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Research Article

Distributed Energy Management for Zero-Carbon Port Microgrid

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A zero-carbon port microgrid that integrates carbon capture power plants is proposed to build the green port and promote the achievement of the dual-carbon goal. To achieve the optimal economic operation of the port microgrid and reduce carbon emissions, an energy management model considering carbon trading mechanisms is established. Furthermore, a distributed energy management method is proposed for the zero-carbon port based on the alternating direction method of multipliers (ADMMs). The simulation results prove the effectiveness and accuracy of the proposed method, which can effectively improve the economy of the port microgrid and reduce the carbon emission of the port.

1. Introduction

With the continuous acceleration of the global economic integration process, shipping has been developing rapidly. As the key nodes to realize the interconnection of maritime trade and transportation, the annual carbon emissions of ports have risen to almost 100 million tons, together with the increasing emission of the harmful gases year by year [1]. Moreover, long-distance transportation will gradually shift from highway transportation to waterway transportation, which will bring greater energy demand [2] and carbon emissions in the future [3]. Therefore, it is extremely essential, for the realization of the dual-carbon goal, to establish a green port and study its energy management issues so as to construct a zero-carbon port microgrid.

The energy management of port microgrid is an optimization problem that needs to consider multiple constraints [4]. At present, many scholars have studied the energy management methods of ports. Kanellos et al. [5] proposed an energy management method based on multi-agent systems to realize the optimal economic port, considering a large number of flexible loads. Parise et al. [6] proposed the port energy master plan on the basis of considering the electrical infrastructures of port facilities. Kermani et al. [7] proposed a comprehensive energy management method based on blockchain technology to reduce the peak power consumption generated by the terminal. With the rapid growth of energy consumption and people's increasing attention to environmental protection, various measures have been taken to reduce carbon emissions from power systems, which are mainly divided into two categories, one is to use the renewable energy and change the low-carbon system framework and the other is to use the market regulation mechanisms, including carbon trading and carbon tax. Both types of carbon reduction measures have been extensively studied by related scholars. Wu et al. [8] proposed a novel carbon-oriented extended planning model for an integrated electricity and gas system with electric vehicle fast-charging stations and demonstrated the validity of the model. Conlon et al. [9] proposed a modeling framework with a trade-off between increased low-carbon generation and decarbonization of heating and vehicle electrification and demonstrated that the framework plus can achieve equivalent emission reductions at lower costs. Fu et al. [10] considered a stepped carbon tax, established a computable equilibrium model, and proved the effectiveness of carbon tax on carbon reduction. With the rapid development of waterway transportation in the future, the energy demand for port microgrids will accordingly increase, followed by the significant growth of carbon emission [11], so how to implement carbon emission reduction for ports has received a lot of attention from scholars. Bo et al. [12] studied the port logistic carbon emission management system through a specific model in the concept of the Internet of things. Li et al. [13] utilized game theory to calculate the cost of government subsidies for using shore power to reduce port carbon emissions. De et al. [14] studied an environmental issue related to fuel consumption and carbon emissions while considering the issue of sustainable container transportation of the port. Kanellos [15] proposed a multi-objective operation scheduling method for large ports, which regulates port power demand to limit port carbon emissions. However, at present, most scholars only reduce port carbon emissions to a certain extent, and few can truly achieve zero-carbon emissions. Therefore, it is indispensable to consider a port microgrid and establish an energy management model for the port microgrid to achieve the lowest or even zero carbon.

The energy management problems can be solved by centralized algorithms and distributed algorithms [16], and the former generally rely on a powerful centralized controller. Wu et al. [17] proposed a cost-effective energy dispatch method for residential smart grid with centralized renewable energy. Olivares [18] proposed a centralized energy management method for island microgrids based on the model predictive control algorithm. Sahoo et al. [19] proposed a novel centralized energy management approach to improve power quality for the hybrid microgrid with solar cells. Long et al. [20] proposed a low-carbon economic dispatch model for multi-energy microgrids to minimize daily operating costs by considering multistep carbon trading, and the simulation results showed that the proposed model can effectively reduce carbon emissions. On account of the large-scale renewable energy on the port microgrid, which presents distributed characteristics, the centralized energy management algorithm with a centralized controller is no longer suitable for solving the energy management problem of the port microgrid [21–23]. Accordingly, distributed energy management algorithms have been widely studied in recent years. Li et al. [24] proposed a distributed algorithm based on event triggering to realize day-ahead and real-time collaborative energy management for multi-energy systems. Gennitsaris and Kanellos [25] proposed a multi-agent real-time distributed demand response system to reduce operating costs and ensure the real-time limitation of ship emissions. Li et al. [26] proposed a consensus-based distributed power system control scheme together with a robust control method to maintain the optimal power dispatch state when the communication fails. Energy management problem for microgrids has also been solved by many scholars using the distributed method. Du et al. [27] proposed a distributed algorithm based on consensus theory and gradient estimation techniques to solve the optimal energy management problem of microgrids faster. Shi et al. [28] defined the energy management problem as an optimal power flow problem and proposed a distributed energy management strategy for the microgrid. Liu et al. [29] proposed a distributed ADMM-based energy management method for multi-microgrid and proved its effectiveness. Although the existing centralized and distributed methods can solve the energy management problem, the distributed characteristics of the power supply device, and the carbon reduction mission of the port microgrid, how to solve the energy management problem of the zero-carbon port microgrid by using the distributed algorithm still needs to be studied.

Overall, a zero-carbon port microgrid with a carbon capture power plant is proposed, of which the optimal economical energy management considering the carbon trading is studied in this study. The innovations of this study can be summarized as follows: constructing the zero-carbon port microgrid, establishing an energy management model, and getting a distributed optimal solution. The specific innovations are as follows:

(1) A zero-carbon port microgrid that integrates a carbon capture power plant is proposed. The carbon capture power plant can capture the carbon dioxide emitted from the combustion of traditional fossil energy, which can greatly realize a green port microgrid. Under the target of low carbon, the port microgrid with the carbon capture power plant can also ensure the reliable and stable operation.

(2) An energy management model considering carbon trading is established. The introduced carbon trading is to deal with the carbon dioxide emitted to the air that has not been captured by the carbon capture power plant, which ensures the realization of the zero-carbon goal of the port. In addition, with the carbon trading, the economic efficiency of the port microgrid can be improved by selling surplus carbon quotas.

(3) An ADMM-based distributed energy management method is proposed to solve the energy management problem of zero-carbon port microgrid and obtain the optimal zero-carbon energy management solution, and the optimality of the proposed method is also illustrated.

The remainder of the study is organized as follows. Section 2 establishes the structure of zero-carbon port microgrid and explains its characteristics. Section 3 builds the energy management model for zero-carbon port microgrid. Section 4 introduces the basic graph theory, and the ADMM-based distributed energy management method is presented. In Section 5, several case studies are presented to show the effectiveness of the proposed algorithm. Section 6 concludes the study.

2. The Structure and Characteristics of Zero-Carbon Port Microgrid

The proposed zero-carbon port microgrid (see Figure 1) contains power devices (i.e., carbon capture power plant,

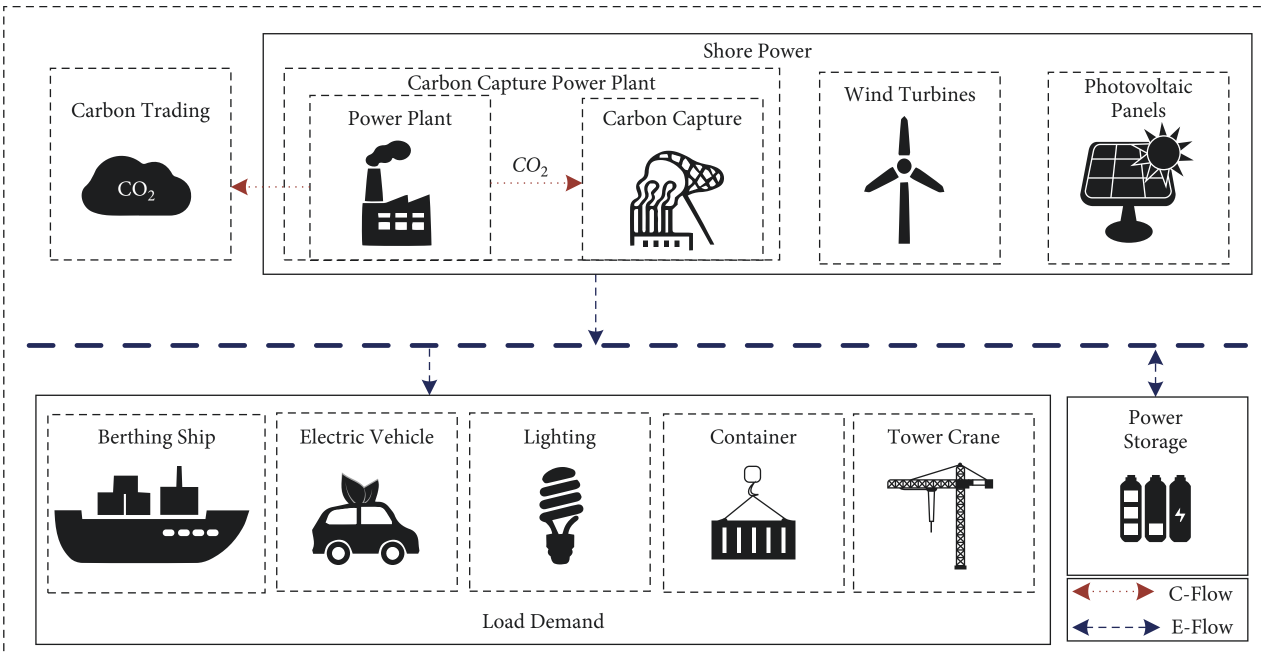

Figure 1: Structure of the zero-carbon port microgrid.

photovoltaic panels, and wind turbines), the loads (i.e., lighting systems, electric vehicles, tower cranes, shore cranes, and berthing ship), and power storage device. The port power plant with the carbon capture device can effectively reduce carbon dioxide emissions. Most of the carbon dioxide produced by fossil energy combustion will be captured by the carbon capture device. Furthermore, a small amount of carbon dioxide emitted into the air will be processed through carbon trading. Therefore, through the comprehensive consideration of carbon capture and carbon trading, a zero-carbon port microgrid can be realized.

Further, the carbon emission treatment process of the port microgrid is presented in detail in Figure 2. Most of the carbon dioxide emitted from fossil fuel combustion can be captured by carbon capture device and stored by carbon storage device. A fraction of the carbon dioxide released into the air that is not captured is processed by carbon trading. The mass of the carbon dioxide captured by carbon capture power plant is directly proportional to the mass of the produced carbon dioxide, which is related to fuel types and fuel emission factors. Among them, the emission factor refers to the mass of the carbon dioxide emitted after burning unit mass fuel. The masses of the carbon dioxide captured and produced are calculated as follows:

$$\begin{aligned} Q_{\mathrm{ccs}} &= \eta Q_{\mathrm{dis}}, \\ Q_{\mathrm{dis}} &= \gamma P_{\mathrm{fu}}, \end{aligned} \tag{1}$$

where Q_{ccs} is the mass of the carbon dioxide to be treated by carbon capture device; η is the efficiency coefficient of carbon dioxide capture; Q_{dis} is the mass of carbon dioxide emitted after fossil fuel combustion; γ is the mass of carbon dioxide emission per unit power; and P_{fu} is the power provided by fossil fuel combustion.

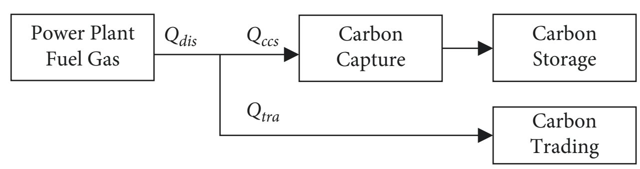

Figure 2: Carbon emission treatment process.

In the process of carbon treatment, carbon capture equipment is actually an electrical device. Since carbon capture is also an electrical load, it consumes part of the power generated by burning fossil fuels. The total power consumption of carbon capture device is divided into two parts. One part is the fixed energy consumption to maintain the normal operation of the carbon capture function, which is independent of the mass of the carbon dioxide captured. The other part is the operation energy consumption of carbon capture device, which is related to the mass of the carbon dioxide to be treated. Hence, the output power of the carbon capture power plant can be expressed as follows [30, 31]:

$$P_{\mathrm{co}} = P_{\mathrm{fu}} - P_{\mathrm{ccs}}. \tag{2}$$

$$P_{\mathrm{ccs}} = P_m + P_{\mathrm{ccso}}. \tag{3}$$

$$P_{\mathrm{ccso}} = \tau \left(Q_{\mathrm{ccs}}\right)^2, \tag{4}$$

where P_{co} is the output power of the carbon capture power plant for the microgrid; P_{ccs} is the total power consumed by carbon capture; P_{ccso} is the operating power consumed by carbon capture; and τ is the coefficient of power consumed by carbon treating.

The carbon dioxide captured by the carbon capture power plant will be stored, and the cost of storing carbon dioxide is as follows:

$$F_{\text{sto}} = C_{\text{sto}} Q_{\text{ccs}}, \tag{5}$$

where F_{sto} is the carbon storage cost of the storage device; C_{sto} is the cost coefficient of sealing carbon per unit mass.

As shown above, the carbon beyond the capacity of the carbon capture device should be processed through carbon trading mechanism to realize zero-carbon port microgrid. The carbon trading mechanism is to take carbon emission rights as a commodity. For a fixed port microgrid, the government imposes carbon emission quotas based on its power generating capacity [32]. If the amount of carbon emitted is less than the allotted amount, the surplus carbon quotas can be sold for a profit. If the amount is more than the allotted amount, it needs to spend money to buy the insufficient part. The relevant formulas can be expressed as follows:

$$F_{\text{tra}} = C_{\text{tra}}\left(\left(Q_{\text{dis}} - Q_{\text{ccs}}\right) - Q_q\right). \tag{6}$$

$$Q_q = \varphi P_{\text{fu}}, \tag{7}$$

where F_{tra} is the carbon trading cost; C_{tra} is the cost coefficient of carbon trading price; Q_q is the carbon emission quota; and φ is the coefficient of carbon emission quota.

3. Energy Management Model for Zero-Carbon Port Microgrid

Considering the structure of the zero-carbon port microgrid proposed in Section 2, the optimization objective is to minimize the operating cost while reducing the carbon emissions of ports. As stated beforehand, port power plants with the carbon capture device can absorb large amounts of carbon dioxide emitted by fossil fuel combustion, while the unabsorbed carbon dioxide is processed according to carbon trading mechanisms. Therefore, different from the objective function of normal energy management problems, the cost function associated with carbon is additionally considered in the objective function of this study. For the reliable and stable operation of the port microgrid in this process, a variety of constraints still need to be considered, such as supply and demand balance constraints, power supply devices, and output power constraints. It is worth noting that the power consumed to achieve carbon capture is considered as part of the load of the port microgrid in the supply-demand balance constraint.

In this section, the model of zero-carbon port microgrid is constructed, where the objective function consists of three parts: the power generation cost, the power storage cost, and the carbon cost, and each part of the objective function is described specifically. The constraints of the zero-carbon port microgrid model are also described, including the equality constraint of supply-demand balance and the conventional inequality constraints.

3.1. Objective Function. The objective of this study was to reduce the carbon emissions while ensuring the economy of the port microgrid. The power supply device of the port microgrid includes power generation device and energy storage device, so the cost of power generation and the cost of power storage are included in the objective function. At the same time, the carbon cost is added to the objective function. To realize carbon emission reduction, the carbon capture power plant is used to process the generated carbon dioxide, and the carbon trading market mechanism is also used to process the emitted carbon dioxide, generating costs or earning profits. Therefore, the objective function of the energy management problem is divided into three parts: power generation cost, power storage cost, and carbon cost, which is expressed as follows:

$$F = \min\left\{F_1 + F_2 + F_3\right\}, \tag{8}$$

where $F_1 F_2$, and F_3 are the port power generation cost, the power storage cost, and the carbon cost, respectively.

3.1.1. Power Generation Cost. The power generation cost of the port microgrid includes the cost of carbon capture power plant, photovoltaic panels, and wind turbines, which can be expressed as follows:

$$\begin{aligned} F_1 &= F_{\text{ccs}} + F_{\text{pv}} + F_w, \\ F_{\text{ccs}} &= \sum_{h_1 \in N_1} a_{h_1}\left(P_{\text{fu},h_1}\right)^2 + b_{h_1} P_{\text{fu},h_1} + c_{h_1}, \\ F_{\text{pv}} &= \sum_{h_2 \in N_2} a_{h_2}\left(P_{\text{pv},h_2}\right)^2 + c_{h_2}, \\ F_w &= \sum_{h_3 \in N_3} a_{h_3}\left(P_{w,h_3}\right)^2 + c_{h_3}, \end{aligned} \tag{9}$$

where F_{ccs}, F_{pv}, and F_w are the power generation costs of carbon capture power plant, photovoltaic panels, and wind turbines, respectively; $a_h b_h$, and $c_h\,(h = 1, 2, 3)$ are the coefficients of the power generation cost; $P_{fu,h}$ and $P_{w_{,h}}\,(h = 2, 3)$ are the output power of photovoltaic panels and wind turbines; and N_1, N_2, and N_3 are the node sets of carbon capture power plant, photovoltaic panels, and wind turbines, respectively.

3.1.2. Power Storage Cost. The power storage cost of the port microgrid can be expressed as follows [33]:

$$F_2 = \sum_{h_4 \in N_4} a_{h_4}\left(P_{s,h_4} + b_{h_4}\right)^2, \tag{10}$$

where P_{s,h_4} is the output power of the power storage device; $F_2 = a_{h_4}(P_s + b_{h_4})^2$, and b_{h_4} is the cost coefficient of the power storage device.

3.1.3. Carbon Cost. To achieve the goal of zero-carbon port, carbon cost must be taken into consideration seriously. Carbon cost includes carbon trading cost and carbon storage cost, which can be expressed as follows:

$$F_3 = F_{\text{tra}} + F_{\text{sto}}. \tag{11}$$

Substituting (3)–(7) into (11), it can be calculated as follows:

$$F_3 = C_{\text{tra}}\left(((1-\eta)\gamma - \varphi) \sum_{h_1 \in N_1} P_{\text{fu},h_1} \right) + C_{\text{sto}}\eta\gamma \sum_{h_1 \in N_1} P_{\text{fu},h_1}. \tag{12}$$

It can be seen that carbon cost is only related to the variable P_{fu,h_1}.

3.2. Constraints. To ensure the secure and stable operation of the zero-carbon port microgrid, the following constraints need to be considered.

3.2.1. Power Balance Constraint. Considering the lighting system and other electrical devices of the port microgrid, combined with the total output of power generation devices, the following constraint can be obtained:

$$\begin{aligned} &\sum_{h_1 \in N_1} P_{\text{fu},h_1} + \sum_{h_2 \in N_2} P_{w,h_2} + \sum_{h_3 \in N_3} P_{\text{pv},h_3} \\ &+ \sum_{h_4 \in N_4} P_{s,h_4} = P_{\text{ccs}} + \sum_{h \in W} L_{p,h}, \end{aligned} \tag{13}$$

where W is the total node set of loads ($W = N_1 \cup N_2 \cup N_3 \cup N_4$); $L_{p,h}$ is the total power load of the port microgrid.

3.2.2. Power Output Constraint. Considering that the power output of the power generation device is within a certain range, there exist upper and lower bounds to guarantee the safety of the port microgrid. So, the power outputs of the power generation device need to satisfy the following constraints [33]:

$$\begin{aligned} &P_{\text{fu}}^{\min} \le P_{\text{fu},h_1} \le P_{\text{fu}}^{\max}, P_{w}^{\min} \le P_{w,h_2} \le P_{w}^{\max} \\ &P_{\text{pv}}^{\min} \le P_{\text{pv},h_3} \le P_{\text{pv}}^{\max}, P_{s}^{\min} \le P_{s} \le P_{s}^{\max}, \end{aligned} \tag{14}$$

where $P_{\text{fu}}^{\min}$, $P_{w}^{\min}$, $P_{\text{pv}}^{\min}$, and $P_{s}^{\min}$ are the minimum output power of each carbon capture power plant, photovoltaic panel, wind turbine, and power storage device, respectively; $P_{\text{fu}}^{\min}$, $P_{w}^{\max}$, $P_{\text{pv}}^{\min}$, and $P_{s}^{\max}$ are the maximum output power of each carbon capture power plant, photovoltaic panel, wind turbine, and power storage device, respectively.

3.2.3. Power Storage Constraint. Too much or too little charged and discharged power will damage the power storage device, so the following constraint can be obtained:

$$SoC_{\min} \le 1 - \frac{P_s}{P_e} \le SoC_{\max}, \tag{15}$$

where P_e is the power storage capacity; $SoC_{\min}$ and $SoC_{\max}$ are the minimum state of charge and the maximum state of charge of the power storage device. (15) can be changed to a box inequality as (14).

4. Distributed Energy Management Method for Zero-Carbon Port Microgrid

Due to the various distributed power generation devices in the considered zero-carbon port microgrid, an ADMM-based distributed energy management method is proposed to solve the above energy management problem and the optimal zero-carbon energy management solution can be obtained.

4.1. Graph Theory. The port microgrid is abstracted into a collection of N node sets, and the interaction relationship between the node sets can be expressed by a weighted directed graph $G = \{V, E, A\}$ [34], where $V = \{v_i, i = 1, \ldots, N\}$ is a node set containing N elements in total; the total number of W elements is N; $E \subseteq V \times V$ is the edge set; and $A = [a_{ij}] \in R^{N\times N}$ is the adjacency matrix of the graph. If $a_{ij} > 0$, it represents $(v_j, v_i) \in E$; that is, node j can transmit information to node i; if $a_{ij} = 0$, it represents $(v_j, v_i) \notin E$; that is, node j cannot transmit information to node i.

4.2. Optimal Condition Analysis. In this section, the optimal conditions of the energy management problem will be analyzed.

(12) is a linear term related to P_{fu,h_1} only, and (9) is a polynomial in which there is a linear term related to P_{fu,h_1}. Therefore, (12) can be combined with the first term in (9) to calculate, and obviously, (9)–(12) can be rewritten as follows:

$$F_i(P_i) = \frac{(P_i - \alpha_i)^2}{2\beta_i} + \phi, \quad i \in 1, 2 \ldots N, \tag{16}$$

where $F_i(P_i)$ is the cost of the ith device; α_i, β_i, and ϕ are equivalent transformation coefficients of the cost functions.

Then, the energy management problem of the zero-carbon port microgrid can be rewritten as follows:

$$\begin{aligned} \min \quad & \sum_{i=1}^{N} F_i(P_i) = \frac{(P_i - \alpha_i)^2}{2\beta_i} \\ \text{s.t.} \quad & \sum_{i=1}^{N} P_i = \sum_{i=1}^{N} L_i + P_{\text{ccso}} \\ & P_i^{\min} \le P_i \le P_i^{\max} \end{aligned}, \tag{17}$$

where $P_i^{\max}$ and $P_i^{\min}$ are the upper and lower power bounds of each device, respectively; $P_{\text{ccso}} = S_i P_i^2$ is the consumed power of the carbon capture power plant, which is related to the power generation of the carbon capture power plant; and S_i is the consumed power coefficient.

The above optimization problem can be solved using the Lagrange multiplier method [35], and the Lagrange function is as follows:

$$L(P_i, \lambda, \overline{\nu}, \underline{\nu}) = \sum_{i=1}^{N} (F_i(P_i)) + \lambda\left(\sum_{i=1}^{N} L_i + P_{\text{ccso}} - \sum_{i=1}^{N} P_{i,t}\right) + \overline{\nu}(P_i - P_i^{\max}) + \underline{\nu}(P_i^{\min} - P_i), \tag{18}$$

where λ, $\overline{\nu}$, and $\underline{\nu}$ are Lagrangian multipliers of equality constraints and inequality constraints, respectively. Without considering the inequality constraints of the problem, derivation of the Lagrangian function can be obtained as follows:

$$\frac{\partial L}{\partial P_i} = \frac{P_i - \alpha_i}{\beta_i} + \lambda(2S_iP_i - 1) = 0. \tag{19}$$

Then, the local optimal solution can be presented as follows:

$$P_i^* = \frac{\alpha_i + \lambda\beta_i}{1 + 2S_iP_i\lambda}, \tag{20}$$

where P_i^* is the local optimal solution without considering the inequality constraints. When considering the inequality constraints, the global optimal solution is described as follows:

$$P_i^* = \begin{cases} \dfrac{\alpha_i + \lambda\beta_i}{1 + 2S_iP_i\lambda}, & P_i^{\min} \le \dfrac{\alpha_i + \lambda\beta_i}{1 + 2S_iP_i\lambda} \le P_i^{\max}, \\ P_i^{\max}, & \dfrac{\alpha_i + \lambda\beta_i}{1 + 2S_iP_i\lambda} > P_i^{\max}, \\ P_i^{\min}, & \dfrac{\alpha_i + \lambda\beta_i}{1 + 2S_iP_i\lambda} < P_i^{\min}. \end{cases} \tag{21}$$

4.3. Distributed Energy Management. As the optimal solution of the energy management problem exists based on the above analysis, the algorithm including three iterations (22)–(24) is given as follows:

$$\lambda_i(k+1) = \lambda_i(k) + \xi_i\left[\sum_{j=1}^{N} a_{ij}\left(\lambda_j(k) - \lambda_i(k)\right)\right] + \psi(k)\Delta\widehat{P}_i(k). \tag{22}$$

$$P_i(k) = \Gamma(\lambda_i(k)) = \begin{cases} \dfrac{\alpha_i + \lambda_i(k)\beta_i}{1 + 2S_iP_i\lambda_i(k)} & P_i^{\min} \le \dfrac{\alpha_i + \lambda_i(k)\beta_i}{1 + 2S_iP_i\lambda_i(k)} \le P_i^{\max}, \\ P_i^{\max} & \dfrac{\alpha_i + \lambda_i(k)\beta_i}{1 + 2S_iP_i\lambda_i(k)} > P_i^{\max}, \\ P_i^{\min} & \dfrac{\alpha_i + \lambda_i(k)\beta_i}{1 + 2S_iP_i\lambda_i(k)} < P_i^{\min}. \end{cases} \tag{23}$$

$$\Delta\widehat{P}_i(k+1) = \Delta\widehat{P}_i(k) + \zeta\left[\sum_{j=1}^{N} a_{ij}\left(\Delta\widehat{P}_j(k) - \Delta\widehat{P}_i(k)\right)\right] + \Delta P_i(k+1) - \Delta P_i(k), \tag{24}$$

where $\xi_i > 0$ is the step size of the algorithm; $\psi(k) > 0$ is the feedback gain; $\Delta\widehat{P}_i(k)$ is the k th iteration of mismatched power; and $P_i(k)$ is the output power of the ith device in kth iteration, which is calculated by λ_i.

For the above algorithm, the following conditions need to be met [35].

Condition 1: the algorithm step size $\xi_i \in (0, 1/\sum_{j=0}^{N} a_{ij})$

Condition 2: the algorithm step size $\zeta \in (0, 1/\max_{i=1,2\ldots N} \sum_{j=1}^{N} a_{ij})$

Condition 3: the feedback gain $\psi(k) > 0$, $\lim_{k\longrightarrow\infty}\psi(k) = 0$, and $\sum_{k=0}^{\infty} \psi(k) = \infty$

As in literature [35], $\lim_{k\longrightarrow\infty} 1_N^T \Delta\widehat{P}(k) = 0$ can be definitely proved with the contradiction method according to conditions 1–3. The convergence can be obtained as follows:

$$\lim_{k\longrightarrow\infty} 1_N^T\Delta\widehat{P}(k) = 0 \longrightarrow \sum_{i=1}^{N} P_i(k) + \sum_{i=1}^{N} \Delta\widehat{P}_i(k) = \sum_{i=1}^{N} L_i. \tag{25}$$

With the above analysis (specific proof can be found in literature [35]), it can be concluded that the supply-demand balance of the port microgrid can be realized asymptotically. Therefore, the energy management problem of the zero-carbon port microgrid proposed in this study can be effectively solved by the algorithm. The algorithm flow chart is shown in Figure 3, and the algorithm steps are shown in Table 1. According to the convergence of the algorithm, the optimal solution can be obtained.

5. Case Analysis

Four cases are given and analyzed for a zero-carbon port microgrid in this section. The communication topology diagram of the zero-carbon port microgrid is shown in Figure 4, including a carbon capture power plant, two photovoltaic panels, two wind turbines, and a power storage device. The parameters of each device are shown in Table 2.

The effectiveness of the energy management method based on the zero-carbon port microgrid is verified in this section. Case 1 utilizes a centralized method to solve the optimization problem. Case 2 studies distributed energy management without the carbon capture power plant. Case 3 studies distributed energy management with the carbon capture power plant and a changing carbon trading price. In Case 4, to further verify the stability of the port microgrid, the change in load demand and plug-and-play power supply devices is considered during the operation of the port

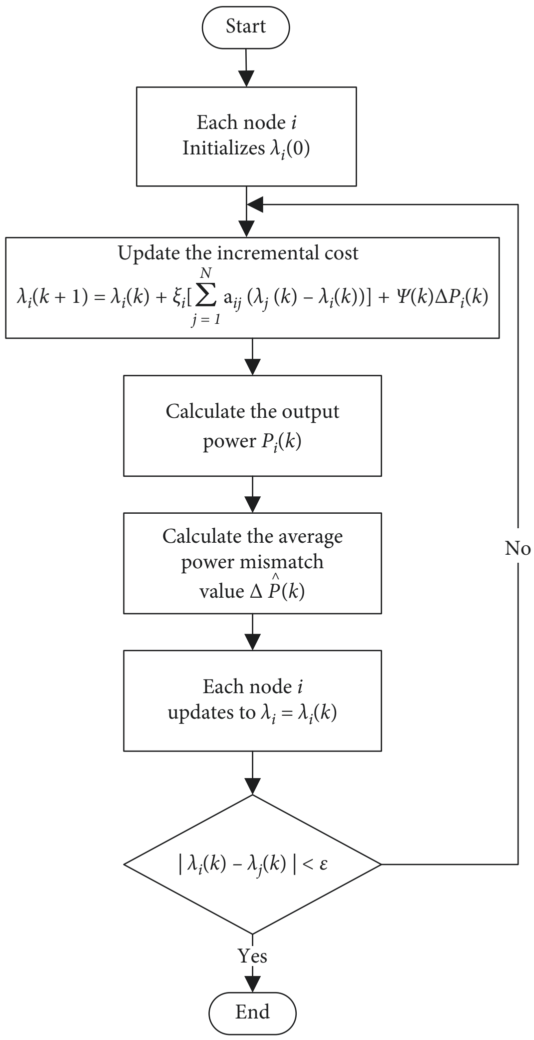

Figure 3: Flow chart of the algorithm.

microgrid. Afterwards, the impact on the total cost of the port microgrid operation and carbon emissions is analyzed.

5.1. Case 1: Centralized Energy Management with Carbon Capture Power Plant. In this case, a centralized method is utilized to solve the energy management problem of the zero-carbon port microgrid. The purpose is to verify the accuracy of the distributed method utilized in this study. The total load of the port microgrid is 1200 MW, and the output power of each device is shown in Figure 5.

The output power of each device can meet the load required by zero-carbon port microgrid, with a total cost of 10,454 \$ and a total carbon emission of 31.79 t. However, owing to the large number of renewable energy power generation devices with distributed physical characteristics, the centralized method is no longer applicable for the energy management problem of zero-carbon port.

5.2. Case 2: Distributed Energy Management without Carbon Capture Power Plant. To verify whether the zero-carbon port microgrid with the carbon-containing power plant proposed in this study can truly achieve carbon emission reduction, the port microgrid in this case utilizes the power plant without carbon capture device, but still considers carbon trading. The simulation results are as follows.

In this case, the total operation cost is 11,386 \$, and the total carbon emission is 144.0 t. The output power of each power generation device is shown in Figure 6(a). It can be seen that the output power of the port power plant is relatively low, because the carbon trading mechanism preferentially selects the power generation device with low-carbon emissions for power generation, but the port microgrid without carbon capture power plant still has high carbon emissions. The carbon emission of port microgrid without carbon capture power plant is shown in Figure 6(b). Although the distributed energy management method utilized in this case is suitable for solving this problem, the port microgrid without the carbon capture power plant has high carbon emissions and serious environmental pollution.

5.3. Case 3: Distributed Energy Management with Carbon Capture Power Plant. In this case, the distributed energy management method is utilized for the zero-carbon port microgrid with the same data as the above cases. Simulation results are shown in Figure 6.

The total operation cost is 11,260 \$, and the total carbon emission is 29.72 t. The power mismatch of each device is shown in Figure 7(c). It is clear, according to the figure, that all the mismatch converges to 0, which proves that the output power of each device can meet the power load demand of the port microgrid. The output power of each device is shown in Figure 8. It can be clearly seen that the value fluctuates slightly at the beginning and then reaches a plateau. The mass of port carbon emission is shown in Figure 7(d), which manifests that the carbon emissions of the port microgrid containing the carbon capture power plant are significantly reduced compared with Figure 7(b). $\lambda(k)$ that refers to Lagrangian iterator is shown in Figure 7(a). The physical characteristics of $\lambda(k)$ refer to the incremental cost of each power generation device in the port microgrid. The iterative operator tends to be stable, which testifies that the distributed method can converge to an optimal solution, which is approximately equal to the result in Case 1.

Since the carbon trading price is changed with the market supply and demand, the influence of the changing carbon trading price on the carbon capture power plant in the zero-carbon port microgrid needs to be studied, as shown in Figures 7(b) and 7(d). Among them, CCP stands for the port microgrid with the carbon capture power plant, and GPP stands for the port microgrid without the carbon capture power plant.

As seen in Figure 8, compared with GPP, the carbon emission of CCP is significantly less. With the carbon trading price increasing, the carbon emissions of GPP have been significantly reduced. Owing to the relatively small carbon emissions of CCP, the change in carbon trading price has little effect on its carbon emissions. Hence, it can be concluded that the integrated carbon capture power plant can greatly reduce carbon emissions of the port microgrid,

Table 1: Distributed energy management algorithm.

Algorithm: distributed energy management algorithm
Initialization:
Each node i initializes $\lambda_i(0)$.
Iteration:
(1): Each node iterates according to local information and exchanges information through neighbors. the power generation device updates its own incremental cost at the next iteration through (22).
(2): Each node calculates the output power of the k th iteration, as shown in (23).
(3): For the output power of each device, the average power mismatch value of all nodes of the port microgrid at $k+1$ th iteration is calculated by the average consistent algorithm, as shown in (24).
Each node i updates to $\lambda_i = \lambda_i(k)$.
Let $k = k+1$, until $\lvert\lambda_i(k) - \lambda_j(k)\rvert < \varepsilon, i = 1, 2, \ldots, N; j = 1, 2, \ldots, N$.($\varepsilon$ is a small positive constant).
End.

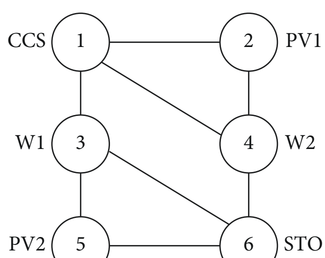

Figure 4: Zero-carbon port microgrid communication topology.

Table 2: Parameters of the device.

Device	a_i	b_i	c_i	$P_i^{\min}$	$P_i^{\max}$
CCS	0.25	2	2	30	300
PV1	0.3	0.029	0	0	300
W1	0.29	0.019	0	0	280
W2	0.21	0.01	0	0	290
PV2	0.21	0.01	0	0	400
STO	0.2	1.6	3.2	−280	280

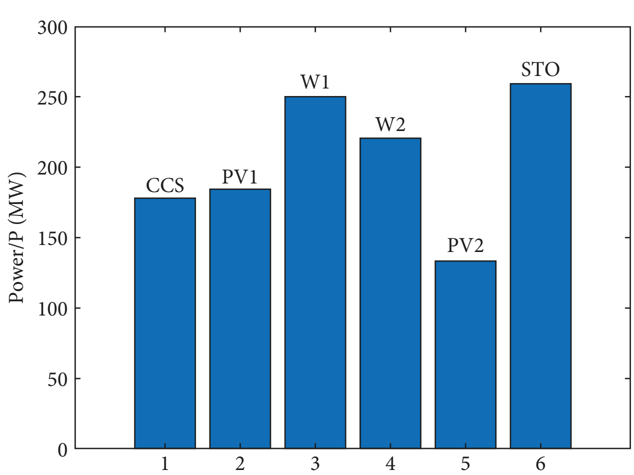

Figure 5: Output power of each device.

which is an effective way to achieve zero-carbon port microgrid.

It can be concluded from Figure 9 that with the carbon trading price increasing, the total cost of CCP becomes lower, while the total cost of GPP becomes higher. The reason is that the carbon capture device can capture most of the carbon emissions from CCP, and CCP can also profit from the carbon trading with surplus quotas. Hence, it is liable to figure out that installing carbon capture device would not only reduce carbon emissions but also reduce the operation cost of zero-carbon port microgrid. The higher the carbon trading price is, the higher the profit, and the lower the total operation cost of the port microgrid will be.

The port microgrids in Case 1 and Case 3 both contain a carbon capture device, and the amount of carbon emissions is 31.9 t and 29.7 t, respectively. The difference is not large, which can illustrate the effectiveness of the distributed energy management method proposed in this study. However, in Case 2, the carbon emission of the port microgrid without carbon capture power plants is 144.0 t, and there is a huge difference in the quantity of the carbon emission. This means that the use of the carbon capture power plant in port microgrid can reduce carbon emission by 79.4%. In conclusion, the zero-port microgrid with carbon capture power plants proposed in this study can effectively reduce carbon emissions.

Case 3 is compared with the previous cases, which shows that the port microgrid including carbon capture power plants proposed in this study can greatly reduce carbon emissions and at the same time verifies the effectiveness of the distributed energy management method. In addition, Case 3 analyzes the impact of the carbon trading unit price on the port microgrid. The higher the carbon trading unit price, the higher the economy of the port microgrid with carbon capture power plants.

5.4. Case 4: Distributed Energy Management considering the Change in Load Demand and Plug-and-Play Power Supply Devices. In this section, the change in load demand and plug-and-play power supply devices are considered during the operation of the port microgrid, and the power supply of each power supply device is analyzed to further explore the stability of the port microgrid. The simulation results of changing the load demand are shown in Figure 10, and the simulation results of considering plug-and-play power supply devices are shown in Figure 11.

Load demand changes occur frequently while the port microgrid is in operation. To study the operation of port microgrid under sudden load demand change, in this case,

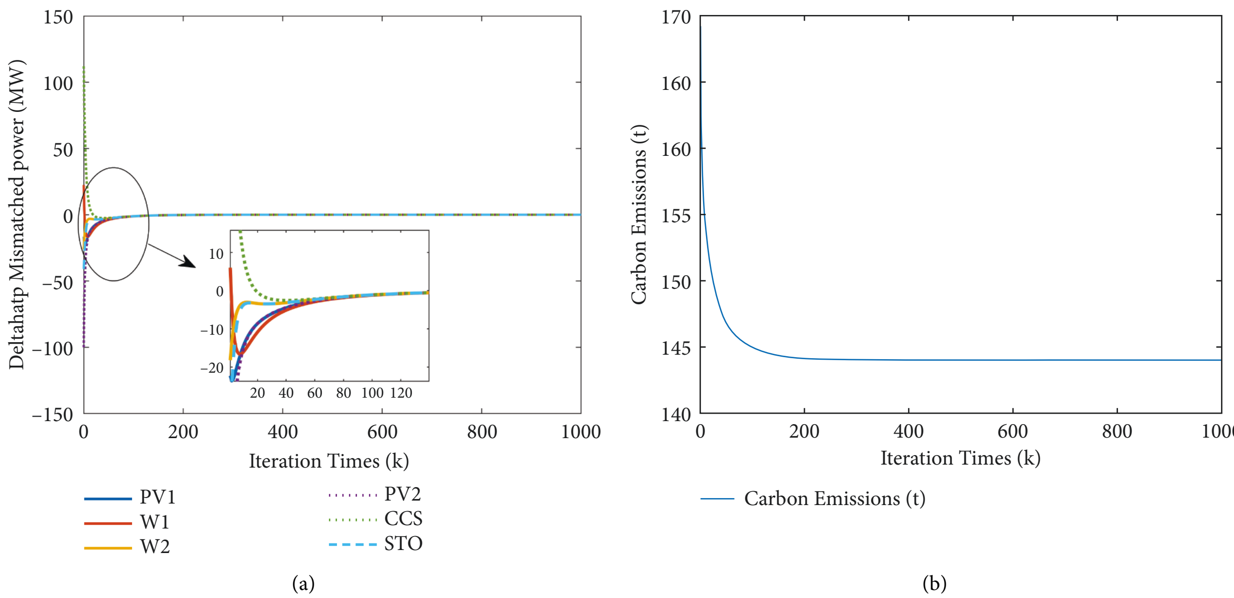

Figure 6: Simulation results. (a) Dynamic curve of output power of each device. (b) Dynamic curve of carbon emissions.

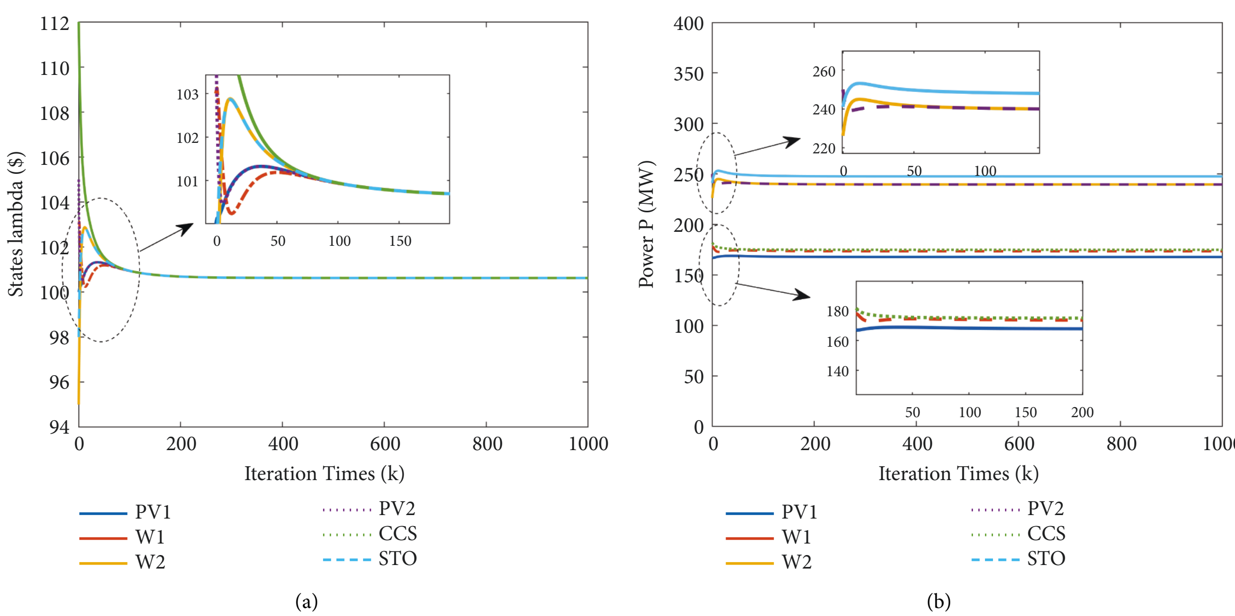

Figure 7: Continued.

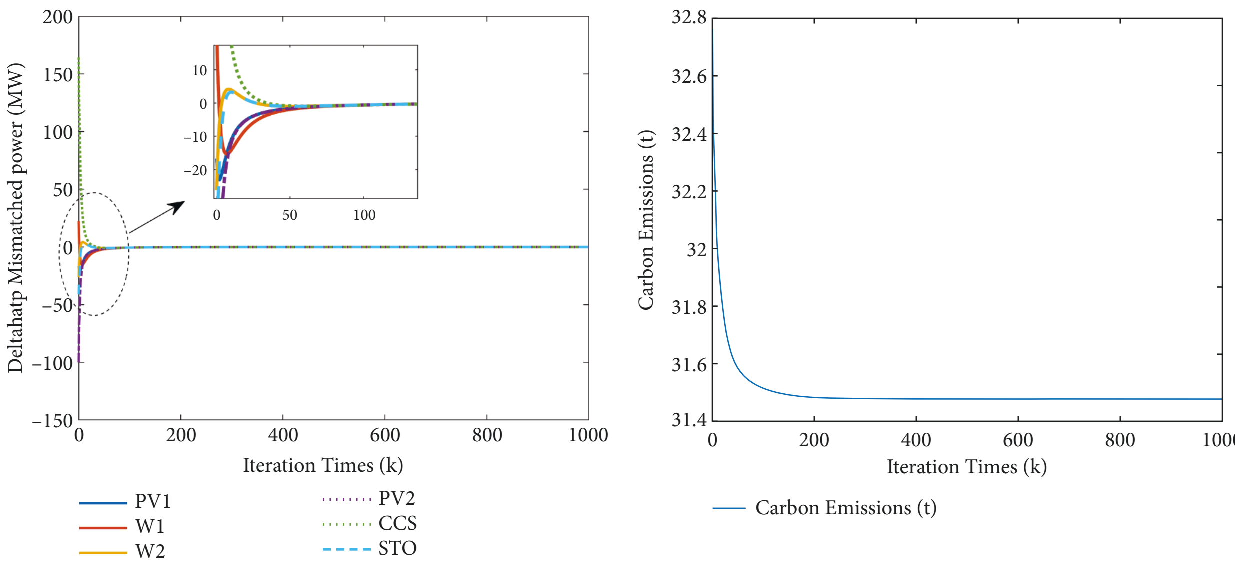

Figure 7: Simulation results. (a) Dynamic curve of iterative operator λ. (b) Dynamic curve of output power of each device. (c) Dynamic curve of power mismatch. (d) Dynamic curve of carbon emissions.

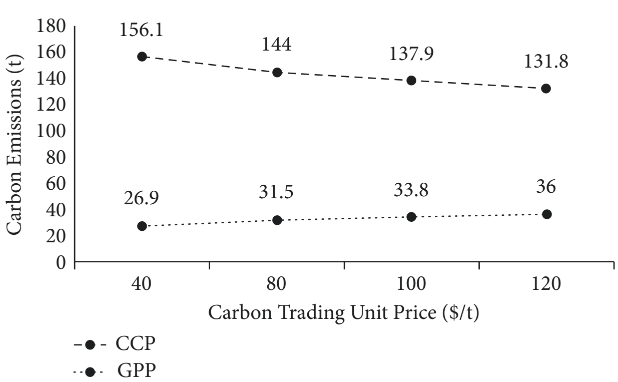

Figure 8: Impact of carbon trading price on carbon emissions.

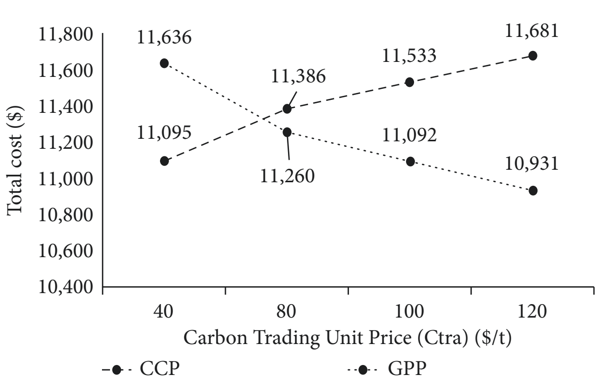

Figure 9: Impact of carbon trading price on total cost.

the port load demand changes from 1200 MW to 1260 MW at the 1000th iteration of the port microgrid. The simulation results are shown in Figure 10, and it can be seen that the cost and carbon emission increase slightly with the increase in the load demand. The optimal operation cost is 11,610 \$, and the carbon emission is 31.66 t. As port's load demand increases by 60 MW, its cost increases by 350 \$, and the increased cost is 3.1% of the total cost. At the same time, the carbon emissions increases by 1.97 t, and the increased carbon emissions are 6.1% of the total carbon emissions. It can be seen that the change in the load demand of the port microgrid has a greater impact on its cost compared with the carbon emission.

As seen in Figure 10(a), the iterative operator has a small fluctuation after the increase in load demand, but soon reaches stability, and there is a small increase compared with the pre-stabilization, which is less than 2% of the original value. It can be seen from Figure 10 that the power supply of each device fluctuates to meet the balance of supply and demand due to the sudden increase in load demand. The power supply for each device increased somewhat in comparison with that before the load demand adjustment, but the fluctuation is extremely tiny and will soon be able to reach stability. As shown in Figure 10(c), although there is a significant rapid change in the mismatched power, stability is still reached after 50 iterations. As load demand increases, carbon emissions increase because carbon capture power plants need to burn more fossil energy to meet the balance between supply and demand. When the load demand suddenly changes while the port microgrid is operating steadily, the port microgrid can still immediately recover stability, demonstrating the stability of the algorithm proposed in this study and further ensuring the reliability of the port microgrid.

To ensure the reliable and stable operation of the port microgrid when the plug-and-play power supply device is interrupted, in this energy management case, at the 1000th iteration, PV1 is interrupted and only five devices remain to handle the port microgrid's power supply. The optimal operation cost is 13358 \$, and the carbon emission is 32.0 t.

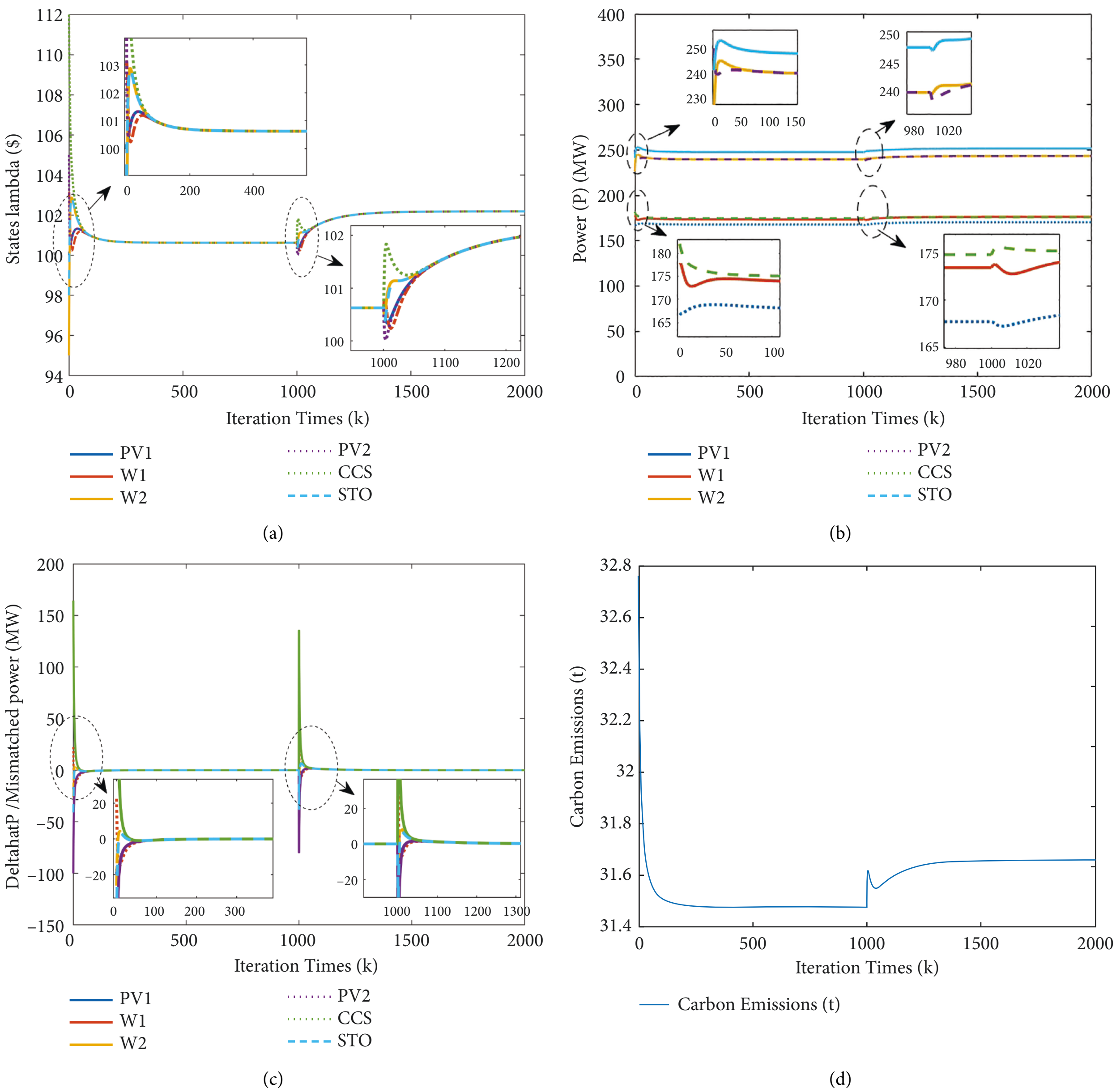

FIGURE 10: Simulation results. (a) Dynamic curve of iterative operator λ. (b) Dynamic curve of output power of each device. (c) Dynamic curve of power mismatch. (d) Dynamic curve of carbon emissions.

Compared with the normal operation of the port microgrid, the optimal operation cost increases by 15.7%, and the carbon emission increases by 7.7%. Although the load demand does not increase, the impact of the interruption of the energy supply device on the optimal operating cost is significant.

As can be seen from Figure 11(a), when PV1 is interrupted, it has a great influence on the iteration operator, and the value rises from 100.7 to 113.8, increasing by 13.1. When PV1 is interrupted, the output power of PV1 suddenly drops to 0, the curve of the power supply of each device fluctuates, and the remaining power supply devices are rapidly adjusted and the power supply is increased to ensure that the port microgrid can continue to operate stably. The curve of $\lambda(k)$ has small curve fluctuation and fast convergence. The curve of mismatched power fluctuates greatly, because at the moment of device interrupt, the power supply gap of 200 MW needs to be made up. Since PV1 is a new energy source and does not release carbon dioxide while in operation, more fossil fuels will need to be burnt to maintain the port microgrid's operation after it has been interrupted, which will increase carbon emissions. Even though the port microgrid fluctuates after interrupting, it can be promptly changed to return to stability, proving the stability of the proposed model and algorithm and further guaranteeing the reliability of the port microgrid.

To sum up, Case 1 uses a centralized algorithm to solve the energy management problem of the port microgrid; Case 2 uses a distributed algorithm to solve the energy management problem of the port microgrid without the carbon

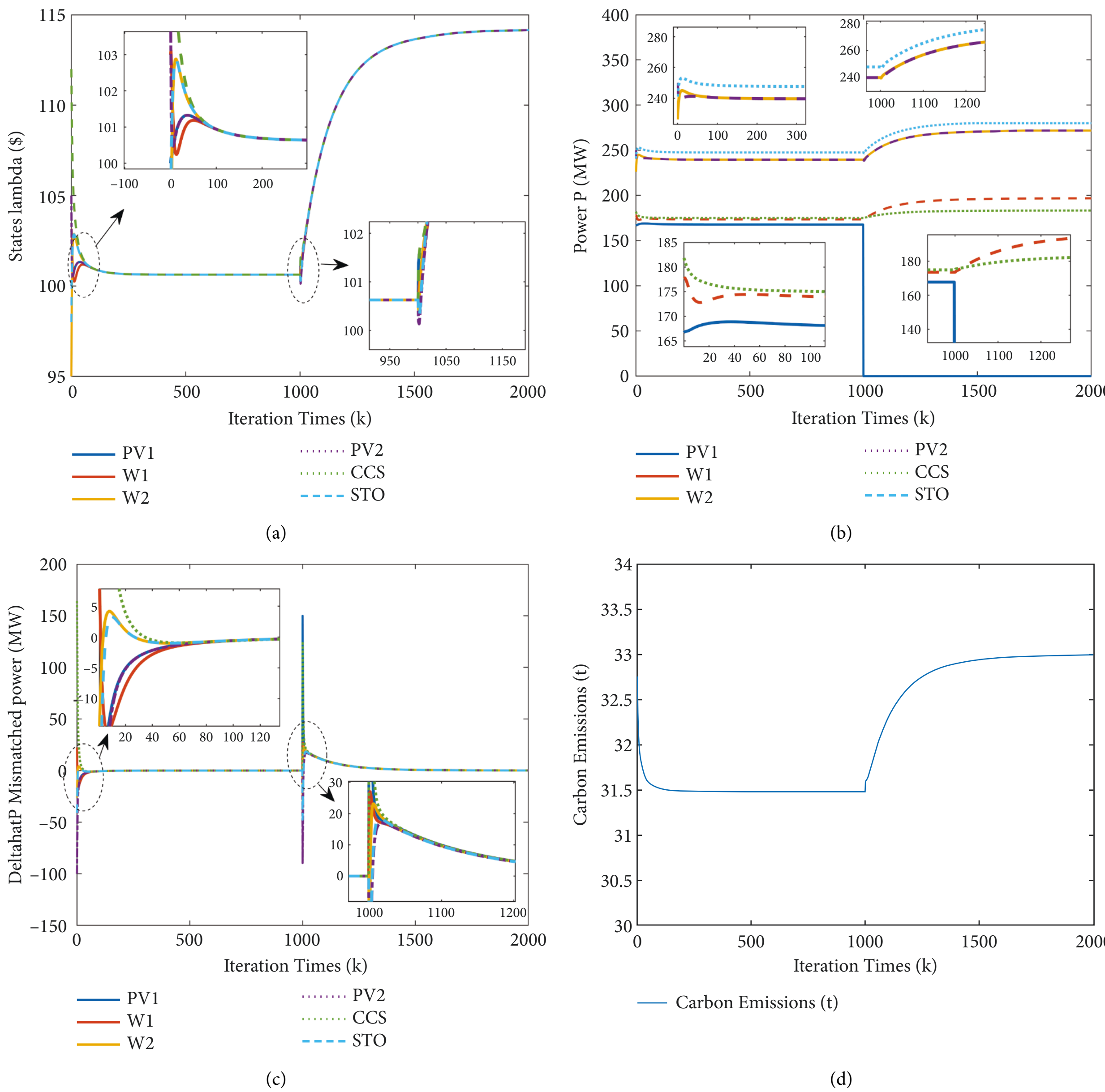

Figure 11: Simulation results. (a) Dynamic curve of iterative operator λ. (b) Dynamic curve of output power of each device. (c) Dynamic curve of power mismatch. (d) Dynamic curve of carbon emissions.

capture device; Case 3 uses a distributed algorithm to solve the energy management problem of port microgrid with carbon capture device and studies the impact of carbon trading price on the zero-carbon port microgrid; and in Case 4, the change in load demand and plug-and-play power supply devices are considered.

The error between the results obtained in Case 1 and Case 3 is less than 8%, which can further verify the accuracy and effectiveness of the algorithm mentioned in this study. However, due to the distributed characteristics of the port microgrid, the centralized algorithm is not suitable for solving the energy management problem of the port microgrid.

In Case 4, when the load demand and plug-and-play power supply devices are changed, the port microgrid is still able to operate reliably and stably after a brief fluctuation, proving the effectiveness of the proposed algorithm.

In conclusion, the port microgrid with carbon capture power plants proposed in this study can effectively reduce carbon emissions, and the distributed energy management method in this study can accurately and quickly solve the energy management problems of zero-carbon port microgrid to ensure the economic, reliable, and stable operation of the port.

6. Conclusions

An energy management problem for a zero-carbon port microgrid, integrating carbon capture power plants, has been studied in this study. With carbon trading mechanisms, an energy management model has been proposed to achieve the optimal economic operation and minimal carbon emissions of the considered port microgrid. Then, due to the distribution characteristics of the port microgrids containing a large amount of renewable energy, a distributed energy management method based on the ADMM has been raised to solve the proposed optimization problem. The simulation results have illustrated that the carbon capture plant can reduce 79.4% of carbon emissions from the port microgrid. The considered energy management problem has also been solved using a centralized algorithm with a difference of 7% with distributed optimal solutions, which has proved the accuracy and effectiveness of the proposed algorithm.

In the future, carbon dioxide captured by carbon capture could be processed and sold to improve the port economics. In addition, to further build the green port, the port will be constructed without fossil fuels for power supply, but to use renewable energy and connect with the main power grid to ensure its operation reliability.

Nomenclature

Q_{ccs}:	Mass of carbon dioxide captured
η:	Efficiency coefficient of carbon dioxide capture
Q_{dis}:	Mass of carbon dioxide emitted after fossil fuel combustion
γ:	Mass of carbon dioxide emission per unit power
P_{fu}:	Power provided by fossil fuel combustion
P_{co}:	Output power of the carbon capture power plant
P_{ccs}:	Total power consumed by carbon capture
P_{ccso}:	Operating power consumed by carbon capture
τ:	Coefficient of power consumed by carbon treating
F_{sto}:	Cost of the carbon storage device
C_{sto}:	Cost coefficient of sealing carbon per unit mass
F_{tra}:	Cost of carbon trading
C_{tra}:	Cost coefficient of carbon trading price
Q_q:	Carbon emission quota
φ:	Coefficient of carbon emission quota
F_1, F_2, and F_3:	Power generation cost, the storage cost, and the carbon cost
F_{ccs}, F_{pv}, and F_w:	Power generation cost of carbon capture power plant, photovoltaic panels, and wind turbines
a_h, b_h, and c_h:	Coefficients of the power generation cost
$P_{\text{fu},h}$ and P_{w_h}:	Output power of photovoltaic panels and wind turbines
N_1, N_2, and N_3:	Node sets of carbon capture power plants, photovoltaic panels, and wind turbines
P_{s,h_4}:	Output power of the power storage device
W:	Total node set of loads
$P^{\min}$:	Minimum output power of each device
$P^{\max}$:	Maximum output power of each device
P_e:	Power storage capacity
$SoC_{\min}$ and $SoC_{\max}$:	Minimum state of charge and the maximum state of charge
$L_{p,h}$:	Total power load of the port microgrid
$F_i(P_i)$:	Cost of the ith device
α_i, β_i, and ϕ:	Equivalent transformation coefficients of the cost functions
P_i^*:	Local optimal solution
ξ_i:	Step size of the algorithm
$\psi(k)$:	Feedback gain
$\Delta\widehat{P}_i(k)$:	kth iteration of mismatched power
$P_i(k)$:	Output power of the ith device in kth iteration.

Data Availability

The data of this study can be obtained by contacting the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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