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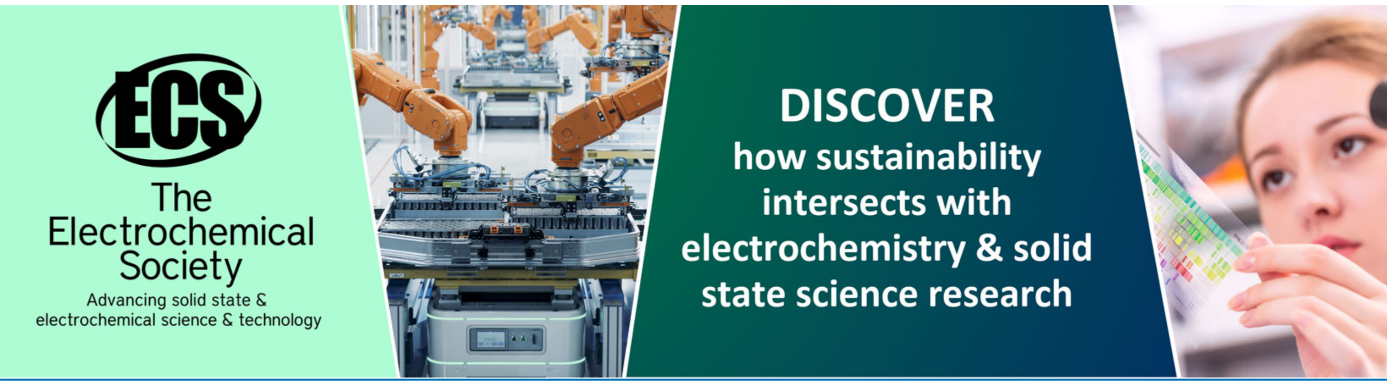

Coordinated Optimization Model of Planning and Operation of Integrated Energy System Based on Mixed Integer Programming

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Abstract. In recent years, the planning and operation of integrated energy system has received extensive attention. The traditional two-stage nonlinear model of planning and operation has problems such as inability to reach the global optimum and low solution efficiency. By linearizing the nonlinear constraints, this paper introduces a coordinated optimization model of planning and operation of integrated energy system based on mixed integer programming, which takes the minimum annual cost as the objective function and considers the coupling characteristics of electrical, thermal, and cooling load. The model achieves the optimal capacity configuration and operating scheme at the same time. Results of the testing data verify the effectiveness of the model.

1. Introduction

With the contradiction between increasing demand for energy and unstable supply of fossil resources becoming more and more prominent, how to rationalize the utilization of renewable energy, reduce environmental pollution and improve the sustainability of energy supply system become an urgent problem to be solved[1]. The integrated energy system combines the generation of electric, cooling and heating power, and achieves coupling conversion in the production, transmission, distribution and consumption of energy, which can effectively improve energy utilization efficiency, system operation economy, and reduce environmental pollutant emissions. Nowadays, the IES has become an important trend in the comprehensive utilization of energy, and thus the capacity planning and operation optimization of IES has become a hot spot in current studies.

The current research on planning and operation of IES is mainly divided into three directions. The first is to study the selection and capacity of equipment under the coupling relationship of electricity, cooling and thermal load[2]~[3]. The second is to take the uncertainty of wind and solar power and the fluctuations of load into consideration by using stochastic or chance constrained programming[4]~[5]. The third is to construct a two-stage optimization model considering the planning and operation problems in coordination to solve the above two problems at the same time[6]~[8].

In recent days, the use of the two-stage optimization model has gradually become the mainstream method to solve the planning and operation problem of IES. However, there are still drawbacks. The prominent one is the non-linearization of this model, which makes it easy to fall into local optimization and the solution speed is relatively slow due to the high iteration times of upper and lower layers[9].

Therefore, this paper constructs a coordinated optimization model of planning and operation of IES based on mixed integer programming by linearizing the nonlinear constraints. This model which can realize the capacity planning and the operation optimization of IES simultaneously can avoid the problems of local optimization and frequent iterations of the traditional two-stage nonlinear model and thus effectively improves the solution efficiency.

2. Typical structure of IES

The IES usually uses electricity and natural gas as the leading energy source and the power grid and natural gas network as the external network for energy supply. It contains various energy conversion equipment and energy storage equipment to meet different energy demand, such as electricity, heat and cold. The typical structure of IES, which consists of an energy input module, an energy conversion and storage module and an energy output module, is shown in Fig.1.

(1) The energy input module includes natural gas network and external power grid, which put electricity and natural gas through transformers and compressors into the next module respectively.

(2) The energy conversion and storage module which contains main equipment plays an important role in energy supply of IES. This paper considers six types of equipment: wind turbine, combined heat and power (CHP), electrical refrigeration, ground source heat pump (GSHP), electric boiler, and energy storage. The wind turbine converts wind energy into electric energy. The CHP realizes the supply of electric and heat power at the same time by gas turbine and waste heat boiler. The GSHP can utilize the shallow heat energy of the land and realize cooling or heating through the input of electric energy. Electric refrigerators and electric boiler equipment can directly convert electrical energy into cold energy and heat energy respectively. Energy storage charges and discharges electric energy due to the peak-valley difference of IES.

(3) The energy output module mainly refers to the energy consumption segment, including electricity, heat and cold load.

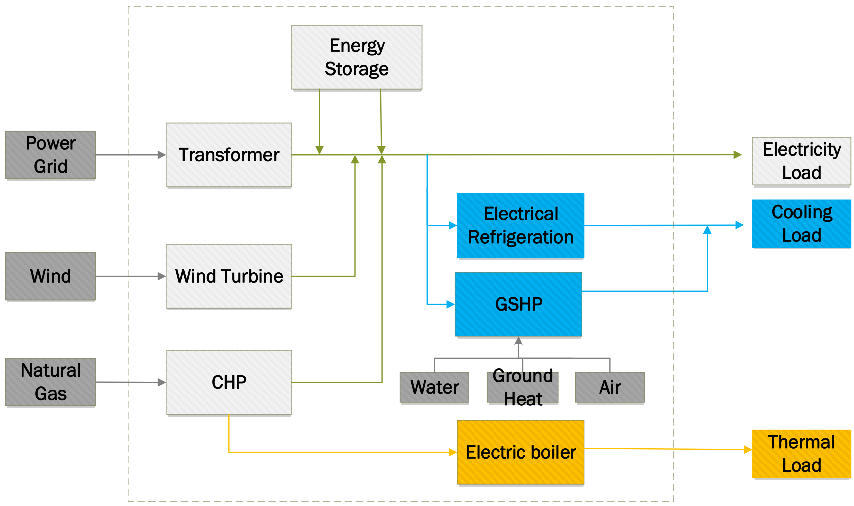


Fig.1 Typical structure of IES

3. Coordinated Optimization Model of Planning and Operation

3.1. Objective Function

The coordinated optimization model takes annual cost C_{total} of IES as the objective function, which includes investment cost C_{cap}, operating cost C_{op} and maintenance cost C_{men} of IES.

$$\min C_{total} = C_{cap} + C_{op} + C_{men} \tag{1}$$

(1) Investment cost

The investment cost C_{cap} of IES is determined by the nominal capacity of equipment and the investment cost per unit capacity.

$$C_{cap} = F\left(r,n\right)\times\begin{pmatrix} C_{cap}^{eb}\times CAP^{eb}\times X^{eb}+C_{cap}^{ac}\times CAP^{ac}\times X^{ac}+C_{cap}^{chp}\times CAP^{chp}\times X^{chp} \\ +C_{cap}^{w}\times CAP^{w}\times X^{w}+C_{cap}^{gs}\times CAP^{gs}\times X^{gs}+C_{cap}^{es}\times CAP^{es}\times X^{es} \end{pmatrix} \quad (2)$$

$$F\left(r,n\right)=\frac{1}{365}\times\frac{r\left(1+r\right)^{n}}{\left(1+r\right)^{n}-1} \quad (3)$$

Where $F\left(r,n\right)$ is the capital recovery factor; r is the annual interest rate of capital; n is the technical lifetime of equipment; C_{cap}^{eb}, C_{cap}^{ac}, C_{cap}^{chp}, C_{cap}^{w}, C_{cap}^{pv}, C_{cap}^{es} are investment costs per unit capacity of electric boiler, electric refrigeration, CHP, wind turbine, GSHP and energy storage respectively; CAP^{eb}, CAP^{ac}, CAP^{chp}, CAP^{w}, CAP^{gs}, CAP^{es} are the nominal capacity unit of electric boiler, electric refrigeration, CHP, wind turbine, GSHP and energy storage respectively; $X^{eb}, X^{ac}, X^{chp}, X^{w}, X^{gs}, X^{es}$ are the number of nominal capacity unit of electric boiler, electric refrigeration, CHP, wind turbine, GSHP and energy storage respectively.

(2) Operation cost

The operation cost of IES includes the purchase cost of electricity and gas.

$$C_{op}=\sum_{k=1}^{24}\left(P_{k}^{in}\times C_{k}^{e}+P_{k}^{chp,g}\times C_{k}^{g}\right) \quad (4)$$

Where P_{k}^{in}, $P_{k}^{chp,g}$ are the electric power provided by the power grid and the gas provided by the natural gas network at time k; C_{k}^{e} is the electricity price at time k; C_{k}^{g} is the gas price at time k.

(3) Maintenance cost

The maintenance cost of IES is determined by the output of equipment and the maintenance cost per unit output.

$$C_{men}=\sum_{k=1}^{24}\begin{pmatrix} C_{men}^{eb}\times P_{k}^{eb,h}+C_{men}^{ac}\times P_{k}^{ac,c}+C_{men}^{chp}\times\left(P_{k}^{chp,e}+P_{k}^{chp,h}\right)+C_{men}^{w}\times P_{k}^{w} \\ +C_{men}^{gs}\times\left(P_{k}^{gs,h}+P_{k}^{gs,c}\right)+C_{men}^{es}\times\left(P_{k}^{es,c}+P_{k}^{es,d}\right) \end{pmatrix} \quad (5)$$

Where C_{men}^{eb}, C_{men}^{ac}, C_{men}^{chp}, C_{men}^{w}, C_{men}^{gs}, C_{men}^{es} are the maintenance cost per unit output of electric boiler, electric refrigeration, CHP, wind turbine, GSHP and energy storage respectively; $P_{k}^{eb,h}$ is the thermal output power of electric boiler; $P_{k}^{ac,c}$ is the cooling output of electric refrigeration; $P_{k}^{chp,e}$, $P_{k}^{chp,h}$ are the thermal and electric output power of CHP unit; P_{k}^{w} is the output power of wind turbine; $P_{k}^{gs,h}$, $P_{k}^{gs,c}$ are the thermal and cooling output power of GSHP; $P_{k}^{es,c}$, $P_{k}^{es,d}$ are the charge and discharge power of energy storage.

3.2.Power balance

The power balance of IES includes electric power balance, thermal power balance and cooling power balance.

$$\begin{cases} P_k^{total,e} = P_k^{in} + P_k^{w} + P_k^{chp,e} - P_k^{gs,e} - P_k^{eb,e} - P_k^{ac,e} - P_k^{es,c} + P_k^{es,d} \\ P_k^{total,h} = P_k^{eb,h} + P_k^{chp,h} \\ P_k^{total,c} = P_k^{ac,c} + P_k^{gs,c} \end{cases} \tag{6}$$

Where $P_k^{total,e}$, $P_k^{total,h}$, $P_k^{total,c}$ are the electric, thermal and cooling load respectively; $P_k^{gs,e}$, $P_k^{eb,e}$, $P_k^{ac,e}$ are the electrical power consumed by GSHP, electric boiler and electric refrigeration respectively.

3.3. Operation constraints

(1) Energy storage constraints

Energy storage constraints include capacity constraints and charge/discharge power constraints.

$$\begin{cases} CAP_{min}^{es} \times X^{es} \le E_k^{es} \le CAP^{es} \times X^{es} \\ 0 \le P_k^{es,c} \le \theta^{es,c} \times CAP^{es} \times X^{es} \times Y^{es,c} \\ 0 \le P_k^{es,d} \le \theta^{es,d} \times CAP^{es} \times X^{es} \times Y^{es,c} \\ Y^{es,c} + Y^{es,d} \le 1 \\ E_k^{es} = E_{k-1}^{es} + (P_k^{es,c} \times \delta^{es,c} + P_k^{es,d} / \delta^{es,d}) \\ E_1^{es} = E_{24}^{es} \end{cases} \tag{7}$$

Where E_k^{es} is the state of charge of energy storage; CAP_{min}^{es} is the minimum capacity unit of energy storage; $\theta^{es,c}$, $\theta^{es,d}$ are standby energy loss ratio of storage battery, which are usually below 30% of the nominal capacity; $Y^{es,c}$, $Y^{es,d}$ are 0-1 integers, which represent the charge and discharge state; $\delta^{es,c}$, $\delta^{es,d}$ are charge and discharge efficiencies respectively; E_1^{es} is the initial state of charge, and E_{24}^{es} is the ending state of charge.

The charge and discharge power constraints of energy storage are nonlinear, therefore big M which is big enough to achieve the linear model is introduced[10]. Let $V_k^{es,c} = X^{es} \times Y^{es,c}$ and $V_k^{es,d} = X^{es} \times Y^{es,d}$, thus:

$$\begin{cases} 0 \le P_k^{es,c} \le \theta^{es,c} \times CAP^{es} \times V_k^{es,c} \\ 0 \le V_k^{es,c} \le Y^{es,c} \times M \\ 0 \le X^{es} - V_k^{es,c} \le \left(1 - Y^{es,c}\right) \times M \end{cases} \tag{8}$$

$$\begin{cases} 0 \le P_k^{es,d} \le \theta^{es,d} \times CAP^{es} \times V_k^{es,d} \\ 0 \le V_k^{es,d} \le Y^{es,d} \times M \\ 0 \le X^{es} - V_k^{es,d} \le \left(1 - Y^{es,d}\right) \times M \end{cases} \tag{9}$$

(2) Wind power constraints

$$CAP_{min}^{es} \times X^{w} \le P_k^{w} \le CAP^{w} \times X^{w} \tag{10}$$

Where CAP_{min}^{es} is the minimum capacity unit of wind turbine.

(3) CHP constraints

CHP constraints include conversion constraints of electric - thermal power, and upper/lower limits of input power.

$$\begin{cases} CAP_{min}^{chp} \times X^{chp} \le P_k^{chp,g} \le CAP^{chp} \times X^{chp} \\ P_k^{chp,e} = \delta^{chp,e} \times P_k^{chp,g} \\ P_k^{chp,h} = \delta^{chp,h} \times P_k^{chp,g} \end{cases} \tag{11}$$

Where $\delta^{chp,e}$, $\delta^{chp,h}$ are gas-electric power and gas-thermal power conversion efficiencies respectively; CAP_{min}^{chp} is the minimum capacity unit of CHP.

(4) GSHP constraints

GSHP constraints include conversion constraints of electric - cooling power and electric - thermal power as well as upper/lower limits of input power.

$$\begin{cases} CAP_{min}^{gs} \times X^{gs} \le P_k^{gs,e} \le CAP^{gs} \times X^{gs} \\ P_k^{gs,h} = \delta^{gs,h} \times P_k^{gs,e} \\ P_k^{gs,c} = \delta^{gs,c} \times P_k^{gs,e} \end{cases} \tag{12}$$

Where $\delta^{gs,h}$, $\delta^{gs,c}$ are electric-thermal power and electric-cooling power conversion efficiencies respectively; CAP_{min}^{gs} is the minimum capacity unit of GSHP.

(5) Electric boiler and electric refrigeration constraints

Power Conversion constraints and upper/lower limits of input power are included here.

$$\begin{cases} CAP_{min}^{eb} \times X^{eb} \le P_k^{eb,e} \le CAP^{eb} \times X^{eb} \\ P_k^{eb,h} = \delta^{eb} \times P_k^{eb,e} \end{cases} \tag{13}$$

$$\begin{cases} CAP_{min}^{ac} \times X^{ac} \le P_k^{ac,e} \le CAP^{ac} \times X^{ac} \\ P_k^{ac,c} = \delta^{ac} \times P_k^{ac,e} \end{cases} \tag{14}$$

Where δ^{eb}, δ^{ac} are electric-thermal power and electric-cooling power conversion efficiencies respectively; CAP_{min}^{eb}, CAP_{min}^{ac} are the minimum capacity unit of electric boiler and electric refrigeration respectively.

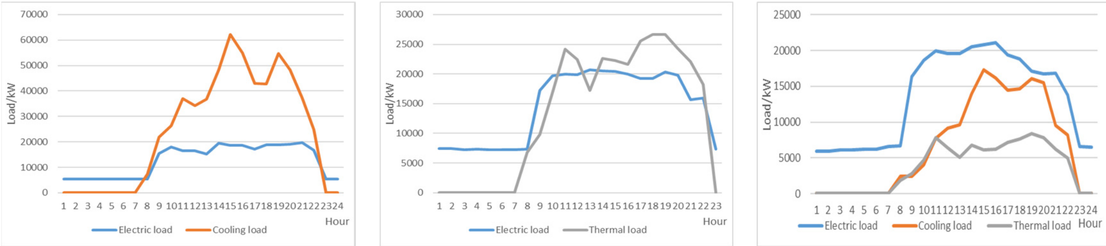
3.4. Model solving method

The coordinated optimization model of planning and operation of IES constructed in this paper transforms the traditional two-stage nonlinear model into a mixed integer linear model which could solve the planning and operation problem at the same time. The branch and bound algorithm which is stable and fast has been adopted widely in solving mixed integer linear model. Thus this paper calls the CPLEX branch and bound algorithm on the GAMS platform to solve the problem.

4. Case study

4.1. Parameters

In this paper, typical daily load curves of three seasons including cooling, heating and transition season are selected for simulation. The electric, heat and cooling load curves of each typical day are shown in Fig.2. Parameters of each kind of equipment and time-of-use (TOU) electricity price can be found in literature [2]. The price of natural gas when converted into unit calorific value is 0.2 yuan /kWh, the discount rate is 4%, and the service life of IES is 20 years.



(a) heating season (b) cooling season (c) transition season

Fig.2 Typical daily load curves in cooling, heating and transition season

4.2. Results

(1) Capacity planning of IES

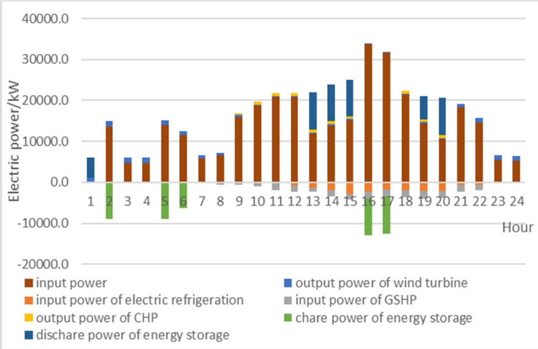
Table 1 Capacity planning results of IES

Equipment	Installation Capacity (MW)	Investment Cost (million yuan)	Operation & Maintenance Cost (million yuan /year)	Annual Cost (million yuan /year)
Electric Boiler	0.10	0.10		
Electric Refrigeration	15.60	23.40		
GSHP	2.00	14.00	573.10	613.07
CHP	59.20	467.68		
Wind Turbine	2.00	8.00		
Energy Storage	30.00	30.00		

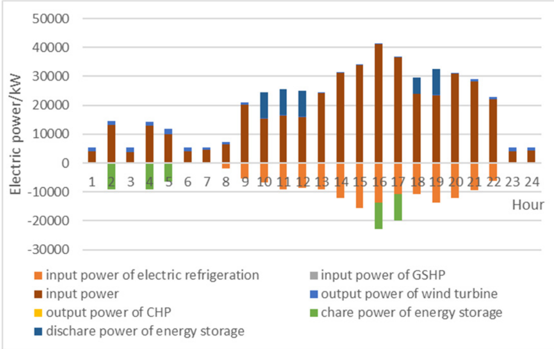
The results of capacity planning are shown in Table 1. The installed capacity of the electric boiler is 0.1MW, and the investment cost is 100,000 yuan. The installed capacity of electric refrigeration equipment is 15.6MW and the investment cost is 23.4 million yuan. The installed capacity of GSHP is 2MW, and the investment cost is 14 million yuan. The installed capacity of CHP is 59.2MW, and the investment cost is 467.68 million yuan. The installed capacity of wind turbine is 2MW, and the investment cost is 8 million yuan. The installed capacity of storage battery is 30MW and the investment cost is 30 million yuan. Under this circumstance, the total investment cost of IES is 543.18 million yuan, the annual operation and maintenance cost is 573.1 million yuan, and the annual cost which is the sum of annual investment cost and operation and maintenance cost is 613.07 million yuan.

It can be seen that among the heating equipment, electric boilers have the smallest capacity where CHP have the largest capacity. Compared with the GSHP and electric boiler, CHP which can supply electricity and heat at the same time while using waste heat, has lower operation and maintenance costs and higher operation efficiency, thus making it the primary equipment for heat supply. Among the cooling equipment, electric refrigeration has the largest capacity, mainly because the investment and operation costs of electric refrigeration are lower than that of GSHP. As for the electric load, the input power from external grid is the main supply of electricity. Considering the low costs of operation and maintenance as renewable energy, the capacity of distributed wind power meets the upper limit of planning capacity. The capacity of energy storage is mainly affected by TOU price and peak-valley load. Only when the difference in price and load can make up for the investment and operation cost, the configuration of energy storage is then reasonable.

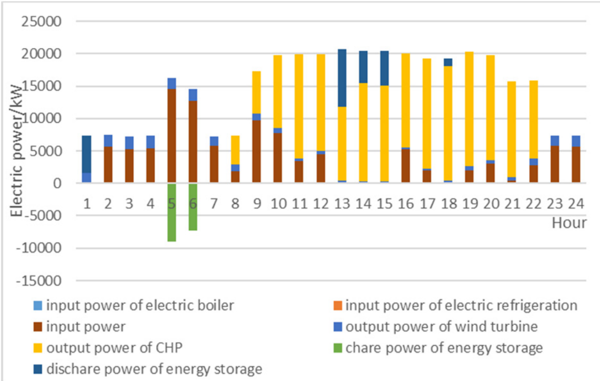
(2) Operation optimization simulation



(a) transition season



(b) cooling season



(c) heating season

Fig.3 Output/input electric power of typical day in cooling, heating and transition season

The electrical output/input power of all kinds of equipment in a typical day during the cooling, heating and transition season is shown in Fig.1. As energy conversion equipment the electric boiler, electric refrigeration and GSPH use electricity as input power, while wind turbine and CHP output electric power to meet electric load together with input power from external grid. The energy storage input electric power in charging state and output electric power in discharging state.

The input/output power of equipment is affected by its installed capacity and the load of IES. As shown in Fig.3, input electric power from external grid is the primary source to meet electric load, followed by output power of CHP, energy storage and wind turbine. For equipment which consumes electricity, the electric refrigeration has the highest power consumption, followed by the GSHP, while electric boilers have the lowest power consumption due to the negligible capacity.

In order to shift the electric load from the peak period to the flat period and the valley period when the electricity price is lower, the energy storage is charged to the maximum capacity during the first valley period (0:00~7:00) and discharged to meet the electric demand during the first peak period (10:00~15:00); it's charged again to the maximum capacity during the first flat period (15:00~18:00) and discharged again during the second peak period (18:00~21:00)).

(3) Analysis of energy storage capacity

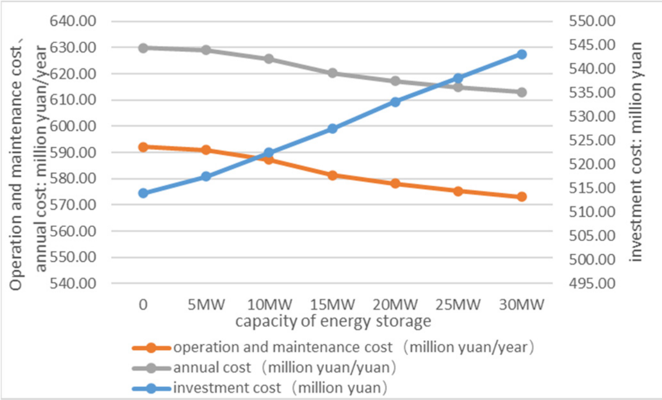


Fig.4 costs of IES under different energy storage capacity

In order to analyse the impact of the energy storage capacity on the costs of IES, the investment cost, operation and maintenance cost and annual cost of IES under different energy storage capacity are calculated, as shown in Fig.4. It can be seen that the operation and maintenance cost decreases with the increase of energy storage capacity, and the investment cost increases with the increase of energy storage capacity. The annual cost which is the sum of annual investment cost and annual operation and maintenance cost decreases with the increase of energy storage capacity. The results show that the energy storage can give full play to the role of peak load shifting and thus reduce the annual cost of IES by lowering the system operation and maintenance cost.

5. Conclusion

On account of local optimum and low calculation speed of the traditional two-stage planning-operation optimization model, this paper introduces a coordinated optimization model of planning and operation of IES based on mixed integer programming, which takes the minimum annual cost as the objective function and considers the coupling characteristics of electrical, thermal, and cooling load. This model realizes the collaborative optimization of capacity planning and system operation. Furthermore, it's verified by a case of IES where the capacity plan is made, the operation of all kinds of equipment at typical days is simulated and the importance of energy storage is demonstrated by analysing the change in annual cost under different capacity. However, there is still room for improvement in this model. Follow-up studies can focus on the uncertainty of the renewable energy, the fluctuation of load and the network constraints of electric, heating and cooling power to make the model more accurate, so as to guide the planning and operation of the integrated energy system.

Acknowledgments

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