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Polymorphic Distributed Energy Management for Low-Carbon Port Microgrid With Carbon Capture and Carbon Storage Devices

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In order to reduce the carbon emission of the port and build a green port, a polymorphic distributed energy management method for the low carbon port microgrid with carbon capture and carbon storage device is proposed. Firstly, this paper presents a low carbon port microgrid in a polymorphic network environment to realize the information interaction among energy subjects in different modes and improve network communication performance among port power generation device, main grid, carbon capture and carbon storage device. Secondly, the energy management model of low-carbon port microgrid is constructed considering the additional carbon capture device and carbon storage device in the port. Then, based on the multi-agent consensus algorithm, a distributed energy management method is proposed, which is respectively oriented to the grid-connected operation mode, island operation mode and switching operation mode of the port microgrid, so as to achieve the economic, low carbon and reliable operation of the port microgrid. Finally, the simulation results of Matlab verify the effectiveness of the proposed method.

Keywords: energy management, polymorphic, carbon tax, distributed, port microgrid

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1 INTRODUCTION

Under the accelerated development of the global economy, the demand for cargo transportation in international trade is growing. As the node of global maritime transport, ports are embracing new development opportunities. However, the large amount of carbon dioxide emitted by the port aggravates environmental pollution (Kinnon et al., 2021) and leads to global warming, which hinders the sustainable development of the port. At the same time, under the influence of IMO regulations and the urgent demand for carbon neutrality in the world (Wang et al., 2018), it is critical to reduce CO_2 emissions from ports and build a low carbon port microgrid.

With the transformation of port energy, utilizing new energy sources to supply power for ports has become an effective way to reduce port carbon emissions (Zhang et al., 2021). However, considering the instability and uncertainty of new energy sources (Li et al., 2021; Wang et al., 2022), it is still necessary to include conventional power plants in the port microgrid to ensure the reliability of the port power supply. Energy management of port microgrid is the key to ensure its reliable operation and has been studied by many experts and scholars. The energy management problem is a complex system optimization problem with the objective of maximizing the operating economy and satisfying multiple constraints for safe and stable operation (Deng et al., 2021; Zhang et al., 2022a).

To address the additional cost of specific types of load demand in ports, Kermani (Kermani et al., 2022) proposed an energy storage system that includes multiple energy storage devices to decline power peaks, reduce energy waste and ensure port economics. Kanellos (Gennitsaris and Kanellos, 2019) proposed a multi-agent based real-time load demand response system to limit port carbon emissions and minimize port operating costs to solve the problem of flexible loads and significant carbon emissions in ports. Most current energy management methods are classified as centralized or distributed algorithms (Yang et al., 2019; Yang et al., 1109; Huang et al., 2022), but for low carbon port microgrid that contains large scale clean energy, due to the distributed nature of its generation devices and loads, distributed algorithms have attracted widespread attention. To tackle the existence of multiple generation modes and load types in ports, Zhang (Zhang et al., 2020) proposed a novel distributed energy management approach for ports based on a multi-agent consensus algorithm to optimize port energy allocation and improve energy efficiency. Aiming at the damage caused by false data injection attacks on port power systems, Shan (Shan et al., 2022) proposed a distributed energy management strategy with a topology reconstruction mechanism to mitigate the impact of the attacks and improve the security of port power systems. Port microgrids are divided into two modes of operation: grid-connected mode and island mode. Meanwhile, the network contains a variety of power generation devices such as conventional power plants, photovoltaic power generation, wind turbine power generation, as well as carbon capture and carbon sequestration device, with the diversified mode. Due to the problems of single IP and low suppression of unknown threats in the existing communication networks (Guan et al., 2018; Hu et al., 2019), it is difficult to adapt to the distributed energy management of the low-carbon port microgrid. Therefore, polymorphic networks, that match the actual low carbon port microgrid, must be developed so that the communication network can obtain polymorphic convergence dynamic. And relevant scholars have already conducted wide exploration on polymorphic networks. Wu (Hu et al., 2020) introduced "structure definability" to all aspects of networks to improve the efficiency, performance, functionality and security of the Internet from the perspective of network architecture and to achieve the requirements of nowadays intelligent, diverse, highly robust and efficient networks. Hu (Hu et al., 2022) proposed a scheme of the polymorphic network element based on codesign of domain-specific software and a heterogeneous resource allocation and replacement method to realize efficient resource utilization. The results show that the proposed scheme can provide a basic platform to support the polymorphic network. In (Salamatian, 2011), Kave proposed two propositions: the Internet of the future should be polymorphic and it should be built on a strong foundation of network science. Zhang (Zhang et al., 2022b) constructed a multilateralised distributed cooperative control framework and proposed a communication topology reconfiguration method applicable to multiple multi-agent systems with different functions after networking in order to address the limitations of cooperative control of a single multi-agent system in a unilateral network environment. Thus it can be seen that the polymorphic network promotes the implementation of distributed control and optimization technology. As existing networks cannot meet the communication needs of modern smart ports, how to build a low-carbon port microgrid in a polymorphic network environment and realize its distributed energy management is the issue that needs attention.

Large-scale clean energy is connected to the port microgrid instead of traditional energy, which has achieved the reduction of pollution and carbon emission in the port to a certain extent. To further reduce carbon emissions, carbon capture devices need to be installed in ports to capture carbon dioxide, capturing the carbon dioxide emitted from conventional power plants in ports and then storing it through carbon sequestration devices, which can minimize the emission of carbon dioxide from port microgrid to the air (Damm and Fedorov, 2008) and promote the implementation of a green port. There have been a lot of researches on carbon capture and storage devices. Mostafa (Mostafa et al., 2018) demonstrated that carbon capture devices are more efficient in reducing CO_2 and less expensive to operate by comparing the CO_2 emission quality and operating costs of CO_2 emissions from power systems that include carbon capture devices with those that use chemical absorption. Alireza (Akbari-Dibavar et al., 2021) integrated carbon capture and storage devices into a conventional power plant and proposed the economic-emission dispatch problem using a Pareto frontier in a multi-objective optimization framework to achieve an economical and low-carbon power system. Fang (Fang et al., 2019) proposed a joint generation and demand-side management method under the Energy Efficiency Operating Index (EEOI) constraint to address the power shortage caused by carbon capture devices on board ships and illustrated the feasibility of carbon capture devices to reduce CO_2 emissions from the shipping industry. In addition to the use of clean energy and the installation of carbon capture and storage devices, market mechanisms represented by carbon taxes and carbon trading have become important initiatives to reduce carbon emissions from ports and ships. Arijit (De et al., 2021) proposed a ship fuel management strategy that took into account carbon taxes and explored the impact of fuel prices and carbon taxes on shipping operations in terms of operating costs. Zhen (Lin et al., 2022), on the basis of considering carbon tax, proposed a mathematical model that minimizes the sum of the total carbon emission cost and the total penalty cost of the port and effectively solved the model by using the heuristic algorithm based on the sequential method, to minimize the carbon emission of the port and optimize the spatial allocation of the port. For the problem of vessel scheduling and cargo flow allocation under the carbon emission trading mechanism, Wang (Yu and Wang, 2015) proposed a ship scheduling and cargo flow allocation model considering the cost of container cargo detention time under the mechanism to achieve the maximum emission reduction and profit for liner companies. But, for now, the use of carbon trading to reduce carbon emissions requires multi-sectoral supervision, and the implementation steps are cumbersome,

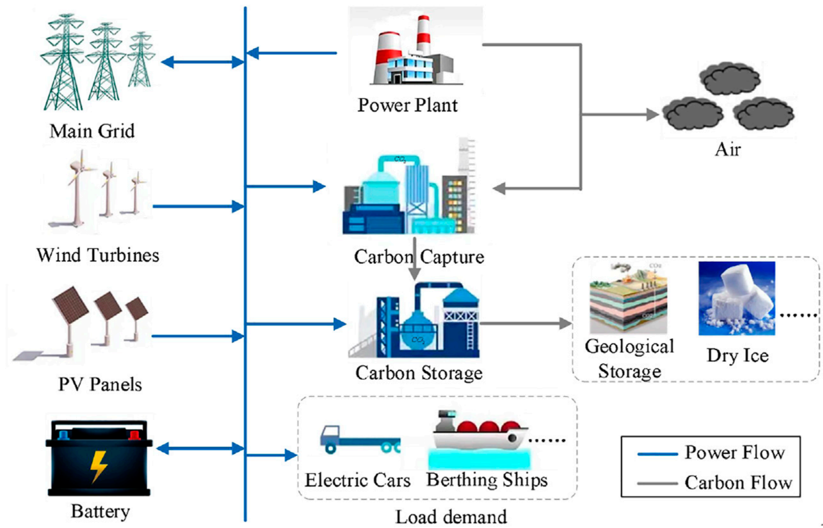

FIGURE 1 | Components of the low-carbon port microgrid.

with the application effect not ideal. Therefore, in the process of distributed energy management for low-carbon port microgrid, how to use the carbon tax to treat the carbon dioxide emitted into the air by the port under the target of reducing the carbon emission of the port and achieving a green port is a critical issue that needs to be solved.

As shown above, this paper is dedicated to constructing a low-carbon port microgrid under the polymorphic network environment and proposes a distributed energy management method under various operating conditions to ensure reliable and economic operation of the port microgrid and to achieve pollution and carbon reduction in the port. The specific contributions are as follows.

1) Construct a low-carbon port microgrid based on the polymorphic network, in order to realize the information interaction among various energy subjects under different modes and improve the performance of network communication among the port power generation device, main grid and carbon capture and storage device.

2) Considering carbon capture and storage devices, the energy management model of the low-carbon port microgrid is constructed. With the objective of minimizing the operating cost of the port microgrid, the power purchase or selling cost of the main power grid and the cost of carbon, as well as considering the supply and demand balance of the port microgrid and other constraints, the energy management model is constructed to achieve economic, low-carbon and reliable operation of the port microgrid.

3) A distributed energy management method for various working conditions of the port microgrid is proposed in this paper. For both grid-connected and island operation modes of the port microgrid, the distributed energy management of the low-carbon port microgrid is implemented based on multi-agent leader-following consensus and average consensus respectively to ensure the reliability and economy of the port.

2 ANALYSIS OF LOW-CARBON PORT MICROGRID ARCHITECTURE UNDER POLYMORPHIC NETWORK

There is a carbon capture device, a carbon sequestration device, and various power generation devices such as the conventional power plant, photovoltaic power generation, and wind turbine power generation in the low-carbon port microgrid, as shown in **Figure 1**.

The port microgrid can be operated in grid-connected mode or island mode. In grid-connected mode, the loads in the port microgrid are powered by the main grid, conventional power plant, photovoltaic power generation, wind turbines, and storage devices. In island mode, the port microgrid is powered by the conventional power plant, photovoltaic power generation, wind turbines and storage devices.

To achieve low-carbon operation, the port microgrid uses the carbon capture device and storage device to treat the carbon dioxide emissions from the conventional power plant. Most of the carbon dioxide emitted is captured by the carbon capture device and a small amount is released into the air. The carbon dioxide captured by the carbon capture device is then encapsulated and stored in a carbon storage device, and this part of carbon dioxide can be used for various purposes, including as a raw material for P2G, making dry ice, etc.

Due to the diverse working conditions and device types of low-carbon port microgrids, it is difficult for the existing traditional communication network architecture to adapt to modern smart low-carbon ports. Therefore, this paper proposes a diversified, specialized and intelligent low-carbon port microgrid based on the polymorphic network, and its network architecture is shown in **Figure 2**. The low carbon port microgrid based on the polymorphic network is mainly divided into three layers: the data layer, the control layer, and the service layer, with different functions. The data

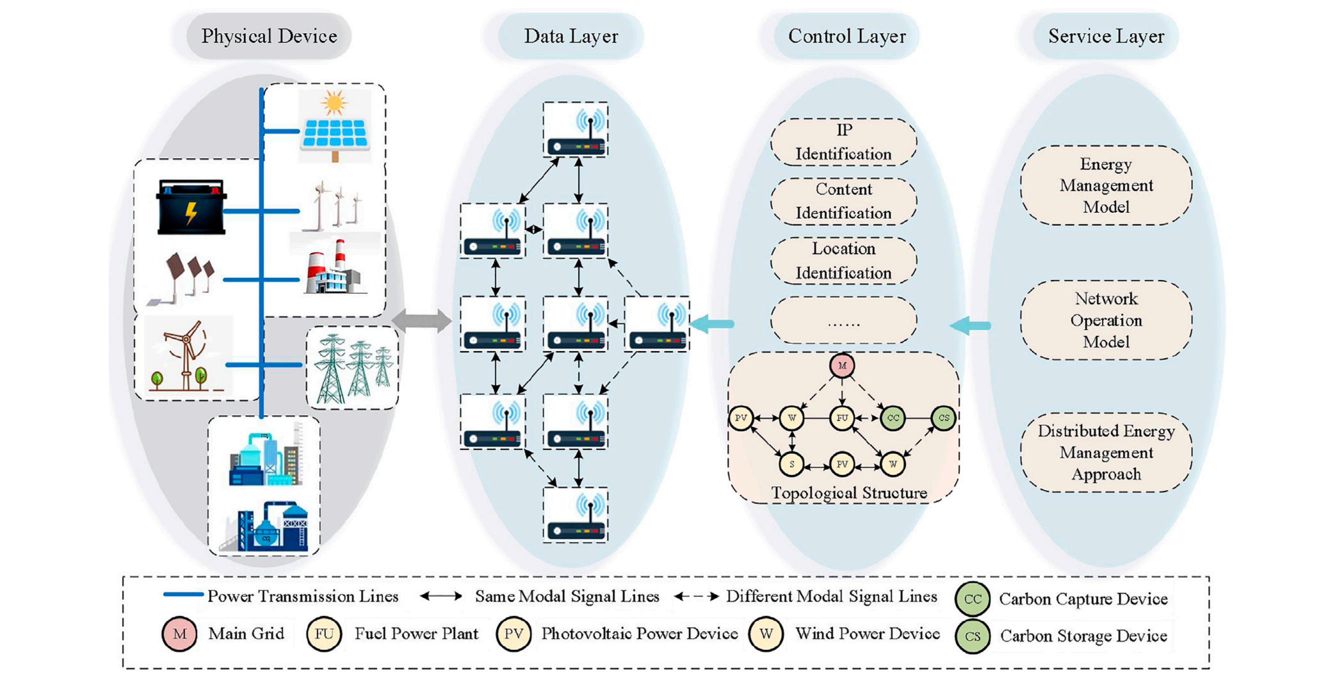

FIGURE 2 | The polymorphic network architecture of low-carbon port microgrid.

layer is mainly responsible for the full-dimensional definition of the topology, protocols, software and hardware, and interfaces of the port microgrid, providing refined services for diversified applications and essential support for the realization of future network intelligence, flexibility, and diversity. The control layer undertakes the service layer upward to address and route between single modality and different modalities, and controls the data layer downward to calculate and convert the different requirements of the upper-layer business into the control information of the data layer. Through the polymorphic controller, the diversified routes are defined according to the service requirements, and the communication topology is constructed according to the constraint conditions to realize polymorphic addressing interconnection and on-demand switching, so as to lay the foundation for the subsequent distributed energy management. The service layer mainly realizes the distributed energy management of the low-carbon port microgrid. The essence of polymorphic network is the process of top-down functional fitting from business requirements to fine-grained resource partitioning on the basis of a fully-dimensional definable network structure. The three layers implement business and service fitting, service and route fitting, route and resource fitting which are driven by business requirements, respectively. First, various device operation models are established, then the low-carbon port microgrid energy management model is constructed, and finally the distributed energy management method is designed according to the port microgrid operation mode.

3 LOW-CARBON PORT MICROGRID ENERGY MANAGEMENT MODEL

3.1 Objective Function

This paper aims to minimize the operating cost of polymorphic low-carbon port microgrid. The objective function includes three parts: one is the operating cost of the power generation and energy storage device; one is the cost of trading with the main grid; the other is the carbon cost. The function is as follows:

$$F = \min\{F_1 + F_2 + F_3\} \tag{1}$$

where, F is the total operating cost of the polymorphic low carbon port microgrid, F is the operating cost of the power generation and energy storage device, F_2 is the cost of trading with the main grid and F_3 is the carbon cost.

3.1.1 The Operating Cost of the Power Generation and Energy Storage Device

The operating costs of power generation and energy storage devices include the conventional power plant generation costs, wind turbine generation costs, photovoltaic generation costs, and energy storage device operating costs. The details are as follows.

$$F_1 = \sum_{n_1} f_{fu} + \sum_{n_2} f_w + \sum_{n_3} f_{pv} + \sum_{n_4} f_s \tag{2}$$

where, f_{fu} is the cost of conventional power plant generation, f_w is the cost of wind turbine generation, f_{pv} is the cost of photovoltaic generation and f_s is the cost of energy storage device operation, n is the total number of powered devices in the port microgrid, $n_1 + n_2 + n_3 + n_4 = n$.

Since the operating cost functions of the considered generation and storage devices are generally in the quadratic form (Teng et al., 2020), they can be uniformly expressed as:

$$f_i = \frac{(P_i - \alpha_i)^2}{2\beta_i} + \varphi_i, i \in 1, 2, 3...n \tag{3}$$

where, f_i is the operating cost of the i th device, P_i is the amount of power supplied by the i th device, $\alpha_i \leq 0$, $\beta_i \geq 0$ and φ_i are the cost coefficients of the i th device.

3.1.2 The Cost of Trading With the Main Grid

When the port microgrid is connected to the main grid, the port and the grid company agree on a trading price for electricity. When the port microgrid generates more electricity than it needs and still has a large surplus, it can sell the excess electricity into the market at the price agreed by the grid company to earn the difference; when the microgrid generates less electricity than it needs, it can buy the required electricity at the price agreed by the grid company to ensure the safe and reliable operation of the port. The cost of trading with the main grid is as follows

$$F_2 = \lambda_0 P_M \tag{4}$$

where, λ_0 is the trading electricity price agreed with the main grid and P_M is the power purchased from (sold to) the main grid.

3.1.3 The Carbon Cost

In the carbon cost, since the carbon storage device needs to store carbon dioxide through a series of methods, and the stored carbon dioxide requires a harsh storage environment, the cost of carbon sequestration should be additionally considered here. For this reason, the carbon cost includes the carbon storage costs and carbon tax costs. And the formula is as follows:

$$F_3 = f_{cs} + f_{tax} \tag{5}$$

where, f_{cs} is the cost of carbon storage, f_{tax} is the cost of the carbon tax.

In the cost of carbon, as the operation of the carbon capture device consumes electricity, it can be seen as an electrical load and is not additionally accounted for in the cost of carbon. However, carbon storage device requires various methods to sequester carbon dioxide. The sequestered carbon dioxide requires a harsh preservation environment, so the cost of carbon sequestration is also considered here. The energy consumption of a carbon capture device includes both operational and fixed energy consumption. Operational energy consumption is proportional to the mass of carbon dioxide captured. With the more carbon dioxide captured, the more operational energy is used. The amount of carbon dioxide that a carbon capture plant can capture is related to the quality of carbon dioxide emitted by conventional power plants. In contrast, the quality of carbon dioxide emitted by the port is related to the amount of electricity produced by the port plant. At the same time, the carbon capture plant consumes a certain amount of power to keep running, even when it is not in operation, and this is used as fixed energy consumption. The relevant equation for the carbon capture device is expressed as follows.

$$\begin{aligned} P_{cc} &= P_{fec} + P_{oec} = P_{fec} + \psi E_{cc} \\ E_{cc} &= \tau E_{fu} = \tau \omega P_{fu} \end{aligned} \tag{6}$$

where, P_{cc} is the total energy consumption of carbon capture device, P_{fec} is the fixed energy consumption of carbon capture device, P_{oec} is the operating energy consumption of carbon capture device, ψ is the energy consumption coefficient of the carbon capture device to capture unit CO_2, E_{cc} is the mass of CO_2 captured by the carbon capture device, τ is the efficiency of the carbon capture device to capture CO_2, E_{fu} is the mass of CO_2 emitted by the port conventional power plant, ω is the mass of CO_2 produced by the unit power output of the conventional power plant in the port, P_{fu} is the electricity produced by the port conventional power plant.

The cost of carbon storage is relative to the quantity of carbon dioxide trapped by the carbon capture device, while its energy consumption is relative to the amount of carbon dioxide stored. The details are as follows

$$\begin{aligned} f_{cs} &= \sigma E_{cc} \\ P_{cs} &= \gamma E_{cc} \end{aligned} \tag{7}$$

where, σ is the cost coefficient of storing unit carbon dioxide, P_{cs} is the energy consumption of carbon storage, and γ is the energy consumption factor of storing a unit of carbon dioxide.

Among the carbon cost, the formula for the carbon tax is as follows.

$$f_{tax} = C_{tax} E_e \tag{8}$$

where, C_{tax} is the unit price of the tax per unit of CO_2 emitted and E_e is the mass of CO_2 emitted into the air by the port microgrid.

3.2 Constraint

To ensure the reliable operation of the port microgrid, the following constraints should be followed.

1) Power balance constraint

$$\sum_{i=1}^{n} P_i + P_M = \sum_{i=1}^{n} P_{load} + P_{cc} + P_{cs} \tag{9}$$

where, P_M is the main grid input and output power, and P_{load} is the load of the port microgrid.

2) Output power constraints for power generation devices

$$P_i^{\min} \leq P_i \leq P_i^{\max} \tag{10}$$

where, $P_i^{\min}$ and $P_i^{\max}$ are the minimum output power and maximum output power of the i th generation device, respectively.

3) Energy consumption constraints for carbon capture devices

$$P_{cc}^{\min} \leq P_{cc} \leq P_{cc}^{\max} \tag{11}$$

where, $P_{cc}^{\min}$ and $P_{cc}^{\max}$ are the minimum and maximum energy consumption of the carbon capture device, respectively.

4) Energy storage constraints

$$SoC^{\min} \leq \left| 1 - \frac{P_s}{P_e} \right| \leq SoC^{\max} \tag{12}$$

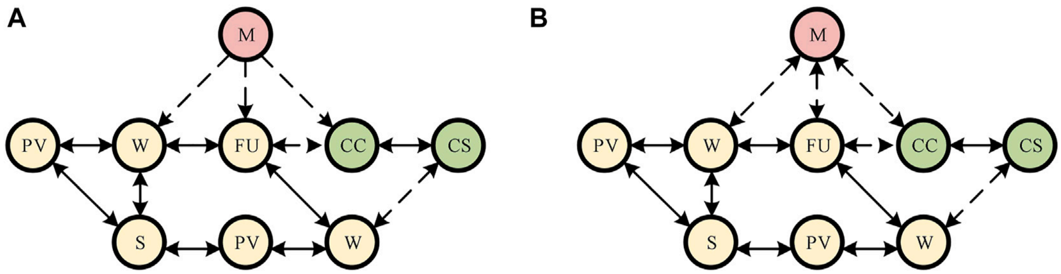

FIGURE 3 | The topology of low carbon port microgrid based on polymorphic network. **(A)** is the topology of the information flow, **(B)** is the topology of the energy flow.

where, P_e is the rated power of the energy storage device, $SoC^{\min}$ and $SoC^{\max}$ are the upper and lower limits of the capacity of the energy storage device, respectively.

4 DISTRIBUTED ENERGY MANAGEMENT METHOD FOR LOW CARBON PORT MICROGRID

The polymorphic port microgrid has two modes of operation: grid-connected mode and island mode. Since there are differences in the energy management methods of the two modes, the distributed energy management methods are designed in this section for the two operation modes and the operation mode switching states, respectively. The topology of the information flow of the low-carbon port microgrid based on the polymorphic network is shown in **Figure 3A**, and the topology of the energy flow is shown in **Figure 3B**, where information can be exchanged between different modes by routing. Information can be exchanged directly within the modes.

4.1 Graph Theory

A directed graph can be represented as $G = \{V, E\}$, N is the number of nodes. Where $V = \{v_1, v_2, v_3, ...v_N\}$ is the set of nodes and $E = \{e_1, e_2, e_3, ...e_M\}$ is the set of lines connecting two points, that is, the set of relations between two points. a_{ij} denotes the edges (v_i, v_j), when $(v_i, v_i) \in E$, $a_{ij} = 1$; when $(v_i, v_i) \notin E$, $a_{ij} = 0$. The adjacency matrix represents the relations between vertices, and $A = (a_{ij})_{N\times N}$, is an N-order square matrix (Li et al., 2020).

4.2 Grid Connection Mode

In the grid-connected mode, since the electricity price of the main grid is not affected by other factors, the main grid does not receive information, but only transmits information. However, in the energy flow, the main grid is able to exchange energy with the generation plant, carbon capture and storage plant. In the event that the port microgrid generates too much power, or does not generate enough power to meet the required load, it can sell power or buy power from the main grid.

Since port microgrids exhibit distributed characteristics, this section proposes a distributed energy management approach for port microgrids in grid-connected mode, where the model for the energy management problem can be written as the following equation.

$$\begin{aligned} \min \quad & \left\{ \sum_{i=1}^{N} F_1 + F_2 + F_3 \right\} \\ \text{s.t.} \quad & \sum_{i=1}^{n} P_i + P_M = \sum_{i=1}^{n} P_{load} + P_{cc} + P_{cs} \\ & P_i^{\min} \le P_i \le P_i^{\max} \end{aligned} \tag{13}$$

Taking (1)–(8) into (13), the objective function is further expressed as:

$$\min \quad \left\{ \sum_{i=1}^{N} \left(\frac{(P_i - \alpha_i)^2}{2\beta_i} + \varphi_i \right) + \lambda_0 P_M + C_{tax} E_e + \sigma E_{cc} \right\} \tag{14}$$

Since in the objective function, E_e and E_e in the carbon cost function are both linearly related to P_i, which can be combined with the power generation cost, the objective function (14) can be organized as the following formula.

$$\min \left\{ \sum_{i=1}^{N} \left(\frac{\left(P_i - \alpha_i^{'}\right)^2}{2\beta_i^{'}} + \varphi_i^{'} \right) + \lambda_0 P_M \right\} \tag{15}$$

where, $\alpha_i^{'}$, $\beta_i^{'}$ and $\varphi_i^{'}$ are the cost coefficients of the collapsed function.

The Lagrangian function of the model for this problem takes the form of:

$$\begin{aligned} & L(P_1, P_2 ..., P_N, P_M, \lambda, \bar{\nu}, \underline{\nu}) \\ & = \sum_{i=1}^{N} \left(\frac{\left(P_i - \alpha_i^{'}\right)^2}{2\beta_i^{'}} + \varphi_i^{'} \right) + \lambda_0 P_M + \lambda \left(\sum_{i=1}^{n} P_i + P_M - \sum_{i=1}^{n} P_{load} - P_{cc} - P_{cs} \right) \\ & \quad + \sum_{i=1}^{n} \overline{\nu_i} \left(P_i - P_i^{\max}\right) + \sum_{i=1}^{n} \underline{\nu_i} \left(P_i^{\min} - P_i\right) \end{aligned} \tag{16}$$

where, λ, $\bar{\nu}$ and $\underline{\nu}$ are all Lagrangian multipliers, and the carbon capture and carbon storage loads can be expressed as $P_{cc} + P_{cs} = D_i P_i$, D_i is a coefficient matrix.

As the low carbon port microgrid distributed energy management model contains inequality constraints, in order to find its optimal solution, its KKT (Karush Kuhn Tucker) condition is analyzed.

$$\begin{cases} \dfrac{\partial L\left(P_1^*, P_2^*..., P_N^*, P_M^*, \lambda^*, \overline{\nu^*}, \underline{\nu^*}\right)}{\partial\{P_1, P_2..., P_N, P_M\}} = 0 \\ \sum_{i=1}^{n} P_i + P_M - \sum_{i=1}^{n} P_{load} - P_{cc} - P_{cs} = 0 \\ \overline{\nu_i^*}\left(P_i - P_i^{\max}\right) = 0 \\ \underline{\nu_i^*}\left(P_i^{\min} - P_i\right) = 0 \end{cases} \tag{17}$$

According to (17), we get:

$$\begin{cases} \lambda^* = \dfrac{P_i - \alpha_i'}{\beta_i'(1 - D_i)} \\ \lambda^* = \lambda_0 \end{cases} \tag{18}$$

Bringing (18) into (17) gives the global optimum result as:

$$P_i^* = \begin{cases} \lambda^*\beta_i'(1 - D_i) + \alpha_i' & \underline{P_i} \le \lambda^*\beta_i'(1 - D_i) + \alpha_i' \le \overline{P_i} \\ \overline{P_i} & \lambda^*\beta_i'(1 - D_i) + \alpha_i' > \overline{P_i} \\ \underline{P_i} & \lambda^*\beta_i'(1 - D_i) + \alpha_i' < \underline{P_i} \end{cases} \tag{19}$$

$$P_M^* = \sum_{i=1}^{n} P_{load} + \sum_{i=n}^{N} D_i P_i - \sum_{i=1}^{n} P_i \tag{20}$$

When in grid-connected mode, the iterative approach of electricity prices follows the leader-following consistency (Chen and Li, 2021), with the following iterative process. According to (21), the amount of power generated by each generating unit can be obtained as:

$$\lambda_i(k+1) = \lambda_i(k) + \mu_i\left[\sum_{j\in N_i} a_{ij}\left(\lambda_j(k) - \lambda_i(k)\right) + a_{i0}(\lambda_0 - \lambda_i(k))\right] \tag{21}$$

The above equation represents that the λ of each node follows the leader-following consensus to the main grid price λ_0 and the node $a_{i0} = 1$, which is capable of receiving direct main grid communication information from the main grid.

According to (21), the power generation capacity of each generation unit can be obtained as follows.

It can be obtained that the power generation capacity of each generation unit is as follows.

$$P_i(k) = \begin{cases} \lambda(k)\beta_i'\ (1 - D_i) + \alpha_i' & \underline{P_i} \le \lambda(k)\beta_i'(1 - D_i) + \alpha_i' \le \overline{P_i} \\ \overline{P_i} & \lambda(k)\beta_i'(1 - D_i) + \alpha_i' > \overline{P_i} \\ \underline{P_i} & \lambda(k)\beta_i'(1 - D_i) + \alpha_i' < \underline{P_i} \end{cases} \tag{22}$$

where, $P_i(k)$ is the amount of electricity generated by the i th node at the k th iteration.

Then, based on the known estimated local mismatch values $P_i(k)$, the formula is as follows.

$$\begin{cases} \rho_i(k+1) = \Delta\widehat{P}_i(k) + \varepsilon\left[\sum_{j\in N_i} a_{ij}\left(\Delta\widehat{P}_j(k) - \Delta\widehat{P}_i(k)\right)\right] + \Delta P_i(k+1) - \Delta P_i(k) \\ \Delta\widehat{P}_i(k+1) = (1 - a_{0i})\rho_i(k+1) \end{cases} \tag{23}$$

where, $\Delta P_i(k)$ is the actual local mismatch at the k th iteration and $\Delta\widehat{P}_i(k)$ is the estimated local mismatch at the k th iteration. $\Delta\widehat{P}_i(k+1) = (1 - a_{0i})\rho_i(k+1)$ means that for the neighbor unit of the main grid, the power complement of the main grid is obtained directly in each iteration. At the $k+1$ th iteration, the estimation of the local power mismatch becomes zero.

$$P_M(k+1) = P_M(k) + \sum_{i=n}^{N} a_{0i}\rho_i(k+1) \tag{24}$$

where, $P_M(k+1)$ is the supplementary power value of the main grid to neighbor nodes at the $k+1$ th iteration, which equals the sum of the supplementary power value of the k th iteration and the mismatch value of all neighbor nodes.

For the above algorithm, for a connected undirected graph G, when the step size of the algorithm satisfies $\mu_i \in (0, \frac{1}{\sum_{j=0}^{N} a_{ij}})$ and $\varepsilon \in (0, \frac{1}{\max_{i=1,2,3...N}\sum_{j=0}^{N} a_{ij}})$, it can be obtained that:

$$\begin{aligned} &\lim_{k\to\infty}\lambda_i(k) = \lambda(0),\ i = 1, 2, 3...N \\ &\lim_{k\to\infty}P_i(k) = P_i^*,\ i = 1, 2, 3...N \\ &\lim_{k\to\infty}\Delta\widehat{P}_i(k) = 0,\ i = 1, 2, 3...N \\ &\lim_{k\to\infty}P_M(k) = \sum_{i=1}^{n} P_{load} + \sum_{i=n}^{N} D_i P_i^* - \sum_{i=1}^{n} P_i^* = P_M^* \end{aligned} \tag{25}$$

where, the value of $P_M(k)$ can be positive or negative.

The low carbon port microgrid under the grid-connected mode considered in this paper can both buy electricity from and sell electricity to the port's main grid, ensuring a balance between energy supply and demand and enabling the economic operation of the port microgrid.

4.3 Island Mode

In island mode, the port microgrid cannot buy power from the main grid and has to be powered by a generation device to supply the load. In this case, not only the economy of the port must be considered, but also its security. The economic optimization of the port microgrid is achieved on the basis that the port load demand can be met. In this section, the incremental cost of the islanding model is corrected by adding a penalty factor to meet the supply-demand balance of the port microgrid. The iterative formula used is as follows.

$$\lambda_i(k+1) = \lambda_i(k) + \mu_i'\left[\sum_{j=1}^{N} a_{ij}\left(\lambda_j(k) - \lambda_i(k)\right)\right] + \zeta(k)\Delta\widehat{P}_i(k) \tag{26}$$

where, μ_i' is the step size of the algorithm and $\zeta(k)$ is the feedback gain.

According to (26), the power generation capacity of each generation unit can be obtained by

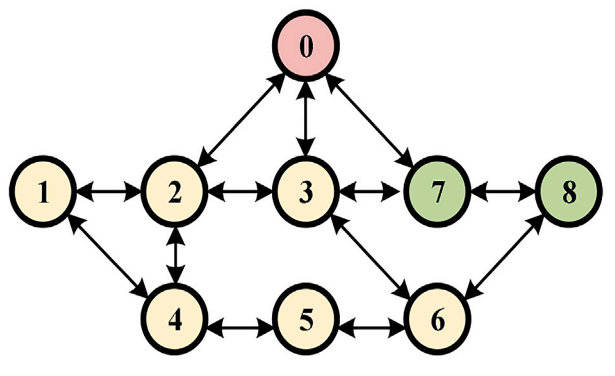

FIGURE 4 | The energy flow topology of the low-carbon port microgrid.

TABLE 1 | The port microgrid energy supply device parameters.

	FU	PV1	PV2	W1	W2	S
α_i	2.1	3.1	2.3	2.9	2.5	2.7
β_i	25	20	26	19	30	10
φ_i	0.44	0.1	0.05	0.2 0	05 0	44

$$P_i(k) = \begin{cases} \lambda(k)\beta_i^{'}\ \ (1-D_i) + \alpha_i^{'} & \underline{P_i} \le \lambda(k)\beta_i^{'}(1-D_i) + \alpha_i{}' \le \overline{P_i} \\ \overline{P_i} & \lambda(k)\beta_i^{'}(1-D_i) + \alpha_i{}' > \overline{P_i} \\ \underline{P_i} & \lambda(k)\beta_i^{'}(1-D_i) + \alpha_i{}' < \underline{P_i} \end{cases} \tag{27}$$

where, $P_i(k)$ is the amount of electricity generated by the i th node at the k th iteration.

Then, according to the known $P_i(k)$, the local mismatch value is estimated, and the formula is as follows.

$$\begin{cases} \rho_i(k+1) = \Delta\widehat{P}_i(k) + \varepsilon'\left[\sum_{j\in N_i} a_{ij}\left(\Delta\widehat{P}_j(k) - \Delta\widehat{P}_i(k)\right)\right] + \Delta P_i(k+1) - \Delta P_i(k) \\ \Delta\widehat{P}_i(k+1) = \rho_i(k+1) \end{cases} \tag{28}$$

where, $\Delta P_i(k)$ is the actual local mismatch value at the k th iteration and $\Delta\hat{P}_i(k)$ is the estimated (local) mismatch value at the k th iteration.

For a connected undirected graph G, when the step size of the above algorithm satisfies $\mu_i^{'} \in (0, \frac{1}{\sum_{j=0}^{N} a_{ij}})$ and $\varepsilon' \in (0, \frac{1}{\max_{i=1,2,3\ldots N}\sum_{j=0}^{N} a_{ij}})$, for feedback gains $\zeta(k)$, it satisfies $\lim_{k\to\infty}\zeta(k) = 0$ and $\sum_{k=0}^{\infty}\zeta(k) = \infty$. $\lambda_i(0)$ is any given initial value, then we can obtain that, in the island mode, when the local estimate of the initial value of the mismatch value satisfies $\Delta\hat{P}_i(0) = \sum_{i=1}^{n} P_{load} + \sum_{i=n}^{N} D_i P_i(0) - \sum_{i=1}^{n} P_i(0)$, it can be obtained that:

$$\begin{aligned} &\lim_{k\to\infty}\lambda_i(k) = \lambda_i^*,\ \ i = 1,2,3\ldots N \\ &\lim_{k\to\infty}P_i(k) = P_i^*,\ \ i = 1,2,3\ldots N \\ &\lim_{k\to\infty}\Delta\widehat{P}_i(k) = 0,\ \ i = 1,2,3\ldots N \end{aligned} \tag{29}$$

In the island model considered in this paper, security and the guarantee of supply and demand balance are more important as the port microgrid is not connected to the main grid. The essence of the algorithm is to follow the average consensus and add a penalty factor for feedback gain to correct the incremental cost in order to achieve safety and economy of port operation.

4.4 Switching Mode

Low carbon port microgrid switching mode operation refers to the process of switching from grid-connected mode to island mode or from island mode to grid-connected mode. In the switching process, it is necessary to realize the economical operation of the port microgrid as much as possible on the basis of ensuring the supply and demand balance. At this time, the iterative process of the electricity price λ is as follows.

$$\lambda_i(k+1) = \lambda_i(k) + \mu_i{}'\left[\sum_{j\in N_i} a_{ij}\left(\lambda_j(k) - \lambda_i(k)\right) + m a_{i0}(\lambda_0 - \lambda_i(k))\right] + \zeta'(k)\Delta\widehat{P}_i(k) \tag{30}$$

where, m denotes the mode of operation of the port microgrid, when in grid-connected mode, $m = 1$, otherwise, $m = 0$; when $m = 1$, λ of each node follows the leader-following consensus to the main grid electricity price λ_0, where $a_{i0} = 1$ represents the node can directly receive the communication information from the main grid; when $m = 0$, λ of each node follows the average consensus, and adopts the penalty factor correction method to tend to λ^*.

According to the above equation, the power generation capacity of each generation unit can be obtained by:

$$P_i(k) = \begin{cases} \lambda(k)\beta_i^{'}\ \ (1-D_i) + \alpha_i^{'} & \underline{P_i} \le \lambda(k)\beta_i^{'}(1-D_i) + \alpha_i{}' \le \overline{P_i} \\ \overline{P_i} & \lambda(k)\beta_i^{'}(1-D_i) + \alpha_i{}' > \overline{P_i} \\ \underline{P_i} & \lambda(k)\beta_i^{'}(1-D_i) + \alpha_i{}' < \underline{P_i} \end{cases} \tag{31}$$

where, $P_i(k)$ is the amount of power generated by the generation unit at the i th node at the k th iteration.

Then, based on the known estimated local mismatch values $P_i(k)$, the formula is as follows.

$$\begin{cases} \rho_i(k+1) = \Delta\widehat{P}_i(k) + \varepsilon'\left[\sum_{j\in N_i} a_{ij}\left(\Delta\widehat{P}_j(k) - \Delta\widehat{P}_i(k)\right)\right] + \Delta P_i(k+1) - \Delta P_i(k) \\ \Delta P_{Mi}(k+1) = m a_{0i}\rho_i(k+1) \\ P_{Mi}(k+1) = m[P_{Mi}(k) + a_{0i}\Delta P_{Mi}(k+1)] \\ \Delta\widehat{P}_i(k+1) = \rho_i(k+1) + a_{0i}[P_{Mi}(k) - P_{Mi}(k+1)] \end{cases} \tag{32}$$

Among them, $\sum_{i=1}^{N}\Delta\hat{P}_i(0) = \sum_{i=1}^{n} P_{load} + \sum_{i=n}^{N} D_i P_i(0) - \sum_{i=1}^{n} P_i(0)$ and $P_{Mi}(0) = 0$.

Then, the power exchanged with the main grid can be expressed as:

$$P_M(k) = \sum_{i=1}^{N} P_{Mi}(k) \tag{33}$$

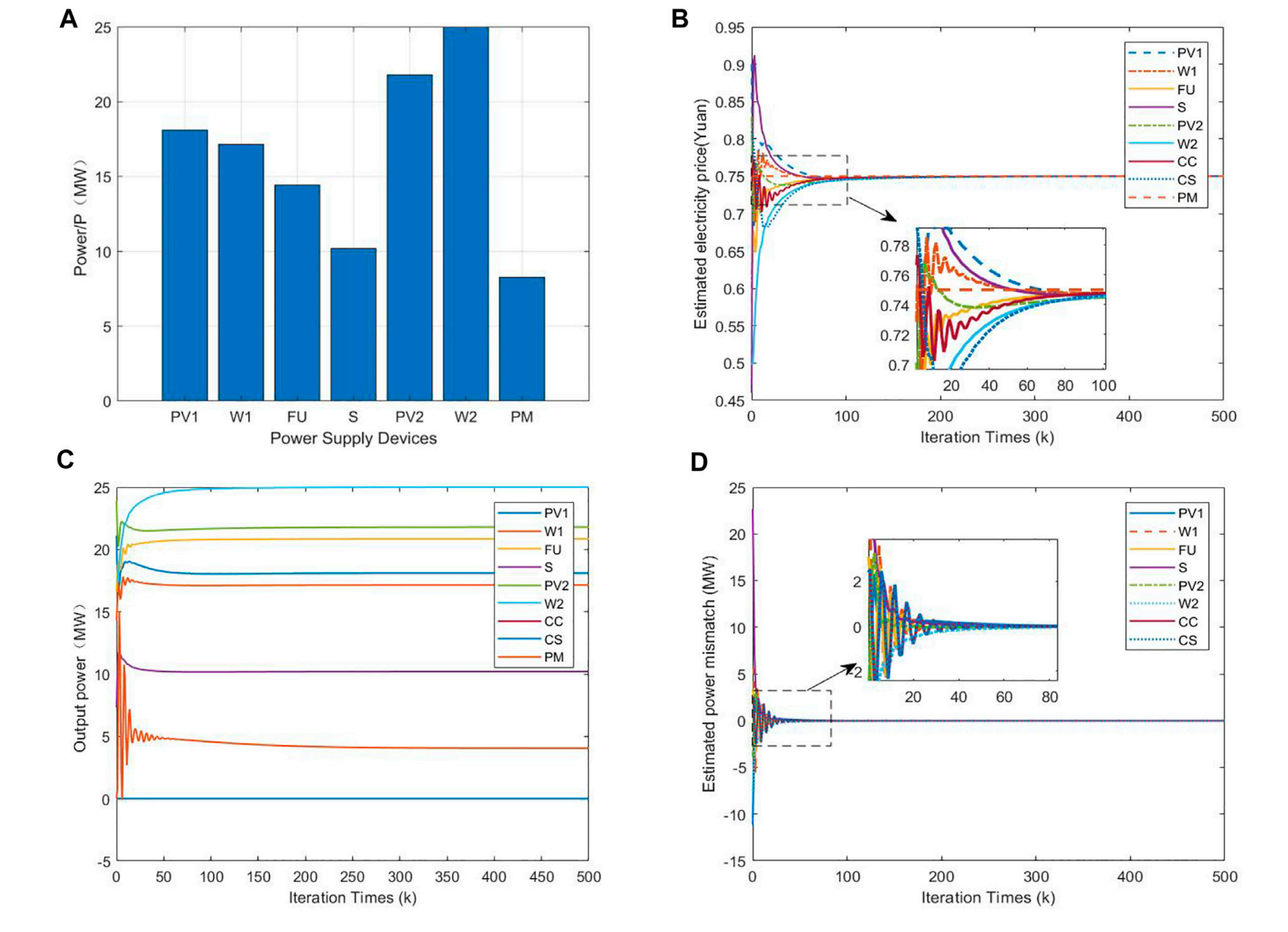

FIGURE 5 | Simulation results of power purchase from the main grid in grid-connected mode. **(A)** is the results of centralized algorithm, **(B)** is the dynamic curve of the electricity price λ, **(C)** is the dynamic curve of the power output, **(D)** is the dynamic curve of the estimated power.

The switching mode considered in this paper is the switching of the port microgrid between grid-connected mode and island mode. With the algorithm used in this paper, the safe and economic operation of the port microgrid can be achieved on the basis of ensuring a balance between supply and demand in the port microgrid.

5 SIMULATION RESULTS

In this paper, Matlab is used to simulate and verify the proposed method. The considered low carbon port microgrid consists of a conventional power plant, two photovoltaic power generation devices, two wind power generation devices, a storage device, a carbon capture device, a carbon sequestration device and the main grid. The energy flow topology of the low-carbon port microgrid based on the polymorphic network is shown in **Figure 4** and the parameters of the power generation device are shown in **Table 1**. The following simulation cases are conducted in grid-connected mode, island mode and switching mode respectively.

5.1 Grid-Connection Mode

For this case, the operation of a polymorphic port microgrid in grid-connected mode is considered and divided into two scenarios: buying electricity from and selling electricity to the main grid.

5.1.1 Purchase Power From the Main Grid

When the low-carbon port microgrid generation cannot meet the required load of the port, the port will purchase power from the main grid to meet the port load demand. In this section, in order to verify the accuracy and convergence of the algorithm, the proposed model is solved using the centralized algorithm and the distributed algorithm, respectively. The simulation results of the centralized algorithm are shown in **Figure 5A**, and the results obtained by the distributed algorithm are shown in **Figures 5B–D**. The total load demand of the port microgrid is 110 MW.

The minimum cost result obtained in the centralized algorithm with grid-connected power purchase is 4,005.39 ¥ of each supply device as shown in **Figures 5B–D**. Since electricity price from the main grid is relatively high, the amount of electricity supplied

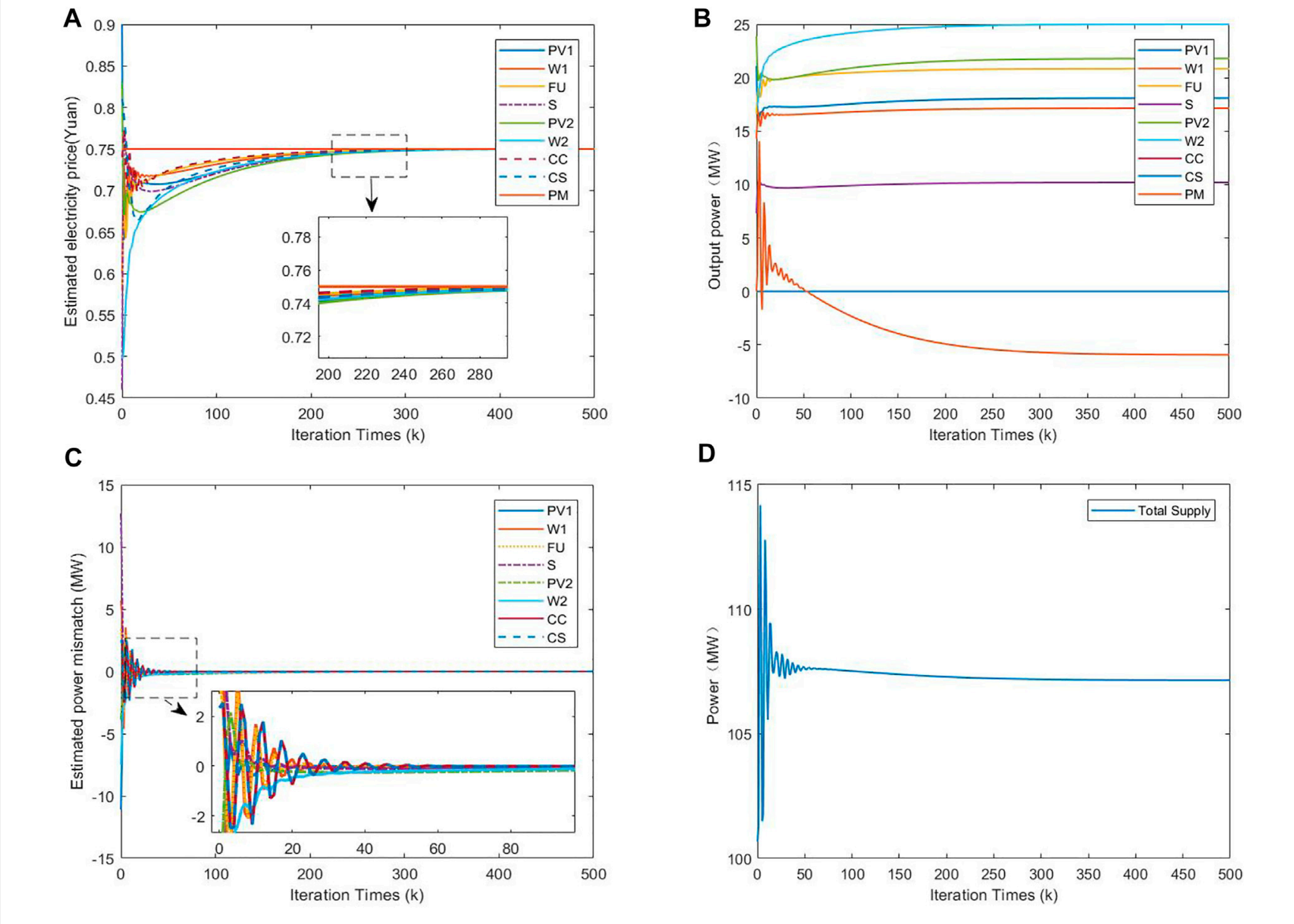

FIGURE 6 | Simulation results of power selling to the main grid in grid-connected mode. **(A)** is the dynamic curve of the electricity price λ, **(B)** is the dynamic curve of the power output, **(C)** is the dynamic curve of the estimated power, **(D)** is the dynamic curve of the total supply.

from the main grid is lower. At the same time, the figure shows that the traditional power plant supplies less power and emits less CO_2, which further illustrates that the model built in this paper can effectively reduce the carbon emission of the port. By using distributed algorithms, the operating cost of the low-carbon port microgrid is 4088.13 ¥, with 4.44 t of CO_2 emitted into the air and 10.36 t of CO_2 treated by carbon capture and storage device which are very little different from the results obtained by the centralized algorithm, further proving the accuracy of the proposed algorithm in this paper. The electricity price λ follows multi-agent leader-following consensus, and $\lambda = 0.75$. The main grid acts as the leader and its final electricity price converges to the electricity price of the main grid when $k = 100$. The power supply of each power generation unit is [4.05, 18.09, 17.15, 20.85, 10.20, 21.80, 24.98], of which 4.05 MW is bought from the main grid to maintain a balance between supply and demand in the port microgrid. The total electricity consumption of the port microgrid is 117.13 MW, which is larger than the initially set load demand of 110 MW. This is because the energy consumption of carbon capture and carbon storage device varies according to the amount of electricity produced by conventional power plants during operation.

5.1.2 Sell Power to the Main Grid

When the generation capacity of the low carbon port microgrid is larger than the load required by the port itself, the port will sell electricity to the main grid to earn a profit. In this simulation case, the total load demand of the port is 100 MW, and the simulation results are shown in **Figures 6A–D**.

In grid-connected mode, when the port load is 100 MW, the operating cost of the low carbon port microgrid is 3,338.28 ¥, the carbon dioxide emitted into the air is 4.44 t, and the carbon dioxide treated by the carbon capture and storage device is 10.36 t. The incremental cost (electricity price) converges to the electricity price of the main power grid when $k = 260$, and $\lambda = 0.75$. The electricity production of each unit is [-5.94, 18.09, 17.15, 20.85, 10.20, 21.80, 24.98]. The total electricity consumption of the port microgrid is 107.13 MW. The main grid supply is negative because the main grid does not supply electricity to the port. There exists excess electricity generation in the port, which is sold to the main grid to make a profit; and the electricity sold to the main grid is 5.94 MW.

As shown in **Figure 5** and **Figure 6**, most of the carbon dioxide emitted from conventional power plants will be treated

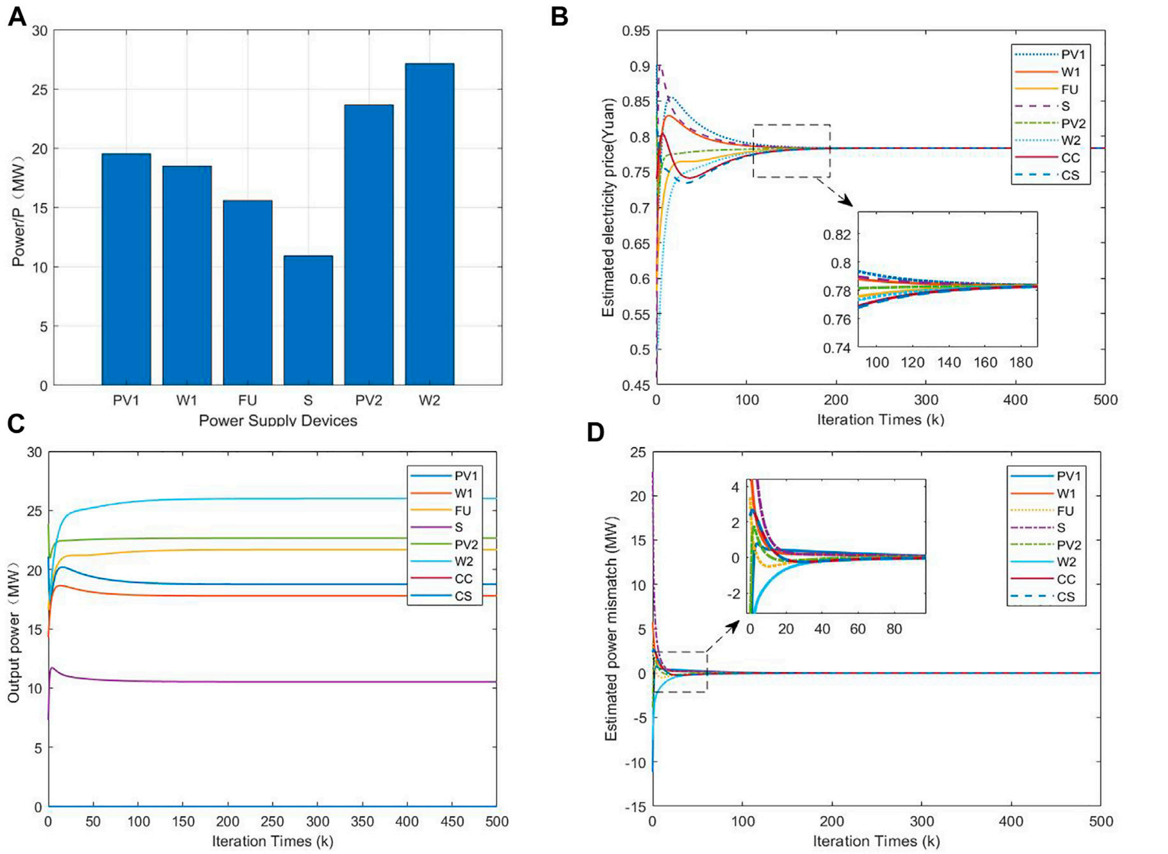

FIGURE 7 | Simulation results in island mode. **(A)** is the results of centralized algorithm, **(B)** is the dynamic curve of the electricity price λ, **(C)** is the dynamic curve of the power output, **(D)** is the dynamic curve of estimated power.

by carbon capture and storage devices, incurring carbon treatment costs. Although carbon dioxide is still being emitted into the air, but most of it is treated by carbon capture and storage devices, which can greatly reduce the pollution to the environment. A small proportion of the carbon dioxide emitted into the atmosphere will be subject to a carbon tax, resulting in higher power generation cost, so the port microgrid produces more electricity from photovoltaic and wind power than conventional power plants. Regardless of whether the port generates less or more than the required port load, the total generation can satisfy the supply-demand balance constraint, and its mismatch value eventually stabilizes at 0, as shown in **Figure 5D** and **Figure 6C**. If the port generates less than the required load for the port, it needs to buy electricity from the main grid, in this case $P_M > 0$, as shown in **Figure 5C**, and conversely, sell electricity to the main grid for profit, as shown in **Figure 6B**. The convergence of the simulation results proves the effectiveness of the proposed algorithm.

5.2 Island Mode

For this case, the operation of a polymorphic port microgrid in island mode is considered. Unlike the grid-connected mode, in the island mode, it is not possible to purchase power from the main grid, so it is essential to ensure the economics and the security of the polymorphic port microgrid. In this section, the centralized algorithms and the distributed algorithms are used to solve the proposed model, and the obtained simulation results are shown in **Figures 7A–D**.

The results obtained using the centralized algorithm are shown in **Figure 7A**, which shows the power supply of each power supply device, and the lowest cost result is 4,035.78 ¥. By using distributed algorithms, the low-carbon port microgrid costs 4,116.80 ¥, and emits 4.61 t of CO_2 into the air, with 10.77 t of CO_2 treated by the carbon capture and storage device. The difference between the results obtained by the centralized algorithm and the distributed algorithm proposed in this paper is small, which can prove the accuracy of the proposed algorithm. In this mode, there is no leader and the values for each unit follow an average consensus under the penalty factor correction method. It can be seen in the graph that the values converge to consistency at k = 25, with a faster convergence rate, $\lambda = 0.78$ at this time. The power supply for each device is [18.76, 17.78, 21.68, 10.53, 22.66, 26.01], and the total power used by the port microgrid is 117.42 MW, which is able to meet the required load of the port.

The cost is reduced compared to the grid-connected mode because the port's power generation device powers all loads. At the same time, as the island mode cannot purchase power from the main grid, to ensure the safety of the port during island mode operation and to meet

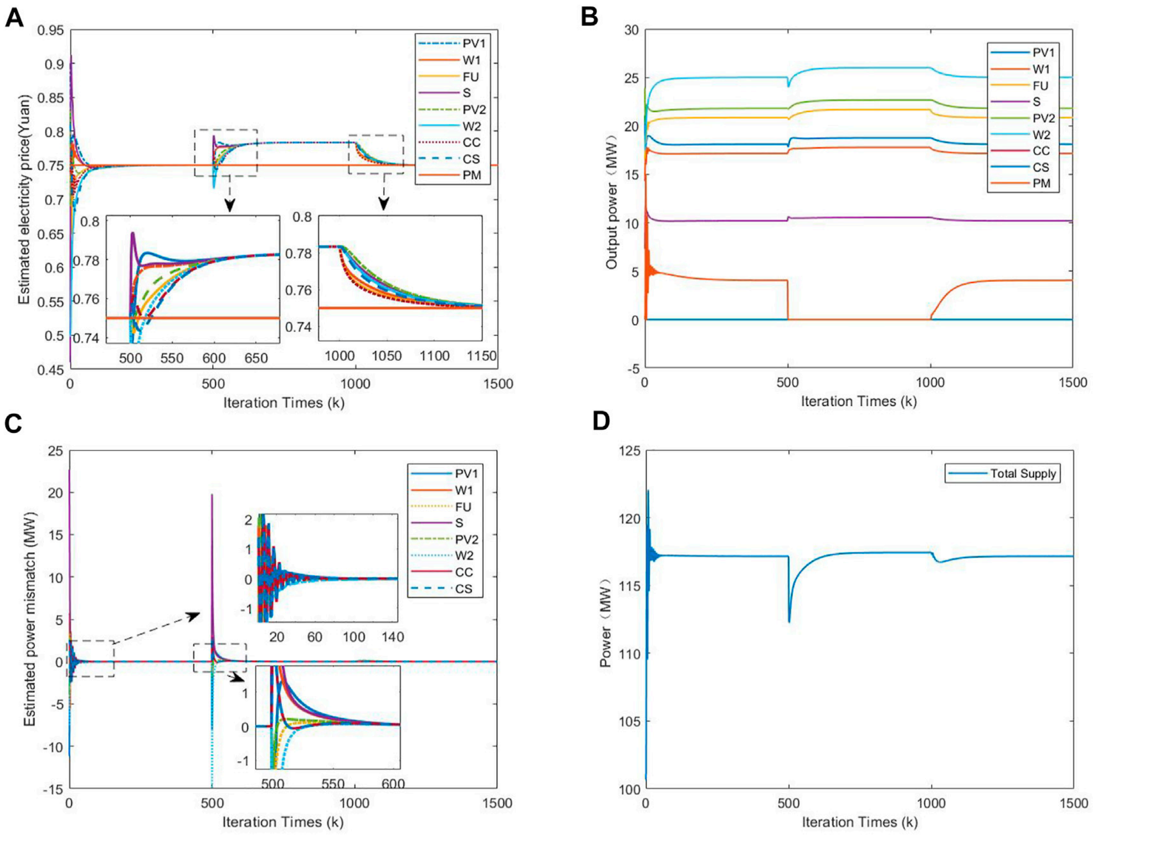

FIGURE 8 | Simulation results of "grid-island-grid" switching mode. **(A)** is the dynamic curve of the electricity price λ, **(B)** is the dynamic curve of the power output, **(C)** is the dynamic curve of estimated power, **(D)** is the dynamic curve of the total supply.

the balance of supply and demand of the port microgrid, the conventional power plant generates more power and emits more carbon dioxide into the air, illustrating that the grid-connected mode can effectively reduce carbon emissions from the port and is more friendly to the environment. In terms of convergence speed, the island model uses average consensus, which is significantly faster than the grid-connected model. The simulation results for both the grid-connected and island modes, which eventually reach convergence, prove the effectiveness of the proposed algorithm.

5.3 Switching Mode

During the operation of the port microgrid, the possible emergencies will lead to its failure to connect with the main grid, changing it from grid-connected mode to island mode, which will make the supply-demand balance and security unable to be guaranteed. While the port, as an essential transport hub node, is obliged to operate continuously and reliably. Therefore, it is necessary to ensure the safety and reliability of the port microgrid during operation. In this section, a distributed energy management algorithm is used to study the switching mode of the port microgrid, which is divided into two switching modes: "grid-connected–island–grid-connected" and "island–grid-connected–island" for energy management. The simulation results are shown in **Figures 8A–D** and **Figures 9A–D**.

5.3.1 Switching "Grid-Island-Grid"

From **Figure 8**, it can be seen that at k = 501, the port microgrid switches from grid-connected mode to island mode; at k = 1001, the port microgrid switches from island mode to grid-connected mode. In grid-connected mode, the devices are supplied with [18.76, 17.78, 21.68, 10.53, 22.66, 26.01]; in island mode, the supply of each device is supplied with [4.05, 18.09, 17.15, 20.85, 10.20, 21.80, 24.98]. After each switchover, the values go out of line with short fluctuations and after about 100 iterations, the port microgrid can reach convergence again after adjustment quickly. From **Figure 8C**, we can see that the mismatch values converge to 0 after switching mode, indicating that the port microgrid can satisfy the supply-demand balance constraint after switching modes.

5.3.2 Switching "Island-Grid-Island"

At k = 501, the port microgrid switches from island mode to grid-connected mode; at k = 1001, the port microgrid switches from grid-connected mode to island mode. **Figure 9** shows that when the port microgrid is switched from grid-connected mode to grid-connected mode, the system values fluctuate more, and the system needs to go through more iterations to reach stability. With the port load all being 110 MW, the total power supply is higher when in island mode, as its conventional power plant generates more power and produces more CO_2, which also represents higher energy consumption of the carbon

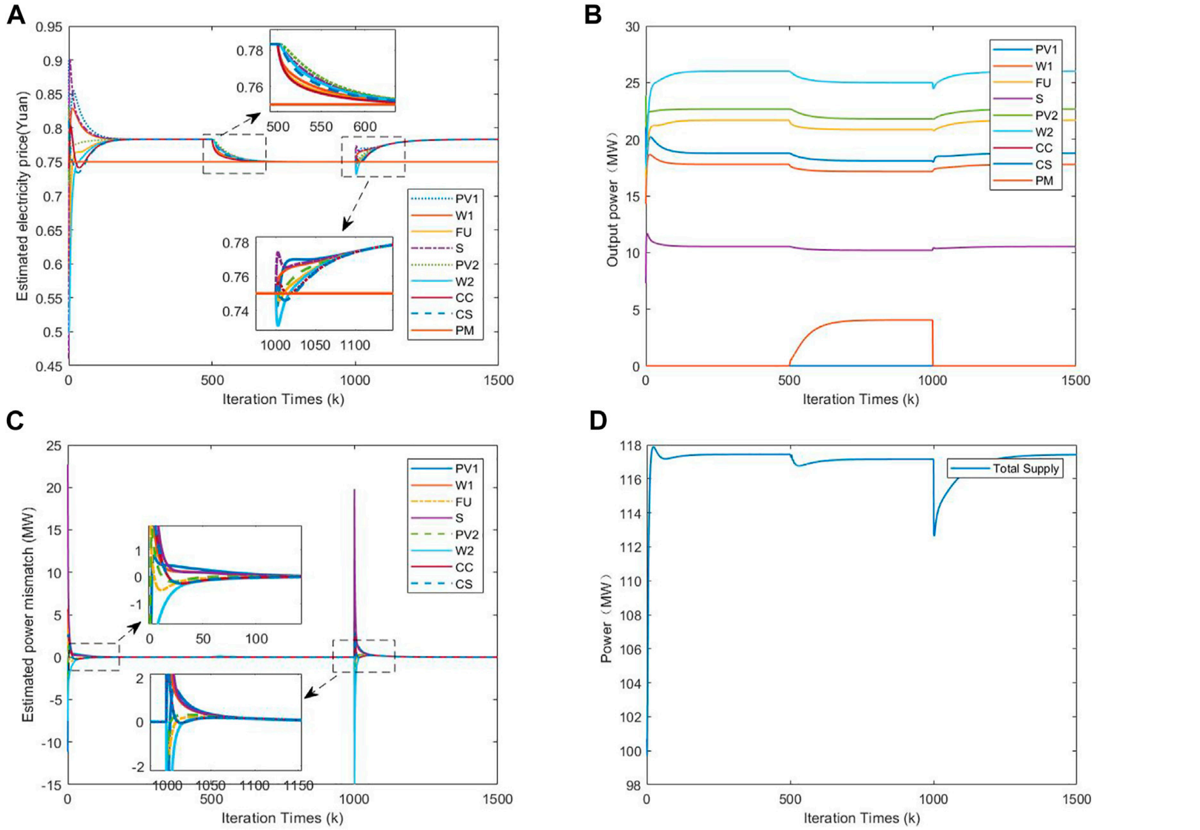

FIGURE 9 | Simulation results of "island-grid-island" switching mode. **(A)** is the dynamic curve of the electricity price λ, **(B)** is the dynamic curve of the power output, **(C)** is the dynamic curve of the estimated power, **(D)** is the dynamic curve of the total supply.

capture device and carbon storage device. At the same time, more CO_2 is emitted into the air in island mode.

In switching mode, the low-carbon port microgrid is still able to reduce the carbon emissions of the port. The simulation results show that the carbon emission is less in grid-connected mode than in island mode, the reason is that in island mode, the conventional power plant needs to generate more electricity to maintain the safe and stable operation of the port microgrid, so the carbon emission is more in island mode.

However, the low-carbon port microgrid is able to operate safely, economically, and at a low carbon level, whether switching from grid-connected mode to island mode or from island mode to grid-connected mode. The simulation results further validate the effectiveness of the algorithm.

6 CONCLUSION

The large amount of carbon emissions from the port leads to serious environmental pollution problems, so building low carbon ports is of great practical importance. In this paper, a low-carbon port microgrid with carbon capture and storage devices has been constructed in a polymorphic network environment, and its energy management problems have been investigated, and distributed solutions have been proposed for various operation modes. Firstly, a low carbon port microgrid in a polymorphic network environment has been proposed, which consists of a data layer, a control layer and a service layer, enabling the information interaction among various energy bodies in different modes and improving the performance of network communication among the power generation device, the main grid and the carbon capture and storage device. Secondly, the energy management model of a low carbon port microgrid has been constructed to minimize the operating cost of the low carbon port microgrid. Then, applicable distributed energy management methods have been proposed for various operating conditions of the port microgrid. For both grid-connected and island operation modes, the distributed energy management of the low carbon port microgrid has been implemented based on the multi-agent leader-following consensus and average consensus, respectively. In addition, the port microgrid grid-connected and island operation switching model has been discussed. Finally, the simulation results have verified the effectiveness of the proposed low-carbon port microgrid energy management method. The distributed energy management method proposed in this paper has reduced the operating cost and carbon emissions of the port microgrid, as well as realized the economical, safe and stable operation of the port.

In this paper, only the low carbon operation in the port microgrid is achieved, but not the zero carbon emission of the port. In the future, we can consider abandoning the use of traditional power plants of the port to supply electricity. The port microgrid has been kept in grid-connected mode, and when its own generation device cannot meet its own load, it purchases insufficient electricity from the main grid to realize the zero carbon operation of the port.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

QS and JS provide research ideas for energy management and microgrid; QX and GX provide formal analysis of the polymorphic network. JS and FY write the original manuscript and are responsible for revisions of the paper. All authors have read and agreed to the published version of the manuscript.

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