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A Two-Layer Energy Management Framework for Manufacturing Plants Considering Dynamics Carbon Emission Factors

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ABSTRACT

The operation of manufacturing plants (MPs) results in considerable energy consumption and carbon emissions. Existing studies typically adopt static carbon emission factors when estimating the carbon footprints of MPs, overlooking their spatiotemporal variability across different nodes of the power distribution network (DN). Thus, in this paper, we propose a two-layer energy management framework that explicitly accounts for dynamic carbon emission factors to achieve coordinated low-carbon operation between the DN and MPs. In the proposed framework, the upper-level model formulates an electricity-carbon sharing problem among MPs, aiming to achieve cooperative utilization of renewable energy and carbon allowances while minimizing the total operation cost. The lower-level model addresses the optimal power flow of the DN, where the carbon emission flow (CEF) theory is employed to calculate the node-level carbon emission factors. These factors are then integrated with locational marginal prices (LMPs) to construct an electricity-carbon integrated pricing mechanism, which dynamically guides the upper-level energy scheduling and sharing decisions of MPs. Case studies demonstrate that the proposed two-layer energy management framework can effectively reduce both operation costs and carbon emissions for MPs.

Keywords: manufacturing plants, local electricity and carbon sharing, carbon emission flows, electricity-carbon integrated pricing.

1. INTRODUCTION

With the accelerating global transition toward carbon neutrality, the manufacturing sector faces increasing pressure to enhance energy efficiency and reduce greenhouse gas emissions. As the core of industrial production, manufacturing plants (MPs) consume large amounts of energy and produce substantial carbon emissions during their operation [1]. Integrating renewable energy sources such as wind turbines (WTs) and photovoltaic (PV) panels into MPs has become an effective pathway toward sustainable and low-carbon manufacturing. However, the large-scale deployment of distributed energy sources also raises challenges related to improving renewable energy utilization rates and ensuring efficient energy scheduling. Consequently, developing an effective energy management strategy for MPs is crucial to achieving coordinated, low-carbon, and cost-efficient industrial operation.

Many existing studies focus on energy management for MPs. For example, ref. [1] proposes a vehicle-to-manufacturing energy interactive framework to improve the energy demand flexibility for the MP. Ref. [2] proposes a time-of-use based electricity demand responses scheme for MPs. Ref. [3] proposes an explainable multi-agent deep reinforcement learning method to realize the control of production line in real time. Furthermore, some studies not only focus on the energy management of MPs but also consider their carbon allowance scheduling. For example, ref. [4] achieves local electricity and carbon allowance sharing among MPs. Ref. [5] proposes a hierarchical energy and carbon allowance management method for the DN and MPs. Ref. [6] proposes a Nash bargaining mechanism to achieve electricity and carbon trading among MPs. However, existing research (e.g., [4-6]) mostly adopt static carbon emission factors to quantify the carbon footprint of MPs, which ignore the spatiotemporal variability of carbon emission factors across different nodes in the power distribution network (DN) and lead to inaccurate carbon accounting.

To overcome the above limitations, this paper proposes a two-layer energy management framework for coordinated low-carbon operation between the DN and MPs. In this framework, the upper-layer model focuses on the MPs, where an electricity-carbon sharing mechanism is developed to enable cooperative utilization of renewable energy and carbon allowances

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among interconnected MPs. The lower-layer model formulates an optimal power flow problem of the DN, and the carbon emission flow (CEF) theory is employed to calculate the spatiotemporally varying node-level carbon emission factors (i.e., node carbon intensity) [7]. Moreover, an electricity-carbon integrated pricing mechanism is introduced to guide the upper-level energy scheduling and sharing decisions of MPs [8].

2. SYSTEM MODEL

2.1 The upper-layer model

Fig. 1 shows the schematic model of interconnected MPs. Each MP i contains multiple energy devices, including a wind turbine (WT), a production line (PL), a diesel generator (DG), and multiple plug-in electric vehicles (PEVs). Specifically, the WT enables local renewable energy generation; the PL is used for product production; the DG can supply electricity for the MP; while EVs are used for employee commuting and product transportation. Fig. 2 depicts the detailed structure of the PL. As shown in this figure, the PL consists of N_i machines and $N_i - 1$ buffers, where each buffer is located between two adjacent machines to temporarily store intermediate products. The electric loads (ELs) of the MP contain a certain proportion of flexible loads, which can participate in demand response programs.

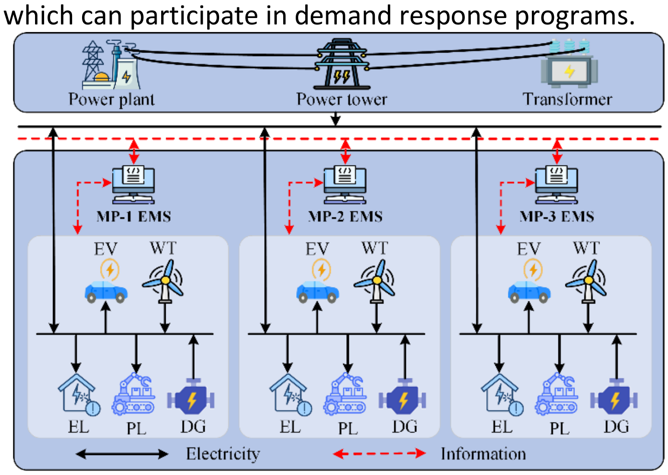

Fig. 1 The schematic model of interconnected MPs

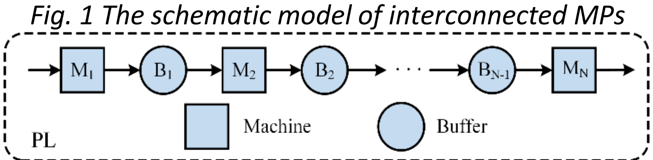

Fig. 2 The system model of the PL

Let $\mathcal{M} = \{1,\ldots,\mathrm{M}\}$ denote the set of M MPs. The operation horizon is set to one day, denoted as $\mathcal{T} = \{1,\ldots,\mathrm{T}\}$, where $\mathrm{T} = 24$. Each time slot is one hour, denoted as $t \in \mathcal{T}$. The detailed models of energy devices and the operation constraints of the MP are formulated as follows:

1) Production lines: In MP i, the set of machines is denoted as $\mathcal{N}_i = \{1,\ldots,\mathrm{N}_i\}$. Due to the sequential connection of various machines and buffers, they can be indexed by $n \in \mathcal{N}_i$. Let $B_{i,n,t}$ denote the occupancy of buffer n, and let $R_{i,n,t}$ denote the production rate of machine n. The operation constraints of the PL are given as follows:

$$B_{i,n,t} = B_{i,n,t-1} + R_{i,n,t}\eta_{i,n}\Delta t - R_{i,n+1,t}\eta_{i,n+1}\Delta t \tag{1}$$

$$0 \le R_{i,n,t} \le R_{i,n}^{\max} \tag{2}$$

$$0 \le B_{i,n,t} \le B_{i,n}^{\max} \tag{3}$$

$$B_{i,n,\mathrm{T}} \ge B_{i,n,0} \tag{4}$$

$$\varpi_i^{\mathrm{PO}} = \sum_{t\in\mathcal{T}} (R_{i,N_i,t}\eta_{i,N_i}\Delta t) \tag{5}$$

$$\varpi_i^{\mathrm{PO}} \ge \varpi_i^{\mathrm{PR}} \tag{6}$$

$$P_{i,t}^{\mathrm{PL}} = \sum_{n\in\mathcal{N}_i} (P_{i,n}^{\mathrm{M}} R_{i,n,t} / R_{i,n}^{\max}) \tag{7}$$

where $\eta_{i,n}$ denotes the product quality rate of machine n; Δt represents a time slot; $R_{i,n}^{\max}$ denotes the maximum production rate of machine n; $B_{i,n}^{\max}$ represents the capacity of buffer n; $B_{i,n,0}$ and $B_{i,n,\mathrm{T}}$ denote the occupancies of buffer n at the initial and terminal time slots, respectively; ϖ_i^{PO} denotes the total produced products during the scheduling horizon; ϖ_i^{PR} represents the expected product output; $P_{i,n}^{\mathrm{M}}$ denotes the rated power of machine n; and $P_{i,t}^{\mathrm{PL}}$ denotes the total power consumption of the PL.

2) Plug-in electric vehicle: Consider that the PEVs will be fully charged when parked in the MP. The set of PEVs in the MP is denoted as $\mathcal{V}_i$, indexed by v. Let $P_{i,v,t}^{\mathrm{PEV,c}}$ denote the charging power of the PEV. The parking period of PEV v is denoted as $\mathcal{T}_{i,v}^{a}$. We have:

$$\sum_{t\in\mathcal{T}_{i,v}^{a}} \eta_{i,v}^{\mathrm{PEV,c}} P_{i,v,t}^{\mathrm{PEV,c}} \Delta t = SOC_{i,v}^{\max} C_{i,v}^{\mathrm{PEV}} - SOC_{i,v}^{\mathrm{ini}} C_{i,v}^{\mathrm{PEV}} \tag{8}$$

$$0 \le P_{i,v,t}^{\mathrm{PEV,c}} \le P_{i,v}^{\mathrm{PEV,c,max}} \tag{9}$$

$$P_{i,v,t}^{\mathrm{PEV,c}} = 0, \forall t \notin \mathcal{T}_{i,v}^{a}, v \in \mathcal{V}_i \tag{10}$$

3) Diesel generator: The generated power of the DG is defined as $P_{i,t}^{\mathrm{DG}}$, which satisfies the following constraints:

$$P_{i,t}^{\mathrm{DG,min}} \le P_{i,t}^{\mathrm{DG}} \le P_{i,t}^{\mathrm{DG,max}} \tag{11}$$

$$R_t^{\mathrm{RD,gen}} \le P_{i,t}^{\mathrm{DG}} - P_{i,t-1}^{\mathrm{DG}} \le R_t^{\mathrm{RU,gen}} \tag{12}$$

where $P_{i,t}^{\mathrm{DG,max}}$ and $P_{i,t}^{\mathrm{DG,min}}$ denote the maximum and minimum power outputs of the DG, respectively; while $R_t^{\mathrm{RU,gen}}$ and $R_t^{\mathrm{RD,gen}}$ represent the ramp up and ramp down limits of the DG, respectively.

4) Wind turbine: The wind power scheduled by the MP is defined as $P_{i,t}^{\mathrm{WT}}$, which should be less than the wind power generation $P_{i,t}^{\mathrm{WT,gen}}$, as follows:

$$0 \le P_{i,t}^{\mathrm{WT}} \le P_{i,t}^{\mathrm{WT,gen}} \tag{13}$$

5) Main grid: Let $P_{i,t}^{\mathrm{GRID}}$ denote the electricity purchased from the main grid. Due to physical limitations of the main grid, it should satisfy the following constraint:

$$0 \le P_{i,t}^{\mathrm{GRID}} \le P_{i}^{\mathrm{GRID,max}} \tag{14}$$

where $P_{i}^{\mathrm{GRID,max}}$ denotes the maximum power that MP i can purchase from the main grid within a time slot.

6) Demand responses: Consider that MPs participate in demand response programs to adjust its electricity consumption. Let $\Delta P_{i,t}^{\mathrm{EL}}$ denote the amount of electricity that is adjusted. The actual electricity load of MP i $P_{i,t}^{\mathrm{EL}}$ and related demand response constraints are described as follows:

$$P_{i,t}^{\mathrm{EL}} = P_{i,t}^{\mathrm{EL,pre}} + \Delta P_{i,t}^{\mathrm{EL}} \tag{15}$$

$$\Delta P_{i,t}^{\mathrm{EL,min}} \le \Delta P_{i,t}^{\mathrm{EL}} \le \Delta P_{i,t}^{\mathrm{EL,max}} \tag{16}$$

$$\sum_{t\in\mathcal{T}} \Delta P_{i,t}^{\mathrm{EL}} = 0 \tag{17}$$

where $P_{i,t}^{\mathrm{EL,pre}}$ denotes the predicted load demands of MP i; $\Delta P_{i,t}^{\mathrm{EL,max}}$ and $\Delta P_{i,t}^{\mathrm{EL,min}}$ denote the upper and lower limits of load adjustment for MP i.

7) Energy balance: Let $P_{i,t}^{j}$ denotes the electricity shared between MP i and MP j. The electricity balance constraint of MP i is formulated as follows:

$$P_{i,t}^{\mathrm{GRID}} + P_{i,t}^{\mathrm{WT}} + P_{i,t}^{\mathrm{DG}} + \sum_{j\in\mathcal{M}\setminus i} P_{i,t}^{j} = P_{i,t}^{\mathrm{PL}} + P_{i,t}^{\mathrm{EL}} \tag{18}$$

$$P_{i,t}^{j} + P_{j,t}^{i} = 0, \forall i \in \mathcal{M}, \forall j \in \mathcal{M}\setminus i, \forall t \in \mathcal{T} \tag{19}$$

If MP i obtains electricity from MP j, $P_{i,t}^{j} > 0$; otherwise, if MP i transmits electricity to MP j, $P_{i,t}^{j} < 0$. Constraint (18) represents the electricity balance constraint within MP i; while constraint (19) represents the electricity sharing balance for MPs i and j.

8) Carbon limitations: The carbon emissions of each MP are composed of three parts: (1) emissions from power transmission in the branches connected to the access node of the MP, (2) internal emissions produced within the MP, and (3) emissions resulting from electricity purchased from the DN. This paper considers that the power generation units and load demand equally share carbon emission responsibility. Let W_i^{buy} and W_i^{sell} denote the carbon allowances purchased or sold by MP i in the carbon market; let W_i^{j} denotes the carbon allowances shared between MPs i and j. Then, the carbon emission constraint of the MP is formulated as follows:

$$\begin{aligned}&\frac{1}{2}\sum_{t\in\mathcal{T}}\sum_{l(\cdot,n)\in n} W_{l,t}\Delta t + \frac{1}{2}\sum_{t\in\mathcal{T}} e_{n,t}\left(P_{i,t}^{\mathrm{DG}} + P_{i,t}^{\mathrm{PL}} + P_{i,t}^{\mathrm{EL}} + \sum_{v\in\mathcal{V}_i} P_{i,v,t}^{\mathrm{PEV,c}}\right)\Delta t \\ &\quad + \sum_{t\in\mathcal{T}} e_{n,t} P_{i,t}^{\mathrm{GRID}}\Delta t \le W_i^{\mathrm{ini}} + W_i^{\mathrm{buy}} - W_i^{\mathrm{sell}} + W_i^{j}\end{aligned} \tag{20}$$

where $W_{l,t}$ denotes the equivalent carbon emissions due to electricity transmission; $l(\bullet,n)\in n$ represents the branch l whose ending node is node n; $e_{n,t}$ denotes the carbon intensity of node n; and W_i^{ini} is the initial carbon allowances of MP i. Note that if MP i obtains carbon allowances from MP j, $W_i^{j} > 0$; otherwise, if MP i transmits carbon allowances to MP j, $W_i^{j} < 0$.

Moreover, the carbon trading and sharing limitations for the MP are as follows:

$$0 \le W_i^{\mathrm{buy}} \le W_i^{\mathrm{buy,max}} \tag{21}$$

$$0 \le W_i^{\mathrm{sell}} \le W_i^{\mathrm{sell,max}} \tag{22}$$

$$W_i^{j} + W_j^{i} = 0, \forall i \in \mathcal{M}, \forall j \in \mathcal{M}\setminus i \tag{23}$$

where $W_i^{\mathrm{buy,max}}$ and $W_i^{\mathrm{sell,max}}$ denote the maximum amounts of carbon allowances that can be purchased or sold in the carbon market during a day.

The objective of each MP is to minimize its operation cost C_i^{MP}, including the electricity purchase cost C_i^{GRID}, DG generation cost C_i^{DG}, demand response cost C_i^{DR}, energy devices maintenance cost C_i^{OM}, and carbon trading cost C_i^{CE}. These terms are defined as follows:

$$C_i^{\mathrm{MP}} = C_i^{\mathrm{GRID}} + C_i^{\mathrm{DG}} + C_i^{\mathrm{DR}} + C_i^{\mathrm{OM}} + C_i^{\mathrm{CE}} \tag{24}$$

$$C_i^{\mathrm{GRID}} = \sum_{t\in\mathcal{T}} \zeta_{i,t}^{\mathrm{GRID}} P_{i,t}^{\mathrm{GRID}} \tag{25}$$

$$C_i^{\mathrm{DG}} = \sum_{t\in\mathcal{T}} \zeta_{i,t}^{\mathrm{DG}} P_{i,t}^{\mathrm{DG}} \tag{26}$$

$$C_i^{\mathrm{DR}} = \sum_{t\in\mathcal{T}} \phi^{\mathrm{EL}} (\Delta P_{i,t}^{\mathrm{EL}})^2 \tag{27}$$

$$C_i^{\mathrm{OM}} = \sum_{t\in\mathcal{T}} (\xi_i^{\mathrm{DG}} P_{i,t}^{\mathrm{DG}} + \xi_i^{\mathrm{WT}} P_{i,t}^{\mathrm{WT}}) \tag{28}$$

$$C_{i,s}^{\mathrm{CE}} = \xi^{\mathrm{CO_2,buy}} W_i^{\mathrm{CO_2,buy}} - \xi^{\mathrm{CO_2,sell}} W_i^{\mathrm{CO_2,sell}} \tag{29}$$

where $\zeta_{i,t}^{\mathrm{GRID}}$ denotes the electricity-carbon integrated price set by the DN; $\zeta_{i,t}^{\mathrm{DG}}$ denotes unit generation cost of the DG; ϕ^{EL} denotes the unit cost related to load adjustment; ξ_i^{DG} and ξ_i^{WT} represent the unit maintenance costs related to the DG and WT, respectively; while $\xi^{\mathrm{CO_2,buy}}$ and $\xi^{\mathrm{CO_2,sell}}$ represent the buying and selling prices of carbon allowances in the carbon market, respectively.

Then, the upper-layer problem (**ULP**) can be formulated as follows:

$$\textbf{ULP:}\ \min C_i^{\mathrm{MP}}$$

subject to (1)-(23),

variables: $\{B_{i,n,t}, R_{i,n,t}, P_{i,v,t}^{\mathrm{PEV,c}}, P_{i,t}^{\mathrm{DG}}, P_{i,t}^{\mathrm{WT}}, P_{i,t}^{\mathrm{GRID}}, \Delta P_{i,t}^{\mathrm{EL}}, P_{i,t}^{j}, W_i^{\mathrm{buy}}, W_i^{\mathrm{sell}}, W_i^{j}\}$.

2.2 The lower-layer model

The lower-layer problem mainly involves the optimal power flow problem. Here, the branch flow model is used to describe the DN model. Let $P_{l,t}^{\mathrm{DN}}$ and $Q_{l,t}^{\mathrm{DN}}$ denote the active and reactive power flows in branch l; let $P_{n,t}$ and $Q_{n,t}$ denote the active and reactive power injection in bus n; let $U_{n,t}$ and $I_{l,t}$ denote the squared magnitudes of bus voltage and branch current, respectively; while let $P_{pcc,t}^{\mathrm{TN}}$ denote the electricity purchased from the transmission network (TN) through the point of common coupling (PCC). The detailed model of the DN can be formulated as follows:

$$P_{pcc,t}^{\mathrm{TN}} + \sum_{l(\cdot,n)} (P_{l,t}^{\mathrm{DN}} - I_{l,t} r_l) + P_{n,t} = \sum_{b(n,\cdot)} P_{b,t}^{\mathrm{DN}} : \lambda_{n,t}^{\mathrm{LMP}} \tag{30}$$

$$\sum_{l(\cdot,n)} (Q_{l,t}^{\mathrm{DN}} - I_{l,t} x_l) + Q_{n,t} = \sum_{b(n,\cdot)} Q_{b,t}^{\mathrm{DN}} \tag{31}$$

$$U_{n,t} = U_{m,t} - 2(r_l P_{l,t}^{\mathrm{DN}} + x_l Q_{l,t}^{\mathrm{DN}}) + I_{l,t}(r_l^2 + x_l^2) \tag{32}$$

$$\sqrt{4\left(P_{l,t}^{\mathrm{DN}}\right)^2 + 4\left(Q_{l,t}^{\mathrm{DN}}\right)^2 + (I_{l,t} - U_{m,t})^2} \le \left(I_{l,t} + U_{m,t}\right) \tag{33}$$

$$U_n^{\min} \le U_{n,t} \le U_n^{\max},\quad I_l^{\min} \le I_{l,t} \le I_l^{\max} \tag{34}$$

where r_l and x_l are resistance and reactance of branch l; $U_n^{\max}$ and $U_n^{\min}$ denote the upper and lower limits of squared node voltage magnitude; $I_l^{\max}$ and $I_l^{\min}$ denote the upper and lower limits of squared branch current magnitude; and $\lambda_{n,t}^{\mathrm{LMP}}$ represents the locational marginal price (LMP) at node n. Note that branch l connects bus m and bus n, and $b(n,\bullet)$ denotes the branch originating from node n.

The electricity purchased from the TN should satisfy the following constraints:

$$P_{pcc}^{\mathrm{TN,min}} \le P_{pcc,t}^{\mathrm{TN}} \le P_{pcc}^{\mathrm{TN,max}} \tag{35}$$

where $P_{pcc}^{\mathrm{TN,max}}$ and $P_{pcc}^{\mathrm{TN,min}}$ denote the upper and lower limits that the DN can purchase electricity from the TN, respectively.

We denote g_n as the power generator located in node n, which belongs to the DN. Let $P_{g_n,t}$ denote the power generated by generator g_n. We have:

$$P_{g_n}^{\min} \le P_{g_n,t} \le P_{g_n}^{\max} \tag{36}$$

$$P_{g_n}^{\mathrm{DOWN}} \le P_{g_n,t} - P_{g_n,t-1} \le P_{g_n}^{\mathrm{UP}} \tag{37}$$

where $P_{g_n}^{\max}$ and $P_{g_n}^{\min}$ denote the maximum and minimum power outputs of generator g_n, respectively; while $P_{g_n}^{\mathrm{UP}}$ and $P_{g_n}^{\mathrm{DOWN}}$ represent the ramp up and ramp down limits of generator g_n, respectively.

The objective of the DN is to minimize its operation cost C^{DN}, including the power generation cost C^{GEN} and electricity procurement cost C^{TN}. These terms are defined as follows:

$$C^{\mathrm{DN}} = C^{\mathrm{GEN}} + C^{\mathrm{TN}} \tag{38}$$

$$C^{\mathrm{GEN}} = \sum_{g_n \in G} \left[a_{g_n} (P_{g_n,t})^2 + b_{g_n} P_{g_n,t} + c_{g_n} \right] \tag{39}$$

$$C^{\mathrm{TN}} = \lambda_t^{\mathrm{TN}} P_{pcc,t}^{\mathrm{TN}} \tag{40}$$

where a_{g_n}, b_{g_n}, and c_{g_n} represent the cost factors of generator g_n; and λ_t^{TN} denotes the unit cost for the DN to purchase electricity from the DN.

Then, the lower-layer problem (**LLP**) can be formulated as follows:

$$\textbf{LLP:}\ \min C^{\mathrm{DN}}$$

subject to (30)-(37),

variables: $\{P_{l,t}^{\mathrm{DN}}, Q_{l,t}^{\mathrm{DN}}, P_{n,t}, Q_{n,t}, U_{n,t}, I_{l,t}, P_{pcc,t}^{\mathrm{TN}}, P_{g_n,t}\}$.

2.3 The carbon emission flow model

To quantify the spatiotemporal distribution of carbon emissions within the DN, the CEF theory is employed to describe the relationship between the power flow and carbon flow. This enables a dynamic description of the carbon responsibility of each node. The detailed description of the CEF model is presented as follows:

Let $e_{n,t}$ denote the node carbon intensity. It reflects the marginal carbon emission responsibility associated with electricity consumed at node n at time slot t. It can be expressed as follows:

$$e_{n,t} = \frac{\sum_{g \in \Gamma_n} P_{g,t}^{\mathrm{DG}} e_g + \sum_{l(\cdot,n) \in \Omega_n} (P_{l,t}^{\mathrm{DN}} - I_{l,t} r_l) \rho_{l,t}}{\sum_{g \in \Gamma_n} P_{g,t}^{\mathrm{DG}} + \sum_{w \in \Psi_n} P_{w,t}^{\mathrm{WT}} + \sum_{l(\cdot,n) \in \Omega_n} (P_{l,t}^{\mathrm{DN}} - I_{l,t} r_l)} \tag{41}$$

where e_g is the carbon emission coefficient of generator g; $P_{l,t}^{\mathrm{DN}}$ is the power flow on branch l; $\rho_{l,t}$ denotes the line carbon intensity of branch l; Γ_n and Ψ_n represents the set of DGs and WTs connected to node n; Ω_n is the set of branches connected to node n; and $l(\cdot,n)$ denotes the branch whose receiving node is node n.

The line carbon intensity $\rho_{l,t}$ is defined as the carbon emissions per unit of energy flow on branch l, which equals the node carbon intensity of its sending node. It can be described as follows:

$$\rho_{l,t} = e_{n,t},\ \forall l(n,\cdot) \in \Omega_n \tag{42}$$

Then, the equivalent carbon emissions of line transmission $E_{l,t}$ can be defined as follows:

$$E_{l,t} = I_{l,t} r_l \rho_{l,t} \tag{43}$$

Based on the node carbon intensity obtained from the CEF model, an electricity-carbon integrated pricing mechanism is constructed to guide the energy scheduling and sharing decisions of MPs. The electricity-carbon integrated price at node n $\zeta_{n,t}^{\mathrm{GRID}}$ can be expressed as follows:

$$\zeta_{n,t}^{\mathrm{GRID}} = \lambda_{n,t}^{\mathrm{LMP}} + \tau e_{n,t} \tag{44}$$

where τ represents the carbon tax. This integrated pricing mechanism can provide dynamic carbon-aware price signals for MPs to perform low-carbon scheduling and electricity-carbon sharing.

3. SOLUTION PROCEDURES

To obtain the electricity and carbon allowance scheduling results for the MPs and the optimal power flows of the DN, we should solve the upper-layer problem (**ULP**) and lower-layer problem (**LLP**) iteratively until the results converge and the two-layer optimization reaches equilibrium.

The solution procedures are presented in Fig. 3.

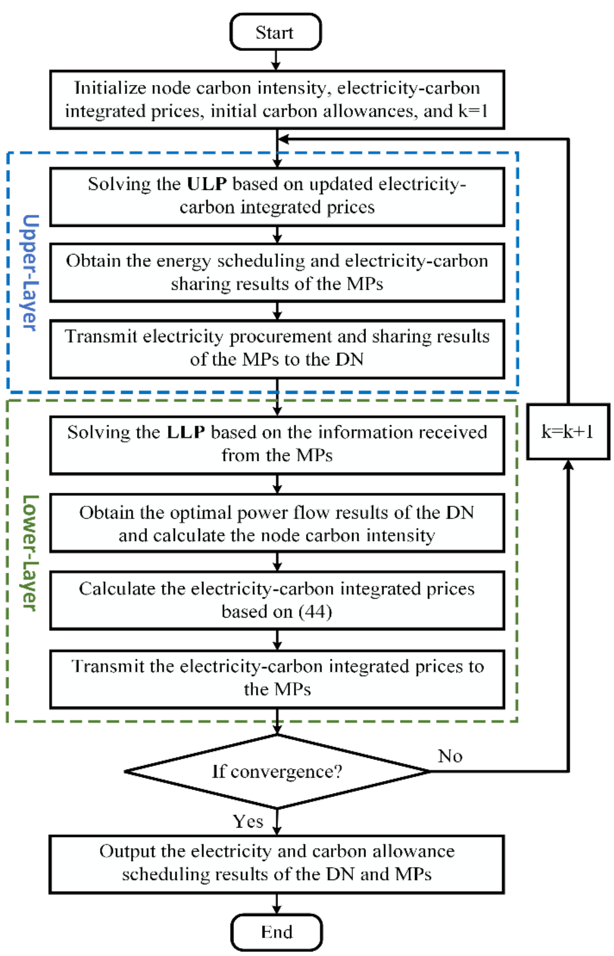

Fig. 3 The solution procedures of the two-layer problem

4. CASE STUDIES

4.1 Simulation settings

Consider that local electricity and carbon sharing are conducted among three MPs. The schematic model and topology of the DN is shown as Fig. 4. As shown in the figure, the DN contains 33 node, and MPs 1-3 connected to the DN through nodes 8, 16, and 24, respectively, while two generators G1 and G2 through nodes 5 and 12, respectively. The electricity retail prices are obtained from ref. [9].

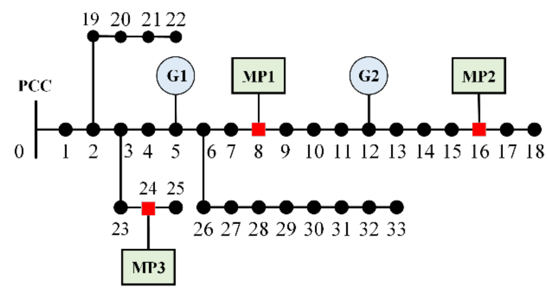

Fig. 4 The schematic model and topology of the DN

4.2 Electricity and carbon allowance sharing results

Fig. 5 shows the electricity sharing results among MPs. As shown in the figure, each MP actively participates in the local electricity sharing. When an MP has surplus renewable energy, it will transfer the excess power to other MPs with higher demand, thereby improving renewable energy utilization and reducing operation cost for MPs.

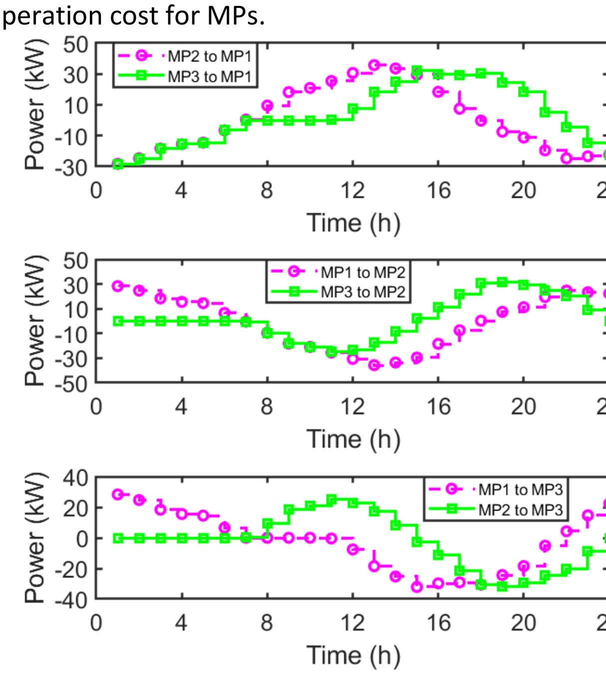

Fig. 5 The electricity sharing results among MPs

Table 1 presents the carbon sharing and trading results among the three MPs. As shown in the table, MP1 and MP2 have lower carbon emissions than their initial carbon allowances, whereas MP3 has relatively higher carbon emissions. Consequently, MP1 and MP2 share their surplus carbon allowances with MP3. This sharing mechanism enables more efficient usage of carbon allowances among MPs.

Table 1 The carbon sharing and trading results for MPs

MPs	Carbon emissions (kg)	Initial carbon allowance (kg)	Shared carbon allowance (kg)	Traded carbon allowance (kg)
MP1	486.52	600	-113.48	0
MP2	539.55	600	-60.45	0
MP3	796.07	600	196.07	22.14

4.3 Demand response results

Fig. 6 illustrates the demand response results of MP1 under the LMP pricing mechanism and the proposed electricity-carbon integrated pricing mechanism. As shown in the figure, the adjusted loads are closely correlated with the variation of node carbon intensity. During periods with higher carbon intensity (e.g., 1:00-8:00), the loads are decreased to achieve operation cost reduction for the MP. Conversely, during periods with lower carbon intensity (e.g., 13:00-16:00), the loads are increased to reduce the carbon footprint of the MP. This figure verifies that the proposed pricing mechanism achieves both economic and environmental benefits by coordinating load adjustments.

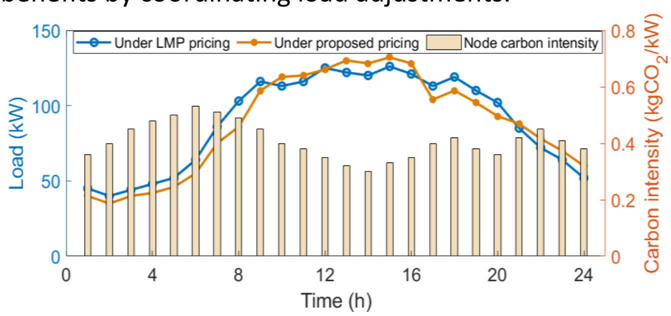

Fig. 6 The adjusted loads of MP1 under different pricing mechanisms

5. CONCLUSIONS

In this paper, we propose a two-layer energy management framework for MPs considering dynamic carbon emission factors in different nodes. The lower layer focuses on the optimal power flow of the DN, while the upper layer establishes an electricity-carbon sharing model among interconnected MPs. Case studies demonstrate that the proposed framework effectively reduces total operation costs and carbon emissions for MPs. In the future, we will further extend the proposed framework to integrated energy systems and develop real-time optimization strategies for electricity-carbon sharing among different energy entities.

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