application of cells, operation costs, fuel, and maintenance should be carried out in the initial examination. A study in 2017 showed that the cost of generating 1 kW electricity of fuel cells is about $2000 [7]. In 2012, the fuel cell industry revenue in the global market increased by $1 billion [100]. In 2010, 140,000 fuel cell stacks were distributed around the world, and the fuel cell cargos experienced an annual growth rate of 85% from 2011 to 2012 [101]. Solid state energy conversion union of the Ministry of Energy found that till January 2011, fuel cells have obtained about $724 to $775 per installed kW. Regarding technological advancements, the U.S. Department of Energy reported a 60% reduction in fuel cell cost from 2006 to 2017 [102]. The LCOE for solid oxide fuel cell in 2013 was about $0.265/kWh [103] while in 2017 is about $0.19/kWh [104].

The cost of generating hydrogen from renewable energies decreased by 80% from 2002 to 2017. Hydrogen can be considered as an energy storage option for cost-effective and long-term energy storage, like seasonal storage, especially for intermittent renewable energies. It can be converted into electricity in clean, convenient, and efficient ways such as fuel cell systems and gas turbines. Therefore, it can store intermittent renewable energy during off-peak demand and then supply electricity during peak demand or when necessary. Therefore, it has a positive impact on the economy of electrical systems.

Hydrogen and fuel cell economy is one of the most critical challenges of this technology. According to the report of the U.S. Department of Energy, the cost of generating hydrogen from centralized or decentralized electrolysis was $0.3/kg to $3.9/kg in 2015, while desired generation cost was $2/kg [105]. The employee costs, financial costs, and institutional and political frameworks (especially, tax, subsidies, environmental standards, and renewable energy incentives) are different in various countries.

4 | DISCUSSION

Table 2 presents pros and cons as well as LCOE of various RETs for green port application. Among various technologies, floating solar power has the lowest LCOE. Economic benefit as well as the maturity of solar PV technology makes it a proper selection for green ports application. However, its high maintainable cost should be considered. The next priority RET for green port application from the LCOE and maturity points of view is floating wind energy. Similar to solar energy, it suffers from maintenance and repair challenges.

TABLE 2 Comparison of various RETs for green port application.

Energy technology	Advantages	Disadvantages	LCOE
Offshore wind power plant (vs. onshore)	• More efficient due to more speed and consistency of wind • More energy generation • Reduced environmental impact • More space to construct in	• More complex infrastructure • Higher installation cost • More challenging maintenance and repair • Less local involvement • Less local jobs • Impact on marine life	$78/MWh for fixed-bottom and $133/MWh for floating [2021]
Offshore solar power plant (vs. onshore)	• Higher performance due to the cooling effect of water and lower dust pollution • Environmental benefits due to reduced water evaporation and algae blooms • Possibility of installation at existing hydropower power plant lakes • No need for land space	• Higher installation cost • Not applicable in small-scale • Disruption to aquatic life • Site selection complications • High requirements for the racking system • Higher maintenance costs	$57/MWh without the ITC and $38/MWh with the ITC [2021]
Ocean thermal energy conversion	• Reliable • Environmental friendly • Low maintenance • Independent of weather conditions • High energy efficiency	• Locality of production • High initial cost • Interfere with navigation • Large-size turbines with expensive liquid • Harmful to marine life • Intermittence	30 to 760 $/MWh [2018]
Tidal energy	• Predictable energy generation • High power output • Maintains efficiency • Low maintenance	• Limited installation sites • High installation costs • Environmental impact • Lack of supply for the demand	225 to 943 $/MWh [2021]
Ocean current energy	• High efficiency • Predictable energy output	• Environmental effects • High installation cost • Location specific • Energy transportation to land	Not Available
Fuel cell	• Readily available • Highly efficient • No noise pollution • No visual pollution • Versatility of use for a range of stationary and mobile applications • No dependency on weather conditions • Good reliability • Low maintenance efforts and costs • Adaptable	• Need for hydrogen extraction • Need for raw materials • Need for hydrogen storage • Highly flammable	$190/MWh [2019]

5 | CONCLUSION

The green port has emerged as an important concept in the shipping industry, driven by the need to reduce carbon emissions and improve the environmental performance of ports. RETs such as solar power, wind power, and fuel cell have been identified as key solutions for reducing the carbon footprint of ports. Many ports around the world have already started to adopt RETs, and the trend is expected to continue in the future. This paper summarizes the potentials, challenges, and economic analysis of RET applications in green ports for a more sustainable future. Despite the potential benefits of RETs, there are also significant challenges that need to be addressed. These challenges include the high initial investment cost, technological limitations, and lack of supportive policies and regulations. This paper concludes that floating solar PV and wind power technologies, considering their technical maturity and lower LCOE are proper options to achieve green port goals. Also, it is expected that fuel cells will be used widely in the green ports because they can supply backup and emergency electricity, can be integrated with microgrids and electric vehicles, and achieve CCHP goals. Other forms of renewable energy that require an aqua environment for operation can supply the energy required by specific parts of a small port.

In terms of prospects, it is expected that the use of RETs in green ports will continue to increase in the coming years. This trend will be driven by the growing awareness of the need for sustainable development, decreasing the installation cost of RETs, and the availability of supportive policies and incentives. The development of innovative technologies such as floating solar panels, wind-powered shipping, and green hydrogen production will also open up new opportunities for the application of renewable energy in green ports. Additionally, the integration of RETs with smart port technologies and digital solutions such as artificial intelligence, blockchain, and the Internet of Things will enable better monitoring, management, and optimization of energy consumption in green ports. This integration will lead to improved energy efficiency, reduced operational costs, and enhanced environmental performance. Collaborative efforts among stakeholders and the continued development of innovative technologies will pave the way for a more sustainable and efficient future for green ports. Quantifying the environmental benefits for quantitative economic–environmental evaluation of RET application in green ports can be considered as future work.

AUTHOR CONTRIBUTIONS

Mohammad Parhamfar: Conceptualization, investigation, resources, writing - original draft. Iman Sadeghkhani: Supervision, visualization, writing - review and editing. Amir Mohammad Adeli: Investigation, resources, writing - original draft.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Authors elect to not share data.

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