1. Case Studies

To verify the correctness and effectiveness of the proposed coordinated planning method of multiple EHs, case studies are carried out on a realistic test system in Tianjin, China [33]. The horizon of multi-stage planning is divided into 3 stages, each with a 5-year planning horizon. The discount rate is 5%.



Fig. 6. Predicted multi-energy load of each district in typical days for 3rd stage

In the test system, there are three geo-distributed EHs to be planned, which are located in the residential district (denoted by District A), the commercial district (denoted by District B), and the industrial district (denoted by District C), respectively. The geographical distance between the arbitrary two districts above is 3km. The predicted multi-energy load curves of each district for 3rd stage in four typical days are shown in Fig. 6, which indicates the seasonal difference and regional difference in multi-energy consumption. And the predicted multi-energy load of 1st stage and 2nd stage are 80% and 90% of that in 3rd stage, respectively.

Based on the computerized modeling method, the multiple EHs to be planned in different districts can be modeled as the standardized digraph, in which candidate energy conversion and storage devices include GB, EB, AC, EC, CHP, HP, BES, and HES.

TABLE I Parameters of Candidate Energy Devices

|  |  |  |  |
| --- | --- | --- | --- |
|  | Capacity | Efficiency | Investment cost (million yuan) |
| GB | 5 MW | 0.94 | 12.5 |
| EB | 5 MW | 0.96 | 15 |
| AC | 4 MW | 1.2 | 10 |
| EC | 4 MW | 3 | 12 |
| CHP | 5 MW |  | 30 |
| HP | 5 MW |  | 30 |
| BES | 5 MW/10 MWh | 0.9 (ch)/0.9 (dis) | 15 |
| HES | 5 MW/10 MWh | 0.9 (ch)/0.9 (dis) | 7.5 |

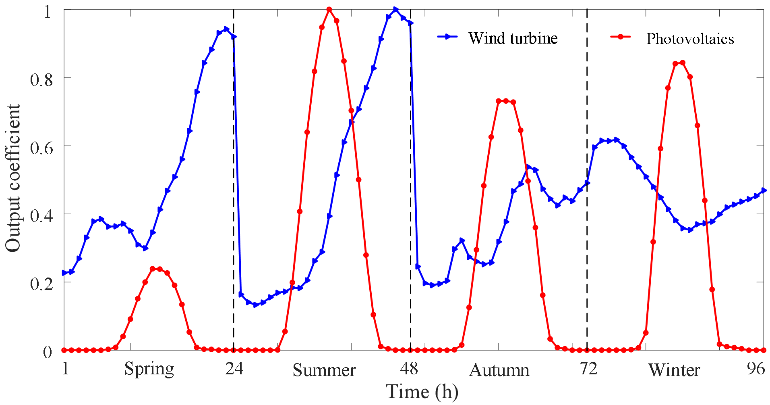


Fig. 7 Output coefficient curves of photovoltaics and wind turbines

The parameters of candidate energy conversion and storage devices are listed in Table I. The efficiencies of other candidate energy devices are set to be constant [5]. The reserve coefficients of energy converters are set to be 0.3. The minimum and maximum SOC values of energy storages are 0.1 and 0.9. In the source side, the capacities of PV and WT are simplified as continuous variables. The output coefficient curves of PV and WT are shown in Fig. 7. Besides, the investment cost of each branch in EH digraphs is assumed to be 0.01 million yuan per year. The investment costs of interconnected lines and pipes are respectively 2 million yuan/km (electricity line), 1.5 million yuan/km (gas pipe), and 1 million yuan/km (heat and cooling pipe). The capacity of each interconnected line or pipe is set to be 5MW.

In each district, a data center with 30000 servers is configured for workload processing. The predicted workload curves of each district for 3rd stage are shown in Fig. 8, and the workload of 1st and 2nd stage are respectively 80% and 90% of that in 3rd stage. Besides, the workload of each stage are composed of 50% delay-sensitive workload and 50% delay-tolerant workload.

For the delay-sensitive workload, the maximum delay is set to be 1s. For the delay-tolerant workload, it must be processed within 24 hours. Benefitted from the DVFS technique [34], the working frequencies of a server include 1/1.5/2.2/2.9/3.4 GHz, and the corresponding service rates are 5/7.5/11/14.5/17 requests/s. The idle electric power of a server is 68W, and the coefficient of dynamic electric power is 5.5. For each data center, the maximum value of the transferred delay-sensitive workload is set to be 0.15×106 requests/s. Each transferred request occupies a bandwidth of 1 Mbps [13]. The maximum value of the stored delay-tolerant workload is set to be 5.4×108 requests. Besides, the PUE values of data centers are assumed as 1.5.



Fig. 8. Predicted workload of each district in typical days for 3rd stage

Other parameters are set as follows. The service life of candidate energy infrastructures is 15 years. Energy prices are the same in each district. Electricity price follows a time-of-use tariff, i.e., 0.34 yuan/kWh (1:00~6:00, 22:00~24:00), 0.62 yuan/kWh (6:00~9:00, 12:00~13:00, 16:00~19:00), and 1.09 yuan/kWh (9:00~12:00, 13:00~16:00, 19:00~22:00). The gas price stabilizes at 2.81 yuan/m³. The gross calorific value of gas is 41.04 MJ/m³ [14]. Besides, the prediction errors of random variables are set to be normally distributed, the mean of which is zero, and the variances are set as follows [35]. i) The variance for both multi-energy load and workload were 2.5% of the predicted value. ii) the variance of PV output is set to be 3.5% of the predicted value. iii) the variance of WT output is set to be 5% of the predicted value. The confidence level is set to be 0.9.

To illustrate how the coordination of multiple EHs and data centers impacts the planning results, five different cases are set in Table II. Case studies are implemented in MATLAB 2022b on a computer with Intel Xeon Processor (2.39 GHz) and 128 GB RAM.

TABLE II Case Comparison

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Case | 1 | 2 | 3 | 4 | 5 | |
| Standardized modeling of multiple EHs | × | √ | √ | √ | √ |
| Spatial transferring of workload | × | × | √ | × | √ |
| Temporal shifting of workload | × | × | × | √ | √ |

* 1. *Planning results analysis*

The coordinated planning results of multiple EHs in different cases are listed in Table III~V.

Table III shows the detailed costs of each case. Compared with case 1, although the operation cost in case 2 is increased, the significant reduction of the investment cost of energy devices in case 2 still contributes to the total cost decrease by 3.89%, which means only optimizing the capacities of multiple EHs with the fixed structure like case 1 cannot obtain the global optimal solution. Based on case 2, case 3 and case 4 respectively consider the spatial transferring of workload and the temporal shifting of workload. Consequently, the total costs of case 3 and case 4 can be further dropped by 2.01% and 2.98%. In case 5, the total cost is finally decreased to 142.06 million yuan, which highlights the effectiveness of the proposed coordinated planning method.

TABLE III Cost Components (Unit: million yuan)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Cost | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
| Investment of energy devices | 72.4 | 56.18 | 55.77 | 53.43 | 55.66 |
| Investment of inside topologies | 0.57 | 0.25 | 0.23 | 0.23 | 0.25 |
| Investment of interconnections | 1.51 | 2.25 | 1.44 | 1.62 | 1.96 |
| Multi-energy purchase | 78.78 | 88.51 | 85.94 | 86.31 | 82.57 |
| Load curtailment | 0.19 | 0.34 | 1.11 | 1.47 | 1.42 |
| Curtailment of renewable energy | 0.16 | 0.1 | 0.18 | 0.17 | 0.2 |
| Total | 153.61 | 147.63 | 144.67 | 143.23 | 142.06 |

TABLE IV Planning Schemes of Energy Devices (Unit: MW)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Case | District | GB | EB | AC | EC | CHP | HP | BES | HES | PV | WT |
| 1 | A | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 1.15 | 5.23 |
| B | 5 | 5 | 8 | 4 | 5 | 5 | 5 | 5 | 0 | 10.40 |
| C | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 11.51 | 20.86 |
| 2 | A | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0.60 | 8.06 |
| B | 0 | 0 | 4 | 4 | 5 | 5 | 0 | 5 | 0 | 13.22 |
| C | 0 | 0 | 8 | 4 | 10 | 5 | 5 | 0 | 10.76 | 16.76 |
| 3 | A | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0.42 | 8.24 |
| B | 0 | 0 | 8 | 4 | 10 | 5 | 0 | 0 | 0.42 | 11.03 |
| C | 0 | 0 | 4 | 4 | 5 | 5 | 5 | 0 | 11.13 | 19.64 |
| 4 | A | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 1.47 | 5.78 |
| B | 0 | 0 | 8 | 4 | 5 | 5 | 0 | 0 | 0.20 | 10.48 |
| C | 0 | 0 | 4 | 4 | 5 | 5 | 5 | 0 | 12.26 | 20.88 |
| 5 | A | 0 | 0 | 4 | 4 | 5 | 0 | 0 | 0 | 0 | 6.13 |
| B | 0 | 0 | 8 | 4 | 5 | 5 | 0 | 0 | 1.80 | 11.93 |
| C | 0 | 0 | 0 | 4 | 5 | 5 | 0 | 0 | 10.33 | 20.92 |

Table IV compares the capacities of energy devices in 3rd stage. Compared with case 1, the configured energy devices of each EH are differentiated in case 2~5. This is because the structures and capacities of EHs are co-optimized according to the local conditions of each district. This also explains why the investment cost of energy devices in case 1 is far more than the investment costs in cases 2~5. In case 3, the spatial transferring of workload is considered, which indirectly makes the spatial distribution of multi-energy load more balanced. Hence, the capacity of AC and CHP in district B increase 4MW and 5MW, respectively. In case 4, benefitted from the temporal shifting of workload, the sequential multi-energy load curves in typical days can be reshaped. Consequently, the capacity of HES and CHP in case 4 decrease by 5MW/10MWh and 5MW, respectively. Case 5 can be viewed as the combination of case 3 and case 4.

Table V- shows the increased capacity of energy devices of case 5 in each planning stage. It can be concluded that the energy devices are invested over the time due to the dynamical consideration of the changes on multi-energy load and workload over the time.

TABLE V Planning Schemes of Energy Device by Planning Stage for Case 1 (Unit: MW)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stage | District | GB | EB | AC | EC | CHP | HP | BES | HES | PV | WT |
| 1 | A | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 1.15 | 5.23 |
| B | 4 | 4 | 8 | 4 | 5 | 5 | 5 | 5 | 0 | 9.73 |
| C | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 11.51 | 20.54 |
| 2 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.67 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.32 |
| 3 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE VI Planning Schemes of Energy Device by Planning Stage for Case 2 (Unit: MW)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stage | District | GB | EB | AC | EC | CHP | HP | BES | HES | PV | WT |
| 1 | A | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0.59 | 8.05 |
| B | 0 | 0 | 4 | 4 | 5 | 5 | 0 | 5 | 0 | 13.22 |
| C | 0 | 0 | 8 | 4 | 5 | 5 | 5 | 0 | 10.76 | 16.74 |
| 2 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 |
| 3 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE VII Planning Schemes of Energy Device by Planning Stage for Case 3 (Unit: MW)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stage | District | GB | EB | AC | EC | CHP | HP | BES | HES | PV | WT |
| 1 | A | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 1.27 | 5.77 |
| B | 0 | 0 | 8 | 4 | 5 | 5 | 0 | 0 | 0.20 | 10.30 |
| C | 0 | 0 | 4 | 4 | 5 | 5 | 0 | 0 | 11.88 | 19.95 |
| 2 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.20 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.18 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0.38 | 0.93 |
| 3 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE VIII Planning Schemes of Energy Device by Planning Stage for Case 4 (Unit: MW)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stage | District | GB | EB | AC | EC | CHP | HP | BES | HES | PV | WT |
| 1 | A | 0 | 0 | 4 | 4 | 5 | 0 | 0 | 0 | 0 | 6.13 |
| B | 0 | 0 | 4 | 4 | 5 | 5 | 0 | 0 | 1.80 | 11.93 |
| C | 0 | 0 | 0 | 4 | 5 | 5 | 0 | 0 | 9.61 | 20.92 |
| 2 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.72 | 0 |
| 3 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE IX Planning Schemes of Energy Device by Planning Stage for Case 5 (Unit: MW)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stage | District | GB | EB | AC | EC | CHP | HP | BES | HES | PV | WT |
| 1 | A | 0 | 0 | 4 | 4 | 5 | 0 | 0 | 0 | 0 | 6.13 |
| B | 0 | 0 | 4 | 4 | 5 | 5 | 0 | 0 | 1.80 | 11.93 |
| C | 0 | 0 | 0 | 4 | 5 | 5 | 0 | 0 | 9.61 | 20.92 |
| 2 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.72 | 0 |
| 3 | A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE IIX Planning Schemes of Interconnected Lines and Pipes in 3rd Stage

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Case | District A - District B | | | | District A - District C | | | | District B - District C | | | | |
| e | g | h | c | e | g | h | c | e | g | h | c |
| 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 |
| 3 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 4 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| 5 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 2 | 1 |

Table IIX presents the planning schemes of interconnected lines and pipes. In case 3, the spatial load regulation of data centers is utilized to coordinate the energy flow and workload flow. Therefore, the quantity of planned interconnected lines and pipes is decreased from 6 (case 2) to 4 (case 3).

The specific planning results of case 5 are visualized in Fig. 9. Figs. 9(a)~(c) show the structures and capacities of EHs in different districts. Fig. 9(d) shows the interconnected relationships of multiple EHs. According to Fig. 9, it can be concluded that the proposed planning method views geo-distributed multiple EHs as a whole system, which can coordinate the differentiated planning and interaction of multiple EHs. Moreover, based on the Internet, the workload transferring can change the spatial distribution of electricity load and cooling load. Therefore, the Internet should be viewed as the virtual interconnected lines among multiple EHs (i.e., the orange dotted lines in Fig. 9(d)).

The cross-district multi-energy flow of case 5 is depicted in Fig. 10, which can be combined with Fig. 9 to illustrate how multiple EHs support each other via interconnected lines and pipes. For example, although the configured AC in Fig. 9(c) cannot satisfy all the cooling load in District C, the cooling load gap in District C can be still filled by the EHs in District A and District B, which is shown in Figs. 10(a)~(b).

It should be noted that the results above are all based on the piecewise linearization with 3 segments. And the computational time of case 5 is about 7.5 hours, which means that although the digraph-based standardized model of EH is highly computerized and can be embedded into coordinated planning mode of multiple EHs conveniently, the burden of seeking solutions is enormous. However, considering the planning horizon for optimal configuration of multiple EHs is typically decades, the hourly computational time is acceptable.



Fig. 9. Detailed planning schemes of multiple EHs in 3rd stage for case 5



Fig. 10. Cross-district multi-energy flow in 3rd stage for case 5

* 1. *Impacts of spatiotemporal load regulation of data centers*

To further illustrate the spatiotemporal load regulation of data centers, the allocation schemes of workload and the electricity consumption of data centers are shown in Figs. 11~13.

Fig. 11 shows the impacts of spatial transferring on the allocation schemes of delay-sensitive workload in the spring typical day of case 3 in 3rd stage. Based on case 2, case 3 further considers the spatial transferring of workload. Consequently, the delay-sensitive workload in each time slot can be dispatched to different districts flexibly (shown as the colored histogram in Fig. 11). However, the total delay-sensitive workload of each time slot remains the same. In Fig. 11, almost all the delay-sensitive workload in District C is transferred to District A and District B, which can effectively ease the local pressure of electricity and cooling supply in District C. After spatial transferring, the reallocated delay-sensitive workload in District B shows a marked increase, especially during the daytime. This phenomenon explains why the capacity of AC and CHP increased in district B of case 3 (shown in Table IV).

Fig. 12 focuses on the delay-tolerant workload in 3rd stage of District B and shows the impacts of temporal shifting on the workload allocation schemes in the spring typical day of case 4. Based on case 2, case 4 further considers the temporal shifting of workload. It means that in a typical day, the delay-tolerant workload can be shifted to different time slots orderly without changing the total delay-tolerant workload. Specifically, in Fig. 12, although the values of the blue line (workload before temporal shifting in case 2) and the red line (workload after temporal shifting in case 4) differ from each other, the areas enclosed by them are equal. The shift-out process of workload commonly occurs in the peak period of electricity tariff (e.g., 13:00~16:00, 19:00~21:00), while the shift-in process often occurs in the valley or normal period. Therefore, the multi-energy purchase cost of electricity purchase can be reduced.



Fig. 11. Allocation scheme comparison of delay-sensitive workload in 3rd stage



Fig. 12. Allocation scheme comparison of delay-tolerant workload in 3rd stage



Fig. 13. Electricity consumption comparison of the data center in District C in 3rd stage

Both the spatial transferring of delay-sensitive workload and the temporal shifting of delay-tolerant workload can change the energy consumption of data centers. Taking the data center in District C as an example, the comparison of its electricity consumption in five cases is shown in Fig. 13.

In case 2, although the flexibility of workload in District C is ignored as in case 1, the structure and schemes of energy devices are different, which means the electricity consumption regulation of data center based on the DVFS technique can be utilized to change the load rate of CHP and HP, and then achieve the overall optimality. In case 3, due to the spatial workload transferring, the workload dispatched to District C during the daytime is decreased remarkably, which leads to the corresponding decrease in electricity consumption. In case 4, the temporal shifting of workload is utilized to change the dispatched workload in each time slot, which can change the peak period of workload. In case 5, the spatiotemporal load regulation of data centers reshapes the spatiotemporal distribution of the electricity load and cooling load in District C, which indicates the coordination mechanism of energy flow and workload flow.

* 1. *Impacts of the renewable energy curtailment risk*

Since the uncertainties of the system will increase the curtailment of renewable energy, the CVaR theory is utilized to limit the “tail risk” of renewable energy curtailment. Besides, a higher confidence level implies a lower tolerance for the “tail risk” of uncertainties in the operation of the system.

Fig. 14 shows the total cost and the capacity of renewable energy under different confidence levels for case 5. It can be concluded that with the increasing of the confidence level, the capacity of the renewable energy will decrease to limit the “tail risk” of the renewable energy curtailment, which further impacts the planning schemes of multiple EHs and contributes to the increase of total cost.



Fig. 14 The total cost and the capacity of renewable energy for case 5under different confidence levels

To enable the public to access the study fully, more details about the case studies can be found in [33].