Li *et al. Complex Eng Syst* 2023;3:1
DOI: 10.20517/ces.2022.46

Complex Engineering Systems

Review

Open Access

Review on key technologies of green power supply for port microgrid

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How to cite this article: Li G, Wang T, Zhou B, Xiao Z, Yan S, Liu B. Review on key technologies of green power supply for port microgrid. *Complex Eng Syst* 2023;3:1. https://dx.doi.org/10.20517/ces.2022.46

Received: 11 Nov 2022 **First Decision:** 15 Dec 2022 **Revised:** 26 Dec 2022 **Accepted:** 1 Jan 2023 **Published:** 31 Jan 2023

Academic Editor: Hamid Reza Karimi **Copy Editor:** Fangling Lan **Production Editor:** Fangling Lan

Abstract
With the development of ship electrification, the demand for energy in ports is increasing. The location and natural resources of ports also create conditions for the development of ship electrification. This paper firstly analyzes the current development status of floating solar power generation technology and offshore wind power generation technology, summarizes the obstacles facing the development of offshore power generation platforms, introduces the materials and structures that can be used for floating power generation platforms, and then introduces the port microgrid topology from three aspects of AC microgrid (AC), DC microgrid (DC) and AC/DC hybrid microgrid (AC/DC) hybrid structure, and compares the three structures. Then the existing control methods are reviewed from the perspective of port capacity planning and the application of distributed control in port energy planning is emphasized. Finally, port energy management strategies are introduced from the perspective of multiple time scales, and relevant cases are listed, and the advantages and disadvantages of management strategies under different time scales are compared. At the end of the paper, several advanced smart ports are given as examples, and the new energy used by each port and its development scale are analyzed, and the future clean and efficient ports are envisioned.

Keywords: Floating power supply platform, ports, microgrid topology, capacity planning, energy management

1. INTRODUCTION

Maritime transport plays a key role in international communication. It is estimated that 90% of the world's trade in goods is carried out by sea. However, most ships use fossil fuels to meet their energy needs, resulting in the emission of pollutant gases, particulate matter, and greenhouse gases (GHG)[1]. The development of clean and renewable energy and large-scale use of port power and charging facilities are the main measures to achieve the port carbon reduction target. Considering the waiting ships outside the port, it is necessary to further extend the port.

In 2015, Norway launched its first fully electric ferry, adding to the growing number of fully electric ships. In such containers, electricity can be generated from renewable resources and storage systems, such as batteries and supercapacitors[2]. Singapore's Jurong Port has a 9.5 MWP solar power system that generates more than 12 million kWh a year and meets 60% of the power demand at the port. Hamburg Port[3] has implemented the overall plan of "Smart Port Energy". One of the sub-projects is the Altona Cruise terminal shore power project. Shore power facilities are connected to the 10 kV medium-high voltage main grid of Hamburg, and the power is transmitted to the terminal frequency converter station through cables, which can provide 12 MVA/6.6 KV/60 Hz or 12 MVA/11 KV/60 Hz power to cruise ships. Shore power facilities are powered by renewable energy, reducing CO_2 emissions by more than half. The microgrids of ports such as Bayonne Tarnos in France, Long Beach in the United States, and Mytilene in Greece also include photovoltaic (PV) power generation systems and wind turbines (WT), which use renewable energy to generate electricity, meet the power demand of critical loads in emergency situations and are used for cold ironing of cargo ships to reduce the emission of polluting gases.

At present, China's ports have only a small amount of renewable energy installed, and the research on the renewable energy network for shore power supply is still in the primary stage. "Ming Qing", the world's largest 400,000-ton super mine ship in Dongjiakou Port (Qingdao)in Shandong Province, China, has successfully connected to the dock shore electricity, marking that the China port is the first in the world to realize the full application of shore electricity for the 400,000-ton super mine ship. The Laotangshan Wharf at Zhoushan Port[4] has completed the first hybrid port power system of high and low voltage in Zhoushan City, with a total capacity of 4030 kVA, which can simultaneously meet the power supply demand of two bulk cargo ships of 150,000 tons and two bulk cargo ships of 50,000 tons. The terminal of Section C in the Beijiang port area of Tianjin Port has been put into operation, which is the first "smart zero-carbon" terminal in the world. The facilities and equipment are driven by electricity, and the "integration of scenery and storage and loading" system realizes the independent supply of green electricity, with zero carbon emission in the whole process. The berth of Nanjing Longtan Port adopts low-voltage shore power and builds 4 sets of 100kVA shore power connection devices, 4 sets of 200 kVA shore power connection devices, and 2 sets of 300 kVA shore power connection devices, with a total capacity of 1800 kVA. Shanghai Port, Guangzhou Port, Qingdao Port, and many other ports have carried out power projects to develop the green intelligent control system.

The literature on "cold-ironing[5]" and "shore power supply[6]"introduces that the onshore power grid supplies power to the berthed ship, avoiding the use of diesel generators on the ship. To reduce the carbon footprint of cold-ironing ships and avoid fossil fuel generation in the main grid, renewable energy, solar panels, wind turbines, and storage options have been increasingly considered[7]. Sadeghi *et al*. proposed the design and optimization of a hybrid renewable energy system (HRESs) with power-sharing capability, using multi-objective particle swarm optimization (MOPSO) and multi-objective Crow search (MOCS) to solve the problem studied so that the system has good economic benefits and reliability[8]. In order to manage these elements, more and more attention has been paid to the development of microgrids in port areas in the last decade. While microgrids have been widely developed worldwide in different areas (cities, remote communities, islands, *etc*.), they are still rare in port areas. This is because of the diversity of port loads (refrigerated containers, quay cranes, ship cold-irons, buildings, *etc*.) and other reasons related to energy management, load forecasting difficulties, and megawatt power demand[9]. In addition, the development of microgrids involves huge investments due to the use of storage solutions and renewable energy sources, leading to problems of investment cost-sharing between authorities and port owners and the management of microgrids from both commercial and energy perspectives[10,11].

This paper summarizes and analyzes the research progress of green power supply technology in port microgrids, and its organizational structure is as follows. The first part introduces the current development status of port green power supply technology, and the second part introduces different power systems, describes photovoltaic power generation in detail, and lists some running cases. The third part introduces the DC microgrid, AC micro power grid, and the scenery storage integration of micro AC/DC hybrid power grid and compares three kinds of systems, and the fourth part introduces the port capacity of micro power grid planning and the existing methods. The fifth part introduces the distributed control method and multi-time scale energy management strategy of port microgrids, and the sixth part lists the existing cases in the world. The last section summarizes the findings and prospects the future research directions.

2. FLOATING WIND-PV-STORAGE POWER SUPPLY PLATFORM

2.1. Floating offshore wind power platform

Offshore wind farms are offshore wind power plants in water depths of about 10 meters, and electricity is generated by turning wind turbines. Compared with onshore wind farms, offshore wind farms have the advantages of not occupying land resources, basically unaffected by topography, higher wind speed, more abundant wind energy resources, larger wind turbine capacity (3-5 MW), and higher annual utilization hours. However, the construction of offshore wind farms is also technically difficult, and the construction cost is generally 2 to 3 times that of onshore wind farms.

In recent years, the UK, Germany, Denmark, the United States, Japan, and other western countries have accelerated the research of offshore wind speed. Chen *et al*. introduce the general situation of the early development of offshore wind in these countries, describe the main characteristics and trends in the development of offshore wind, enumerate the German electric field and the ocean buoyancy postures in typical cases such as wind turbine experiment[12]. Luo *et al*. review the offshore wind power grid general topology structure, offshore wind reliability evaluation methods and indexes, models of offshore wind power, collection systems in offshore wind farms, the reliability evaluation method of offshore wind power is proposed, the failure probability of different components in the offshore wind power grid and fault repair time for each component[13]. On this basis, the operational reliability improvement technology of offshore wind power is discussed from the aspects of the system and components. Ge *et al*. introduce key technologies of intelligent operation control and maintenance of offshore wind farms[14], including offshore wind power prediction technology, offshore wind power operation control technology, offshore wind power equipment maintenance and management technology, and the comprehensive utilization of offshore wind power and sea area. In addition, the differences between offshore wind power and onshore wind power are analyzed according to the factors of offshore weather environment, resource characteristics, geographical location, equipment operation, and so on. Based on this, the challenges and possible solutions in the above technology fields are summarized, and the research status and achievements of these technologies are analyzed and summarized. Li *et al*. present a flexible high-voltage large-capacity DC transformer topology[15], explored based on the active bridge arm and thyristor valve group, the diode valve combination way of the new converter. This combines the thyristor valve, diode group, and low conduction loss, high power density, advantages of the series configuration, special characteristics of the voltage of the active bridge arm, and highly controllable current waveforms. Thus, with high-efficiency flexible commutation, highly controllable power conversion, and the input and output DC current smooth, there is no need to install a filter. Compared with the existing flexible DC power transmission modular multilevel converter offshore platform, the technical economy of the proposed DC transformer topology is illustrated.

Offshore wind power is the focus of renewable energy development in China at present and in the next few decades. However, compared with onshore wind power, offshore wind power faces challenges such as high life-cycle electricity cost and the large impact of large-scale grid connection, and digitalization and intelligence are the key to solving the above problems. The full DC offshore wind farm proposed by Li *et al.* is a cutting-edge technology supporting the large-scale and far-reaching development of offshore wind power[15], which is expected to improve the gathering and sending efficiency of wind power and reduce the volume of offshore platforms. The 100 kV/100 MW DC transformer is a technical bottleneck for the full DC offshore wind farm to be broken urgently. Research on key technologies of intelligent operation control and maintenance of offshore wind farms can provide support and reference for reducing cost and increasing efficiency of offshore wind power and large-scale safe and economic grid connection.

2.2. Floating photovoltaic power generation platform

In recent years, photovoltaic power generation technology has developed significantly. Considering issues such as land costs, transmission costs, and water competition between power generation and agricultural production, there is an increasing number of studies on floating PV. The offshore environment can make full use of sunlight and is an ideal location for building photovoltaic power plants. Using floating technology to install a solar photovoltaic system on the water is a new idea. A floating photovoltaic power station adopts photovoltaic power station technology and floating technology, which has great development potential.

Agrawal *et al.* evaluated the technical potential of floating solar photovoltaic power generation through simulation, and discussed the development of floating solar photovoltaic technology from the aspects of future photovoltaic potential, water saving and land-saving potential, and took Rajghat dam in southern Uttar Pradesh, India as an example to estimate its annual power generation and reduced water evaporation[16]. Trapani and Redón Santafé reviewed various floating PV projects realized between 2007 and 2013 and envisaged future projects installed on the ocean using a composite laminated film material, which will make the structure flexible and be able to adapt to the waves in the ocean and inundation of the submersible array in adverse weather conditions[17]. Oliveira-Pinto and Stokkermans noted that the experience from inland floating solar energy projects can be used to expand and migrate from inshore to offshore conditions, explore floating methods in the marine environment, and investigate photovoltaic technology and solar power for floating in marine conditions[18]. That paper also discussed the currently available technologies, challenges and risks of the design and construction of the projects in the marine environment. Floating in the sea is more flexible than a conventional rigid glass module, and thus Sahu *et al.* introduced several key elements and put forward a hexagon photovoltaic array, which enables the whole system to follow the movements of the waves, thus minimizing the waves caused damages[19]. At the same time, the effect of these parts and all kinds of design schemes are further described[19].

2.3. Photovoltaic power supply platform with energy storage

Wind speed is affected by weather, geography, and other factors, while its size and wind direction will change regularly, and photovoltaic output is also closely related to weather changes. The change in light intensity and temperature will affect the size of output, resulting in great randomness, volatility, and intermittence of wind power and photovoltaic output. Scenery installed capacity of the entire network capacity is small, and scenery output fluctuations do not cause a negative influence on the power grid. However, as the scene is increasingly connected to the electricity grid capacity, the influence of randomness, volatility, and intermittent scenery output characteristics on the safety and stability of power system operation is more and more significant, greatly reducing the power quality. It considerably affects the grid connection of wind power generation and the frequency modulation and peak regulation of the power grid. The development of energy storage technology makes it possible to solve the output fluctuation of wind power generation.

Ning *et al*. introduced the basic principle of energy storage to smooth the output fluctuation of wind-power generation[20], expounded the research status of energy storage system control methods when wind-power generation fluctuation is smooth, and summarized the similarities and differences of various existing methods. Zhao and Cui introduced the photovoltaic system capacity ratio analysis optimization calculation using the leveling of the KWH cost concepts. The optimal energy storage system configuration and the project yield of this method were verified when compared with the optical storage system under different storage configurations and the existing load power and PV systems under the optimization calculation[21]. Gao *et al*. established eight kinds of wind-wind-load composite Copula models by combining the actual offshore wind farm power, photovoltaic power plant power and grid load, and proposed a hybrid time-varying Copula model based on rattan structure, which can more accurately describe the high-dimensional wind-wind-load dependence structure[22]. Sun *et al*. established the coordination relationship model between photovoltaic and energy storage systems[23], carried out the coordination optimization of energy storage devices under different output conditions of renewable energy, and proposed the voltage stability control method of regional power grid based on the coordination of distributed photovoltaic and energy storage. Recent studies in[24,25] proposed a method for different photovoltaic units and hybrid energy storage units to cooperatively suppress the bus voltage fluctuation and keep the load side voltage stable.

Although the floating power supply platform is predicted to have great development prospects, various limitations prevent the technology from being used commercially on a large scale. The near harbor is a complex environment that requires a consideration of the external environment such as geographical factors, climatic environment, solar emissivity, and so on, and requires the components to be able to withstand saltwater, strong ocean currents, waves, and wind. The current low maturity of the industry leads to a lack of direct reference standards for design in port environments. However, the industry can look to more established industries such as offshore oil and gas, or offshore renewable energy (MRE) such as offshore wind.

3. TOPOLOGICAL STRUCTURE DESIGN OF MICROGRID SYSTEM NEAR PORT

In the past decade, maritime transport has been responsible for nearly 90% of the world's overseas trade and logistics, accounting for 3% to 5% of total greenhouse gas emissions. This could rise to 18% by 2050, according to research by the International Maritime Organization (IMO). There is an urgent need for a more efficient maritime transport system, improving the efficiency of all the subsidiary energy subsystems. Today, seaport microgrids are seen as a viable way to improve overall system flexibility as well as mitigate growing environmental concerns. However, with the trend of electrification, the connection between port and ship is no longer limited to logistics but extended to power, which makes future maritime transport management a complex transport-power multi-microgrid coordination problem. Seaport microgrid is a representative and promising technology for shaping future green maritime transportation.

3.1. Harbor AC microgrid

The offshore wind power is connected to the onshore power grid. When charging, the ship is connected to shore power through AC/DC converter, and all the energy is transmitted to the ship through AC connection. The AC/DC converter, which charges the battery, is placed on the boat in a similar way to an on-board electric car charger. For small battery-powered fishing and recreational boats, shore-charging with a standard three-phase 400 V AC plug is the most common solution, which is also common in industrial environments. However, dedicated infrastructure should be built for passenger or car ferries that need more electricity to recharge the batteries on board. The power rating required for port infrastructure may vary depending on the number of ships calling at the port and the capacity of the batteries on board.

Karimi *et al.* described a charging system based on AC shore power[26]. Figure 1A shows a DC marine propulsion system based on AC shore power. In addition to the grid interface, there is a fixed battery storage system, which is usually slowly charged from the grid. Charging at night or off-peak hours not only reduces the strain on the local grid but also takes advantage of cheaper electricity. Transformer T12 is a 50 Hz transformer that reduces the grid voltage to the shore bus voltage and isolates the shore bus from the grid. The converter C15 acts as a charger and is responsible for rectifying the energy received from the shore. The C12 converter is directly connected to the onboard battery B11 to control the transfer of power during charge and discharge. Similarly, the converter C17 controls the energy of the onshore battery B12. In addition, the converter C16 acts as a rectifier when the onshore battery is charged and an inverter when the shipboard battery is charged. To reduce costs, some onboard propulsion systems have battery packs connected directly to the main bus, eliminating the need for a DC/DC converter. At this point, C15 controls the charging power. However, for multi-bus propulsion systems, each bus should have a dedicated charging converter, such as the C15, which controls the charging power balance of each onboard battery pack. Figure 1B shows the AC ship propulsion system based on AC shore power. The shore charging system is the same as that in (a), but it is connected to the AC propulsion system. An AC charging solution for an AC propulsion system requires synchronizing the voltage, phase, and frequency of the onboard power system to the onshore grid prior to connection. To avoid the synchronization process and to shorten the time, a dedicated active or passive rectifier, C27, can be used instead of a converter, C21. For the system in Figure 1B, a shipboard transformer can be added to provide current isolation or to adjust the voltage between the AC grid and the shore bus, but adding on-board transformers would result in higher costs and lower energy efficiency.

3.2. Harbor DC microgrid

At present, the mainstream ships use low-voltage AC power supply, and its shore power system also uses low-voltage AC systems. However, with the continuous enhancement of the functions of various types of ships and the increase of electrical equipment, medium pressure ships will become the main trend of ships in the future. The ship integrated power system represents the future development direction of the ship power system, and its power transmission and distribution subsystem adopts the medium voltage DC distribution network.

Compared to AC microgrids, DC grids have greater reliability and efficiency, simpler controls, and natural interfaces with renewable energy sources, as well as electronic load and energy storage systems. Dragicevic *et al.* studied typical power supply hardware topologies and their applicability to different emerging smart grid applications, and outlined the current state of development of DC MG protection and grounding technologies, but did not solve the problem of arc not being naturally extinguished due to DC current breakdown[27].

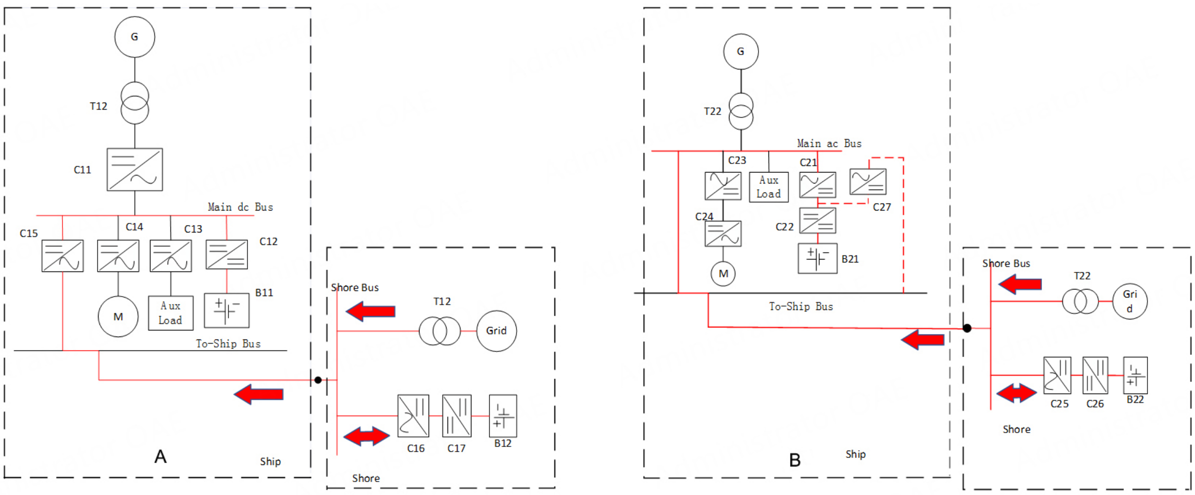

Figure 1. Marine propulsion system based on AC shore power.

Figure 2A depicts a DC marine propulsion system based on DC shore power. By comparing the power converters in Figures 1A and 2A, it is clear that the shipborne converter C15 has been replaced by the land-based C35. In this scheme, the charger converter (C32) can be removed, and the shipboard battery pack can be connected directly to the DC main bus. Onshore DC/DC converters can be installed at plugs to control charging power and reduce ship weight. Figure 2B depicts an AC marine propulsion system based on DC shore power. The ship bus is connected to the input end of the converter C42, so the charging path is the same as in Figure 2A

3.3. Harbor AC/DC hybrid microgrid

Hybrid AC-DC microgrids are a promising alternative to existing distribution systems to achieve near/net zero energy building goals. However, hybrid microgrid has increasingly high requirements for compact structure, seamless integration of distributed generators and load, and flexibility of control, which cannot be fully met by traditional grid architecture. Yu *et al*. proposed an integrated, reconfigurable AC-DC hybrid microgrid architecture and its layered control strategy with flexible control[28]. Yu *et al*. proposed a scalable and reconfigurable cluster architecture for hybrid microgrids and the corresponding decentralized control method[29].

Due to the gradual popularization of medium voltage direct current (MVDC) ships, namely the diversification of new energy sources in the port area, the future port is actually an AC/DC hybrid power system, as shown in Figure 3. Table 1 compares the advantages and disadvantages of the three microgrids.

4. CAPACITY PLANNING OF MICROGRID SYSTEM NEAR PORT

How to plan the capacity of photovoltaic and energy storage will directly affect the cost and benefit of grid-connected optical storage microgrid. Effectively solving this problem can greatly impact the promotion of new energy microgrids. However, capacity planning research based on limited historical data faces two major difficulties: firstly, photovoltaic power generation is uncertain, and it is difficult to accurately estimate its corresponding probability distribution; secondly, the photovoltaic power generation has high dimensionality, that is, the photovoltaic power generation situation of each day and time period in a longer dispatch period should be considered. Therefore, Xu *et al*. put forward the research idea of dimensionality reduction based on scene clustering analysis and then proposed an optimization method to deal with the uncertainty of photovoltaic power generation[30]. Wang *et al*. proposed a flexible DC grid capacity planning

Table 1. Comparison of microgrid structure

	DC	AC	AC/DC
Advantage	Simple renewable energy grid, high reliability and efficiency, simple control	Long-distance transmission and voltage conversion are convenient, power generation equipment is simple, and arc is easy to extinguish	Suitable for a variety of renewable energy generation
Disadvantage	The development of DC microgrid protection and grounding technology is limited	Complex to control and use	The cost is high, the structure is complex, and the control is difficult

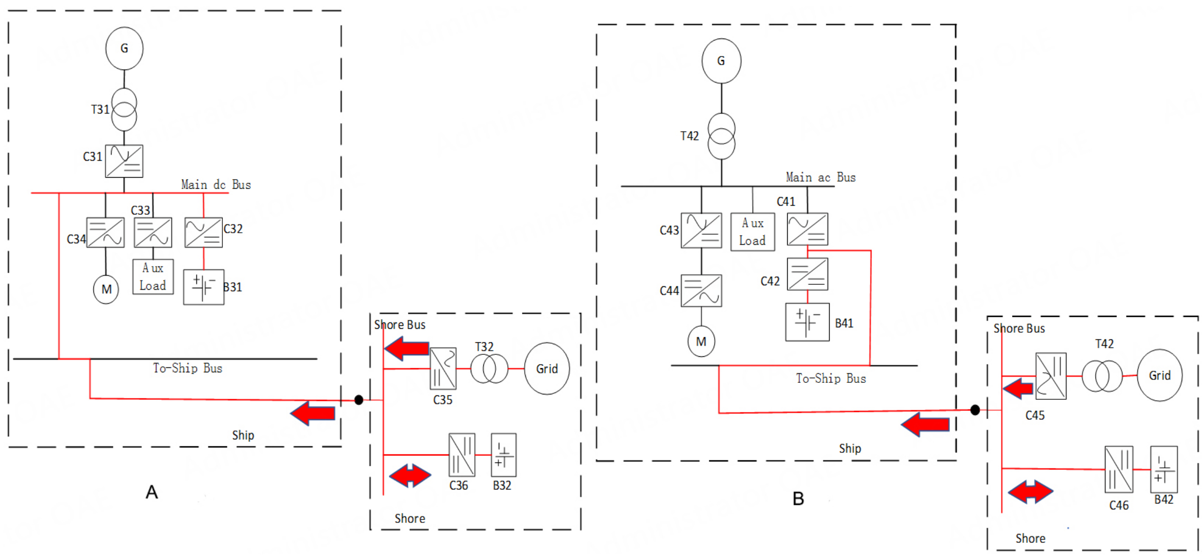

Figure 2. Marine propulsion system based on DC shore power.

method for large-scale new energy access[31], and proposed a joint optimization model that comprehensively considered the output characteristics of energy storage power sources, DC grid transmission capacity, and new energy generation constraints. Ju *et al*. proposed a two-tier robust wind and firewood storage capacity planning model by comprehensively considering the cost parameters[32], wind energy resource uncertainty, and standby demand in the planning process of independent microgrids. Aiming to solve the typical day selection problem of microgrid capacity planning, Zhong *et al*. and Guo *et al*. constructed a comprehensive evaluation index system for typical day selection and proposed a two-stage planning capacity allocation method[33,34].

The first result of the OptimaGRID project determines the scale of renewable resources based on the availability and local needs of renewable energy resources[35]. The design is suitable for a microgrid in the Tanos area of Bayonne Port, which contains a 150 KW photovoltaic array and two 50 KW wind turbines. The 800 KWh REDOX battery has a maximum power of 126.6 kW and an annual energy of 96 MWh. Finally, HOMER and EUROSTAG software are used to determine whether the amount of the microgrid power supply meets the demand of the port and test its dynamic operation. But the system cannot meet the requirements of cold ironing. In order to ensure the continuity of service, Parise *et al*. compare the structure of microgrid and the layout of power generation system[36], so as to ensure the power supply of critical loads in emergency situations in terms of energy management. The power grid includes photovoltaic and wind power generation equipment, with an annual energy of 150-200 MWh and a maximum power of 140 MW. Gennitsaris and Kanellos proposed a multi-agent real-time demand side management system[37] (including reefer containers, berth ships, wind turbines, *etc*.) applicable to cold ironing of freezers in commercial ports

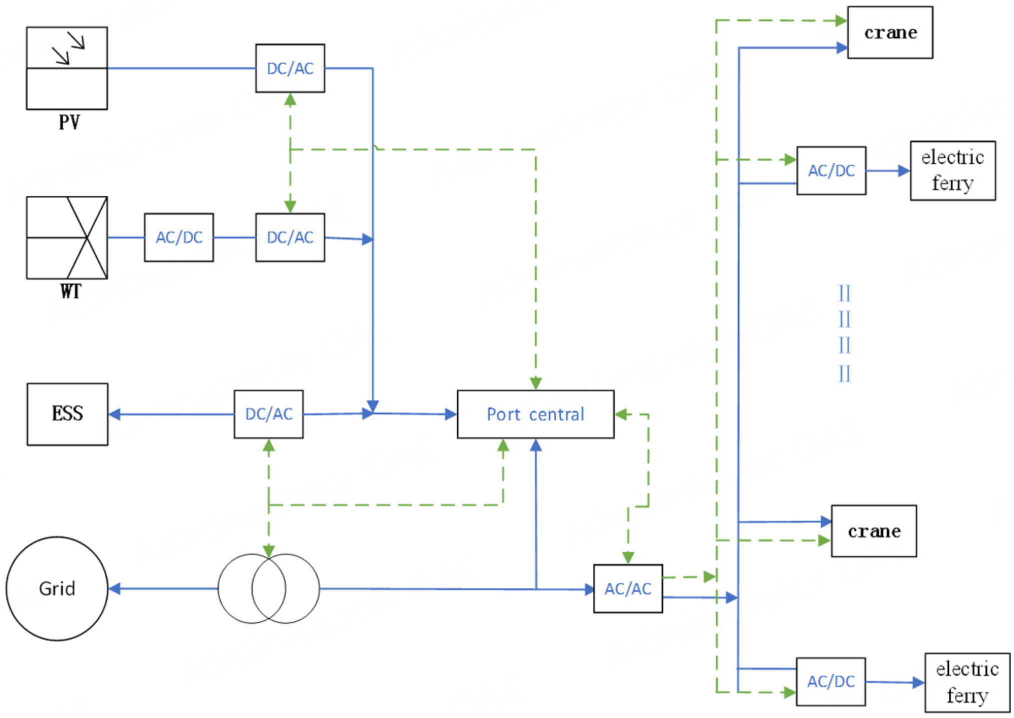

Figure 3. AC/DC hybrid microgrid topology.

and ships, and designed the required communication lines. The system has a maximum power of 30 MW and the required communication lines are designed to minimize operating costs, pollutant emissions and wind power fluctuations. Gutierrez-Romero *et al*. design port power grids that meet the requirements of onshore power supply and RES scale based on the needs of different types of ships[38]. Considering the available area of PV, its output power can reach 9.7 MW, onshore wind turbine 36.3 MW and offshore wind turbine 16 MW, with a daily output of 314 MWh and a maximum power of 13.1 MW. Cold ironing of ships via land power and the use of the RES system can reduce carbon dioxide emissions from moored auxiliary generators by 10,000 tons per year. These three systems include a cold ironing system but no energy storage system. The microgrid referred to Kotrikla *et al*. contains a 5 MW PV system and a 6 MW wind turbine with a daily output of 22 MW hours and a maximum power of 900 kW[39]. While the system also has no energy storage, it connects the surplus of renewable generation to the onshore grid to power other loads. Renewable energy provides the energy needed for cold ironing through the main grid at low power without storage. Ahamad *et al*. introduce the optimal design of microgrid, give the size and energy planning of microgrid, and evaluate the performance of microgrid for load power supply[40]. The integrated system consists of a 200 KW PV, a 4.95 MW wind generator and a 465 MWh grid-connected battery, with a daily output of 39 MWh and a maximum power of 5.2 MW. The optimization results and sensitivity were analyzed by using the HOMER software. Wang *et al*. propose a two-stage optimization framework to solve the optimal design problem of a seaport hybrid renewable energy system[41]. Kumar *et al*. propose a microgrid suitable for electric ferry charging and cold ironing, which includes a 33 MW photovoltaic power generation device, a 30 MW wind turbine, and a 35 MWh lithium-ion battery[42]. However, the system is limited due to line congestion, battery power and capacity.

5. INTELLIGENT CONTROL METHOD AND ENERGY MANAGEMENT STRATEGY OF NEAR PORT MICROGRID SYSTEM

Because the port scale expands unceasingly, the traditional port will bring more energy consumption and harmful gas emissions, noise, such as environmental pollution. Marine exhaust has become one of the major air pollution sources in China's port cities. Construction of green ports and improving port energy using clean purification rate are around the corner. It is necessary to adjust measures to local conditions for the development of distributed photovoltaic (PV) in the harbor and distributed wind. Exploring effective energy management strategies is one of the key aspects when constructing a port microgrid in the future.

5.1. Distributed control method

A harbor microgrid is designed to manage all energy-related issues within a harbor area. However, so far, research on this topic has been limited. Ahamad *et al.* modeled the harbor microgrid and simulated the steady-state and transient behaviors of the harbor microgrid when it provides shore power supply to berthing ships[40]. As the ship enters and leaves the port continuously, there will always be an insertion operation, which may bring a large pulse to the power grid. From this perspective, seaport controls are similar to electric car charging stations. However, since the port microgrid is usually composed of many subsystems, most of which operate independently, the traditional centralized control framework may lead to inefficiency. Distributed control architecture has great advantages in realizing real-time coordination and is not restricted by the above problems. Distributed scheme distributes computing and communication burden to distributed controller and has stronger robustness to communication failure. At present, distributed framework has been widely used in distributed control and automation of land-based power systems. Because of this huge advantage, the distributed control method is also suitable for the control of harbor microgrids. It has good flexibility for network reconfiguration, and its voltage/frequency adjustment facilitates plug and play of the ship in cold ironing mode.

Zhong *et al.* analyzed the problems caused by voltage overlimit and network loss increase caused by large-scale distributed new energy generation access to the safe and stable operation of the distribution network and proposed a data-driven distributed voltage control method for high-proportion new energy generation cluster[43]. Li *et al.* and Deng *et al.* studied the impact of large-scale new energy access on the distribution network and proposed different methods[44,45]. Ma *et al.* and Liu *et al.* put forward a new distributed control method for the current and voltage sharing problem of a DC microgrid[46,47]. Yang *et al.* and He *et al.* applied distributed control technology to port lighting control[48,49], which improved the intelligent management level of port lighting control and reduced the energy consumption of port lighting facilities.

5.2. Energy management for demand response at multiple time scales

Renewable energy generation and load demand change in real time, and thus considering multi-time scale energy management has gradually become the mainstream[50]. Roy *et al.* list the main components of port microgrid, and then review the research on the scale and energy management of port microgrid[51].

For the study of energy management at a long time scale, Chen *et al.* adopt stochastic energy network theory to deal with the power balance problem to optimize the capacity of islanded microgrid for the uncertainty of source and charge[52]. Hu *et al.* propose a two-stage day-ahead energy management strategy including centralized control and distributed control[53]. Li *et al.* consider day-ahead load forecasting and renewable energy forecasting and set the interval as 1 h to propose a distribution optimization strategy[50]. Huang *et al.* propose a scheduling framework based on the two-level model, which adopts the advanced real-time two-stage stochastic optimization method combined with the TOF price mechanism to fully coordinate the energy management decisions of various market stakeholders[54].

For energy management research on a short time scale, in order to improve the system operation reliability and reduce network losses, the drooping slop-reactive power joint optimization is carried out based on the day-ahead scheduling results[55]. Xiao *et al*. establish an intra-day rolling optimal scheduling model based on the model predictive control method to ensure that the microgrid has a certain adjustable capacity while consuming renewable energy[56]. For studies on shorter time scales. Gong *et al*. divide microgrid energy management into five-time scales: 1 day ahead, 30 min to 1 h within the day, 5 to 15 min, 1 min and real-time scheduling, which make the scheduling plan more accurate and reduce the pressure of real-time adjustment[57].

In the study of real-time energy management, Bao *et al*. comprehensively consider different generation side resources to establish a real-time scheduling model and improve the prediction accuracy of wind power[58]. Ma *et al*. develop a real-time and cost-effective residential load scheduling framework[59], whose cost-effectiveness can vary with different consumption patterns and is very sensitive to load behavior. Arun *et al*. propose a heuristic algorithm for real-time load scheduling, which aims to reduce the electricity bill while keeping the total consumption under the maximum demand limit[60]. Ye *et al*. solve the real-time demand-side management problem of microgrids equipped with renewable energy and storage systems, and show that game-theoretic energy scheduling supported by communication networks can smooth the peak-to-average ratio (PAR) of power consumption[61].

In the selection of multiple time scales, the selection of a long time scale is generally 1 day, and the selection of a short time scale is different. A dense time scale will increase the solution time of the scheduling plan, while a sparse time scale will increase the pressure of real-time adjustment. Therefore, it is necessary to select an appropriate time scale for energy management research of microgrids. Table 2 lists the advantages and disadvantages of different time scale controls.

6. SOME COMMERCIALLY OPERATIONAL CASES IN THE WORLD

Jurong Port was built in 1963 and has served Singapore as its main port of entry for more than 50 years. Sunseap Leasing, a unit of Singapore's leading solar system developer Sunseap Group, has partnered with the port to develop the 76,000-square-metre system, which sits atop the Jurong Harbor Warehouse. With a solar power system of 9.5 MWP, the port generates more than 12 million kWh of electricity per year, which is expected to provide 60% of the port's total electricity demand and reduce carbon dioxide emissions by up to 5200 tons per year. The port will further integrate 5 MWp's photovoltaic modules and eventually become the world's first zero-carbon footprint port. Due to the intermittency of PV integration, 10,000 to 15,000 MWh of PV energy per year will remain untapped until 2018. Therefore, Jurong Port urgently needs microgrid technology to facilitate the integration of renewable energy[62].

The port of Hamburg and the city of Hamburg have invested in renewable energy since the German city of Hamburg pioneered wind energy in the early 1990s. Wind energy has been central to Hamburg's renewable energy strategy, with the port area accounting for half of wind energy production and the city also participating in the development of offshore wind farms. Large turbines are being tested off the coast at Cuxhaven and Brunsbuttel, and the scheme is playing a major role in boosting renewable energy in the ports to facilitate the development of solar facilities on the docks and warehouse roofs. Two units are already in service. Hamburg's port also uses solar thermal energy. The HPA office's hot water is generated by a solar thermal unit on the roof, saving 56,000 kW/h of electricity per year.

The Netherlands Energy Research Centre, the Netherlands Institute for Applied Scientific Research, the Netherlands Institute of Oceanography, the ABU Dhabi National Energy Company, and the Ocean Energy

Table 2. Compare multiple time scale management

	Length of time	Advantage	Disadvantage
Long time scale	One day or more than 24 h	Take into account more aspects, and reduce the pressure of real-time adjustment	Limited time domain selection
Short time scale	Not sure (hours, minutes)	Smaller error, more accurate	Not in time
real-time	Within a minute, a few seconds	The response is faster and timelier	The control is complex and error-prone

Table 3. The case of current operation

Country	Harbor	Load	RES
Denmark	Copenhagen[40]	E = 38 MWh/day P_{max} = 5.2 MW	PV (200 KW) WT (4.95 MW)
Greece	Mytilene[39]	E = 22 MWh/day P_{max} = 900 kW	PV (5 MW) WT (6 MW)
USA	Long Beach[36]	E = 150-200 MWh/day P_{max} = 140 MW	PV, WT
Spain	Cartagena[38]	E = 314 MWh/day P_{max} = 13.1 MW	PV (until 9.7 MW) WT (onshore: 36.3 MW; Offshore: 16 MW)
Singapore	Jurong port	E = 200 MWh/day	PV, WT

Company affiliated with the Delft University of Technology, the Netherlands, jointly developed, constructed and operated the world's first offshore floating photovoltaic power station (Bellini,8.5 kW modular PV system). It has been in operation since November 2019 and has successfully withstood multiple storms. The pilot program aims to expand to 50 KWp in the short term and will be tested for a year[63]. Table 3 shows some existing examples of WT and PV generation at some ports.

7. CONCLUSIONS

The development of floating technology and renewable energy generation technology has solved the problem of port energy shortage. However, the floating technology is greatly affected by wind and waves, and the floating power generation platform only stays near the port. Port load capacity is large, and energy management is complex. Flotsam and energy management strategies suitable for ports are being explored. Future renewable energy generation at ports will involve deep sea areas, and thus the use of offshore wind power and energy management will need to be more coordinated. This paper reviews the current utilization of renewable energy and intelligent control strategies of smart seaports. In the future, efficient control strategies of smart seaports will be used to improve energy conversion efficiency and build clean ports.

DECLARATIONS

Acknowledgments

Special thanks to the Intelligent Electrical Science and Technology Research Institute, Northeastern University (China), for providing technical support for this research.

Authors' contributions

Made substantial contributions to conception and design of the study: Li G, Wang T, Zhou B
Provided administrative, technical, and material support: Xiao Z, Yan S, Liu B

Availability of data and materials

Not applicable.

Financial support and sponsorship
This work was supported in part by the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources under Grant LAPS21007, in part by the Guang-dong Basic and Applied Basic Research Foundation under Grant 2021A1515110778, in part by the Fundamental Research Funds for the Central Universities Grant N2104014, in part by the Joint Funds of the National Natural Science Foundation of China under Grant U22B20115.

Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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