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A Low carbon Building-level Integrated Energy System Planning Method Considering Fuel Cell and Multiple Energy Storage

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ABSTRACT

To ameliorate the climate change which caused by environmental problems and achieve the carbon neutrality proposed by Chinese government in 2020, renewable energy like photovoltaic and wind power play an increasingly important role in energy consumption. To address the random fluctuation and insufficient consumption brought by renewable energy, integrated energy system (IES) is one of the solutions to cope with these problems. This study focuses on the planning problem of IES and proposes a planning model, which takes both minimum total costs and CO2 emission as the objectives. To further reduce the carbon emission, fuel cells (FC) which uses hydrogen as fuel to provide both electricity and heat, as well as multi-energy storage systems (ESS) are considered as options in IES planning. A real multi-energy office building in Shanghai, in which photovoltaic, multi-energy storage equipment, fuel cell, electric vehicle (EV) and other equipment are included as planning options, is used as numerical example to verify the effectiveness of proposed planning method for building-level IES. Moreover, the operation scenarios and functions of ESS in IES are analyzed.

Keywords: Building-level integrated energy system, low carbon, fuel cell, energy storage system, optimal planning.

NONMENCLATURE

Abbreviations	
IES	Integrated Energy System
FC	Fuel Cell
ESS	Energy Storage System
EV	Electric Vehicle
EH	Energy Hub
SOFC	Solid Oxide Fuel Cell
PEM	Polymer Electrolyte Membrane
Symbols	
P	Output of equipment
X	investment decision variables
$\mathcal{C}$	Coupling matrix of Energy Hub model
IC	Investment cost of equipment
SUB	Substation outside the building
m	Coefficient to convert costs
k_s	Number of days in a year of typical day s
r	Cost of purchased electricity/gas
C^{tax}	Tax for carbon emission
ε	Emission coefficient of fuel
η	Charge/Discharge efficiency of ESS
S	Charge/Discharge power of ESS
Ω	Set of fuel cell to be selected
SE	The amount of energy stored in ESS
$P_{charger}^{EV}$	Power of EV charger
Ψ	Set of commuting and parking time of EVs
α	Charge/Discharge efficiency of ESS
β	Energy loss coefficient of EVs
e, h, g, l	Electricity, heat, gas, light

1. INTRODUCTION

Climate change caused by environmental problems is a major issue of common concern to all mankind. More than 70 countries have committed to working toward net-zero emissions by 2050 and to enhance their international climate pledges under the Paris Agreement to ensure that global warming is controlled below 2 degrees Celsius. Among them, China proposes to reach the peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. In this context, renewable energy such as photovoltaic and wind energy

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has developed rapidly. Besides, the rapid development of related technologies such as power-to-gas (P2G) and fuel cell (FC) has greatly increased the demand for hydrogen, which will further accelerate the process of achieving zero carbon emission. However, there are also many serious problems that renewable energy brings to the energy system. To further improve the consumption capacity of renewable energy and make better use of the strong coupling and synergy between different energy systems, the concept of Energy Internet has become another important topic in the energy industry after the Smart Grid[1]. As the physical carrier of Energy Internet, Integrated Energy System (IES) breaks the boundary between different energy systems and promotes energy efficiency to the greatest extent. In this study, we take building-level IES as our research object.

For IES, one of the most important equipment is multi-energy conversion equipment, in which different forms of energy are transformed and coupled with each other. This paper mainly considers the FC which can convert gas into electricity and heat at the same time. FC power systems offer a unique combination of high efficiency, wide size range, modularity, and compatibility with cogeneration[2]. Although system cost and durability remain as the major challenge for FC, related technologies develop fast thus FCs are wildly considered in IES planning problems. A IES including solid oxide fuel cell (SOFC) and wind-powered P2G is studied in [3], a two-level multi-objective optimization method involving multiple time scales is carried out to get an optimal operation scheme with low wind curtailment and total life cost of the system. Reference [4] focus on a residential FC system and proposes a novel operational planning method based on a surrogate model to get the minimum operational cost. Such studies have verified the effectiveness of FC as energy conversion equipment in IES, and optimize the operation of the system to get the minimum cost or emission.

In addition, in order to further strengthen the capacity of new energy consumption and solve the problem of time mismatch between new energy output and load demand, energy storage technology has developed rapidly. In IES, energy storage equipment can balance the difference of response time of different energy systems. Energy storage equipment is widely considered in the studies of IES nowadays. In [5] and [6], multiple energy storage system (ESS) is implied to improve the economy of IES operation.

This paper focus on the planning of building-level IES from the perspective of economy and environment. Different from the multi-objective optimization method used in most existing studies, we convert carbon emissions into carbon tax and add it into the total cost to consider, so as to unify the unit differences between costs and carbon emissions. In this way we solve the problem that it is difficult to choose weights for different objective functions in multi-objective problem and obtain an exact optimization scheme. The proposed model is used to get the optimal size of ESS and multi-energy equipment such as FC, the optimal operation scheme is also given based on the load of typical days.

2. MODEL FORUMULATION

IES is usually divided into single-area system and multi-area system according to the scale and geographical factors. Building-level IES is a typical single-area IES and it is not necessary to consider the energy transmission and the network topology which make its mathematical model relatively simple. This sector first introduces the Energy Hub model for IES modeling, then proposes the planning model of building-level IES which considers fuel cell, energy storage system, electric vehicle, photovoltaic and so on.

2.1 Modified Energy Hub Model

The Energy Hub (EH) model is a two-port model used to describe the relationship between energy input and output of IES. Since it was proposed in 2007 by the ETH Zurich in the project "vision of future energy network" [7], it has been widely used in the modeling of IES and its effectiveness has been verified. The typical structure of EH model is shown in Fig 1. One of the biggest advantages of EH model is its simplicity: different forms of energy are put into the energy hub and then convert into different forms of energy output to the load side.

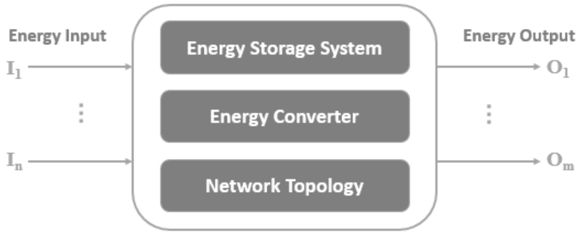


Fig 1 A schematic of the Energy Hub.

As its name suggests, the EH model is a hub for different kinds of energy. Basically, it consists of energy converter which is used to transform energy into different forms and network topology of different energy systems which are used to transport different forms of energy. The mathematical model can be shown as[8]:

$$O = \mathcal{C} I \qquad (1)$$

We use O (m×1 vector) and I (n×1 vector) to represent the input energy and output energy of IES respectively, $\mathcal{C}$ (m×n matrix) is the coupling matrix which reflects the coupling relationship, such as the efficiency of energy conversion equipment and the specific parameters of energy transmission network between input and output. With this coupling matrix, we can only focus on the input and output energy of IES. Another advantage of the EH model is that it can be adjusted easily according to specific requirement. When the ESS is considered in IES, the mathematical model can be modified as follow[8]:

$$O = \mathcal{C}I - S \tag{2}$$

S represents the total output (charge/discharge power) of ESS at every time slot, when EV and some other elements is integrated in the EH, we can modify the model accordingly. In this study, modified energy hub is used to model the building-level IES with ESS.

2.2 Proposed Model of Building-level IES Planning

Based on the EH model, a planning model for building-level IES considering ESS, FC and EV is proposed.

2.2.1 Objective function

For most IES planning problem, the main goal is to minimize the total cost or maximize the total income of IES. As mentioned above, this study also takes reducing carbon emission as the other goal to achieve carbon neutrality. To combine these two goals into a single objective function, carbon emission is converted into carbon tax and counted as part of total cost. The objective function of the planning model can be shown as follows:

$$\min(f^{inv}(X) + f^{ope}(P,S) + f^{carbon}(P)) \tag{3}$$

where

$$f^{inv} = X^{ESS} \cdot IC^{ESS} + \sum_{i\in\Omega} X_i^{FC} \cdot IC_i^{FC} \tag{4}$$

$$f^{ope} = m\sum_{s=1}^{Scenes} k_s \sum_{t=1}^{24}[\sum_{i\in\Omega} P_{s,t,i}^{FC} \cdot r_i^g + (P_{s,t}^{SUB} + \sum_{j=1}^{NEV} S_{s,t,j}^{EV,in} + S_{s,t}^{BESS,in}) \cdot r_{s,t}^e] \tag{5}$$

$$f^{carbon} = m \cdot C^{tax} \sum_{s=1}^{Scenes} k_s \sum_{t=1}^{24} \varepsilon (P_{SOFC,s,t}^{FC} + P_{NG\_PEM,s,t}^{FC}) \tag{6}$$

$$\Omega = \{SOFC,\ NG\_PEM,\ HG\_PEM\}$$

The objective function is to minimize the total cost which consists of investment cost, operational cost and carbon tax which are respectively represented by f^{inv}, f^{ope} and f^{carbon}. Formula (4) shows that the investment cost includes the investment of ESS and all kinds of FCs, it is related to the investment decision variables X which represents the capacity of ESS or the number of FCs that will be invested. In this model, three kinds of FCs are taken as options. The first is polymer electrolyte membrane fuel cell (PEM) consuming hydrogen, which is denoted by HG_PEM. The other two are SOFC and PEM which are reformed to consume relatively cheaper fuel, natural gas. The second type PEM is denoted as NG_PEM. Operational cost includes the electricity and gas that bought from outside. It is related to the operational decision variables P and S which represent output of different equipment and the charge or discharge power of ESS respectively. $Scenes$ and NEV denote the number of typical days and EVs respectively. Cost of carbon emission can be indicated by formula (6), it is related to FCs that consume natural gas.

2.2.2 Constraints

1) Energy balance

The supply-demand balance constraint can be obtained from formula (2):

$$L \le \mathcal{C}P - S^{ESS} - S^{EV} \tag{7}$$

$$\begin{aligned} L_{s,t}^e = {} & \mathcal{C}_{l-e}^{SOLAR} P_{s,t}^{SOLAR} + \sum_{i\in\Omega} \mathcal{C}_{g-e,i}^{FC} P_{i,s,t}^{FC} + \mathcal{C}_{e-e}^{SUB} P_{s,t}^{SUB} + \\ & \eta_{in}^{BESS} S_{s,t,in}^{BESS} - S_{s,t,out}^{BESS} / \eta_{out}^{BESS} + \eta_{in}^{EV} S_{s,t,in}^{EV} - S_{s,t,out}^{EV} / \eta_{out}^{EV} \end{aligned} \tag{8}$$

$$L_{s,t}^h \le \sum_{i\in\Omega} \mathcal{C}_{g-h,i}^{FC} P_{i,s,t}^{FC} + \eta_{in}^{TESS} S_{s,t,in}^{TESS} - S_{s,t,out}^{TESS} / \eta_{out}^{TESS} \tag{9}$$

L, P, S^{ESS} and S^{EV} represent the load of IES, output of different equipment, energy output of ESS and EV. For electricity, the supply must be equal to the demand (without considering power losses), but for heat system, the supply can be equal or larger than the demand as formula (8)—(9) indicate. BESS and TESS represent battery and thermal ESS respectively. η is the efficient of charge or discharge of ESS.

2) Output limits of FC and substations

The second group of constraints are the output limitation of different equipment. Constraints (10)—(11) show the power limits for FCs and substation, related to the investment decision on FCs, namely X_i^{FC} :

$$0 \le P_{i,s,t}^{FC} \le X_i^{FC} \cdot P_{i,\max}^{FC},\ i \in \Omega \tag{10}$$

$$0 \le P_{s,t}^{SUB} \le P_{\max}^{SUB} \tag{11}$$

3) ESS-related constraints

The next important set of constraints is for BESS:

$$SOC_{lower}^{BESS} * SE_{\max}^{BESS} \le SE_{s,t}^{BESS} \le SOC_{upper}^{BESS} * SE_{\max}^{BESS} \tag{12}$$

$$SE_{s,t}^{BESS} = SE_{s,t-1}^{BESS} + S_{s,t,in}^{BESS} - S_{s,t,out}^{BESS} \tag{13}$$

$$S_{s,t,in/out}^{BESS} \le \alpha^{BESS} S_{\max}^{BESS} \tag{14}$$

$$SE_{s,1}^{BESS} = SE_{s,24}^{BESS} \tag{15}$$

$$S_{s,t,in}^{BESS} \cdot S_{s,t,iout}^{BESS} = 0 \tag{16}$$

SE is the amount of energy stored in the ESS. Formula (12) is a constraint for state of charge (SOC), for battery ESS (BESS), the lower and upper limits are usually set as 0.1 and 0.9 to maximize the life of ESS. Formula

(13) reflects the energy change of ESS, since the energy loss have been considered in the EH model, it is not necessary to consider it here. α is the coefficient used to limit the charge and discharge power, usually taken as 0.25. Formula (15) shows that the energy stored in the ESS has to be equal at the beginning and end of each typical day. Constraint (16) means that the BESS cannot charge and discharge at the same time. The constraints for thermal ESS (TESS) are similar.

It should be noticed that formula (16) is nonlinear which will complicate the model and thus more difficult to solve. It can be recast by the Big M Method as follows:

$$S_{s,t,in}^{BESS/TESS} \le M \cdot X_{s,t}^{BESS/TESS} \tag{17}$$

$$S_{s,t,out}^{BESS/TESS} \le M \cdot (1 - X_{s,t}^{BESS/TESS}) \tag{18}$$

Where M is a big constant, $X_{s,t}^{BESS/TESS}$ is a binary variable which reflects the state of ESS, when ESS is in the charging mode, $X_{s,t}^{BESS/TESS}=1$, otherwise (when it is discharging), $X_{s,t}^{BESS/TESS}=0$.

4) EV-related constraints

$$SOC_{lower}^{EV} * SE_{\max}^{EV} \le SE_{s,t}^{EV} \le SOC_{upper}^{EV} * S_{\max}^{EV} \tag{19}$$

$$SE_{s,t}^{EV} = SE_{s,t-1}^{EV} + S_{s,t,in}^{EV} - S_{s,t,out}^{EV},\ t \in \Psi_{parking} \tag{20}$$

$$SE_{s,t}^{EV} = (1-\beta) SE_{s,t-1}^{EV},\ t \in \Psi_{commuting} \tag{21}$$

$$S_{s,t,in}^{EV} \le P_{charger}^{EV} \tag{22}$$

$$S_{s,t,out}^{EV} \le \alpha^{EV} S_{\max}^{EV} \tag{23}$$

$$SE_{s,1}^{EV} = SE_{s,24}^{EV} \tag{24}$$

EVs are essentially BESS, its operation states are divided in two parts, commuting state and parking state. When used for commuting, EV cannot be charged or discharged. β is used to describe the energy loss per hour in commuting state, it is related to the speed of EV, road condition and other factors. β is regarded as a constant in this model for convenience and taken as 0.15. When EVs are parked in the building, they are regarded as BESS and limited by constraints (19)—(24). So far, the planning model for building-level IES is completed, this is a MILP model and can be solved directly by CPLEX solver.

3. CASE STUDY

To verify the effectiveness of the proposed planning model, a real building in Shanghai is taken as numerical case. For this building, energy inputs include gas, electricity and solar energy, the outputs include electricity, heating and cooling energy. The equipment to be invested include ESS and FCs, in order to better highlight the impact of carbon emissions in the planning, three kinds of FCs that consume different fuels are taken as options which has been mentioned before. As for existing equipment, such as solar panels and electric vehicles, we mainly focus on their operation optimization without considering their investment. All parameters of these equipment are shown in Table 1 and Table 2. In this sector, some data processing methods and planning results will be shown first. Then we will make a specific analysis of the application scenarios and significant roles of the ESS based on this real planning case.

Table 1 Related parameters of FCs

FCs	IC/10⁴RMB	C_{g-e}	C_{g-h}	$P_{e,\max}^{FC}$	$P_{h,\max}^{FC}$
SOFC	80	0.63	0.28	4.5KW	2KW
NG_PEM	30	0.34	0.5	4.2KW	6.2KW
HG_PEM	295	-	-	60KW	60KW

Table 2 Related parameters of other equipment

	IC/10⁴RMB	$S_{in,\max}$	$S_{out,\max}$	$SE_{\max}$
BESS	0.15/KWh	0.25 $SE_{\max}$	0.25 $SE_{\max}$	-
TESS	-	0.5 $SE_{\max}$	0.5 $SE_{\max}$	100KWh
EV	-	7KW	0.25 $SE_{\max}$	54KWh*10

3.1 Data Processing Methods and Planning Results

The data need to be processed include the load profiles and the output of solar panels. For multi-energy loads, although there are three types of load demand, i.e. cooling/heating/electricity, only electricity and heating load need to be considered since the cooling load is all supplied by air conditioner. The data we have is the annual cooling/heating/electricity load of another similar building-level IES. Combined with the maximum heating and electricity load of the building to be planned, which are 4000kW and 160kW respectively, the load of the building can be obtained. However, it could greatly add to the computation difficulty if 8760-hour load is all included in IES planning, thus K-means clustering is used to cluster the annual load into 4 typical days.

For solar power, there are 1000KW solar panels installed in the building. We have the light intensity of 8760h in Shanghai and the power generation of 100kW solar panels in a year as reference. K-means clustering method can be also used to get the output of solar power in 4 typical days (96h). The three curves obtained by K-means clustering method are shown in Fig 2.

To deal with the high price of hydrogen, HG_PEM contains its own P2G unit and uses valley time electricity price for hydrogen production. As for energy price, the time-of-use electricity price of Shanghai is adopted. The price of natural gas is 2.57 RMB / m^3. At present, the carbon emission tax in Shanghai is about 40 RMB / ton of carbon dioxide. According to the Paris Agreement, the carbon tax should reach US \$40—80 by 2020 and US

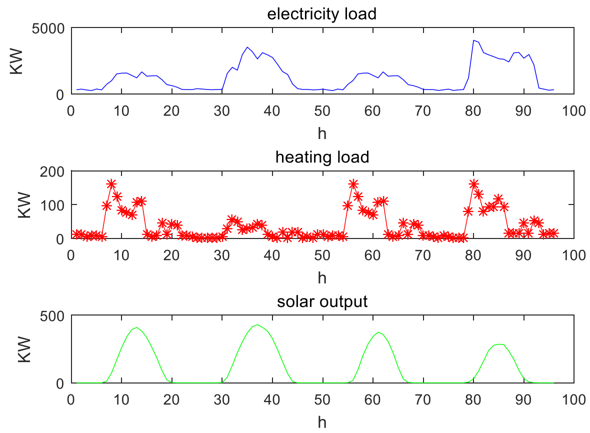


Fig 2 Load and solar output curve of 4 typical days.

$50—100 by 2030. Although the carbon tax is far from meeting the expectations, we set the carbon tax at different gradients to observe the changes in the planning results. Based on 4 typical days, the planning results can be obtained as Table 3 and Table 4 show.

It can be seen that although the comprehensive efficiency of SOFC is relatively high, it will not be installed in any case because of its high investment cost and relatively low efficiency of gas to heat. What is greatly affected by the carbon tax is the choice of PEM that using different fuels. Due to the high investment of PEM that using hydrogen, when carbon tax is relatively low, it prefers PEM using natural gas. When the carbon tax increases gradually, PEM fueled by hydrogen gradually replaces that fueled by natural gas. From Table 4 we can know that the increase of carbon tax leads to more gas purchase costs, which is used to support the operation of PEM fueled by hydrogen and reduce carbon emissions. Although the price of 1200RMB/ton is rather high and cannot be reached in a short time, with the increasingly strict requirements for environmental protection and the development of carbon trading mechanism, this price will be reasonable in the future.

3.2 Analysis on ESS

This section takes the planning results obtained under the condition that carbon tax in 200 RMB/ton as an example to analyze the important role of ESS. In this planning scheme, the operation of each equipment in 4 typical days is shown in Fig 3. It can be seen that the electric load is supplied by output of multiple equipment including substation, photovoltaic, BESS and EVs. The BESS reshape the load curve of electricity to pursue a maximum profit. As for heating load, it is supplied by two different kinds of PEM and TESS. Sometimes the output of the PEM exceeds the heating load, TESS stores this part of heat and releases it in other periods, also in order to obtain the maximum benefit.

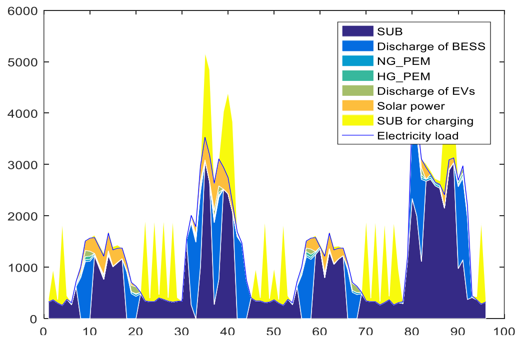
Table 3 Planning scheme under different carbon tax

Carbon tax	BESS	SOFC	NG_PEM	HG_PEM
40RMB/ton	6200KWh	0	19 sets	0
200RMB/ton	6400KWh	0	9 sets	1 set
400RMB/ton	6300KWh	0	9 sets	1 set
1200RMB/ton	6400KWh	0	0	2 sets

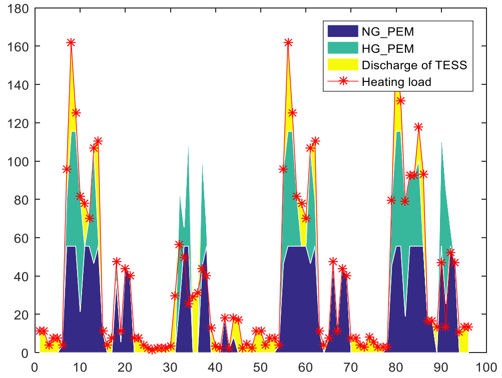
Table 4 Cost under different carbon tax/10^4RMB

Carbon tax (RMB/ton)		40	200	400	1200
Investment Cost		1503	1487	1508	1561
Operational Cost	Gas	159	198	215	266
	Electricity	4715	4698	4675	4601
	Carbon tax	5	16	12	0
Total Cost		6382	6399	6410	6427

Fig 4 includes the charging power of BESS and TESS in different periods and the electricity price, in which the function of ESS is better illustrated. It can be seen that the time-of-use electricity price in a day is divided into three stages: peak, shoulder and valley price based on time of the day. For BESS, purchasing electricity at valley hours and using stored electricity to meet the load at peak hours will gain great benefits, namely, energy arbitrary. Although there is also potential profit from purchasing electricity at shoulder hours for load in peak hours, the price gap is not big enough yet but the service life of BESS is limited, thus less charging happened at



(a) Electricity output and load



(b) Heating output and load

Fig 3 Operation of equipment in four typical days.

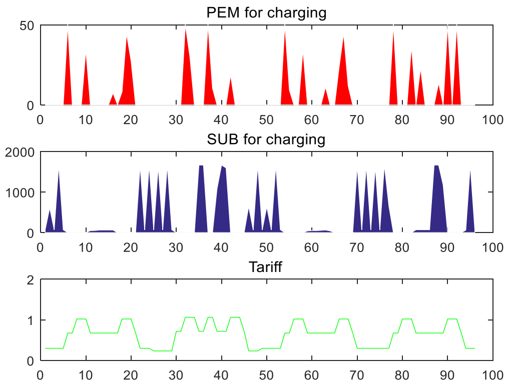


Fig 4 Charging power of BESS/TESS and tariff

shoulder hours. As for TESS, its charging period is opposite to that of BESS. During peak hours, due to the high electricity price, PEM is likely to produce electricity and heat, i.e. operated in cogeneration state, which is energy-efficient, the excess heat will be stored by TESS.

In addition, BESS can smooth the solar energy output. When the demand is small or the electricity price is low, BESS will store the excess electricity and release it when the demand is high or the electricity price is high. For TESS, when its capacity is adjusted, the construction and operation of PEM will change significantly. TESS can optimize the operation of PEM and improve its service life, so as to maximize the profits of whole IES.

4. CONCLUSION

Under the background of the improvement of global environmental protection awareness, this paper focus on the planning problem of building-level IES and proposes a planning model to minimize the total cost and carbon emission of the IES. It mainly considers the construction of ESS and FCs, as well as the operation of solar energy and EVs. With the numerical case, the effectiveness of model has been proved and we could conclude that the FC fueled by hydrogen will play a more important role in the future when stricter restrictions are put forward on carbon emission.

Besides, multiple ESS is also a key point of this study. Through case analysis, the significant role of ESS in the operation of IES has been proved. BESS can bring great benefits through electricity price difference. At the same time, it could smooth renewable energy fluctuation to maximize the renewable's utilization efficiency. TESS can solve the time mismatch between supply and demand and greatly improve the operation efficiency of IES.

However, there are still some limitations of this study such as the negligence for the modeling of network topology and the system uncertainty. In order to make the model more accurate and eliminate the impact of uncertainty, the planning model will be further improved in the future. Besides, after the introduction of carbon trading mechanism, future research will focus on its impact on achieving carbon neutralization.

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