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Distributed low-carbon energy management method for port microgrid based on we-energies under polymorphic network

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In order to reduce port pollution and carbon emissions and improve the utilization rate of clean energy, a port microgrid based on we-energies (WEs) and its polymorphic distributed low-carbon energy management method is proposed. First, this study considers a variety of heterogeneous Wes, such as ship we-energies (SWEs), to establish a polymorphic energy management system for port microgrids and to achieve reliable information exchange between WEs under different communication networks. Second, considering the bidirectional energy transmission characteristic of the port WEs, the operating cost function of heterogeneous WEs is established. In addition, with the objective of economic and low-carbon operation of port microgrids, the energy management model of a port microgrid is constructed, and the optimal solution is obtained based on distributed optimization theory. Finally, simulation cases are performed to verify the effectiveness of the proposed method.

KEYWORDS

port microgrid, clean energy, low carbon, distributed energy management, we-energy, polymorphic network

1 Introduction

With the development of the shipping industry, maritime transport is responsible for nearly 90% of global trade in goods. As important transportation hubs for sea and land transport, ports consume huge amounts of energy (Coppola et al., 2016; Huang et al., 2022). In addition, ships and large port equipment emit a lot of air pollutants, causing poor air quality in the port and the surrounding environment (Tang et al., 2018; Alamoush et al., 2020). Therefore, in order to solve the problem of port energy consumption and environmental pollution, it is urgent to build a green and low-carbon port microgrid with clean energy as the main energy (Nikolaos and Theocharis, 2021). In order to ensure the reliability of operation of the port microgrid, it is crucial to study its energy management issues (Çağatay and Jasmine, 2019).

The essence of port microgrid energy management is an optimization problem with constraints, which requires meeting the conditions of reliable operation for port microgrid and minimizing port operating costs by using suitable optimization strategies (Hein et al., 2021). Research results on port microgrids have mainly considered the uncertainty of renewable energy supply on the energy supply side (Çağatay and Jasmine, 2021) and the reliability of supplying flexible loads such as ships on the demand side (Parise et al., 2016; Fang et al., 2020). Considering the presence of a large number of flexible loads in the port power system, an energy management model with multiple decision variables and constraints has been proposed to vary the flexible loads' power demand at high loads or high electricity prices in order to optimize the operating costs of the port power system (Kanellos et al., 2019). Studies on energy management in port microgrids are often solved by using centralized optimization methods (Olivares et al., 2014; Kermani et al., 2020). The centralized methods rely on the design of the centralized controller, which will need to be redesigned if the structure of the port microgrid changes. At the same time, although the centralized controller is capable of handling huge amounts of data in the microgrid, its failure would cause huge losses to the port. To sum up, the centralized methods have problems such as difficult network expansion and single point of failure. Moreover, port microgrids with large-scale clean energy present a distributed structure, so the distributed methods are attracting extensive attention of researchers (Li et al., 2020; Li et al., 2021). In the distributed methods, each agent needs to obtain information about its neighbors with the help of a communication network and performs local calculations based on the exchange of information between itself and its neighbors to achieve distributed energy management (Yang et al., 2019). For port power systems with flexible loads, such as ships, a distributed hierarchical control method has been proposed to solve the problem of reducing the operating costs of the port power system (Gennitsaris and Kanellos, 2019). A multiobjective operation scheduling method based on an innovative virtual fuzzy electricity price has been proposed to address the problem of carbon emissions for large ports in a short period of time (Kanellos, 2019). A distributed alternating direction method of multipliers algorithm has been proposed for the existence of energy entities with different energy forms in the port energy system, in which the energy bodies only share local information with their neighbors to complete the information update, solving the problem of optimal operating costs of the port energy system (Zhang et al., 2020). A distributed hierarchical topology reconfiguration approach has been proposed for port power systems with false data attacks, solving the problem of energy management in port power systems with an unknown and arbitrarily large number of attacked nodes (Shan et al., 2022).

The high level of clean energy connected to the port microgrid increases the flexibility of the energy supply and gives rise to a manufacturing and marketing integration of energy main body – WEs, which contains at least one type of energy production equipment or energy consumption equipment (Sun et al., 2017; Sun et al., 2019). According to the type of energy consumption of the power generating equipment, the port microgrid includes traditional energy generating equipment WEs (TWEs) and clean energy generating equipment WEs (CWEs). However, as more and more all-electric ships fueled by clean energy come into service (Wen et al., 2021; Zhang et al., 2021), they can either be connected directly to the shore power plant with generators switched off and powered by the port microgrid for the purpose of reducing pollution (Fang et al., 2020) or they can be used as power generators to supply electricity to the shore loads, giving them manufacturing and marketing integration of behavior. Therefore, all-electric ships fueled by clean energy can also be considered a dynamic type of WE in port, namely ship WEs (SWEs). The bidirectional energy transmission characteristic of WEs makes them both energy suppliers and energy consumers (Sun et al., 2019), to the extent that the operating costs of WEs are no longer just the cost of the power generating equipment. This not only increases the complexity of the WE operating cost function but also creates difficulties in modelling the energy management of the port microgrid. In addition, the distributed energy management methods for the considered port microgrid rely on the information interaction between WEs, which is based on the premise that all WEs need to be in the same communication network. However, the SWEs and various heterogeneous WEs ashore are always in different traditional communication networks. Due to the problems of closed network element structure and single communication mode in the traditional communication network, the network convergence has a low support capability, with the result that the information interaction between the WEs based on the traditional communication network cannot be realized, thus, the distributed energy management of the port microgrid cannot be realized. In recent years, the polymorphic network is a newly emerging type of smart network in different communication networks, which uses a dynamic combination of resources and network reconfiguration to enhance the functions, performance, and other needs of the network and fundamentally meet the service needs of network intelligence, diversity, personality, high tenacity, and high performance (Hu et al., 2019). Polymorphic network breaks the traditional network structure to achieve flexible interconnection of heterogeneous networks, and new networks with hybrid addressing based on polymorphic identification can achieve efficient interaction of different data in space (Hu et al., 2020). The implementation of distributed energy management for port microgrids based on WEs can be guaranteed under a polymorphic network.

In summary, this study is dedicated to solving the energy management problem of port microgrids containing WEs and proposes a distributed method under a polymorphic network, with the following main contributions:

1) A polymorphic energy management system was established for a port microgrid based on WEs. Considering various WEs in different communication networks, such as SWEs and CWEs in the port microgrid, in order to guarantee the information interaction between neighbor WEs, the port microgrid energy management system was established based on a polymorphic network to realize distributed energy management.
2) Considering the bidirectional energy transmission characteristic of WEs, the operating cost function for WEs was constructed. The manufacturing and marketing integration of the behavior of WEs meant that the operating cost for WEs not only included the cost of WE’s power generation but also the cost or benefit of trading with neighbor WEs or the main grid. We constructed operating cost functions for WEs with incremental cost as a variable, simplified the cost functions based on rotation symmetry, and analyzed the convexity of the operating cost functions.
3) Considering the cost of carbon emissions, a port microgrid energy management model was constructed, and a distributed solution method was proposed. With the objective of minimizing the operating cost of all WEs and the carbon emissions of the port, taking into account the constraints on the reliable operation of the port microgrid, the energy management model of port microgrid was constructed, and a distributed energy management strategy was proposed based on a multi-agents consensus algorithm.

The structure of the rest of the article is as follows. In Section 2, a polymorphic energy management system for WE-based port microgrid is established. In Section 3, the port microgrid energy management model is established, and a distributed solution method is proposed. In Section 4, the proposed method is validated by simulation using MATLAB. Finally, the results of the study are summarized.

2 Polymorphic energy management system for port microgrid based on WEs

The port microgrid considered in this study is composed of a large number of WEs, which can be classified according to the type of power generating equipment: TWEs and CWEs. In particular, CWEs include wind turbine WEs (WWEs) and photovoltaic generating equipment WEs (PWEs). Unlike traditional ships that use shore power after berthing, all-electric ships fueled by clean energy are also dynamic WEs for port microgrids – SWEs. The widespread presence of WEs gives the port microgrid a distributed characteristic and requires a distributed method based on a multi-agents system to solve the port microgrid energy management problem. Distributed energy management relies on the interaction of information between agents corresponding to each WEs, provided that all the agents are in the same communication network and that their communication topology meets certain constraints. However, the shore-based WEs and berthing SWEs are in different communication networks, making information interaction between neighbor agents impossible. Polymorphic network supports polymorphic identification, such as content identification and identity identification. Identification based on polymorphic addressing can realize flexible networking and provide a channel for information interaction between WEs in different communication networks. Therefore, a polymorphic energy management system for a port microgrid was constructed, and its structure is shown in Figure 1.

As can be seen in Figure 1, the port microgrid polymorphic energy management system consists of a data layer, a control layer, and a service layer from the bottom up. The function of the data layer is fitting the routing and resources of a variety of heterogeneous infrastructure platforms, providing basic data support and security for the construction of port microgrid network elements, receiving operational data, and broadcasting the scheduling instructions. The control layer is used for polymorphic addressing for heterogeneous WEs based on different identities and forming a dynamic communication topology network following certain constraints so as to enable peer-to-peer information interaction between neighbor WEs. The function of the service layer is to enable the energy management of the port microgrid. First, the generating cost functions of different WEs are obtained, and various WEs’ operating cost functions are established, considering the bidirectional energy transmission characteristic. Second, the energy management model of the port microgrid with the economic and low-carbon objective is constructed. Finally, based on the communication topology of the WEs given by the control layer, a distributed solution method is designed to realize the distributed energy management of the port microgrid.

In summary, the polymorphic energy management system of the port microgrid is based on a polymorphic network to achieve the compatibility of heterogeneous traditional communication networks, which enables the interaction of information between WEs in different modes and lays the foundation for the subsequent implementation of distributed energy management in the port microgrid.

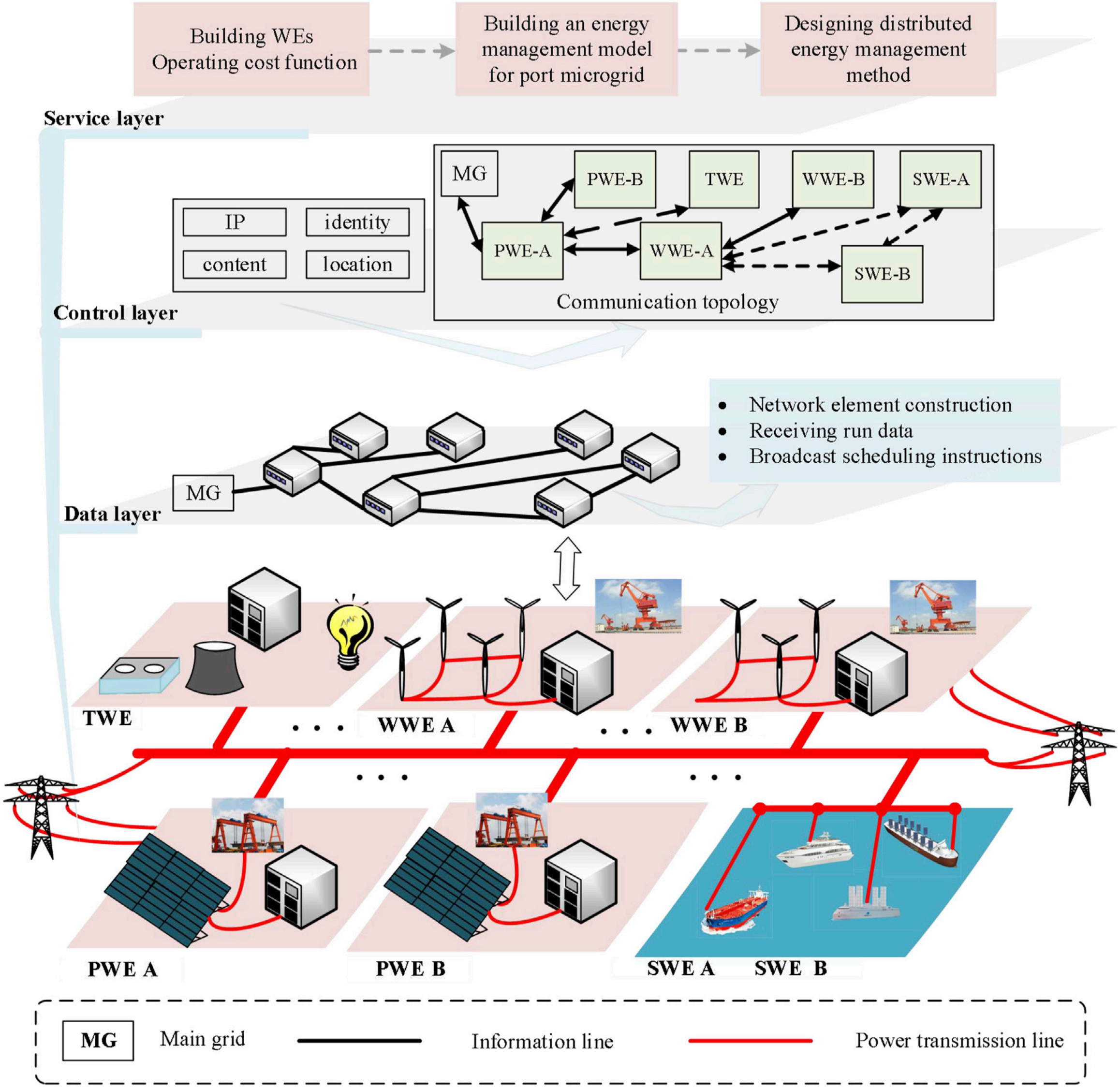


FIGURE 1
Port microgrid polymorphic energy management system.

3 Distributed energy management for port microgrid

3.1 Communication network

Port microgrid energy management relies on the exchange of information between neighbor WEs, and its communication topology is represented as $G(V, E, A)$, which is an undirected and strongly connected graph (Liu et al., 2017), where the set of nodes $V = \{v_1, v_2, v_3, \ldots, v_n\}$ denotes the finite non-empty set of all WE nodes in G. The set of edges $E = \{e_1, e_2, e_3, \ldots, e_n\}$ denotes the existence of communication paths between WEs and neighbors in G. A is the matrix of connection weights for information interactions between WEs. $a_{ij} > 0$ if there is a path of information exchange between any heterogeneous WEs v_i and v_j; otherwise, $a_{ij} = 0$. It is worth noting that there are no self-looping connected paths in G, that is, there is no $a_{ii} = 0$ in graph G.

3.2 Operating cost function of WEs

The bidirectional energy transmission of WEs in port microgrids complicates their operating cost, which includes not only the cost of generating equipment but also the cost associated with energy interaction between WEs. As the energy consumed by the load in the WE can be supplied by the WE itself, neighbor WEs *via* the microgrid, or even the main grid. Therefore, the operating cost of individual WE in the port microgrid in this study includes the following: the generating electricity cost of the WEs, the cost of purchasing electricity from neighbors and the main grid, and the cost of selling electricity to neighbors and the main grid. Based on the above-stated analysis, the operating cost of individual WE in the port microgrid is expressed as follows:

$$\begin{aligned}\tilde{f}(P_{rk}) = {} & C_{ok}(P_{rk}) - \sum_{j=1}^{N} a_{kj} P_{rk} P_{k\to j} + \sum_{j=1}^{N} a_{jk} P_{rj} P_{j\to k} \\ & + P_{rg}\left[P_{load}^{k} + P_{loss}^{k} + \sum_{j=1}^{N} a_{kj} P_{k\to j} - P_k - \sum_{j=1}^{N} a_{jk} P_{j\to k}\right],\end{aligned} \tag{1}$$

where $C_{ok}(P_{rk})$ represents the generating cost function expressed with incremental cost as a variable, $P_{k\to j}$ represents the port WE k supplying energy to WE j, P_{load}^{k} represents the load of the WE k, P_{loss}^{k} represents the energy loss from the WE k, P_{rg} represents the main grid electricity price, P_{rk} represents the incremental cost of WE k, depending on the output power of generating equipment for the WE, P_k represents the power generation from WE k, and a_{jk} represents that the WE k can transmit electricity to the WE j.

Remark 1. The unit price of electricity trading between WEs is the incremental cost of each WE's generation equipment.

Assuming a port microgrid containing N WEs, and considering the bidirectional energy transmission between WEs, based on the constructed operating cost function of the individual WE, the operating cost of the port microgrid can be expressed as follows:

$$\begin{aligned}\sum_{k=1}^{N}\tilde{f}(P_{rk}) = {} & \sum_{k=1}^{N} C_{ok}(P_{rk}) - \sum_{k=1}^{N}\sum_{j=1}^{N} a_{kj} P_{rk} P_{k\to j} + \sum_{k=1}^{N}\sum_{j=1}^{N} a_{jk} P_{rj} P_{j\to k} \\ & + \sum_{k=1}^{N} P_{rg}\left[P_{load}^{k} + P_{loss}^{k} + \sum_{j=1}^{N} a_{kj} P_{k\to j} - P_k - \sum_{j=1}^{N} a_{jk} P_{j\to k}\right],\end{aligned} \tag{2}$$

where N represents the number of WEs in the port microgrid.

Noting that $a_{jk}P_{rj}P_{j\to k}$, $a_{kj}P_{rk}P_{k\to j}$, and $a_{kj}P_{k\to j}$, $a_{kj}P_{j\to k}$ have a special symmetry structure in the port microgrid, a rotational symmetry-based analysis yields

$$\begin{aligned}& \sum_{k=1}^{N}\sum_{j=1}^{N} a_{jk} P_{rj} P_{j\to k} - \sum_{k=1}^{N}\sum_{j=1}^{N} a_{kj} P_{rk} P_{k\to j} = 0 \\ & \sum_{k=1}^{N} a_{kj} P_{k\to j} - \sum_{k=1}^{N} a_{jk} P_{j\to k} = 0.\end{aligned} \tag{3}$$

According to Eq. 3, it can be seen that the cost of energy interaction between WEs in the port microgrid offsets each other. Therefore, the operating cost function of port microgrid based on WEs can be expressed as

$$\begin{aligned}\tilde{f}(P_r) & = \sum_{k=1}^{N} C_{ok}(P_{rk}) + P_{rg}\left[P_{load} + P_{loss} - \sum_{k=1}^{N} P_k\right] \\ & = \sum_{k=1}^{N} C_{ok}(P_{rk}) + P_{rg}\left[P_{load} + P_{loss} - \sum_{k=1}^{N}\frac{(P_{rk} - b_k)}{2a_k}\right] \\ & = \sum_{k=1}^{N}\left[C_{ok}(P_{rk}) - \frac{P_{rg}P_{rk}}{2a_k} + \frac{P_{rg}b_k}{2a_k} + P_{rg}\left(P_{load}^{k} + P_{loss}^{k}\right)\right] \\ & = \sum_{k=1}^{N} f^{k}(P_{rk}).\end{aligned} \tag{4}$$

Remark 2. Due to the manufacturing and marketing integration of WEs, the energy supply–demand balance of the WE is ensured by considering the electricity trading between WEs and the electricity trading between the WE and the main grid. Furthermore, the relationship between the incremental cost P_{rk} and the power generation P_k of the kth WE has the following relationship:

$$P_{rk}(P_k) = \frac{dC_k(P_k)}{dP_k}. \tag{5}$$

For CWEs and TWEs, the cost function $C_k(P_k)$ with the power generation P_k of the kth WE is generally a convex quadratic function (Huang et al., 2016; Kanellos, 2019); therefore, $P_{rk} = 2a_kP_k + b_k$, where a_k and b_k denote the generating cost coefficients, respectively, $a_k > 0$, $b_k > 0$. In turn, it can be obtained that $P_k = \frac{(P_{rk} - b_k)}{2a_k}$. The second row in model **(4)** makes variable substitution according to the relationship between P_k and P_{rk}.

3.3 Convexity analysis

As the process of analyzing the operating cost function of WEs requires modeling with the incremental cost P_{rk}, the generating cost function of WEs also needs to be converted to a function with P_{rk}. Thus, the equivalence of the generating cost function for the WEs with P_{rk} and P_k as variables is defined as

$$C_{ok}(P_{rk}) \cong C_k(P_k) = C_k\left(C_k'^{-1}\left(C_k'(P_k)\right)\right) = C_k\left(C_k'^{-1}(P_{rk})\right). \tag{6}$$

The character of the port microgrid operating cost function is closely related to the design of subsequent distributed energy management methods for the port microgrid, so it is necessary to prove whether the constructed port microgrid operating cost function is convex. As P_{rk} in the port microgrid operating cost function Eq. 4 is transformed so that the two added terms $\frac{P_{rg}b_k}{2a_k}$ and $-\frac{P_{rg}P_{rk}}{2a_k}$ are linearly related to P_{rk}. Whether the constructed operating cost function of the port microgrid is convex depends critically on whether the WE generating cost function with the incremental cost P_{rk} is convex. To prove that the equivalently transformed cost function $C_{ok}(P_{rk})$ of the WEs is convex, we present **Lemma 1**.

Lemma 1. It is assumed that the cost function of electricity generation $\boldsymbol{C_k(P_k)}$ of the WE is a smooth convex function and satisfies the inequality condition:

$$(C''_k(P_k))^2 - C'_k(P_k)C'''_k(P_k) \geq 0. \tag{7}$$

Then, the cost function $\boldsymbol{C_{ok}(P_{rk})}$ of electricity generation with the incremental cost $\boldsymbol{P_{rk}}$ as the variable for the WE is a smooth convex function.

Proof. The cost function $\boldsymbol{C_{ok}(P_{rk})}$ of electricity generation from WEs is a smooth convex function that yields the second order derivative of the function $\boldsymbol{C_{ok}(P_{rk})}$ with $\boldsymbol{P_{rk}}$ as the variable.

$$\begin{aligned}\frac{\partial^2 C_{ok}(P_{rk})}{\partial P_{rk}^2} &= \frac{\partial\left[C'_k\left(C'^{-1}_k(P_{rk})\right)\dfrac{1}{C''_k\left(C'^{-1}_k(P_{rk})\right)}\right]}{\partial P_{rk}} \\ &= \frac{C''_k(P_k) - C'_k(P_k)\dfrac{C'''_k(P_k)}{C''_k(P_k)}}{(C''_k(P_k))^2} \\ &= \frac{(C''_k(P_k))^2 - C'_k(P_k)C'''_k(P_k)}{(C''_k(P_k))^3}.\end{aligned} \tag{8}$$

From **Lemma 1**, we know that $(C''_k(P_k))^2 - C'_k(P_k)C'''_k(P_k) \geq 0$ and $C_k(P_k)$ is a smooth convex function, and we know that $(C''_k(P_k))^3 > 0$. Therefore, the conclusion $\frac{\partial^2 C_{ok}(P_{rk})}{\partial P_{rk}^2} > 0$ is obtained from Eq. 7, and the cost function described by incremental cost is a smooth convex function, that is, $\boldsymbol{C_{ok}(P_{rk})}$ is a convex function. **The proof is completed**.

Since the cost function of electricity generation $C_k(P_k)$ for WE is a smooth quadratic convex function, based on **Lemma 1**, $\boldsymbol{C_{ok}(P_{rk})}$ is also a smooth convex function and therefore the port microgrid operating cost function is a smooth convex function.

3.4 Energy management model of port microgrid

In order to build a green, low-carbon, and economic port microgrid, the objective of energy management for port microgrid is to minimize the operating cost and carbon emissions. Based on the operating cost function for port microgrid and considering the cost of port carbon emissions, the energy management model for port microgrid is constructed as follows:

$$\begin{aligned} &\min \sum_{k=1}^{N} f^k(P_{rk}) + eco\sum_{k=1}^{m} Em^k(P_{rk}) \\ &s.t. \quad P_{k,min} \leq P_k \leq P_{k,max} \end{aligned}, \tag{9}$$

where $\boldsymbol{N = m + n}$, $\boldsymbol{m}$ represents the number of TWEs, $\boldsymbol{n}$ represents the number of CWEs, $\boldsymbol{eco}$ represents the cost per unit of carbon emissions, $\boldsymbol{Em^k(.)}$ represents the carbon emissions generated by traditional energy generating equipment from WEs, and $\boldsymbol{P_{k,min}}$ and $\boldsymbol{P_{k,max}}$ represent the minimum and maximum output of electricity generating equipment from WE $\boldsymbol{k}$, respectively.

Remark 3. The first term in Eq. 9, namely the operating cost of the port microgrid based on WE, is a convex function. The second item is the cost of carbon emissions for WE. As CWEs do not produce carbon emissions, that is, $\sum_{k=1}^{n} Em(P_k) = 0$, only the cost of carbon emissions for TWEs are considered. The cost functions of carbon emissions for TWEs are quadratic in relation to the output power of the equipment (Pourakbari-Kasmaei et al., 2020). To ensure uniformity of variables in the port microgrid energy management model, the cost functions of carbon emissions for TWEs need to be expressed in the form of the incremental cost $\boldsymbol{P_{rk}}$. After transformation by Eq. 5, $\boldsymbol{P_{rk}}$ is linearly related to $\boldsymbol{P_k}$, so that the cost functions of carbon emissions for TWEs with incremental cost $\boldsymbol{P_{rk}}$ are also convex functions after variable replacement through **Lemma 1**. In summary, the objective function of the energy management model for the port microgrid is convex. In addition, as the energy supply–demand balance of every WE is ensured, the energy supply–demand balance of the whole port microgrid is also ensured. Therefore, there is a potential supply–demand balance constraint in the objective function of the port microgrid energy management model and only the output power constraints of generating equipment for the WE need to be considered. Therefore, the port microgrid energy management problem is essentially a convex optimization problem with inequality constraints and can be solved by distributed methods.

3.5 Distributed energy management method

Considering the distributed structure presented by the port microgrid, the convex optimization problem **(9)** with inequality constraints can be solved based on the distributed optimization method **(10)**.

$$\begin{cases} P^* - g\left(P^* - \alpha\left(\nabla f(P^*) + Lz^*\right)\right) = 0 \\ LP^* = 0 \end{cases}, \tag{10}$$

where $\boldsymbol{P^* = \{P_{rk}^*, k = 1, \ldots, N\}}$, $\boldsymbol{\alpha}$ represents the update step (positive number), different steps affect the reliability of the method, $\boldsymbol{L}$ represents the Laplace matrix, $\boldsymbol{\nabla f(.)}$ represents the gradient of the objective functions for port microgrid, $\boldsymbol{g(.)}$ represents the projection operator, $\boldsymbol{\Omega'}$ represents a hyper-rectangular set, $\boldsymbol{\Omega' = \{P_{rk} \in R_r^N : P_{rk}^{min} \leq P_{rk} \leq P_{rk}^{max}\}}$, and the projection operator $\boldsymbol{g(.)}$ is equivalently described as

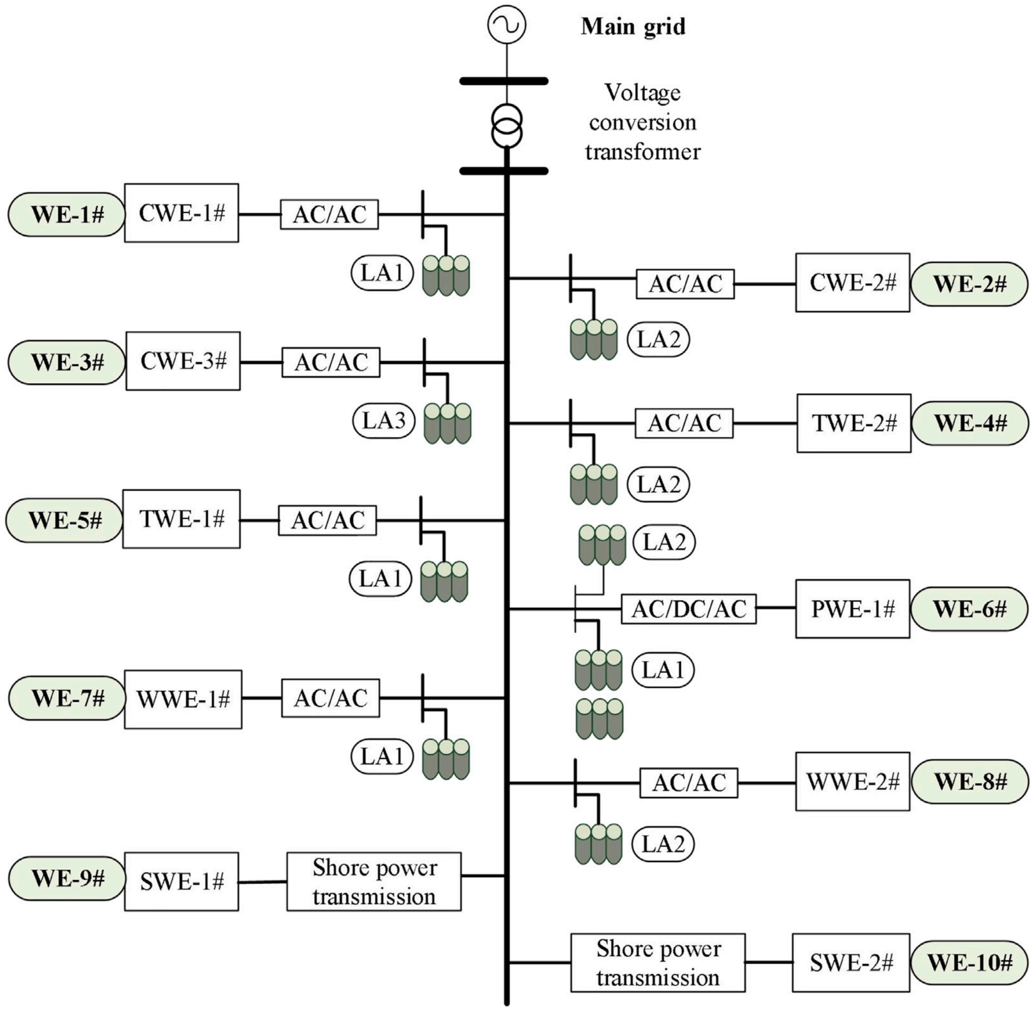


FIGURE 2
Simulation and validation model of a port microgrid based on WEs.

$$P_{rk} = \begin{cases} P_{rk}^{max} & P_{rk} > P_{rk}^{max} \\ P_{rk} & other \\ P_{rk}^{min} & P_{rk} < P_{rk}^{min} \end{cases}.$$

According to Eq. 10, a distributed solution method for the energy management problem for the port microgrid is proposed. The method is expressed in the following iterative way:

$$\begin{cases} P_{rk+1} = g\left(P_{rk} - \alpha\left(\nabla f\left(P_{rk}\right) + L\left(z_k + P_{rk}\right)\right)\right) \\ z_{k+1} = z_k + LP_{rk+1} \end{cases}. \tag{11}$$

Since model **(9)** is differentiable and its gradient is continuous as a convex function, and there exists an auxiliary variable z satisfying condition **(10)** (Liu et al., 2017), the incremental cost of WEs can converge to an optimal solution, and then a distributed optimal solution to the energy management problem for the port microgrid is obtained.

4 Simulation

4.1 Port microgrid simulation model based on WEs

In this subsection, we used MATLAB as an experimental tool to verify the effectiveness of the distributed energy management method for the port microgrid proposed in this article. The considered port microgrid model based on WEs is shown in Figure 2.

The port microgrid model contains 10 WEs, including 6 CWEs (2 WWEs and 1 PWE), 2 TWEs, and 2 SWEs. The port microgrid has a total of 41555W of load and line losses. The electricity required is provided by both the main grid and the WEs, at the cost of 5 Yuan per unit of carbon emissions. It is assumed that there are no energy losses in the generating

TABLE 1 Parameters of power generating equipment.

Energy type	a	b	c	P_i^{min}	P_i^{max}	α_i	β_i	γ_i
TR energy	0.000533	0.869	213.1	50	200	0.0000004	0.3	4.5
Clean energy1	0.008890	0.333	200	37.5	150	0	0	0
	0.000741	0.833	240	45	180	0	0	0
Clean energy2	0.0001	0.50000	10	0	180000	0	0	0
	0.0005	0.20000	15	0	125000	0	0	0

TABLE 2 Operating data of WEs.

	WE-1	WE-2	WE-3	WE-4	WE-5
Distributed method	37.5	37.5	37.5	122.9	122.9
Centralized method	37.5	37.5	37.5	122.6	122.6
	WE-1	WE-2	WE-3	WE-4	WE-5
Distributed method	8000.0	8000.0	25000.0	112.7	112.7
Centralized method	7997.3	7997.3	24987.0	112.5	112.5
Port microgrid	Distributed method	Cost	30821.0	Carbon emissions	82.8
	Centralized method	Cost	30801.0	Carbon emissions	82.6

equipment during the simulations for the heterogeneous WEs. The parameters related to the operation of the generating equipment in the heterogeneous WE during regular operation of the microgrid are shown in Table 1 (Huang et al., 2016).

4.2 Case 1: Traditional port microgrid energy management model with P_k

An energy management model with the objective of minimizing the operating cost and carbon emissions of the port microgrid, without considering the trading of electricity between WEs and the trading of electricity between the WE and the main grid, is as follows:

$$
\begin{aligned}
& \min \sum_{k=1}^{N} f^k(P_k) + eco\sum_{k=1}^{m} Em^k(P_k) \\
& \text{s.t.}\quad \begin{array}{l} P_{k,min} \le P_k \le P_{k,max} \\ P_{load} + P_{loss} = P_{MG} + \sum_{k=1}^{N} P_k \end{array}
\end{aligned} \quad . \tag{12}
$$

It is assumed that the total energy losses remain constant during the regular operation of the port microgrid. It was solved by using the centralized method and the distributed method based on the leader-following consensus algorithm (Huang et al., 2016), respectively. The results of the operation of each generating equipment in the port microgrid are shown in Table 2.

According to Table 2, the centralized method and the leader-following consensus method result in different operating costs for the port microgrid, namely 30,821 Yuan and 30,801 Yuan, respectively.

4.3 Case 2: Traditional port microgrid energy management model with P_{rk}

$$
\begin{aligned}
& \min \quad F(P_r) = \sum_{k=1}^{N} C_{ok}(P_{rk}) + P_{rg}P_{MG} \\
& \text{s.t.} \quad \begin{array}{l} \sum_{k=1}^{N} P_k + P_{MG} = P_{load} + P_{loss} \\ P_k^{min} \le P_k \le P_k^{max} \end{array}
\end{aligned} \quad . \tag{13}
$$

In this study case, the load demand, transmission line energy losses, and main grid electricity price are kept constant in the port microgrid, and a distributed method (Liu et al., 2017) is used to solve the port microgrid energy management problem **(13)**. The parameter α is taken as 0.000001, and the incremental cost of the heterogeneous WEs converges around 0.9 when the simulation reaches the 300000th step. The operation of the microgrid is analyzed considering the operating cost of the WEs. Figure 3 shows the simulation curves based on the distributed method. Table 3 shows the output of WEs power generating equipment through different cases.

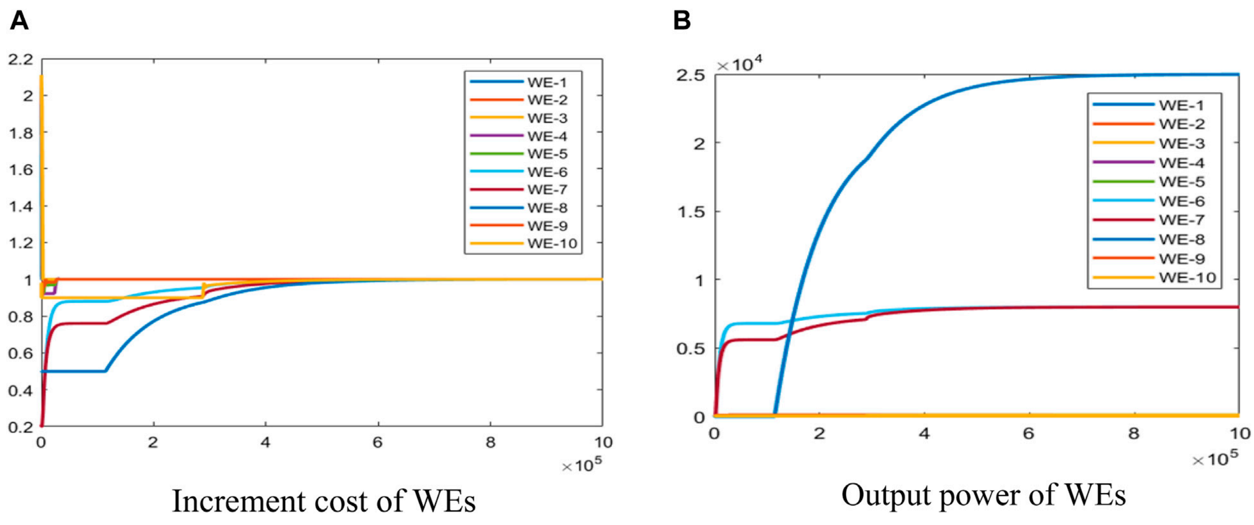


FIGURE 3
Operating curves of WEs. **(A)** Increment cost of WEs. **(B)** Output power of WEs

TABLE 3 Operating data of WEs by using the distributed method.

	WE-1	WE-2	WE-3	WE-4	WE-5
Case 2	37.5	37.5	37.5	122.7	122.7
Case 3	37.5	37.5	37.5	122.6	122.5
	WE-1	WE-2	WE-3	WE-4	WE-5
Case 2	7997.6	7997.6	24979.5	112.5	112.5
Case 3	7997.5	7997.4	24986.9	112.5	112.5
Port microgrid	Case 2	Operating cost	30381.0	Carbon emissions cost	413.2
	Case 3		30792.0		412.7

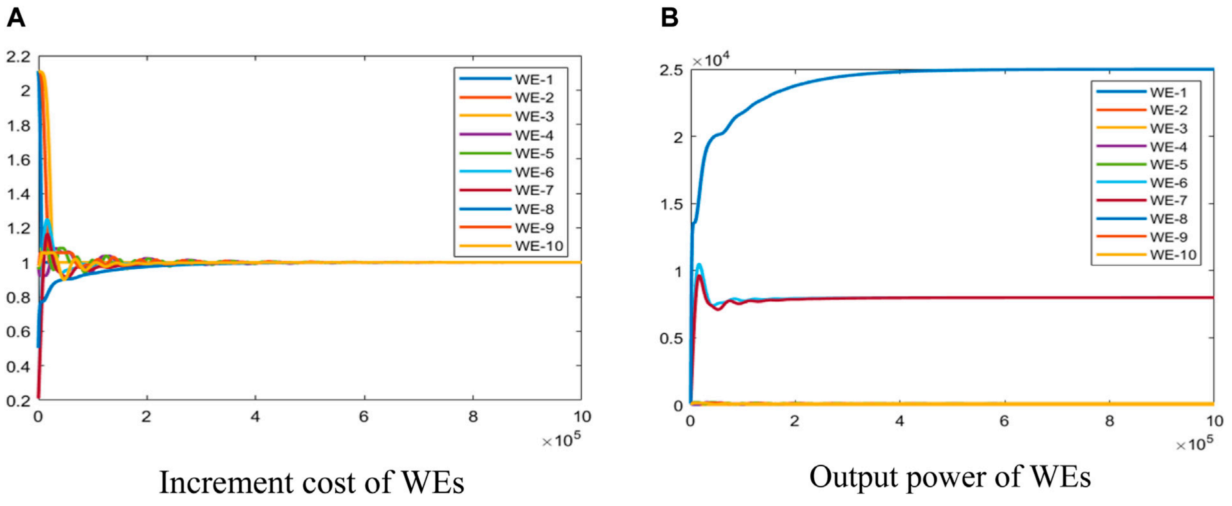
As can be seen from Figure 3, the incremental cost of WEs is ultimately 1.0 Yuan per kWh. In the port microgrid, TWEs are operating, and there is not only the operating cost of the WE but also carbon emissions cost. According to Table 3, the operating cost of the port microgrid during regular operation of the heterogeneous WEs is 30,381 Yuan. This case has a lower operating cost compared with Case 1 without carbon emissions cost.

4.4 Case 3: The proposed model and method

In this case, the distributed method **(11)** proposed in this article is used to solve the energy management problem **(9)** for the port microgrid. It is assumed that load demand, transmission line energy losses, and main grid electricity price in the port microgrid remain constant. α is taken as 0.000000015, and the incremental cost of the heterogeneous WEs converges around 1.0 when the simulation reaches the 300000th step. Figures 4 and 5 show the simulation curves obtained based on the distributed method.

A comparative analysis between Case 3 and Case 1 shows that the power output of heterogeneous WEs does not differ significantly under the three solution methods. Therefore, the distributed method proposed in this paper can enable port microgrid energy management. As can be seen from Figure 4, the incremental cost of WEs converges to 1.0 Yuan per kWh when the port microgrid is operating steadily. The output power and operating cost of the heterogeneous WEs in the port microgrid during regular operation can be seen in Table 3. The operating cost of the port microgrid is 30,792 Yuan, of which the cost of carbon emissions is 412.7 Yuan. In this study case, there are not only low operating costs but also low carbon emissions.

A comparison between Case 1 and Case 3 shows that the distributed solution method proposed in this article can solve the port microgrid energy management problem, indicating



Increment cost of WEs

Output power of WEs

FIGURE 4
Operating curves of WEs. **(A)** Increment cost of WEs. **(B)** Output power of WEs

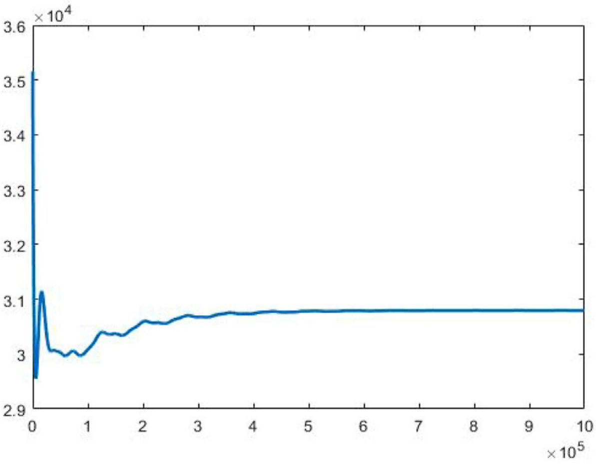


FIGURE 5
Operating cost of the port microgrid.

the effectiveness of the distributed solution method proposed in this article. In addition, Case 3 has lower operating costs compared with Case 1. The comparison between Case 2 and Case 3 shows that Case 3 is able to maximize the use of clean energy, which not only reduces the operating cost of the port microgrid but also reduces carbon emissions, contributing to the development of a green and low-carbon port.

5 Conclusion

The large-scale use of clean energy in port microgrids has given rise to WEs in the port, and the widespread presence of WEs has made the port microgrid a distributed structure. A distributed energy management strategy for WE-based port microgrid under a polymorphic network has been proposed in this article. First, this article has established a polymorphic energy management system for port microgrids based on WEs, ensuring reliable information interaction between heterogeneous WEs, including SWEs, and laying the foundation for the subsequent implementation of distributed energy management. Then, considering the characteristic of bidirectional energy transmission between WEs in the port, the operating cost function of WEs has been analyzed and established. Furthermore, an energy management model for the port microgrid has been constructed considering both the operating cost and the carbon emissions of WEs. Finally, this article has proposed a distributed method to solve the energy management problem of the port microgrid based on the multi-agents consensus method. Through the comparison and analysis of different simulation cases, it has been concluded that the method proposed in this article can not only reduce the operating cost of the port microgrid but also reduce carbon emissions, which can help the development and construction of the green low-carbon 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

HL constructed the polymorphic energy management system for the port microgrid. FT built the model, designed the method, and adapted the article. The experimental simulations, data processing, and draft writing were carried out by JW. QZ collated and revised the format of the references. CS participated in proofreading and organizational management. All authors have read and agreed to the publication of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

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