

Distributed Dispatch of Multiple Energy Systems Considering Carbon Trading

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Abstract—As an integrated carrier of energy production, transmission, distribution, conversion, storage, and utilization, multiple energy systems (MESs) have significant low-carbon potential. This paper proposes a hierarchical distributed dispatch model of MESs considering carbon trading, which is composed of the lower autonomous operation level of each MES and the upper coordinated control level. Different carbon emission sources are considered, including combined heat and power (CHP) units, gas boilers, and power to gas (P2G) devices. The transactive control (TC) mechanism is used to solve the model by introducing a virtual price signal. In the case study based on a 3-MES system, the effectiveness of the proposed distributed method is proved by comparison with a centralized algorithm. Meanwhile, the impacts of different carbon prices on MESs with different resource endowments are analyzed from the aspects of scheduling results, carbon emissions, clean energy consumption rate, and comprehensive operating costs.

Index Terms—Carbon trading, distributed optimal dispatch, transactive control, multiple energy systems.

I. INTRODUCTION

WITH the increasingly prominent fossil energy crisis and global climate change, the concept of a low-carbon economy emerges at this historic moment [1], [2]. As an integrated carrier of energy production, transmission, distribution, conversion, storage, and utilization, multiple energy systems (MESs) can realize flexible complementarity between different energy forms and effectively improve energy consumption efficiency and renewable resources absorption capacity, which is in line with the sustainable development requirements of low-carbon, high-quality and high-efficiency [3]–[5]. It is of great significance to research how to fully exploit the low-carbon advantages of MESs.

In recent years, low-carbon factors have been introduced into the optimization model in the form of objective functions or constraints related to carbon emissions or costs. For example, a multi-objective economic scheduling model of combined heat and power (CHP) units is established by T. Niknam *et al.* [6] to minimize greenhouse gas emissions. To accommodate more wind power in integrated electrical and heating systems, a low-carbon economic dispatching strategy is proposed, which reduces the total system costs by 3.71% [7]. In [8], the total carbon emissions of the system are limited to a given threshold by converting carbon emissions into an inequality constraint. The improved double-carbon model is incorporated into the operation constraints of the units, thereby refining the carbon capture process [9]. In practice, the cap-and-trade policy is widely applied to fully mobilize the enthusiasm of participants and effectively limit the total emissions of the system [10]. As a market-oriented carbon abatement mechanism, carbon emission permits are treated as a freely tradeable commodity. Additional costs are generated when the actual carbon emission exceeds the carbon quota allocated for free. In addition, profits can be obtained by selling the remaining permits.

The optimal operation of MESs with carbon trading has attracted great attention among domestic and foreign scholars. Comprehensively considering the security constraints of the natural gas network and power network, reference [11] proposed a joint economic operation model for an integrated electricity and natural gas system based on carbon trading to minimize generation and carbon trading costs. A ladder-type calculation model considering carbon trading cost is constructed by T. Qin *et al.* [12] according to different intervals of carbon emissions, and the influence of carbon trading price and coupling component capacity on scheduling results is analyzed in detail. Furthermore, the carbon trading cost is introduced into the optimal dispatch of multi-regional MESs, which is verified in two-area MESs with 6 energy hubs (EHs) and three-area MESs with 33 EHs [13]. In the study by Z. S. Wang *et al.* [14], the carbon emission coefficients of different energy chains are first calculated based on life cycle assessment, and then the carbon trading model is introduced into the decision indicators of the economic operation in the off-grid and grid-connected MES. In addition, the effectiveness of concentrated solar power plants and carbon capture power plants with carbon trading is discussed from the perspective of multi-scale wind power consumption [15]. At present, carbon emission sources considered in most literature are power

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generation units, such as conventional coal-fired and gas-fired units. Few studies have been conducted on the low-carbon benefits of some new equipment, such as power to gas (P2G) devices [16], [17].

In addition, traditional economic dispatch is primarily based on centralized algorithms with complete information. With the access of numerous flexible resources with dispersed geographical locations and distinctive features, massive data and the game between multi-agents have emerged, which brings great challenges to the operation and management of MESs [18]. Centralized dispatch cannot provide robustness and flexibility matched with highly decentralized ownership and decision-making rights, while distributed dispatch emphasizes independent decision-making and individual intelligence of participants, which results in better scalability, privacy protection, and more uniform computing and communication burden [19]. Thus far, a variety of distributed algorithms have been developed, such as the alternating direction method of multipliers (ADMM), Benders decomposition, analytical target cascading (ATC), and the consistency algorithm (CA). Among them, transactive control (TC) [20] is broadly employed in the coordinated operation, which introduces a virtual price signal to achieve energy balance and autonomous decision making. It has also been verified in some demonstration projects, such as GridSmart and PowerMatching. In [21], a real-time rolling charging management strategy based on the TC framework is established to protect the privacy of electric vehicle users and realize self-organization optimization. The TC mechanism is also applied in the energy management of homes and micro-grids [22], [23].

To sum up, this paper proposes a collaborative optimal dispatching method of distribution-level MESs considering the carbon trading mechanism. The main results of this paper are briefly summarized as follows:

1) A hierarchical distributed low-carbon dispatch model of distribution-level MESs based on the TC framework is established. The lower level is responsible for the autonomous operation of each MES, where the carbon trading costs of different carbon emission sources are considered, including CHP units, gas boilers, and P2G devices. The upper layer is designed for coordinated control considering the security constraints of the power system, where the virtual electric price is taken as a regulating signal between the two layers to achieve a global energy balance and self-organizing optimization of different MESs.

2) From the dispatching results, carbon emissions, and clean energy consumption rate, the influence of different carbon trading prices on distribution-level MESs with different resource endowments is discussed, exploring the relationship between the resource endowment and the sensitivity to the change of carbon trading prices. The guiding role of the existing carbon trading mechanism is also analyzed.

The rest of this paper is organized as follows. Section II introduces the EH model and carbon trading cost model of MES. Section III proposes a distributed dispatch method for MES based on the TC framework, which is composed of the upper coordinated control layer and the lower autonomous operation layer. Section IV presents a case study and analyzes

the influence of carbon trading on scheduling results. Finally, a conclusion is presented in Section V.

II. MODELING OF MULTIPLE ENERGY SYSTEMS

The structure and modeling process of the underlying MES are introduced in this section, including the EH model and carbon trading cost model.

A. Energy Hub Model

EH is defined as an input-output multi-port model to describe the complex coupling relationship between electricity, heat, gas, and other forms of energy, which plays an important role in the planning and operation of MESs. Therefore, the EH model is adopted in this study.

The typical MES proposed in this paper is shown in Fig. 1, which is primarily composed of the wind turbine (WT), the photovoltaic (PV), CHP units, gas boilers (GB), electric boilers (EB), P2G devices, and energy storage. The specific modeling process is illustrated as follows:

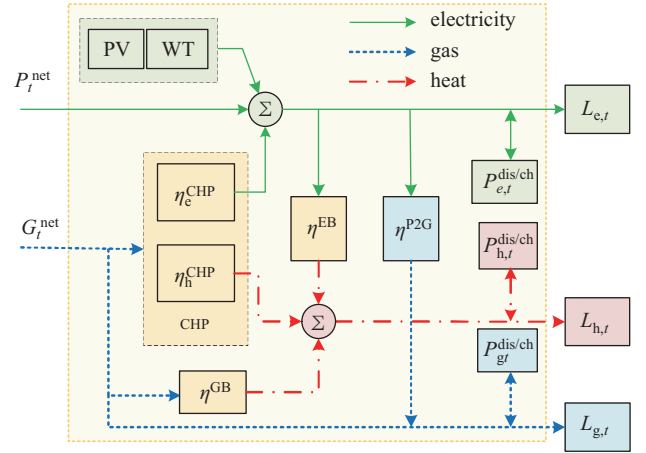


Fig. 1. Structure of typical MES in this paper.

1) Combined Heat and Power Unit

$$\begin{bmatrix} P_t^{\text{CHP}} \\ H_t^{\text{CHP}} \end{bmatrix} = \begin{bmatrix} \eta_e^{\text{CHP}} \\ \eta_h^{\text{CHP}} \end{bmatrix} G_t^{\text{CHP}} \quad (1)$$

$$G_{\min}^{\text{CHP}} \leq G_t^{\text{CHP}} \leq G_{\max}^{\text{CHP}}, \quad \forall t \quad (2)$$

$$|G_t^{\text{CHP}} - G_{t-1}^{\text{CHP}}| \leq G_{\text{ramp}}^{\text{CHP}}, \quad \forall t \quad (3)$$

where G_t^{CHP} , P_t^{CHP} , and H_t^{CHP} denote the gas consumption, power output, and thermal output of the CHP unit at time t respectively; η_e^{CHP} , η_h^{CHP} denote the gas-electricity and gas-thermal conversion efficiency situated between $[0, 1]$. Equations (2)–(3) are the operation constraints, where $G_{\min}^{\text{CHP}}$ and $G_{\max}^{\text{CHP}}$ are the lower and upper bounds of gas consumption, and $G_{\text{ramp}}^{\text{CHP}}$ is the maximum ramp rate of the CHP unit.

2) Gas Boiler

The model of GB is formulated as:

$$H_t^{\text{GB}} = \eta^{\text{GB}} G_t^{\text{GB}} \quad (4)$$

$$G_{\min}^{\text{GB}} \leq G_t^{\text{GB}} \leq G_{\max}^{\text{GB}}, \quad \forall t \quad (5)$$

$$|G_t^{\text{GB}} - G_{t-1}^{\text{GB}}| \leq G_{\text{ramp}}^{\text{GB}}, \quad \forall t \quad (6)$$

where G_t^{GB} and H_t^{GB} are the gas consumption and thermal output of the GB respectively, and η^{GB} is the gas-thermal efficiency. $G_{\min}^{\text{GB}}$, $G_{\max}^{\text{GB}}$, and $G_{\text{ramp}}^{\text{GB}}$ are parameters related to power and ramping limits.

3) Electric Boiler

Similar to the GB, the model of EB can be represented by:

$$H_t^{\text{EB}} = \eta^{\text{EB}} P_t^{\text{EB}} \quad (7)$$

$$P_{\min}^{\text{EB}} \leq P_t^{\text{EB}} \leq P_{\max}^{\text{EB}}, \quad \forall t \quad (8)$$

$$|P_t^{\text{EB}} - P_{t-1}^{\text{EB}}| \leq P_{\text{ramp}}^{\text{EB}}, \quad \forall t \quad (9)$$

where P_t^{GB} and H_t^{GB} denote the electricity input and thermal output of the EB, and η^{EB} denotes the electricity-thermal efficiency. $P_{\min}^{\text{EB}}$, $P_{\max}^{\text{EB}}$, and $P_{\text{ramp}}^{\text{EB}}$ denote its minimum input, maximum input, and maximum ramping rate, respectively.

4) Power to Gas Device

According to different products, P2G technology can be classified into two types: power to hydrogen and power to natural gas. Considering the risks of hydrogen embrittlement and penetration in the pipeline when hydrogen is directly injected into the natural gas system, P2G technology refers to the latter here. The comprehensive conversion efficiency η^{P2G} is 45%–60% in the whole process [24]. P2G can be modeled as follows:

$$G_t^{\text{P2G}} = \eta^{\text{P2G}} P_t^{\text{P2G}} \quad (10)$$

$$P_{\min}^{\text{P2G}} \leq P_t^{\text{P2G}} \leq P_{\max}^{\text{P2G}}, \quad \forall t \quad (11)$$

$$|P_t^{\text{P2G}} - P_{t-1}^{\text{P2G}}| \leq P_{\text{ramp}}^{\text{P2G}}, \quad \forall t \quad (12)$$

where (10) represents the energy conversion equation, and (11)–(12) are operation constraints.

5) Energy Storage

The classical equation of state of charge (SOC) is employed to describe the output characteristics of energy storage as follows:

$$E_{x,t+1}^{\text{ES}} = (1 - \alpha_x^{\text{ES}}) E_{x,t}^{\text{ES}} + (P_{x,t}^{\text{ch}} \eta_x^{\text{ch}} - P_{x,t}^{\text{dis}} / \eta_x^{\text{dis}}) \Delta t \quad (13)$$

$$E_{x,\min}^{\text{ES}} \leq E_{x,t}^{\text{ES}} \leq E_{x,\max}^{\text{ES}}, \quad \forall t \quad (14)$$

where x refers to the type of energy storage and $x = e, h, g$ represents electricity, thermal, and gas respectively. $E_{x,t}^{\text{ES}}$ and $E_{x,t+1}^{\text{ES}}$ denote the SOC of energy storage at time t and time $t + 1$, and Δt is the time interval. α_x^{ES} , η_x^{ch} , and η_x^{dis} denote the self-discharge efficiency, charge efficiency, and discharge efficiency, respectively. $P_{x,t}^{\text{ch}}$ and $P_{x,t}^{\text{dis}}$ represent the charge and discharge power limited by (15):

$$\begin{cases} I_{x,t}^{\text{ch}} + I_{x,t}^{\text{dis}} \leq 1, \quad \forall t \\ P_{x,\min}^{\text{ch}} I_{x,t}^{\text{ch}} \leq P_{x,t}^{\text{ch}} \leq P_{x,\max}^{\text{ch}} I_{x,t}^{\text{ch}}, \quad \forall t \\ P_{x,\min}^{\text{dis}} I_{x,t}^{\text{dis}} \leq P_{x,t}^{\text{dis}} \leq P_{x,\max}^{\text{dis}} I_{x,t}^{\text{dis}}, \quad \forall t \end{cases} \quad (15)$$

where $I_{x,t}^{\text{ch}}$ and $I_{x,t}^{\text{dis}}$ are introduced to ensure that charging and discharging behaviors do not happen at the same time.

Meanwhile, a certain adjustment margin is reserved for the next scheduling period. Therefore, it is assumed that:

$$E_{x,t_c}^{\text{ES}} = E_{x,t_e}^{\text{ES}} \quad (16)$$

where t_c and t_e denote the start time and end time of the scheduling period.

6) Wind Turbine and Photovoltaic

$$0 \leq P_t^{\text{WT}} \leq P_{\text{pre},t}^{\text{WT}}, \quad \forall t \quad (17)$$

$$0 \leq P_t^{\text{PV}} \leq P_{\text{pre},t}^{\text{PV}}, \quad \forall t \quad (18)$$

where P_t^{WT} and P_t^{PV} are the actual output of WT and PV at time t , while $P_{\text{pre},t}^{\text{WT}}$ and $P_{\text{pre},t}^{\text{PV}}$ are the predicted values.

7) Energy Balance Constraint

For the whole MES, the energy balance equation is presented as:

$$\begin{aligned} P_t^{\text{net}} + P_t^{\text{PV}} + P_t^{\text{WT}} + P_t^{\text{CHP}} - P_t^{\text{EB}} - P_t^{\text{P2G}} \\ + P_{e,t}^{\text{dis}} - P_{e,t}^{\text{ch}} = L_{e,t} \\ H_t^{\text{CHP}} + H_t^{\text{GB}} + H_t^{\text{EB}} + P_{h,t}^{\text{dis}} - P_{h,t}^{\text{ch}} = L_{h,t} \\ G_t^{\text{net}} + G_t^{\text{P2G}} - G_t^{\text{CHP}} - G_t^{\text{GB}} + P_{g,t}^{\text{dis}} - P_{g,t}^{\text{ch}} = L_{g,t} \end{aligned} \quad (19)$$

where $L_{e,t}$, $L_{h,t}$, and $L_{g,t}$ stand for the values of multivariate loads at time t ; P_t^{net} and G_t^{net} are the exchange power with the main grid and external gas network, which satisfy the following security constraints:

$$P_{\min}^{\text{net}} \leq P_t^{\text{net}} \leq P_{\max}^{\text{net}}, \quad \forall t \quad (20)$$

$$G_{\min}^{\text{net}} \leq G_t^{\text{net}} \leq G_{\max}^{\text{net}}, \quad \forall t \quad (21)$$

B. Carbon Trading Cost Model

Ignoring carbon emissions from renewable generators, and energy storage, carbon emission sources in the MES include CHP units and GB. Therefore, the equipment involved in carbon trading is the CHP unit, GB, and the P2G device.

For each carbon emission source, if the actual carbon emission exceeds the carbon quota allocated for free, it needs to purchase the excess portion in the carbon trading market. Then, the remaining quota can be sold. Therefore, the carbon trading cost models can be established as follows:

1) Combined Heat and Power Unit

The CHP unit serves as one of the main carbon emission sources in the MES. The total carbon emission intensity and quota are assumed to be proportional to the actual output, and the carbon-related cost $C_{\text{CO}_2,t}^{\text{CHP}}$ can be calculated as:

$$C_{\text{CO}_2,t}^{\text{CHP}} = \pi_{\text{CO}_2,t} (E_t^{\text{CHP}} - e^{\text{CHP}}) (P_t^{\text{CHP}} + H_t^{\text{CHP}}) \quad (22)$$

where $\pi_{\text{CO}_2,t}$ denotes the carbon trading price; E_t^{CHP} and e^{CHP} are defined as the carbon emission intensity and quota per unit power supply, which are 0.5647 kg/kWh and 0.424 kg/kWh respectively according to [14], [15].

2) Gas Boiler

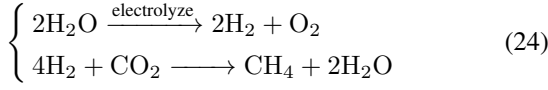
Similarly, the carbon trading cost model is presented as follows:

$$C_{\text{CO}_2,t}^{\text{GB}} = \pi_{\text{CO}_2,t} (E_t^{\text{GB}} - e^{\text{GB}}) H_t^{\text{GB}} \quad (23)$$

where E_t^{GB} and e^{GB} are set to 0.5647 kg/kWh and 0.152 kg/kWh according to [14].

3) Power to Gas Device

The P2G device can absorb CO_2 captured in power plants or biogas. As formulated in (24), the conversion process of P2G can be divided into two steps: electrolytic hydrogen production and methanation, during which the volume of the consumed CO_2 is equal to that of the produced CH_4 .



Taking the combustion calorific value of natural gas α_{CH_4} as 9.87 kWh/m^3 , the output of the P2G device can be converted into the equivalent volume of CH_4 , and the carbon emission intensity reduced by the P2G device can be further obtained.

$$E^{\text{P2G}} = \rho_{\text{CO}_2} V_{\text{CO}_2} = \rho_{\text{CO}_2} \frac{G_t^{\text{P2G}}}{\alpha_{\text{CH}_4}} \quad (25)$$

where $\rho_{\text{CO}_2} = 1.977 \text{ kg/m}^3$ denotes the gaseous density of CO_2 .

AS the P2G device is not a carbon emission source, its carbon quota is set to zero. Thus, the carbon trading cost is calculated as follows:

$$C_{\text{CO}_2,t}^{\text{P2G}} = -\pi_{\text{CO}_2,t} E^{\text{P2G}} G_t^{\text{P2G}} \quad (26)$$

III. DISTRIBUTED LOW-CARBON DISPATCHING OF MESs

The proposed distributed scheduling framework of MESs considering carbon trading is presented in Fig. 2. The framework is a bi-level optimal model composed of the lower autonomous operation level and the upper coordinated control level, which are executed by their respective energy management system (EMS) and a virtual coordinator, respectively. The lower layer is aimed at realizing the internal low-carbon economic dispatch of each MES, and the upper layer is responsible for the collaborative operation of MESs and capacity constraints on the transformer connected to the main grid to ensure the security of the entire system. By introducing the TC mechanism, only the information of energy demand and virtual electricity price is expected to be exchanged between the two layers.

A. Lower Autonomous Operation level

The lower autonomous operation level is aimed at minimizing the comprehensive operation costs of each MES. For the n -th MES, the optimization model is described as follows:

$$\begin{aligned} \min \sum_{t=1}^T (C_{b,t}^n + C_{yw,t}^n + C_{\text{CO}_2,t}^n) \\ \text{s.t.} \quad (1)-(21), \forall n, t \end{aligned} \quad (27)$$

where the comprehensive costs consist of the external energy purchase cost $C_{b,t}^n$, equipment operation and maintenance cost $C_{yw,t}^n$, and carbon trading cost $C_{\text{CO}_2,t}^n$. The detailed calculation method is as follows:

$$\begin{cases} C_{b,t}^n = \pi_{e,t} P_{n,t}^{\text{net}} + \pi_{g,t} G_{n,t}^{\text{net}} \\ C_{yw,t}^n = \pi_{\text{CHP}} (P_{n,t}^{\text{CHP}} + H_{n,t}^{\text{CHP}}) + \pi_{\text{GB}} H_{n,t}^{\text{GB}} + \pi_{\text{EB}} H_{n,t}^{\text{EB}} \\ \quad + \pi_{\text{P2G}} G_{n,t}^{\text{P2G}} + \pi_{\text{ES},x} (P_{x,n,t}^{\text{ch}} + P_{x,n,t}^{\text{dis}}) \\ C_{\text{CO}_2,t}^n = C_{\text{CO}_2,n,t}^{\text{CHP}} + C_{\text{CO}_2,n,t}^{\text{GB}} + C_{\text{CO}_2,n,t}^{\text{P2G}} \end{cases} \quad (28)$$

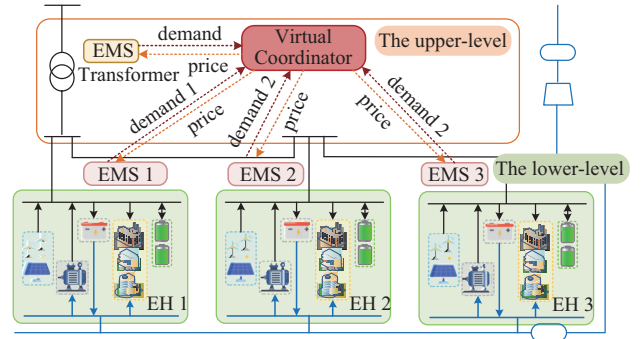


Fig. 2. Distributed dispatch framework of MESs.

where $\pi_{e,t}$ and $\pi_{g,t}$ are the electricity and natural gas prices at time t , respectively.

B. Upper Coordinated Control Level

The upper coordinated control level is designed to minimize the total operating costs of N interconnected MESs and simultaneously satisfy the capacity bound of the transformer $[P_{\min}^T, P_{\max}^T]$. The corresponding optimization model is formulated as:

$$\begin{aligned} \min \sum_{n=1}^N \sum_{t=1}^T (C_{b,t}^n + C_{yw,t}^n + C_{\text{CO}_2,t}^n) \\ \text{s.t.} \quad \begin{cases} \sum_{n=1}^N P_{n,t}^{\text{net}} - P_t^T = 0, \forall t \\ P_{\min}^T \leq P_t^T \leq P_{\max}^T, \forall t \\ (1)-(21), \forall n, t \end{cases} \end{aligned} \quad (29)$$

Mathematically, the original objective function can be converted into (30) based on the Lagrange relaxed method.

$$\begin{aligned} \min L = \min \left\{ \sum_{n=1}^N \sum_{t=1}^T (C_{b,t}^n + C_{yw,t}^n + C_{\text{CO}_2,t}^n) \right. \\ \left. + \sum_{t=1}^T \lambda_t \left(\sum_{n=1}^N P_{n,t}^{\text{net}} - P_t^T \right) \right\} \\ = \min \left\{ \sum_{n=1}^N \sum_{t=1}^T ((\pi_{e,t} + \lambda_t) P_{n,t}^{\text{net}} + \pi_{g,t} G_{n,t}^{\text{net}} \right. \\ \left. + C_{yw,t}^n + C_{\text{CO}_2,t}^n) - \sum_{t=1}^T \lambda_t P_t^T \right\} \end{aligned} \quad (30)$$

where λ_t refers to the Lagrange multiplier related to the power balance equation at time t . The original problem can be further decoupled into $N + 1$ subproblems corresponding to $N + 1$ participants, as shown in (31)–(32).

For the n -th MES,

$$\begin{aligned} \min \sum_{t=1}^T (\pi_{e,t} + \lambda_t) P_{n,t}^{\text{net}} + \pi_{g,t} G_{n,t}^{\text{net}} + C_{yw,t}^n + C_{\text{CO}_2,t}^n \\ \text{s.t.} \quad (1)-(21), \forall t \end{aligned} \quad (31)$$

For the transformer,

$$\begin{aligned} \min - \sum_{t=1}^T \lambda_t P_t^T \\ \text{s.t.} \quad P_{\min}^T \leq P_t^T \leq P_{\max}^T, \forall t \end{aligned} \quad (32)$$

C. Solution Based on TC Framework

The core idea of the TC framework is to introduce a key parameter $\pi_{\lambda,t} = \pi_{e,t} + \lambda_t$, which can be understood as a virtual electricity price signal, reflecting the security constraints of the power system. Each MES performs autonomous optimization at this price signal $\pi_{\lambda,t}$ and then updates $P_{n,t}^{\text{net}}$. The iterative clearing is adopted until the supply and demand balance is achieved. The detailed solution steps are illustrated in Fig. 3.

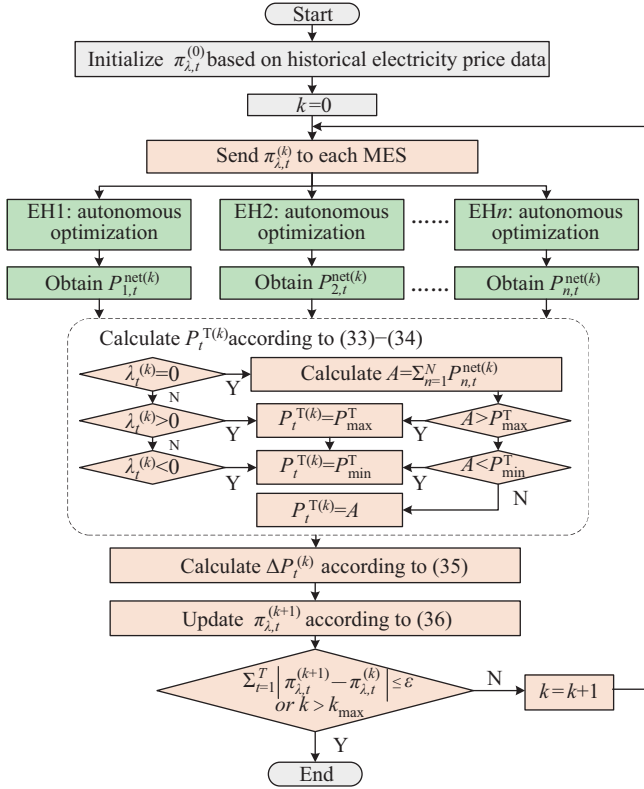


Fig. 3. Solution flow chart based on TC framework.

1) $\pi_{\lambda,t}^{(0)}$ is initialized according to the historical real-time electricity price. In other words, $\lambda_t^{(0)} = 0$ at this time.

2) Set the maximum number of iterations as $k_{\max}$. For the k -th iteration, autonomous optimization under $\pi_{\lambda,t}^{(k)}$ is performed to obtain $P_{n,t}^{\text{net}}$ in each MES.

3) Subsequently, the power flowing through the transformer is modified by (33)–(34).

$$P_t^T(k) = \begin{cases} P_{\max}^T, & \lambda_t^{(k)} > 0 \\ P_{\min}^T, & \lambda_t^{(k)} < 0 \end{cases} \quad (33)$$

When $\lambda_t^{(k)} = 0$,

$$P_t^T(k) = \begin{cases} P_{\min}^T, & \sum_{n=1}^N P_{n,t}^{\text{net}(k)} < P_{\min}^T \\ \sum_{n=1}^N P_{n,t}^{\text{net}(k)}, & \text{others} \\ P_{\max}^T, & \sum_{n=1}^N P_{n,t}^{\text{net}(k)} > P_{\max}^T \end{cases} \quad (34)$$

4) The imbalance of the whole power system $\Delta P_t^{(k)}$ is calculated, and $\pi_{\lambda,t}^{(k+1)}$ is updated according to (35)–(36).

$$\Delta P_t^{(k)} = P_t^T(k) - \sum_{n=1}^N P_{n,t}^{\text{net}(k)}, \quad \forall t \quad (35)$$

$$\pi_{\lambda,t}^{(k+1)} = \pi_{\lambda,t}^{(k)} + \nu^{(k)} \Delta P_t^{(k)}, \quad \forall t \quad (36)$$

where $\nu^{(k)}$ denotes the step length of the k -th iteration.

5) When $\sum_{t=1}^T |\pi_{\lambda,t}^{(k+1)} - \pi_{\lambda,t}^{(k)}| \leq \epsilon$ or $k > k_{\max}$, iteration is stopped. Otherwise, steps 2)–5) are repeated.

IV. CASE STUDY

The proposed distributed low-carbon dispatching scheme is performed in the interconnected 3-MES system, as shown in Fig. 2. All 3 MESs contain the CHP units, GB, EB, electric energy storage (EES), and thermal energy storage (TES). Certain differences exist in load characteristics and resource endowments among different MESs.

MES1: with clean energy, P2G devices, and gas energy storage (GES);

MES2: with clean energy, and without P2G devices and GES;

MES3: includes a coal-fired unit with higher carbon emissions, and without clean energy, P2G devices, and GES.

The typical load curves and the predicted outputs of clean energy for each MES are presented in Fig. A1, and the corresponding parameters of the equipment are referred to [14], [17] and listed in Table AI. In addition, the carbon trading price π_{CO_2} is set from 0 to 0.5 yuan/kg to further explore the effect of carbon trading on different MESs.

TABLE I
COMPARISON OF RESULTS OF TOTAL OPERATIONS COSTS BETWEEN THE PROPOSED METHOD AND THE CENTRALIZED METHOD

π_{CO_2}	The centralized method (yuan)	The proposed method (yuan)	The percent error (%)
0	81373.98	82737.72	1.6482
0.025	81906.23	83275.37	1.6441
0.05	82438.49	83813.02	1.6400
0.075	82970.74	84350.67	1.6359
0.1	83503.00	84888.32	1.6319
0.125	84035.25	85425.97	1.6279
0.15	84567.50	85963.63	1.6240
0.175	85099.76	86501.28	1.6202
0.2	85632.01	87038.93	1.6164
0.225	86164.27	87576.58	1.612
0.25	86695.66	88112.83	1.6262
0.275	87220.47	88659.13	1.6226
0.3	87745.28	89189.44	1.6192
0.325	88270.09	89719.75	1.6157
0.35	88760.10	90268.57	1.6710
0.375	90484.74	90822.52	0.3719
0.4	91015.27	91349.36	0.3657
0.425	91324.10	92481.17	1.2511
0.45	91849.07	93003.51	1.2412
0.475	92345.30	93525.84	1.26225
0.5	92906.68	94048.17	1.21373

A. Comparison of the Proposed Distributed and Centralized Algorithms

To verify the effectiveness of the proposed method, we have compared the results at different carbon trading prices with those of the centralized optimization based on the CPLEX solver, as shown in Table I. Although the total comprehensive costs of the proposed algorithm are slightly higher, a minimal difference is presented between the two calculation modes. The maximum error is 1.6710% when the carbon trading

is not considered, and the minimum error is 0.3657% when the carbon trading price is 0.4 yuan/kg. The average error is approximately 1.4%, which indicates the proposed method can converge near the optimal solution.

B. Analysis of Influence of Carbon Trading on Different MESs

1) Dispatching Results

When carbon trading is not considered, the scheduling results of the three MES are shown in Fig. 4.

For MES1, a typical bimodal electric load curve is presented, while the thermal consumption gently varies throughout the day. Fig. 4(a) shows that the power consumption is primarily met by the WT and PV from 7:00 to 17:00 because renewable energy is plentiful during that period. From 7:00 to 10:00, MES1 sells electricity to the main grid to obtain additional benefits. After 18:00, the output of PV is sharply reduced due to weather factors. Therefore, the main power supplier is transferred to the external power network. From 20:00 to 22:00, the EES operates to relieve the pressure during peak hours. The CHP unit remains near maximum capacity almost all day. According to the results of thermal dispatching, the CHP unit and EB cover the overwhelming majority of the heating load, while the GB serves as the auxiliary equipment in the scheduling plan because both the CHP unit and GB are gas-consuming equipment, and their total output level will be restricted by the capacity of natural gas pipeline connected to

MES1. During 4:00–6:00, the TES stores the remaining heat energy. The gas-consuming equipment in MES1 is primarily the CHP unit. The P2G device is used during the peak hours of gas consumption (13:00, 19:00–20:00). As the electrical load during this period is also heavy, the output of the EB is reduced and the GB is applied alternatively, which further increases the gas demand. The introduction of the P2G device provides a more flexible dispatching scheme.

For MES2, different energy sources have different consumption peak hours, which occur at 8:00 for heat and gas, and at 18:00 for electricity and gas. As shown in Fig. 4(b), the CHP unit is at a low output level on the whole. MES2 is primarily powered by clean energy and the main grid, and the EES does not work, which is different from that of MES1. Furthermore, the actual heating suppliers vary from time to time. For example, the CHP unit and EB work jointly during 1:00–4:00, while EB and GB operate during 4:00–10:00. With the arrival of the peak hours of power consumption after 10:00, the output of EB gradually decreases, and the GB is regarded as the main heating equipment. From 13:00 to 15:00, TES is used to meet the total thermal demand. Gas is consumed primarily by the CHP unit before 4:00 and by the GB after 4:00.

For MES3, the power and thermal consumption remain at a relatively high level all day, while the gas consumption is concentrated from 6:00 to 22:00. As an area without clean

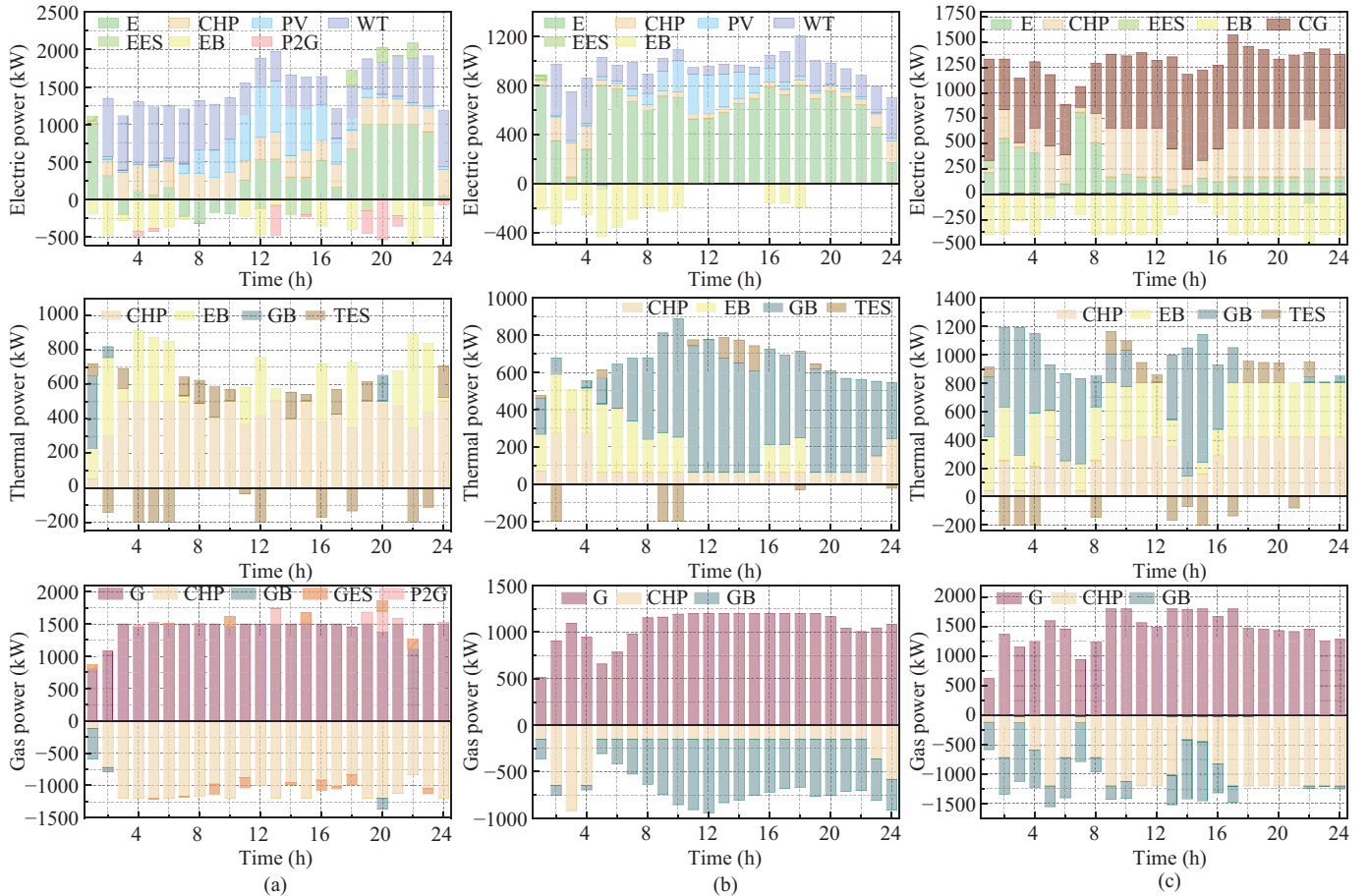


Fig. 4. Dispatching results of (a) MES1, (b) MES2, and (c) MES3 without carbon trading.

energy, MES3 is primarily powered by the conventional coal-fired unit and the CHP unit. In the process of dispatching, the EES is not used. According to the results of thermal dispatching, the output of each piece of equipment is relatively scattered rather than concentrated on the specific equipment, and the utilization rate of the EB is relatively high. Excess heat energy is stored by the TES during 2:00–4:00 and 13:00–15:00, and it is released during 18:00–20:00 to relieve the heating consumption peak. Moreover, as shown in Fig. 4(c), the gas-consuming equipment only includes the GHP unit and GB, and the former consumes more gas, especially during 11:00–12:00 and 18:00–24:00.

When the carbon trading cost is considered, different MESs have different sensitivities to the changes of the carbon trading price. In particular, the dispatch results of MSE1 do not change until π_{CO_2} increases to 0.4 yuan/kg. For MES2, the scheduling strategy varies when π_{CO_2} is 0.35 yuan/kg, and it adjusts again at 0.4 yuan/kg. In terms of MES3 with high carbon density, the original plan changes at 0.225 yuan/kg, and a new dispatching plan is generated when π_{CO_2} is greater than 0.4 yuan/kg, which means that MES3 is relatively sensitive to the change of the carbon trading price.

For comparison, the dispatch results of MESs when π_{CO_2} is 0.425 yuan/kg are analyzed. As presented in Fig. 5(a), the dispatching plan of MES1 during 0:00–1:00 obviously adjusts compared with the original plan without carbon trading. The main heating equipment shifts from the GF to EB, which has

a low carbon footprint. Additionally, the operation strategy of the P2G device from 12:00 to 14:00 also changes. A visible improvement is observed on the output level of the P2G device, which can bring additional carbon-related benefits, but at the same time, the output of the GF also increases.

As shown in Fig. 5(b), for MSE2, only the scheduling results during 0:00–8:00 change, as reflected in the output variation of the GB and EB. It becomes more low-carbon due to an increased output proportion of the EB. In addition, the heat-accumulating time of TES also slightly changes, which varies from 2:00 to 4:00.

As shown in Fig. 5(c), for MES3, the increase of the carbon trading price primarily limits the output of the conventional coal-fired unit with high carbon emissions during 0:00–1:00, which drops from 1000 kW to 410.245 kW, and the declining power gap is supplemented by the main grid. However, a minimal difference is observed in the heat and gas dispatching results between the two scenarios.

2) Carbon Emissions

For each MES, the total actual carbon emissions and paid carbon emissions at different carbon trading prices are shown in Table II. The overall carbon emission level follows the order of $\text{MES3} > \text{MES2} > \text{MES1}$, which is consistent with the resource endowment of each MES. Then, MES3 is primarily powered by the CHP unit, the GB, and the conventional coal-fired unit with high carbon intensity, so the actual carbon emissions are relatively high. Furthermore, the carbon emis-

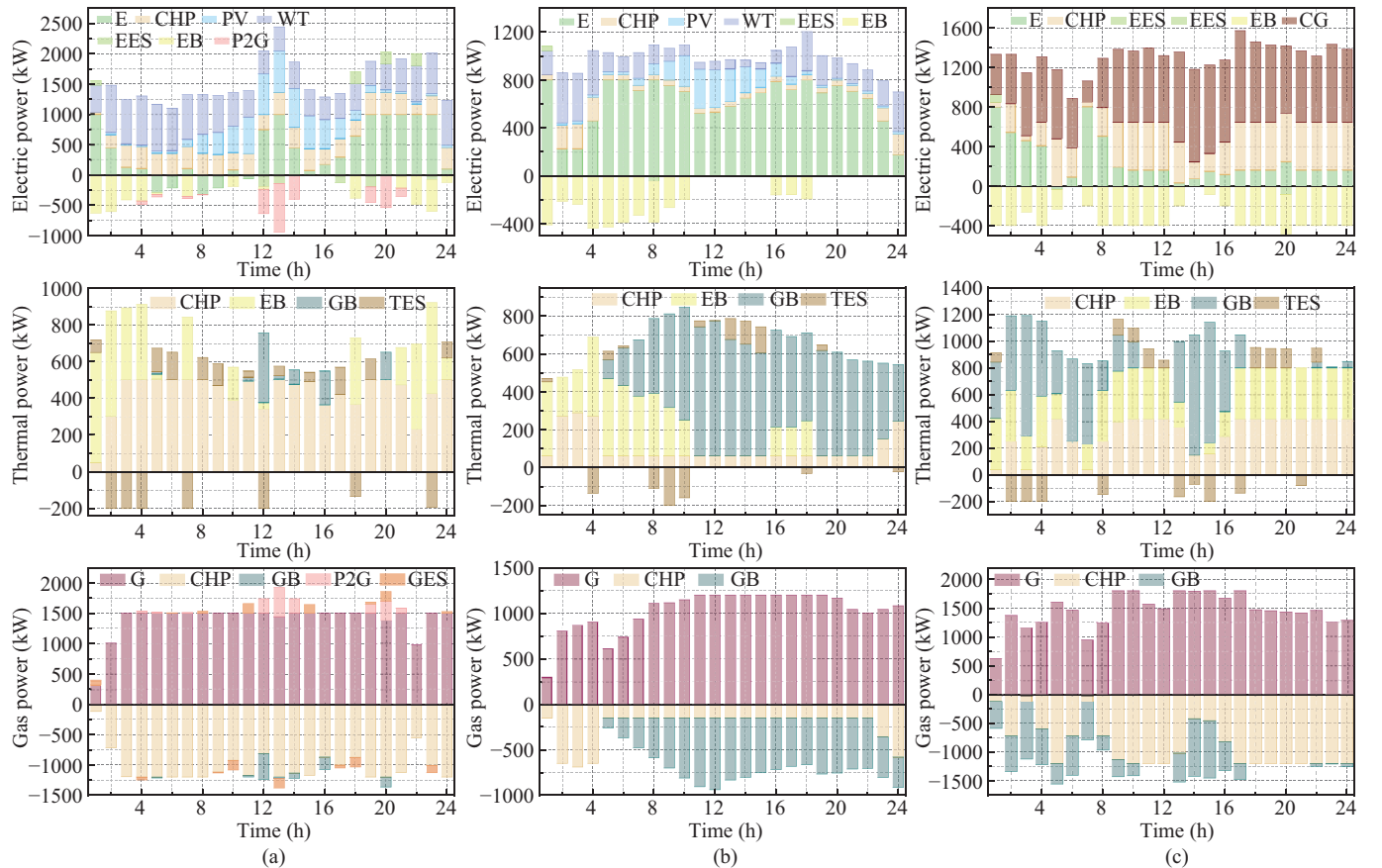


Fig. 5. Dispatching results of (a) MES1, (b) MES2, and (c) MES3 when the carbon trading price is 0.425 yuan/kg.

TABLE II
TOTAL ACTUAL CARBON EMISSIONS AND PAID CARBON EMISSIONS OF
DIFFERENT MESS AT DIFFERENT CARBON TRADING PRICES

π_{CO_2} (yuan/kg) Carbon emissions	[0, 0.225]	(0.225,0.35]	(0.35, 0.4]	(0.4, 0.5]
MES1(actual)	7640.48	7640.48	7640.48	7553.12
MES1(paid)	2583.37	2583.37	2583.37	2522.76
MES2(actual)	8211.80	8211.80	7958.08	7800.06
MES2(paid)	4774.99	4774.99	4636.07	4520.59
MES3(actual)	35885.35	35122.24	35122.24	35116.96
MES3(paid)	14147.67	13853.89	13853.89	13850.03

sion decreases to varying degrees with the increase of the carbon trading price for all MESSs, which demonstrates that the application of carbon trading plays a certain role in reducing the carbon emissions of MESSs.

To further explore the effect of carbon trading on emission reduction, the actual carbon emissions at each period under different carbon trading prices are exhibited in Fig. 6. The carbon emissions of MES1 during 0:00–2:00 and 9:00–10:00 are significantly reduced, as the original output of the GB is replaced by the EB. It also decreases at 13:00 because of the application of the P2G device. Although the total actual carbon emissions are decreasing, not all periods present a downward trend, such as 11:00 and 13:00. The reason for this phenomenon is that the increase of carbon emissions caused by the GB is more than that absorbed by the P2G device during these periods. For MES2, the carbon emissions are reduced to varying degrees from 0:00 to 8:00, as the output of the EB becomes higher. For MES3, the reduction of carbon emissions is primarily concentrated in the period from 0:00 to 1:00, and it does not change much in the other periods.

3) Clean Energy Accommodation Rate

From the perspective of the clean energy accommodation rate, as presented in Table III, the overall consumption level of MES1 is higher than that of MES2, and both of them show an upward trend with the increase of the carbon trading price, which increases by 2.27% and 2.79%, respectively. However, it should be noted that the clean energy accommodation rates remain unchanged when π_{CO_2} is less than 0.4 yuan/kg, which means the carbon trading price acts as a stimulus to the clean energy accommodation only when it rises to a certain level.

TABLE III
CLEAN ENERGY ACCOMMODATION RATE OF MES1 AND MES2 AT
DIFFERENT CARBON TRADING PRICES

π_{CO_2} (yuan/kg)	[0, 0.4]	(0.4, 0.5]
MES1	96.10%	98.37%
MES2	92.62%	95.42%

4) Comprehensive Operation Costs

With regard to the comprehensive operation costs of MESSs, as shown in Fig. 7, the carbon trading cost of MES3 is the highest, while that of MES1 is the lowest among the three MESSs. When the carbon trading price increases, the carbon trading cost and its proportion also increases. However, for all MESSs, the carbon trading cost is much lower than the external energy purchase cost and operation and maintenance costs, especially when the carbon price is at a low level.

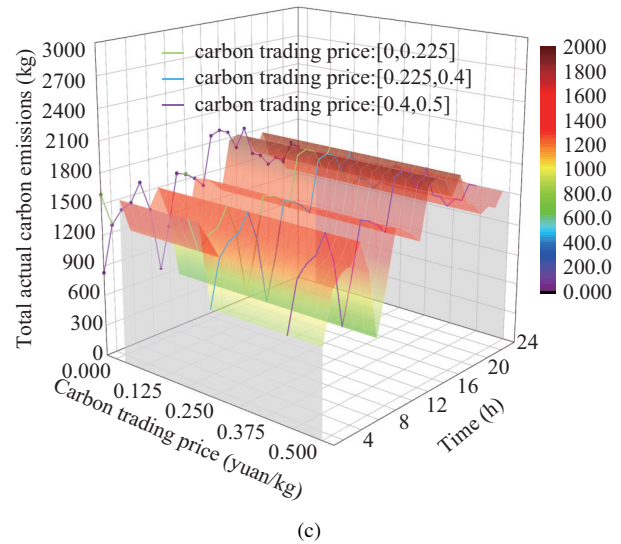
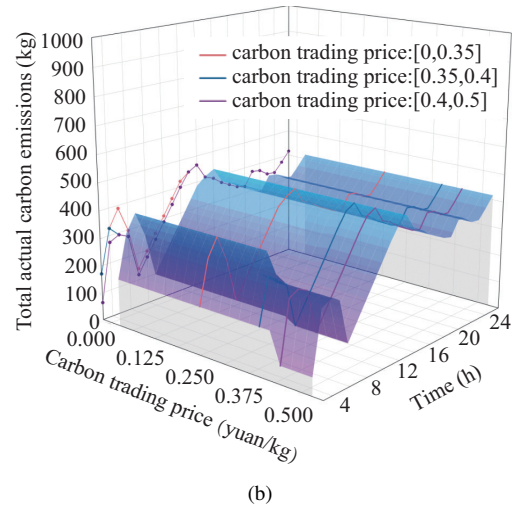
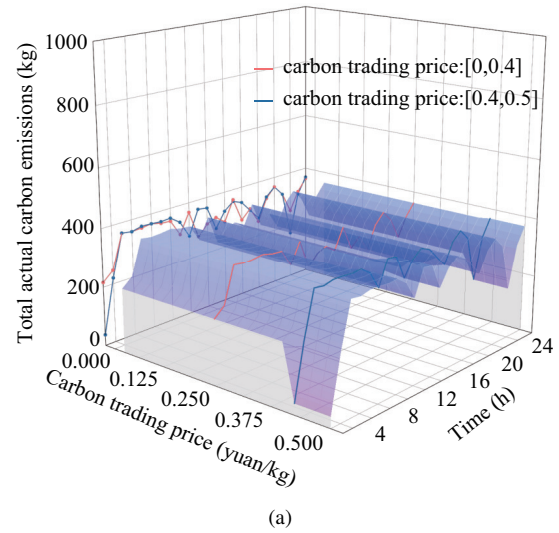


Fig. 6. Total carbon emissions of (a) MES1, (b) MES2, and (c) MES3 at different carbon trading prices.

The reason is that the majority of the carbon emissions can be covered by free carbon quotas for carbon emission sources, and the additional carbon-related costs are not high. In the

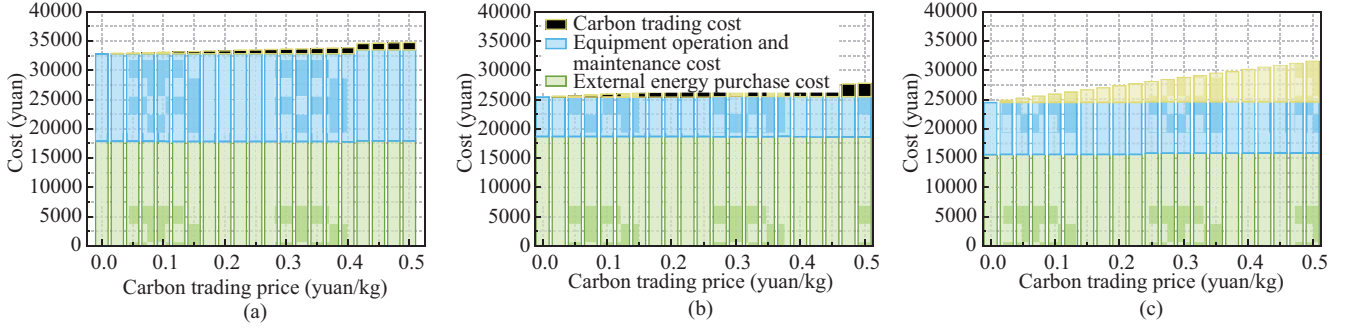


Fig. 7. Costs of (a) MES1, (b) MES2, and (c) MES3 at different carbon trading prices.

low-carbon scheduling model proposed in this paper, carbon trading cost is introduced into the objective function to reflect the influence of carbon, therefore, it is less sensitive to the change of the carbon trading price.

To sum up, the comparison and analysis of carbon trading are summarized as follows:

1) The MESs with different resource endowments have different sensitivities to the changes of the carbon trading price, among which the carbon-intensive MESs are the most sensitive.

2) With the increase of carbon prices, the main heating supplier gradually shifts from gas boilers to electric boilers, and the output of conventional coal-fired units is limited. The application of P2G devices can provide more flexible and low-carbon scheduling schemes.

3) Although the introduction of the carbon trading mechanism can reduce the total carbon emissions and improve the accommodation rate of clean energy, the overall guide effect is not obvious due to relatively low carbon trading costs, especially when the carbon trading price is at a low level.

V. CONCLUSION

In this paper, a hierarchical low-carbon dispatching model of MESs based on the TC framework is established, which realizes the distributed decision of the individual MES and collaborative operation of the interconnected MESs. In the case study, the effectiveness of the proposed method is verified compared with the centralized optimal algorithm, and the impacts of carbon trading on different MESs with various resource endowments are compared and analyzed. It is shown that the sensitivity to the change of carbon trading prices is closely related to the resource endowment of each MES, and the MES with higher carbon density is more sensitive. The introduction of carbon trading can reduce the total carbon emissions and improve the clean energy accommodation rates; however, the overall guide effect is not obvious due to a high proportion of free carbon quotas, especially when the carbon trading price is at a low level. Therefore, future research can be further extended to more reasonable carbon quota allocation methods and energy-carbon transactions between different MESs. Additionally, it is worth studying how to develop more efficient distributed algorithms with better robustness and convergence performance to adapt to the operation of MESs.

APPENDIX

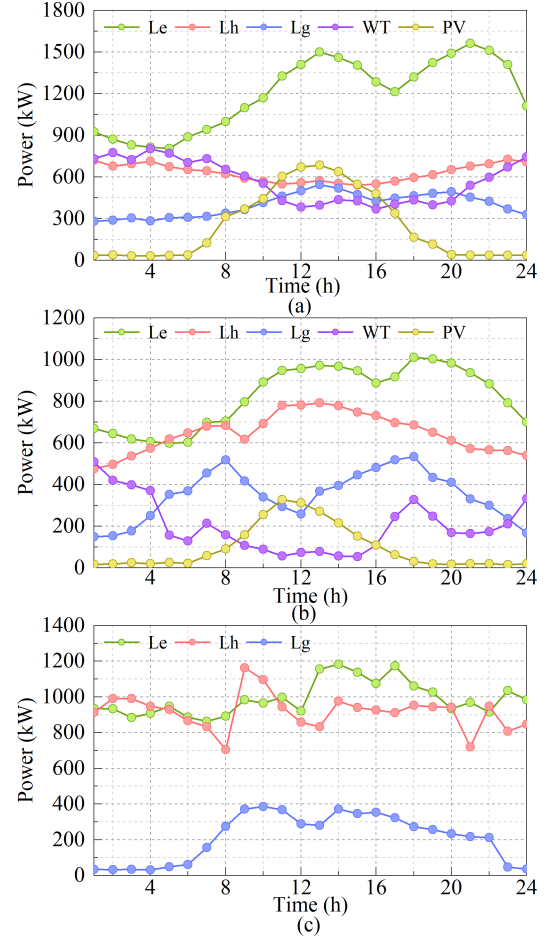


Fig. A1. Profiles of the energy demands and the forecast WT and PV power of (a) MES1, (b) MES2, and (c) MES3.

 TABLE AI
PARAMETERS OF EQUIPMENT IN DIFFERENT MESs

Parameters	MES1	MES2	MES3
CHP			
$G_{\max}^{\text{CHP}}$ (kW)	1200	1500	1200
G^{CHP} (kW)	120	150	120
η_e^{CHP}	0.3	0.3	0.4
η_h^{CHP}	0.42	0.45	0.35
e^{CHP} (kg/kWh)	0.424	0.424	0.424
E^{CHP} (kg/kWh)	0.5647	0.5647	0.5647
GB			
$G_{\max}^{\text{GB}}$ (kW)	800	800	1000
$G_{\min}^{\text{GB}}$ (kW)	0	0	0
η_{GB}	0.9	0.9	0.9

TABLE AI
PARAMETERS OF EQUIPMENT IN DIFFERENT MESSs (CONTINUED)

	Parameters	MES1	MES2	MES3
EB	e^{GB} (kg/kWh)	0.152	0.152	0.152
	E^{GB} (kg/kWh)	0.5647	0.5647	0.5647
	P_{max}^{EB} (kW)	800	800	400
	P_{min}^{EB} (kW)	0	0	0
	η^{EB}	0.95	0.95	0.95
P2G	P^{P2G} (kW)	800	—	—
	P^{P2G} (kW)	0	—	—
	η^{P2G}	0.6	—	—
	e^{P2G} (kg/kWh)	0	—	—
	E^{P2G} (kg/kWh)	0.2003	—	—
CG	P_{max}^{CG} (kW)	—	—	1000
	P_{min}^{CG} (kW)	—	—	0
	e^{CG} (kg/kWh)	—	—	0.798
	E^{CG} (kg/kWh)	—	—	1.303
	E^{CG} (kg/kWh)	—	—	1.303
EES	$P_{e,max}^{ch/dis}$ (kW)	200	120	200
	$P_{e,min}^{ch/dis}$ (kW)	0	0	0
TES	$P_{h,max}^{ch/dis}$ (kW)	200	200	200
	$P_{h,min}^{ch/dis}$ (kW)	0	0	0
GES	$P_{g,max}^{ch/dis}$ (kW)	160	—	—
	$P_{g,min}^{ch/dis}$ (kW)	0	—	—

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