Journal of Physics: Conference Series

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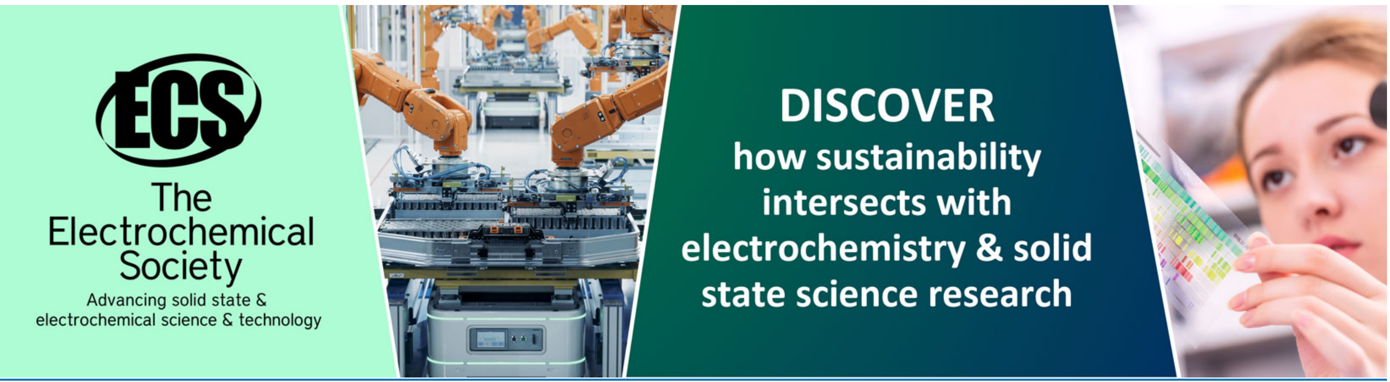
To cite this article: Junhai Wang *et al* 2023 *J. Phys.: Conf. Ser.* **2473** 012004



Hierarchical Collaborative Planning of County Energy Internet

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Abstract: Building a County Energy Internet (CEI) is crucial for achieving green and low-carbon transition and sustainable development of county energy systems. This paper proposes a bi-level collaborative planning method for CEI to configure devices' capacities in multiple regional CEIs (RCEIs) and plan the interconnected networks simultaneously. Firstly, the models of multi-energy devices and networks are constructed. Then, an optimal partitioning method based on a clustering algorithm is proposed to divide the CEI into multiple RCEIs by considering the load distribution pattern and complementary characteristics. On top of that, a bi-level planning model for CEI is established, wherein the lower-level problem aims at configuring the capacities of devices in RCEIs through mixed-integer linear programming (MILP), while the upper-level problem is the determination of the interconnected multi-energy network topologies by searching the minimum spanning tree. This two-level planning problem is resolved iteratively, in which the network topologies of CEI and energy imbalance in each RCEI are shared information. Case studies on the modified CEI validate the effectiveness and practicality of the proposed method.

1. Introduction

In recent years, under the dual pressure of increasing energy consumption and the "Carbon Peak, Carbon Neutral" strategic goal, the relationship between energy supply and demand is increasingly tense, and the change of energy utilization mode is imminent [1] [2]. How to improve the efficiency of energy use, reduce the cost of energy use, reduce environmental pollution and achieve sustainable development of energy is gradually becoming a common concern [3]. The county energy internet (CEI) integrates multiple energy resources to improve energy efficiency and energy supply reliability, which is a crucial and practical way to advance the energy transition.

At present, the planning of CEI includes the capacity configuration of multi-energy devices and the planning of multi-energy networks [4]. In [5], three investment constraint schemes are used to simulate the economic operation of the system based on typical daily load characteristic curves in different seasons and to establish an optimal capacity allocation model for the integrated energy system that takes into account the investment cost constraint and minimizes the total annual cost and CO2 emissions. A planning model containing an operational module for developing steady-state optimal multiple energy flows for the industrial enterprise under consideration, and a multi-stage extension module for optimizing investment decisions are proposed in [6] to address the challenges of integrated energy system planning considering coupled electric, gas, and thermal systems. By using the particle swarm optimization method, an integrated energy system planning model combining the constraints from the power grid, natural gas pipeline, and heating network is effectively resolved in [7], which considers the wind power integration on the supply side and the load fluctuation on the demand side. In [8], a probability-interval-based IES planning method is proposed to achieve expansion planning of traditional facilities and electricity storage systems, in which a conditional value-at-risk-based probability-interval method is developed to describe the uncertain wind power. A novel methodology involving both kernel density estimation and shortest path methods is proposed in [9] to optimize the transmission network, which can select the locations of the energy stations, determine the distribution of the energy networks, and reduce the total network length.

However, with the extremely fragmented and uneven distribution of energy generators and multi-energy loads within the county energy system [10], CEI planning faces huge challenges. To this end, this paper proposes a hierarchical collaborative planning method for CEI to achieve capacity allocation and network topology planning. First of all, the generators and loads are divided into several energy sectors by the proposed optimal partitioning method. Then, a two-level planning model for CEI is developed to determine the capacities and locations of devices and the multi-energy network topologies, in which the lower level aims at configuring multiple devices, and the upper level is a minimum spanning tree search problem. The proposed method is solved iteratively, wherein the shared information between two levels is the power imbalance of each sector and the network topology. A test system with undefined electric and thermal networks is utilized to verify the proposed method.

The remainder of this paper is presented as follows: the models of devices and networks in the county energy system is established in Section II. The optimal partitioning method and the hierarchical collaborative planning method are presented in Section III. A case study is carried out in section IV. Conclusions are summarized in Section V.

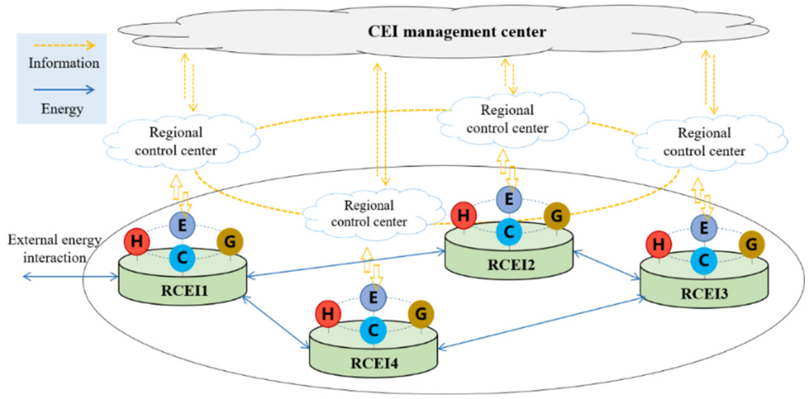

Figure 1. Schematic diagram of the typical structure of CEI.

2. Modeling of county energy internet system

2.1. Structure of CEI

With the spread of distributed energy resources and the innovation of system management paradigms, the CEI presents the characteristics of extensive interconnection, highly integrated, and hierarchical cooperation. In general, as shown in Fig. 1, the CEI tends to be hierarchically distributed and have multi-level coordination, wherein the regional control center is responsible for multi-energy equipment control and end-user management in a single regional CEI (RCEI). As for the CEI management center, it has the functions of multi-regional coordination, centralized CEI operation, and interaction with external parties. In addition, multiple RCEIs are interconnected, and the energy interactions are managed by the CEI management center in order to achieve resource sharing on a larger scale.

Besides, by installing various energy coupling equipment such as combined heat and power (CHP) units, gas boilers (GBs), heat pumps (HPs), electrical coolers (ECs), absorption chillers (ACs), and distributed PVs (DPVs), various forms of energy such as electricity, heat, cool and gas can be coupled and complemented with each other, thus improving the overall energy efficiency and achieving the energy self-balance of RCEI. Energy storage devices such as battery energy storage systems (BESSs) and heat storage tanks (HSTs) are installed to provide extra flexibility for the RCEI. An overall multi-energy coupling relation and structure in an RCEI is comprehensively depicted in Fig. 2.

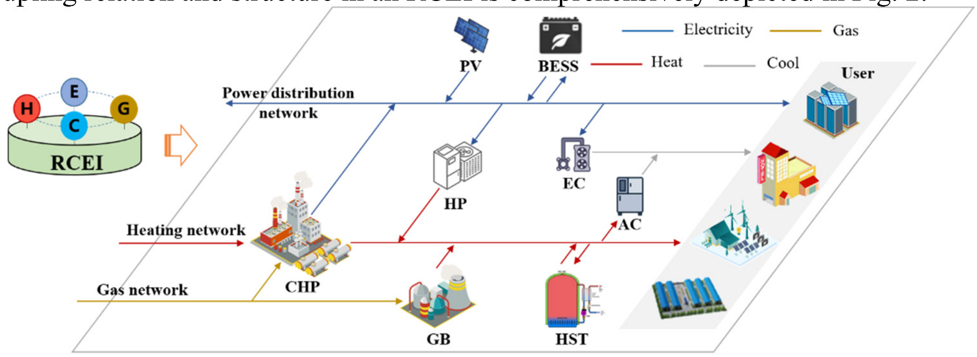

Figure 2. Schematic diagram of multi-energy coupling in a RCEI.

2.2. Modeling of multi-energy devices

The operational constraints of multi-energy devices can be given by

$$\pi_{i,k} P_{i,k}^{\min} \le P_{i,t} \le \pi_{i,k} P_{i,k}^{\max}, \ \forall i \in \mathcal{N}_{\mathrm{RCEI}}, \pi_{i,k} \in \{0,1\} \tag{1}$$

where $P_{i,k}^{\max}$ and $P_{i,k}^{\min}$ represent the maximum and minimum technical power limits, respectively; k indicates the type of devices; $\pi_{i,k}$ is a binary variable that indicates whether the kth device is installed; $P_{i,t}^{\mathrm{e}}$ is the output power of the ith device.

For multi-energy conversion devices such as CHP, HP, and AC, the coupling relations among electric, thermal and cooling power are described by

$$H_{i,t}^{\mathrm{k}_1} = \eta_{\mathrm{gh}}^{\mathrm{k}_1} P_{i,t}^{\mathrm{gas,k}_1}, \ H_{i,t}^{\mathrm{k}_2} = \kappa_{\mathrm{eh}}^{\mathrm{k}_2} P_{i,t}^{\mathrm{k}_2}, \quad C_{i,t}^{\mathrm{k}_3} = \eta_{\mathrm{ec}}^{\mathrm{k}_3} P_{i,t}^{\mathrm{k}_3}, \quad C_{i,t}^{\mathrm{k}_4} = \eta_{\mathrm{hc}}^{\mathrm{k}_4} H_{i,t}^{\mathrm{k}_4}, \quad \forall i \in \mathcal{N}_{\mathrm{RCEI}} \tag{2}$$

PV is the prominent RES in a county, and the electric power generation of PV can be given by

$$0 \le P_{i,t}^{\mathrm{PV}} \le \pi_i^{\mathrm{PV}} S_i^{\mathrm{PV,max}} \qquad \forall i \in \mathcal{N}_{\mathrm{RCEI}}, \pi_i^{\mathrm{PV}} \in \{0,1\} \tag{3}$$

where $S_i^{\mathrm{PV,max}}$ is the maximum capacity of PV to be installed; π_i^{PV} is the binary indicator; $P_{i,t}^{\mathrm{PV}}$ is the electric power output of PV.

The BESS and HST are installed in RCEI to provide extra flexibility, and the corresponding detailed operational characteristics can refer to Literature [11]. In this paper, the installed capacity and rated charging and discharging power of the energy storage equipment are decision variables, which should satisfy the relations expressed below

$$\begin{cases} P_{i,\mathrm{dis}}^{\mathrm{BESS,max}} = \pi_i^{\mathrm{BESS}} P_{i,\mathrm{dis}}^{\mathrm{BESS,max}}, \ P_{i,\mathrm{ch}}^{\mathrm{BESS,max}} = \pi_i^{\mathrm{BESS}} P_{i,\mathrm{ch}}^{\mathrm{BESS,max}} \\ C_i^{\mathrm{N,BESS}} = \pi_i^{\mathrm{BESS}} C_i^{\mathrm{N,BESS}}, \quad \dfrac{C_i^{\mathrm{N,BESS}} \eta_{i,\mathrm{dis}}^{\mathrm{BESS}}}{P_{i,\mathrm{dis}}^{\mathrm{BESS,max}}} \ge T_{\min}^{\mathrm{BESS}}, \ \forall i \in \mathcal{N}_{\mathrm{RCEI}}, \pi_i^{\mathrm{BESS}} \in \{0,1\} \end{cases} \tag{4}$$

$$\begin{cases} H_{i,\mathrm{dis}}^{\mathrm{HST,max}} = \pi_i^{\mathrm{HST}} H_{i,\mathrm{dis}}^{\mathrm{HST,max}}, \quad H_{i,\mathrm{ch}}^{\mathrm{HST,max}} = \pi_i^{\mathrm{HST}} H_{i,\mathrm{ch}}^{\mathrm{HST,max}} \\ C_i^{\mathrm{N,HST}} = \pi_i^{\mathrm{HST}} C_i^{\mathrm{N,HST}}, \quad \dfrac{C_i^{\mathrm{N,HST}} \eta_{i,\mathrm{dis}}^{\mathrm{HST}}}{P_{i,\mathrm{dis}}^{\mathrm{HST,max}}} \ge T_{\min}^{\mathrm{HST}}, \quad \forall i \in \mathcal{N}_{\mathrm{RCEI}}, \pi_i^{\mathrm{HST}} \in \{0,1\} \end{cases} \tag{5}$$

where $C_i^{\mathrm{N,BESS}}$ and $C_i^{\mathrm{N,HST}}$ are the rated installed capacity of BESS and HST, respectively; π_i^{BESS} and π_i^{HST} indicate whether the BESS and the HST are selected; $P_{i,\mathrm{dis}}^{\mathrm{BESS,max}}$ and $P_{i,\mathrm{ch}}^{\mathrm{BESS,max}}$ denote the electric discharging and charging power limits of the BESS, respectively; $H_{i,\mathrm{dis}}^{\mathrm{HST,max}}$ and $H_{i,\mathrm{ch}}^{\mathrm{HST,max}}$ are the thermal discharging and charging power limits of the HST, respectively; $\eta_{i,\mathrm{dis}}^{\mathrm{BESS}}$ and $\eta_{i,\mathrm{dis}}^{\mathrm{HST}}$ represent the discharging efficiency of BESS and HST, respectively; $T_{\min}^{\text{BESS}}$ and $T_{\min}^{\text{HST}}$ are the minimum continuous discharging time for BESS and HST, respectively.

2.3. *Modeling of multi-energy networks*

2.3.1 Power distribution network (PDN): In terms of PDN operation and dispatch, the transmission losses can be approximated by introducing the line transmission loss coefficient. The line transmission loss and the power flow equations can be expressed as

$$P_{ij,t}^{\text{out}} = (1-\varepsilon_{ij})P_{ij,t}^{\text{in}},\ \ P_{ij,t}^{\text{out}} = \sum_{k\in\mathcal{C}_j} P_{jk,t}^{\text{in}} + \hat{P}_j^{\text{D}},\ \forall(i,j)\in\mathcal{B}^{\text{PDN}} \tag{6}$$

where $P_{ij,t}^{\text{in}}$ indicates the electric power injected into line (i,j) at time t; $P_{ij,t}^{\text{out}}$ denotes the electric power flowing out of the line (i,j) at time t; ε_{ij} is the line transmission loss coefficient that is proportional to the length of the line; $\hat{P}_j^{\text{D}}$ denotes the net load of node j.

2.3.2 Distinct heating network (DHN): Likewise, the loss of DHN can be captured by introducing a transfer loss coefficient

$$H_{ij,t}^{\text{out}} = (1-\delta_{ij})H_{ij,t}^{\text{in}},\ H_{ij,t}^{\text{out}} = \sum_{k\in\mathcal{C}_j^h} H_{jk,t}^{\text{in}} + \hat{H}_j^{\text{D}}, \forall(i,j)\in\mathcal{B}^{\text{DHN}} \tag{7}$$

where $H_{ij,t}^{\text{in}}$ indicates the thermal power injected into pipeline (i,j) at time t; $H_{ij,t}^{\text{out}}$ denotes the thermal power flowing out of the pipeline (i,j) at time t; δ_{ij} is the transfer loss coefficient that is proportional to the length of the line; $\hat{H}_j^{\text{D}}$ denotes the net thermal load of node j.

3. Optimal partitioning and planning of CEI

3.1. *Optimal partitioning method for CEI*

An optimal partitioning method (OPM) is developed herein to achieve a reasonable division of the CEI into several RCEIs. The OPM aims to find a better division with the smallest integrated energy moment (IEM). Wherein, the IEM is the product of the inter-regional distance and the energy imbalance of each region. Both loads and sources are treated as nodes with three attribute values, namely the pseudo load, abscissa and ordinate. The pseudo load is either the load value or the capacity of source. On top of that, the IEM between node i and j can be given by

$$\text{IEM}_{ij} = \frac{1}{2}\bullet(\widehat{P}_i^{\text{D}} + \widehat{P}_j^{\text{D}} + \widehat{G}_i^{\text{D}} + \widehat{G}_j^{\text{D}})\bullet\sqrt{(x_i-x_j)^2+(y_i-y_j)^2} \tag{8}$$

where $\widehat{P}_i^{\text{D}}$ and $\widehat{G}_i^{\text{D}}$ are the pseudo electric and gas load at node i, respectively; x_i and y_i are the abscissa and ordinate of node i, respectively.

Based on the *k*-means algorithm [12], for a given N_c initial cluster center $C^0 = \left\{C_1^0,\ldots,C_k^0,\ldots,C_{N_c}^0\right\}$, each load and source will be grouped into the cluster that has the minimum IEM between them and the cluster center. When all the loads and sources travel through, the cluster centers will be updated by calculating the means of pseudo load, abscissa, and ordinate corresponding to every element within each cluster. This clustering procedure will continue until the cluster center keeps unchanged.

3.2. *Hierarchical collaborative planning of CEI*

In this section, a hierarchical collaborative planning method for CEI is developed to find the optimal installed capacities of devices and the optimal network topology for interconnecting the RCEIs.

3.2.1 Lower-level problem: The objective aims to minimize equipment installation costs and system operating costs while ensuring adequate energy supply, given by

$$\min C^{\mathrm{RCEI}} = \sum_{i \in N_{\mathrm{RCEI}}} C_i^{\mathrm{inv}} + \sum_{t=1}^{24} \left\{ \sum_{k \in \mathcal{N}_i^{\mathrm{fa}}} \gamma_k^{\mathrm{m}} \pi_k P_{k,t} + \gamma^{\mathrm{CO_2}} (P_{i,t}^{\mathrm{g,CHP}} + P_{i,t}^{\mathrm{g,GB}}) + (\gamma_t^{\mathrm{e}} P_{i,t}^{\mathrm{e,ex}} + \gamma_t^{\mathrm{g}} P_{i,t}^{\mathrm{g,ex}}) \right\}$$

$$s.t.\ (1)-(7) \tag{9}$$

$$\sum_{k \in \mathcal{N}_i^{\mathrm{fa}}} \pi_k P_{k,t}^{\mathrm{e}} + P_{i,t}^{\mathrm{e,ex}} = P_{i,t}^{\mathrm{D}}, \sum_{k \in \mathcal{N}_i^{\mathrm{fa}}} \pi_k H_{k,t} = H_{i,t}^{\mathrm{D}}, \qquad \forall i \in \mathcal{N}_{\mathrm{RCEI}}$$

$$C_i^{\mathrm{inv}} = \sum_{k \in \mathcal{N}_i^{\mathrm{fa}}} \lambda^k \pi_k S_k \cdot \frac{r(1+r)^{y^k}}{(1+r)^{y^k}-1} \tag{10}$$

where C^{RCEI} and C_i^{inv} denote the overall cost and equipment installation cost of the ith RCEI, respectively; λ^k and γ_k^{m} are the installation cost coefficient and maintenance coefficient of equipment, respectively; γ_t^{e} and γ_t^{g} are the price for purchasing electricity and gas, respectively; $\gamma^{\mathrm{CO_2}}$ is the carbon tax price; π_k is the binary variable that indicates whether the equipment is installed; r is the discount rate; S_k the installed capacity of the kth equipment; y^k is the maximum service life of the equipment; $P_{k,t}$ is the operating power of the kth equipment; $P_{i,t}^{\mathrm{e,ex}}$ and $P_{i,t}^{\mathrm{g,ex}}$ are the external electric and gas exchange power, respectively; $P_{i,t}^{\mathrm{D}}$ and $H_{i,t}^{\mathrm{D}}$ denote the electrical and thermal loads corresponding to the ith RCEI, respectively; Δt is the dispatch time interval. Obviously, the lower-level problem is a large-scale MILP problem, and it can be resolved by the prevailing commercial solvers such as GUROBI.

3.2.2 Upper-level problem: The interconnected network planning problem is a minimum spanning tree (MST) search problem. Each RCEI is treated as an isolated vertex, and it is located at the corresponding cluster center obtained by the OPM. The weight of an edge between any two vertices is the product of the construction cost per unit length of the corresponding transmission line and pipeline and the length of the edge given by

$$\mathcal{W}_{ij} = \varphi_1 \sum_{k \in \mathcal{N}^{\mathrm{PDN}}} \pi_k^{\mathrm{PDN}} \lambda_k^{\mathrm{PDN}} \mathcal{L}_{ij}^{\mathrm{PDN}} + (1-\varphi_1) \sum_{k \in \mathcal{N}^{\mathrm{DHN}}} \pi_k^{\mathrm{DHN}} \lambda_k^{\mathrm{DHN}} \mathcal{L}_{ij}^{\mathrm{DHN}} \tag{11}$$

where $\mathcal{L}_{ij}^{\mathrm{PDN}}$ and $\mathcal{L}_{ij}^{\mathrm{DHN}}$ are the length of transmission line and pipeline between vertex i and j, respectively; λ_k^{PDN} and λ_k^{DHN} are the construction cost per unit length of the kth transmission line and pipeline, respectively; π_k^{PDN} and π_k^{DHN} are binary variables that indicate whether the kth transmission line or pipeline is selected; φ_1 is a preference factor between 0 and 1, which can be set artificially. In this paper, the Prim algorithm is adopted to resolve the interconnected network planning problem, and the detailed procedure can refer to Literature [13].

4. Case study

4.1. Test system description

A regional county energy system in the northern Zhejiang Province, China, is selected as the subject to verify the proposed method. The test system originally contained 40 load nodes, 4 CHP units, and 10 PV plants. The maximum electrical, thermal, and cooling loads in the whole area are 162.19 MW, 70.95 MW, and 84.64 MW, respectively. The originally installed capacities of CHP and PV are 126.2 MW and 15.19MW. The CHP locates at nodes 3, 4, 7, and 10, and the PV connects to nodes 1-10. In this study, one typical day is obtained through clustering. Other detailed parameters of devices and energy purchase prices can refer to [4] [14] [15].

4.2. Optimal partition results

According to the forecast of loads and PV generation, the proposed optimal partitioning method is utilized to divide the dispersed distributed loads and generators into several sectors. From the optimal partition results depicted in Fig. 3, it is apparent that the original CEI is divided into ten independent energy supply zones. For each zone, there exists one load and one generator at least, which ensures that part of the regional load can be supplied by the local generator to improve the reliability of the energy supply. In addition, there is only one load inside 5-10 zones because these zones are industrial parks with high load density. The electrical, thermal, and cooling loads after partition are shown in Fig. 4. The load in zones 3, 5, and 6 is large, while the load in other regions is small.

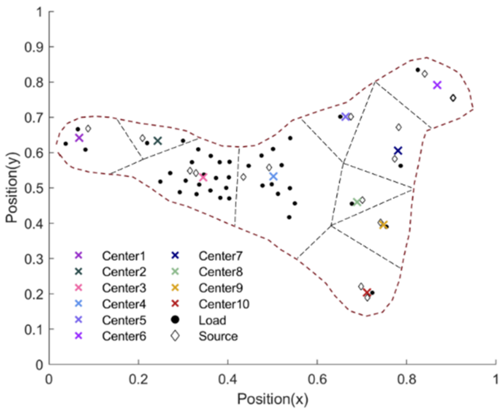

Figure 3. Schematic diagram of optimal partition results.

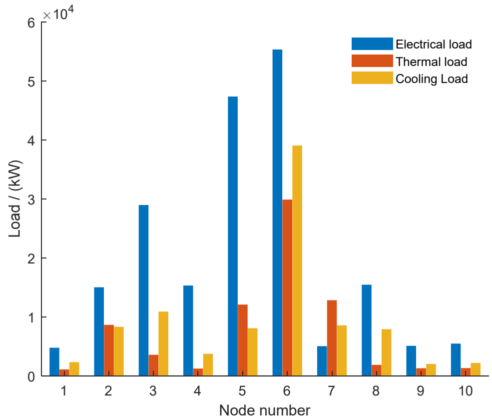

Figure 4. The electrical, thermal, and cooling loads after partition.

Table 1. Optimal configuration results.

Type of device	Scenario 1		Scenario 2	
	Locations	Installed capacities (MW/MWh)	Locations	Installed capacities (MW/MWh)
HP	1, 6, 8	30.00	**3, 6, 9**	30.00
AC	2-8	29.60	2-8	29.60
EC	1-10	61.86	1-10	61.86
PV	5, 6	69.90	5, 6	69.90
BU	6, 8	6.00	**6, 10**	6.00
HST	4	20.00	4	20.00
Construction cost (yuan)	3.815×10^7		3.815×10^7	

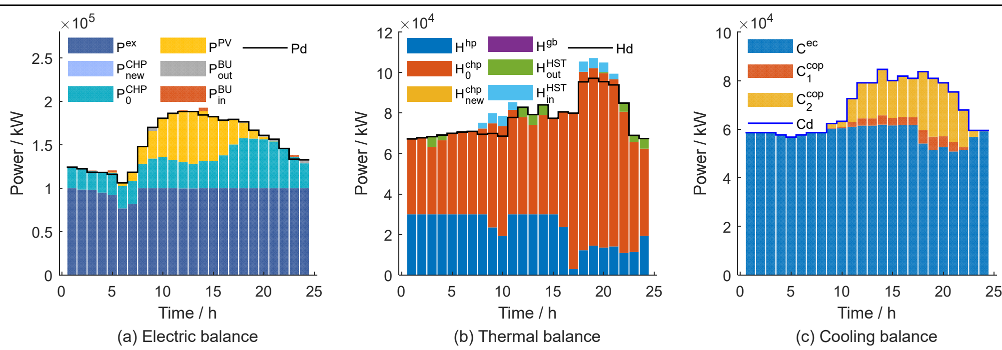

Figure 5. Diagram of energy balance: (a) electric balance, (b) thermal balance, (c) cooling balance.

4.3. Optimal partition results

Based on the partitioning results, the proposed hierarchical collaborative planning method is used to optimally plan the CEI. To validate the effectiveness of the proposed method, two scenarios are set up:

Scenario 1: the network is planned first, and then the device capacity is configured;

Scenario 2: collaborative device capacity configuration and network planning.

From the configuration results listed in Table 1, it can be found that the construction cost in Scenario 1 is the same as that in Scenario 2, as the configured capacities of multi-energy devices are almost the same in the two scenarios. But the locations of HPs and Bus are further optimized by collaboratively optimizing the capacities of devices and planning the multi-energy networks, thus decreasing the energy transmission losses.

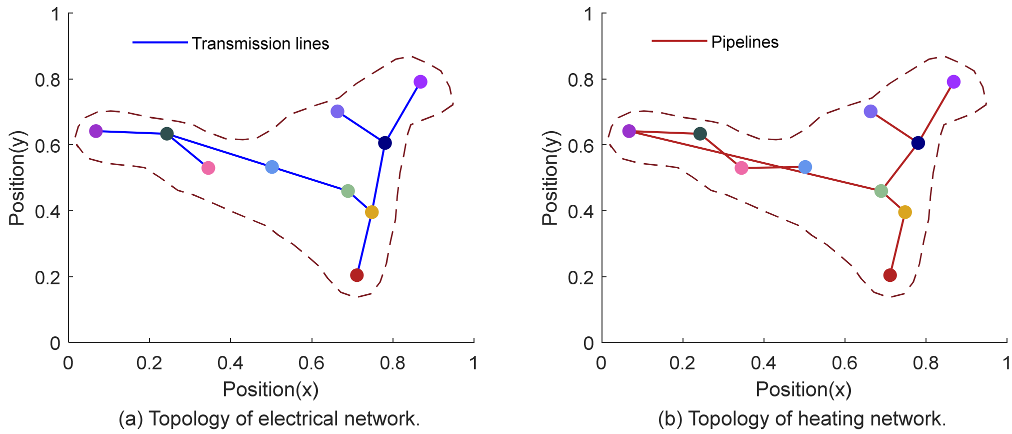

Figure 6. Topologies of multi-energy networks: (a) electrical network, (b) heating network.

The optimal daily energy outputs of multi-energy devices are presented in Fig. 5. From the diagram of electrical power balance, more than 63.60% of its electricity is supplied by the upstream grid. The local generators and newly installed PV power provide surplus power. Considering the scarcity of resources in this county, investing in new PV generation can improve the power self-sufficiency rate in this area. The thermal power balance shows that the HST plays a crucial role in ensuring the balance between supply and demand. The HST charges and discharges frequently during the valley thermal load and peak electrical load hours to maintain energy balance. The high-efficiency HP is installed to provide a large amount of thermal power. As for the cooling power balance, the EC provides 84.16% of the cooling loads, as the EC is highly efficient and economical.

From the topologies of the planned interconnected multi-energy networks depicted in Fig. 6, ten RCEIs are connected by the electrical and heating networks, and thus the multiple energy resources distributed in RCEIs can be utilized and shared to improve the self-balancing ability of CEI. The proportion of the local power supply to the load before planning is 44.49%, and it reaches 66.49% after planning. However, if those RCEIs are not interconnected, the local power supply of nodes 1, 2, 3, 5, 8, and 9 are less than 10% of loads, thus inducing weak self-balancing ability. To sum up, the proposed method can rationally configure the capacities of devices and plan the interconnected networks among RCEIs.

5. Conclusion

In this paper, a hierarchical collaborative planning method for County Energy Internet is developed to configure the capacities of multi-energy devices and plan the interconnected multi-energy networks. The optimal portioning method is proposed to divide multiple loads and sources into several regional county energy internet, avoiding unnecessary cross-regional energy transfer losses. A hierarchical collaborative planning problem is established, in which the lower level is responsible for device capacity configuration, and the upper level aims at planning the interconnected networks. By solving the two-level problems iteratively, the optimal network topology and device capacities,ands location, are obtained. The case study on a modified county energy internet verifies the effectiveness and practicality of the proposed method.

Acknowledgments
This work was supported by the science and technology project of State Grid under Grant 5400-202119156A-0-0-00.

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