CASE STUDIES

A. Case Description

Case studies are carried out on a realistic test system in Tianjin, China, which can be described as Fig. 1. 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. Besides, there is a data center integrated in each EH to process the enormous workload of EH.

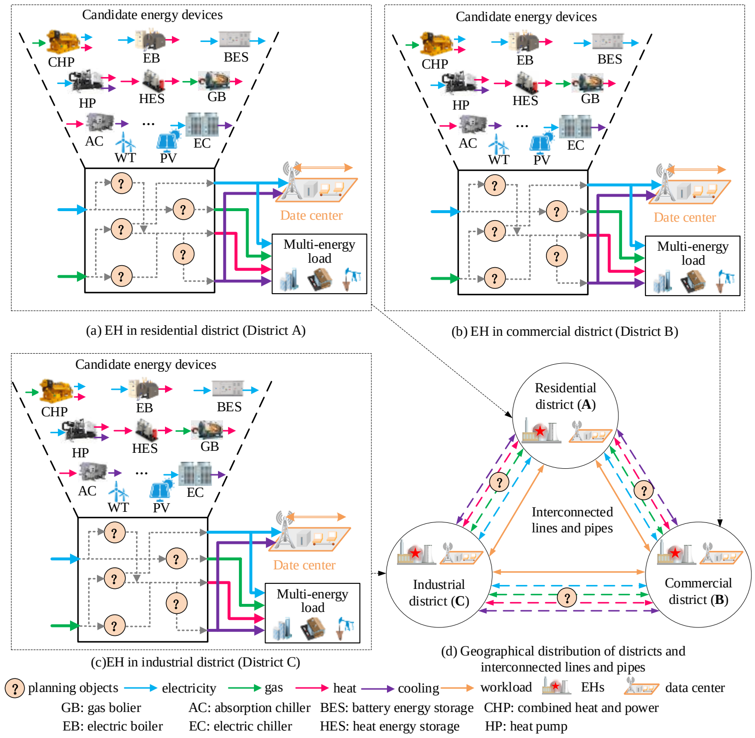

Fig. 1. Test system of multiple EHs integrated with data centers

B. Parameters

The horizon of multi-stage planning is divided into 3 stages, each with a 5-year planning horizon. The discount rate is 5%.

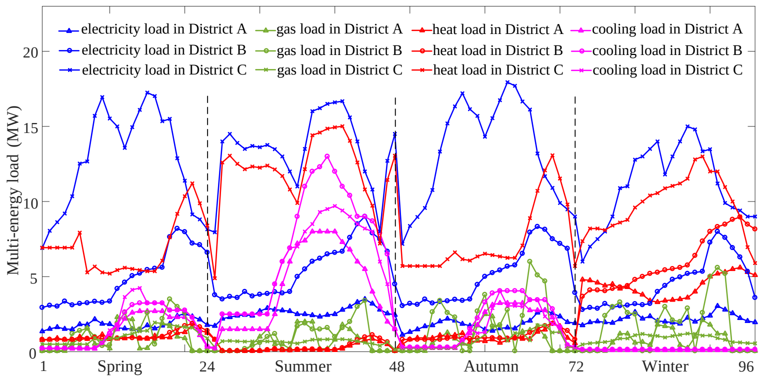

Fig. 2. Predicted multi-energy load of each district in typical days for 3rd stage

The predicted multi-energy load curves of each district for 3rd stage in four typical days are shown in Fig. 2, the detailed data of which can be found in the sheet A of the excel file named "Data_of_case_study.xlsx". And the predicted multi-energy load of 1st stage and 2nd stage are set as 80% and 90% of that in 3rd stage, respectively.

The candidate energy conversion and storage devices include GB, EB, AC, EC, CHP, HP, BES, and HES. 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 [1]. 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. 3, and the detailed data can be found in the sheet B of the excel file named "Data_of_case_study.xlsx". 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.

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	$f(\bar{N}_{CHP,t})$	30
HP	5 MW	$f(\bar{N}_{HP,t})$	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

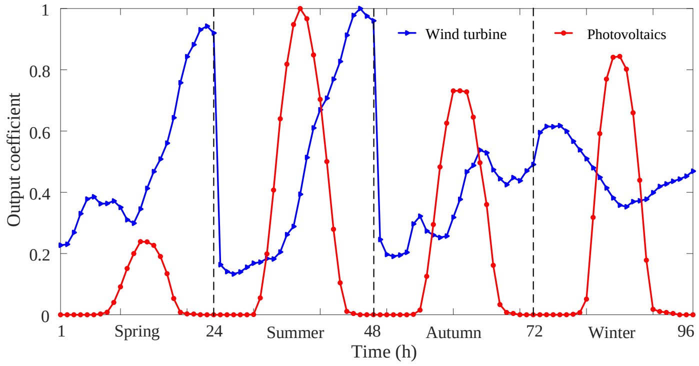

Fig. 3. Output coefficient curves of photovoltaics and wind turbines

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. 4, the detailed data of which can be found in the sheet C of the excel file named "Data_of_case_study.xlsx", and the workload of 1st and 2nd stage are set as 80% and 90% of that in 3rd stage, respectively. 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 [2], 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 0.15×10^6 requests/s. Each transferred request occupies a bandwidth of 1 Mbps [3]. The maximum value of the stored delay-tolerant workload is set to be 5.4×10^8 requests. Besides, the PUE values of data centers are assumed as 1.5.

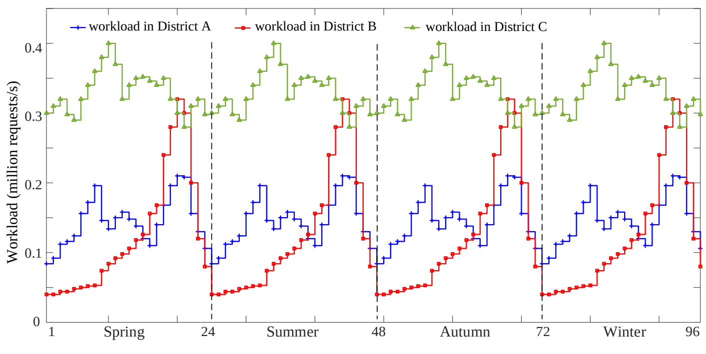

Fig. 4. Predicted workload of each district in typical days for 3rd stage

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 [4]. 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 [5]. 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 SETTING

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

C. *Planning results*

The coordinated planning results of multiple EHs in different cases are listed in Table III~XV. Table III shows the detailed costs of each case.

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	87.51	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	146.63	144.67	143.23	142.06

Table IV compares the capacities of energy devices of each case in 3rd stage.

TABLE IV PLANNING SCHEMES OF ENERGY DEVICES IN 3RD STAGE OF EACH CASE (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 V presents the planning schemes of interconnected lines and pipes in 3rd stage of each case.

TABLE V PLANNING SCHEMES OF INTERCONNECTED LINES AND PIPES IN 3RD STAGE OF EACH CASE

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 VI-X show the increased capacity of energy devices of each case in each stage.

TABLE VI INCREASED CAPACITY OF ENERGY DEVICE IN EACH STAGE OF 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 VII INCREASED CAPACITY OF ENERGY DEVICE IN EACH STAGE OF 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	0.02
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 INCREASED CAPACITY OF ENERGY DEVICE IN EACH STAGE OF 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	0.40	8.24
	B	0	0	8	4	5	5	0	0	0	11.03
	C	0	0	4	4	5	5	5	0	10.70	19.19
2	A	0	0	0	0	0	0	0	0	0.16	0
	B	0	0	0	0	0	0	0	0	0.42	0
	C	0	0	0	0	0	0	0	0	0.42	0.45
3	A	0	0	0	0	0	0	0	0	0	0
	B	0	0	0	0	5	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0	0

TABLE IX INCREASED CAPACITY OF ENERGY DEVICE IN EACH STAGE OF CASE 4 (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 X INCREASED CAPACITY OF ENERGY DEVICE IN EACH STAGE OF 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 XI~XV show the increased numbers of interconnected lines and pipes in each stage of each case.

TABLE XI INCREASED NUMBERS OF INTERCONNECTED LINES AND PIPES IN EACH STAGE OF CASE 1

Stage	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	0	0	1	0	1	0	0	1
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	0	0	0	0	0	0	0

TABLE XII INCREASED NUMBERS OF INTERCONNECTED LINES AND PIPES IN EACH STAGE OF CASE 2

Stage	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	1	0	0	0	0	0	1	1	1	0	1	0
2	0	0	0	0	0	0	0	0	0	0	0	1
3	0	0	0	0	0	0	0	0	0	0	0	0

TABLE XIII INCREASED NUMBERS OF INTERCONNECTED LINES AND PIPES IN EACH STAGE OF CASE 3

Stage	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	1	1	0	0	0	0	1	0	1	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0

TABLE XIV INCREASED NUMBERS OF INTERCONNECTED LINES AND PIPES IN EACH STAGE OF CASE 4

Stage	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	1	1	0	0	0	0	1	0	1	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0

TABLE XV INCREASED NUMBERS OF INTERCONNECTED LINES AND PIPES IN EACH STAGE OF CASE 5

Stage	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	1	0	0	1	1
2	0	0	0	0	0	0	0	0	0	0	1	0
3	0	0	0	0	0	0	0	0	0	0	0	0

The specific planning results of case 5 in each stage are visualized in Fig. 5-Fig. 7.

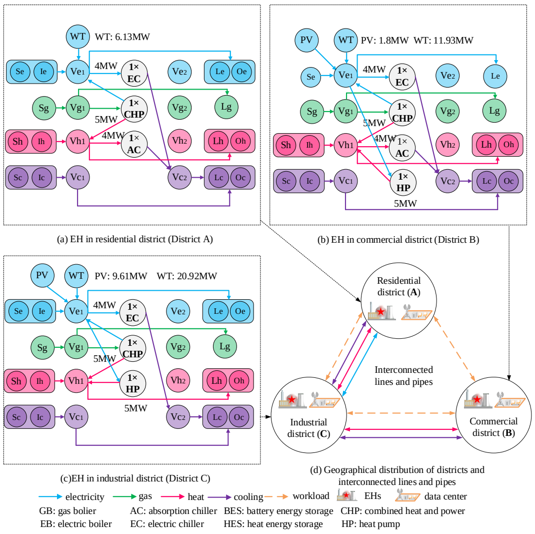

Fig. 5. Detailed planning schemes of multiple EHs in 1st stage of case 5

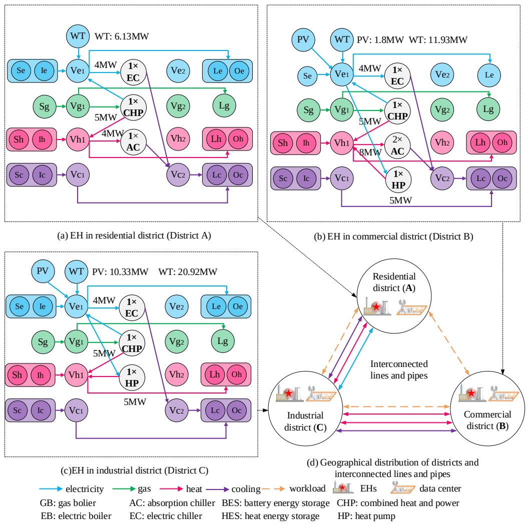

Fig. 6. Detailed planning schemes of multiple EHs in 2nd stage of case 5

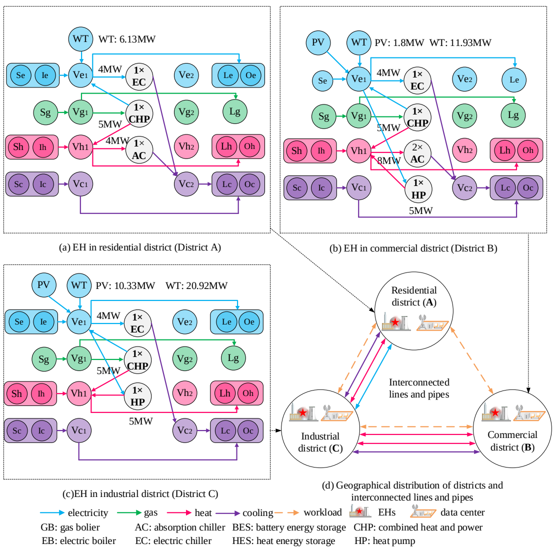

Fig. 7. Detailed planning schemes of multiple EHs in 3rd stage of case 5

The cross-district multi-energy flow in each stage of case 5 are depicted in Fig. 8~Fig. 10, and the detailed data of Fig. 8~Fig. 10 can be found in the sheet D~F of the excel file named "Data_of_case_study.xlsx", respectively.

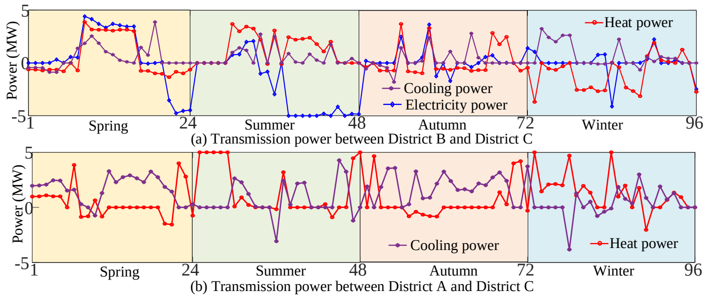

Fig. 8. Cross-district multi-energy flow in 1st stage of case 5

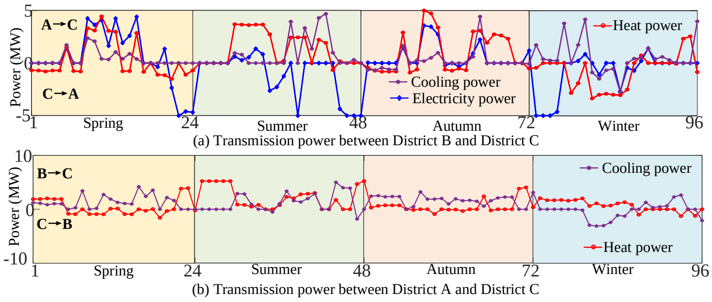

Fig. 9. Cross-district multi-energy flow in 2nd stage of case 5

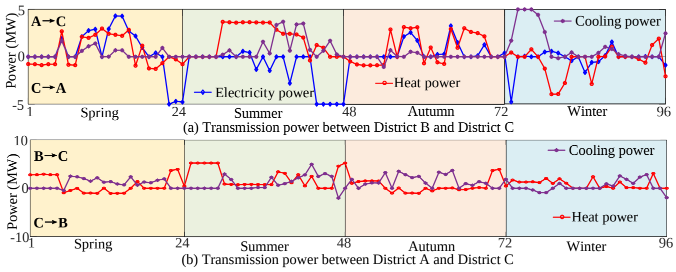

Fig. 10. Cross-district multi-energy flow in 3rd stage of case 5

Fig. 11~13 show the impacts of spatial transferring on the allocation schemes of delay-sensitive workload in the spring typical day of case 3 in each stage, the detailed data of which can be found in the sheet G~I of the excel file named “Data_of_case_study.xlsx”.

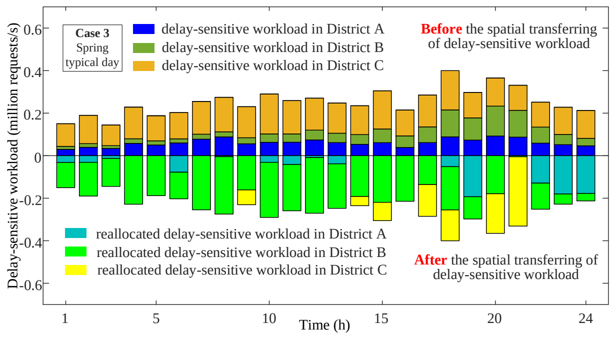

Fig. 11. Allocation scheme comparison of delay-sensitive workload in 1st stage of case 3

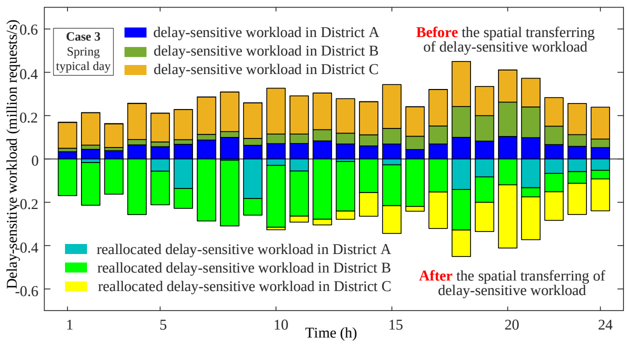

Fig. 12. Allocation scheme comparison of delay-sensitive workload in 2nd stage of case 3

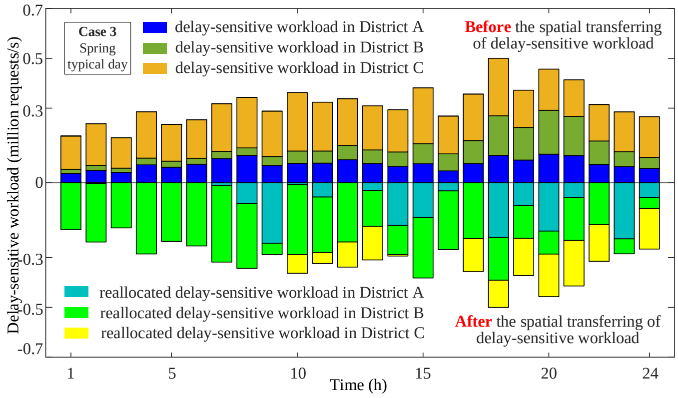

Fig. 13. Allocation scheme comparison of delay-sensitive workload in 3rd stage of case 3

Fig. 14~16 show the impacts of temporal shifting on the workload allocation schemes of district B in the spring typical day of case 4 in each stage, the detailed data of which can be found in the sheet J~L of the excel file named “Data_of_case_study.xlsx”.

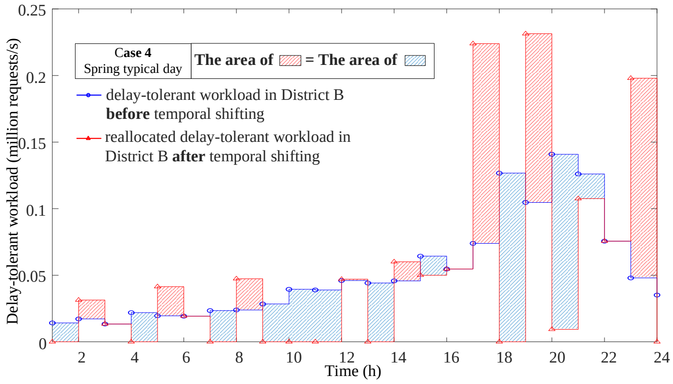

Fig. 14. Allocation scheme comparison of delay-tolerant workload in 1st stage of case 4

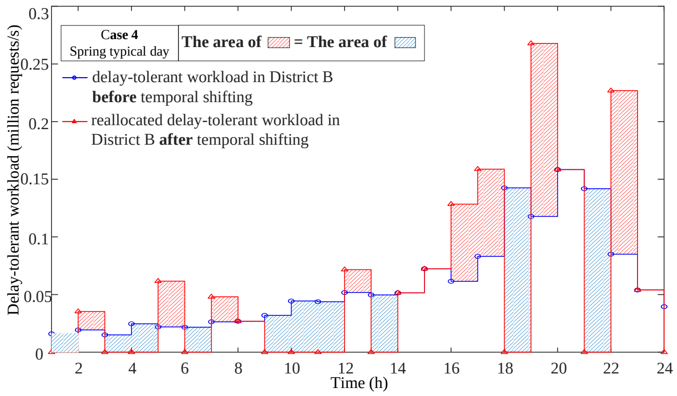

Fig. 15. Allocation scheme comparison of delay-tolerant workload in 2nd stage of case 4

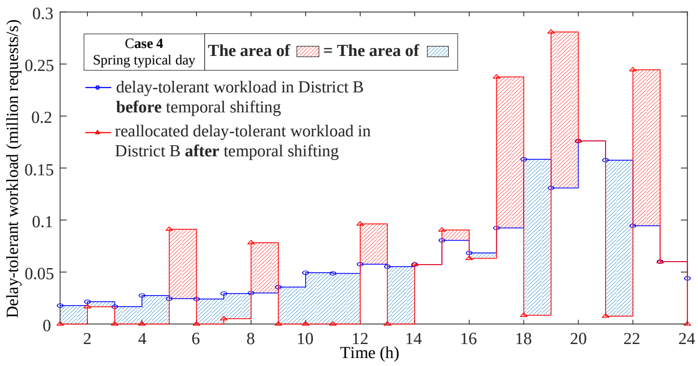

Fig. 16. Allocation scheme comparison of delay-tolerant workload in 3rd stage of case 4

Fig. 17~19 show the comparison of electricity consumption for the five cases in each stage of District C, and the detailed data can be found in the sheet M~O of the excel file named "Data_of_case_study.xlsx".

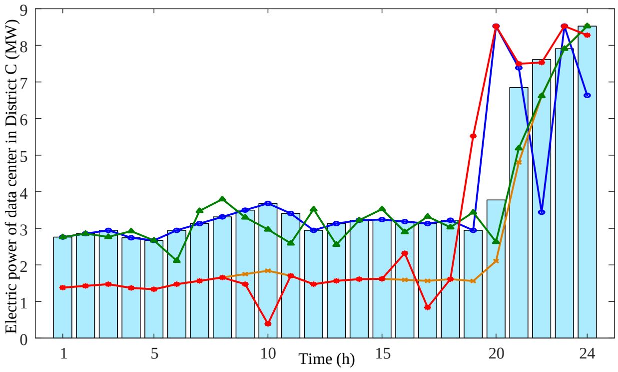

Fig. 17. Electricity consumption comparison of the data center in 1st stage for District C

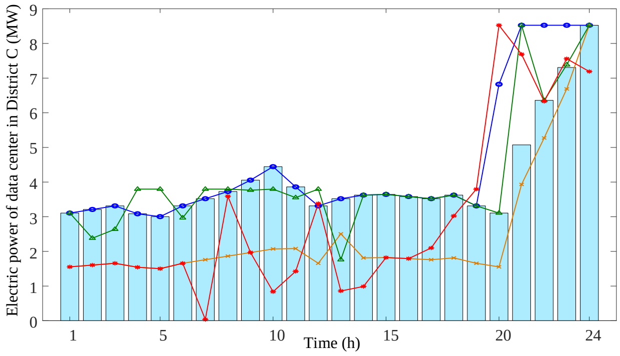

Fig. 18. Electricity consumption comparison of the data center in 2nd stage for District C

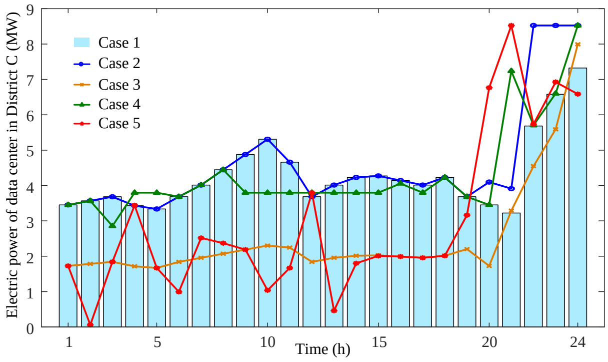

Fig. 19. Electricity consumption comparison of the data center in 3rd stage for District C

Fig. 20 shows the total cost and the capacity of renewable energy under different confidence levels for case 5, the detailed data of which can be found in the sheet P of the excel file named "Data_of_case_study.xlsx".

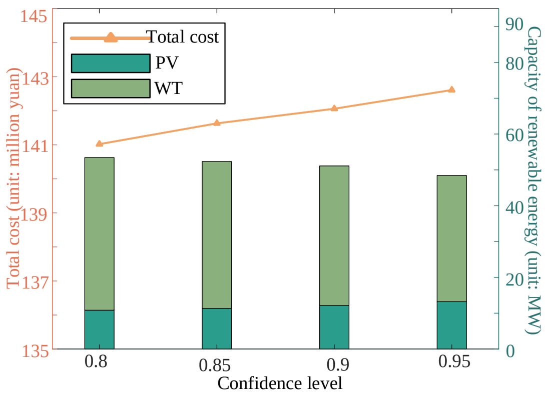

Fig. 20. The total cost and the capacity of renewable energy for case 5 under different confidence levels

It should be noted that the results above are all based on the piecewise linearization with 3 segments.

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