Optimal Planning Method of Integrated Energy System Considering Carbon Cost from the Perspective of the Whole Life Cycle

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Abstract. China commits its goal of peak carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060. The integrated energy system (IES) is one of the critical approaches to achieving the commitments. While the prevailing evaluation method for calculating the carbon emissions of IES neglected parts of factors influence, the result could not reflect the carbon emissions comprehensively. Considering the insufficiency above, in this paper, the evaluation method of carbon emission based on the whole life cycle of IES is proposed. First, based on the IES energy hub model, a typical park's carbon emission model has been established. Then, the carbon emission coefficients of energy and equipment in production, transportation and operation are analysed, respectively. Hence, a low-carbon operation optimisation model of the IES is proposed. Later, with the lowest annual carbon emission of the integrated energy system as the optimisation target, the IES's optimal carbon emission allocation and operation plan are proposed, based on the balance between energy supply and demand in the process of energy and equipment use and operation. As a result, the carbon emission of the IES of the park reduces effectively.

1. Introduction

China has repeatedly stated to the world on international occasions its goal of peak carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060, emphasising its commitment to green and low-carbon development [1]. The 13th Five-Year Plan for Electricity Development states that China's power development should gradually focus on the development of environmentally friendly, safe and highly productive renewable energy systems, optimizing the capacity allocation of units and absorbing overcapacity [2]. China's power industry accounts for about 50% of the country's total CO\textsubscript{2} emissions [3]. Therefore, increasing the proportion of low-carbon renewable energy in the power industry, improving energy use efficiency, optimising unit capacity allocation, as well as absorbing overcapacity, is conducive to the development of China's low-carbon economy [2].

The integrated energy system is based on the complementary characteristics of electricity, heat, gas and other energy types as well as the principle of energy gradient utilization [4], and provides unified planning and coordinated and optimized operation of multi-energy systems, so that the production, transmission, distribution, transformation, storage and consumption of different energy sources can be organically coordinated under a multi-temporal scale, which helps to reduce the cost of energy use and
improve energy utilization efficiency [5]. In recent years, China has been paying more attention to energy conservation and environmental protection, and the proportion of total clean energy consumption to total energy consumption has been increasing in recent years, which has formed a trend of clean energy gradually replacing high pollution and high energy consumption traditional energy. IES can forecast energy supply and demand, improve the utilization rate of clean energy, and promote the large-scale consumption of clean energy [6]. IES uses a variety of heterogeneous energy supply, can accept a variety of clean energy, can form a single or multiple integrated energy system supply system according to the area of individual use area, so that IES has flexibility, reliability, low carbon and scalability [7]. In the context of low carbon development, along with the continuous research on IES, how to develop low carbon IES has become a hot issue in current research. With the goal of carbon peaking and carbon neutrality, the requirements for low-carbon IES should also be further improved. In order to achieve low carbon operation, the integrated energy system of the park needs to consume as much low carbon renewable energy as possible while meeting normal operation. IES can greatly enhance the flexibility of the system, and the cooling, heating and electricity demand of end-users can be met by various forms. When the theoretical output of renewable energy is greater than the space for consumption, it can be stored directly through electric storage, or it can be used to supply heat to users through electric-to-heat conversion, and in the case of surplus heat supply, electricity can be stored indirectly through electric-to-heat conversion + storage, which in turn enhances the flexibility of the whole system in terms of electricity consumption and the level of renewable energy consumption, thereby reducing overall carbon emissions.

Domestic and foreign scholars have started researches on the low-carbon operation of IES, but issues including carbon emission transfer in the process of energy coupling and transformation, and the promotion of the optimal operation of IES from the perspective of low carbon, remained to be further studied. Presently, the carbon trading market is being gradually promoted throughout the country. By establishing legal carbon emission rights, carbon trading is able to trade such rights, then costs are followed with carbon emission and benefits are followed with carbon emission reduction. Such mode is a trading mechanism that can effectively reduce carbon emission [8]. However, there are still few studies on the impact of carbon trading price on IES.

Life Cycle Assessment (LCA), which covers the whole life cycle of products, originated from the European and American research on industrial products in the 1970s [9]. Based on the law of conservation of energy and the law of conservation of mass, the life cycle assessment could be used to calculate the carbon emissions generated by the energy and equipment used by IES during the production, transportation and applied stages, leading to a more accurately determination on the total carbon emission of the system [10]. Such a method therefore is significant for comprehensively assessing the actual IES carbon emissions.

2. Carbon emission calculation method of IES based on LCA

The essence of an integrated energy system is to apply multiple energy technologies to realize the close connection between multiple energy supply and diversified energy demand, as shown in Figure 1. These technologies cover multiple links of energy production, energy conversion, energy consumption. The traditional calculation method takes electricity and gas purchased as the two major carbon sources, calculated the overall carbon emission of the system as the consumption of corresponding fuel (electricity/natural gas) multiplied by the corresponding emission factor.
Fig. 1. The connection between the supply and demand of the integrated energy system.

However, the total carbon emissions of the IES cannot be adequately characterised if only the carbon emissions from fossil energy generation are considered. For this reason, it is necessary to introduce the LCA energy chain carbon analysis method, which aims to analyse the system not only in terms of the direct greenhouse gas emissions generated by the system activity itself or by the input materials, but also in terms of the accompanying effects of the operation of the system or the material-related transformations, i.e. the total carbon emissions generated per unit of energy provided by the IES.

Firstly, the greenhouse gases emitted by IES were determined as metering pollutants, and every energy source in IES was divided into energy chains according to the order of energy activities. Then, the transmission links are summarized and simplified. Finally, the carbon emission coefficient generated by energy activities in every link is measured. The main measurement sources on the power generation side are coal power, new energy power generation and natural gas, while carbon emissions in the secondary energy’s (such as electricity) transmission and distribution links are not taken into consideration since the energy storage is mainly focused on the electricity consumption side.

The life-cycle carbon emission accounting formula is based on the calculation of conventional carbon emissions, and its value is equal to the sum of the carbon emissions in every stage, which can be expressed as:

\[ C_1 + C_2 + \ldots + C_n \]  

where, \( C \) represents the total carbon emission in the whole life cycle; \( C_1, C_2, \ldots \) and \( C_n \) represent the corresponding carbon emission value in each emission process.

1. Life cycle carbon emissions of coal power
   LCA greenhouse gas emissions from coal power calculating scope involves three parts: coal production, coal transportation and coal-fired power generation [13]. Emissions from mining are mainly coal bed methane emissions, coal spontaneous combustion and energy consumption emissions, emissions from transportation are mainly energy consumption emissions from coal transportation, and emissions from power generation are mainly emissions from coal-fired power generation and related auxiliary activities.

2. Life cycle carbon emissions of wind power and photovoltaics
   The greenhouse gas emissions of wind power, photovoltaic and other new energy LCA can be divided into two segments: production and construction, and transportation. The greenhouse gas emissions of the operation segment mainly come from the energy consumption of transportation and equipment maintenance during the production and replacement of consumables, and this part of emissions is negligible compared to the emissions of the production and construction phase. There have been many studies on the life cycle carbon emissions of wind power and photovoltaic [14]-[17], and this study cites Guo [16], who concluded that the life cycle carbon emission factors of wind power and photovoltaic are 9.5 gCO₂/kWh and 86 gCO₂/kWh respectively.

3. Carbon emissions during the life cycle of natural gas
   Natural gas by source includes oilfield gas and coal gas. Oilfield natural gas LCA greenhouse gas emissions include the extraction, transportation and use of natural gas, while the life cycle of coal gas
includes coal mining, transportation, conversion, natural gas transportation and use, and there are differences in their carbon emission factors, which are 0.48 kg CO$_2$/kWh [18] and 0.54 kgCO$_2$/kWh respectively [18]. To simplify the calculation, the life-cycle carbon emission factor for natural gas is 522 gCO$_2$/kWh, weighted according to the composition of natural gas market in China at this stage [19].

(4) Life cycle carbon emissions of energy storage equipment
Since the indirect use process of electrical energy storage equipment has a large carbon footprint throughout its life cycle, and waste disposal is difficult, this part of the carbon footprint should also be measured in the total carbon footprint for IES. Therefore, the life-cycle boundary of energy storage equipment is defined as the cradle-to-gate process, which takes into account the production, construction, transportation and waste recycling [20]. The actual operating life of the energy storage system is related to its selected battery model, frequency modulation participation, etc., which affects the determination of the replacement coefficient. This article uses typical lithium iron phosphate battery parameters to model the carbon emissions of energy storage equipment in the park. In this scenario, depth of discharge (DOD)=80%, charge-discharge efficiency 90%, estimated cycle life n=2500 times, daily charge-discharge times m= 1. The replacement coefficient is approximately 0.15, so that the indirect emission of the electric energy storage equipment during use is 13.7 gCO$_2$/kWh. Energy storage equipment waste is generally entrusted to relevant companies for professional treatment, which is generally divided into centralized landfill and metal recycling. In order to simplify the calculation, it is assumed that the energy storage equipment waste is uniformly commissioned by a site 200km outside the park. It is further obtained that the electrical energy storage equipment is being discarded. The carbon emissions produced during the process are 7 gCO$_2$/kWh. Finally, the life cycle carbon emission coefficient of energy storage equipment is 112 gCO$_2$/kWh.

The LCA emission coefficients of each carbon source are shown in Table 1:

| Carbon source          | Carbon emission factor |          |          |          |          |
|------------------------|------------------------|----------|----------|----------|----------|
|                        | Construction and       | Operation/ | sum      | unit     |
|                        | transportation links    | generation link |          |          |
| Coal power             | 119.2                  | 856.0    | 975.2    | gCO$_2$/kWh |
| Wind power             | 9.5                    | 0        | 9.5      | gCO$_2$/kWh |
| Photovoltaic           | 86                     | 0        | 86       | gCO$_2$/kWh |
| natural gas            | 164                    | 357      | 522      | gCO$_2$/kWh |
| Energy storage         | 91.3                   | 20.7     | 112      | gCO$_2$/kWh |

3. Optimal model of IES Considering Carbon Cost
3.1 The mathematical model of IES
The model of IES is described as Energy Hub (EH) [11] shown in Figure 2. This architecture can accurately describe the energy flow and transformation relations in different links of the integrated energy system, but the structure is relatively complex, and the optimization solution needs to be determined both among different links and among different technical paths in the same link, resulting in a difficult implantation of modelling and solving. Therefore, global optimal is tough to realize.
This paper solves the problem by assuming that the input energy of the EH has M kinds and the output energy has N types, the energy conversion matrix can be used to describe the energy conversion relationship, as follows:

\[
\begin{bmatrix}
E_{1\text{out}} \\
E_{2\text{out}} \\
\vdots \\
E_{M\text{out}}
\end{bmatrix} = T
\begin{bmatrix}
E_{1\text{in}} \\
E_{2\text{in}} \\
\vdots \\
E_{M\text{in}}
\end{bmatrix}
\]

Where, \( E_{i\text{out}} \) represents the energy output of the EH; \( E_{i\text{in}} \) represents the energy input of an EH; \( T \) is an N by M matrix.

According to the direction of energy flow, the integrated energy system can generally be divided into energy production, energy conversion, energy storage, energy transmission, and energy use. It is necessary to carry out mathematical modelling for the key equipment of each link, and clarify the constraints, mainly including System energy balance constraints, energy storage equipment constraints, interaction power constraints with the main network, controllable unit constraints, climbing constraints, and gas source point constraints.

(1) Energy production

The energy production link of the integrated energy system is mainly the process of converting primary energy such as wind energy and solar energy into electric energy. This process can be expressed as:

\[
e_{f,m,hr}^{\text{in}} = \sum_{\text{egg}} e_{\text{egg},f,m,hr}^{\text{in}}
\]

Among them, \( e_{f,m,hr}^{\text{in}} \) refers to the primary energy consumption; \( e_{f,\text{max}}^{\text{in}} \) is the available primary energy; \( f \) refers to different types of primary energy; \( m \) refers to different months, and \( hr \) refers to each hour of the day.

The consumption of solar and wind energy is limited by the available amount of local resources, and cannot exceed the maximum available amount of resources at that moment. The above relationship can be expressed as:

\[
e_{f,m,hr}^{\text{in}} \leq e_{f,m,hr}^{\text{max}}
\]

(2) Energy conversion
Energy conversion equipment includes gas turbines, heat pumps, electric refrigerators, etc. There is a certain efficiency in the conversion between different energies, and usually the range of change is not large when the equipment is running stably. Therefore, the mathematical model of the energy conversion unit can be simply expressed as:

\[ q_{\text{out}} = q_{\text{in}} \eta(P) \]  

(5)

Among them, \( q_{\text{out}} \) and \( q_{\text{in}} \) respectively represent the output and input of a certain energy conversion equipment, \( \eta(P) \) represents the energy conversion efficiency, and its value is related to the load factor \( P \).

Certain energy conversion equipment, such as heat pumps/refrigerators, usually have different operating modes in winter and summer, namely heating conditions and cooling conditions. The coefficient of performance (COP) of the heat pump/refrigerator is different under heating and cooling conditions. Therefore, the input and output relationship is as follows:

\[ \sum_{\text{ter}} \left( e_{\text{ter,hr,er}}^{\text{out}} \eta_{\text{ter,sec,er}}^{\text{heating}} + e_{\text{ter,hr,er}}^{\text{cooling}} \eta_{\text{ter,sec,er}}^{\text{cooling}} \right) = \sum_{\text{ter}} \left( e_{\text{ter,hr,er}}^{\text{in}} \eta_{\text{ter,sec,er}}^{\text{heating}} + e_{\text{ter,hr,er}}^{\text{cooling}} \eta_{\text{ter,sec,er}}^{\text{cooling}} \right) \]  

(6)

Among them, \( \text{ter} \) refers to different tertiary energy carriers, namely heat, electricity and cold, \( \text{ter} \in \{p, h, c\} \), \( c \) refers to cold; \( e_{\text{ter,hr,er}}^{\text{out}} \) denotes the output of tertiary energy carriers produced in the energy conversion process; \( \eta_{\text{ter,sec,er}}^{\text{heating}} \) and \( \eta_{\text{ter,sec,er}}^{\text{cooling}} \) are energy conversion technologies in heating mode and the coefficient of performance in the cooling mode; \( j_{\text{heating}} \) and \( j_{\text{cooling}} \) are 0-1 variables, which indicate whether the heat pump/refrigerator is working under what conditions.

(3) Energy transmission

The integrated energy system of the park mainly has two kinds of energy transmission: electricity and heat. The power transmission loss of the integrated energy system of the park is almost negligible, so the energy transmission link is mainly considered Hot net. As a network system for heat energy transmission and exchange, the heating network reflects the changes between the temperature and the heat medium in the node. At present, the transmission medium of domestic heating system is mainly hot water [12]. The heating network model is mainly to model the heat energy loss. According to the basic principle of thermal steady-state heat transfer, the thermal energy loss is:

\[ \Delta Q = 2\pi \frac{T_H - T_e}{R} l \]  

(7)

Among them, \( \Delta Q \) is the pipeline heat loss during transmission, \( T_H \) is the water supply temperature, \( T_e \) is the average temperature of the medium around the pipeline, \( R \) is the average thermal resistance per unit length of the pipeline, and \( l \) is the length of the pipeline.

(4) Energy storage

The entrance energy of the energy storage link is equal to the export energy of the energy conversion link. Energy storage equipment can increase the freedom of operation of energy production technology and energy conversion technology. The energy generated in the energy conversion link is equal to the sum of the export energy of the energy storage equipment and the net energy storage of the corresponding energy storage equipment. Among them, the net energy storage refers to the difference between the energy released by the energy storage device and the energy stored. The energy balance of energy storage equipment can be expressed as:

\[ e_{\text{ter,m,hr}}^{\text{out}} = e_{\text{ter,m,hr}}^{\text{in}} + e_{\text{ter,m,hr}} - e_{\text{ter,m,hr}}^{\text{net}} \]  

(8)
Among them, \( e_{\text{ter}}^{\text{out}} \) refers to the outlet energy of the energy storage device; \( e_{\text{ter}}^{-} \) refers to the energy released by the energy storage device; \( e_{\text{ter}}^{+} \) refers to the energy stored in the energy storage device.

At each moment, the total stored energy in the energy storage device changes with the net stored energy, which can be expressed by the following formula:

\[
E_{\text{ter},m,hr+1} = E_{\text{ter},m,hr} + e_{\text{ter},m,hr} - e_{\text{ter},m,hr} / \eta_{\text{ex,ter}} \geq 0
\]  

(9)

Among them, \( E_{\text{ter}} \) represents the energy contained in the energy storage device; \( \eta_{\text{ex,ter}} \) represents the efficiency of the energy storage device. The energy exported from the energy storage link must be greater than the terminal demand at each moment.

### 3.2 The objective function of the model

In previous studies on the optimal operation of integrated energy systems, most of the goals have been to minimize the total annual cost of the system. The total annual cost includes investment costs, operation and maintenance (O&M) costs, and fuel costs. The investment cost is determined every year from the depreciation of the total equipment investment to its operating period, as shown in the following formula:

\[\text{Min } f = C_{\text{capital}} + C_{\text{O&M}} + C_{\text{fuel}}\]  

(10)

Investment cost, operation and maintenance (O&M) cost and fuel cost are respectively determined by the following three formulas:

\[C_{\text{capital}} = \sum_{\text{inv}} \text{inv}_{\text{inv}} \cdot \text{Cap}_{\text{inv}} \cdot \frac{1}{1-(1+I)^{-Y}} + \sum_{\text{n}} \text{n}_{\text{n}} \cdot \text{Cap}_{\text{n}} \cdot \frac{1}{1-(1+I)^{-Y}} \]  

(11)

\[C_{\text{O&M}} = \sum_{\text{inv}} \text{OM}_{\text{inv}} \cdot \sum_{\text{n}} \text{n}_{\text{n}} \cdot e_{\text{inv},n,hr} \cdot d_{n} + \sum_{\text{n}} \text{n}_{\text{n}} \cdot \text{Cap}_{\text{n}} \]  

(12)

\[C_{\text{fuel}} = \sum_{\text{f}} \sum_{\text{hr}} (e_{\text{f},n,hr} \cdot P_{\text{f},hr} + e_{\text{g},n,hr} \cdot P_{\text{g},hr}) \cdot d_{n} \]  

(13)

Among them, Inv represents the unit investment cost of the equipment; \( Y \) represents the life of the equipment; \( I \) represents the depreciation rate, which is set to 10% in this study; OM represents the unit operating cost; \( d_{n} \) represents the number of days per month; \( P_{\text{f},hr} \) and \( P_{\text{g},hr} \) respectively represent the hourly fuel price and grid electricity price.

In previous studies, operation and maintenance costs mainly considered fuel/electricity costs, as well as system maintenance, operation and maintenance. With the introduction of carbon peak and carbon neutral goals, as China proposes a carbon peak and carbon neutral vision, the use of market means to reduce carbon emissions has attracted much attention, and the carbon emissions cost of the integrated energy system should also be integrated into the objective function for optimization.

The carbon trading mechanism is a mechanism that treats carbon emissions as a commodity. By assigning a certain carbon emission credit to each carbon emission source, if the actual carbon emission of the carbon emission source is greater than the allowance, you need to go to the carbon trading market to purchase the excess credit; Conversely, when the actual carbon emissions of the carbon emission source are less than the allocated amount, the remaining carbon emissions can be sold as commodities on the market. Under the carbon emission trading mechanism, carbon emission companies will spontaneously look for production or operation methods with lower carbon emissions in order to maximize their own interests. It not only promotes the energy saving and emission reduction of enterprises, but also makes carbon emissions have economic value.
This study combines the carbon trading mechanism to introduce the cost of carbon emissions into the total cost of the integrated energy system, and provides innovative ideas for the optimization of the integrated energy system that considers economy and low-carbon behavior. The carbon transaction cost model of the integrated energy system is as follows:

\[ C_{co2} = S_{co2,t} \left( E_{total} - E_{rate} \right) \]  

(14)

Among them, \( S_{co2,t} \) is the trading price of carbon emission rights in period \( t \). \( E_{total} \) and \( E_{rate} \) are the total emissions of the system and the given carbon emission allowances, respectively.

The objective function of the integrated energy system optimization taking into account the carbon cost is:

\[ \text{Min } f = C_{\text{capital}} + C_{O&M} + C_{\text{fuel}} + C_{co2} \]  

(15)

4. Model solving method

The carbon emission model constructed in this paper can be solved by using LINGO for mixed certificate integer programming. The steps are as follows:

- Step 1: Determine the type of input energy and output energy;
- Step 2: When calculating unit time \( t \), the output energy of \( i \) input energy in each stage of production, conversion, transmission and storage;
- Step 3: Calculate the total output energy \( S \) of each energy link for 8760 hours a year, and output the optimal result when the adjacent results meet the error value.

The specific flow chart is shown in Figure 3:

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Fig. 3. Flow chart of solving carbon emission model
5. Case analysis

5.1 Case Introduction

The example in this paper is based on a typical park with a design life of 25 years and energy demand for cooling, heat and electricity. The energy production units in the park’s integrated energy system are photovoltaic power generation units, fans and gas boilers, the energy conversion units are electric compression chillers, the energy storage equipment is storage batteries, the equipment parameters are shown in Table 2, and the topology of the park’s integrated energy system is shown in Figure 4.

| Equipment name          | Investment costs(Yuan/kW) | Maintenance costs(Yuan/kW) | Effectiveness |
|-------------------------|---------------------------|---------------------------|---------------|
| Photovoltaic power      | 4000                      | 0.005                     | —             |
| generation              |                           |                           |               |
| Wind turbine generator  | 3000                      | 0.005                     | —             |
| Gas boiler              | 130                       | 0.05                      | 0.8           |
| Electric refrigeration  | 1023                      | 0.01                      | 4.0           |
| Battery                 | 1259                      | 0.01                      | 0.9           |

Fig. 4. Topology diagram of the park’s IES

The calorific value of natural gas is 36MJ/Nm³, and the purchase cost is 3.3 Yuan/Nm³, and its CO₂ emission is 1.8kg/Nm³. The electricity purchase price of the system adopts the local time-of-use electricity price. The specific price is shown in Table 3. The energy used for power generation from the external grid is a combination of coal, nuclear, biomass, natural gas, renewable energy, etc. The unit calorific value is 29.270MJ, and the unit comprehensive energy is used for power generation to produce 3.411kg CO₂.

| Time period     | Electricity price (Yuan) | time                   |
|-----------------|--------------------------|------------------------|
| Peak price      | 1.4                      | 10:00-14:00;18:00-20:00|
| Parity price    | 0.87                     | 07:00-09:00;15:00-17:00 |
|                 |                          | 21:00-22:00            |
| Valley price    | 0.37                     | 00:00-06:00;23:00-00:00|

The typical daily power load curve of the park is shown in Figure 5. The load increases slightly from 0:00 to 6:00. There was a slight decrease, and the load rebounded slightly from 18:00 to 19:00, and then from 19:00 to 23:00, the load showed an overall downward trend.
The heating load curve of the heating season in the park is shown in Figure 6. The load increases hourly from 0:00 to 13:00, reaches the maximum around 13:00, and then the load starts to decrease slowly, and the heating load from 13:00 to 23:00 shows a downward trend.

The cooling load curve in the cooling season of the park is shown in Figure 7. The load decreases slightly from 0:00 to 4:00, the load increases gradually from 4:00 to 15:00, reaches the maximum at 15:00, and the load shows a downward trend from 15:00 to 23:00.

5.2 Scene setting
In order to deeply analyse the impact of the full life cycle carbon cost on the planning and design of the park's integrated energy system, combined with the objective function in Section 3.2, this study constructs three scenarios for analysis by introducing different objective functions:

- **Scenario 1**: In the integrated energy system optimization design model, the objective function only considers the main equipment investment, fuel consumption, power purchase costs, and operation and maintenance costs, and does not consider carbon emissions/carbon transaction costs.

- **Scenario 2**: Incorporate carbon emissions/carbon transaction costs into the objective function of the integrated energy system optimization planning and design, and consider the corresponding costs caused by direct fuel emissions and indirect emissions from external power sources. Among them, the carbon emission coefficient of fuel emissions comes from
the "Provincial Greenhouse Gas Inventory Compilation Guidelines", and the indirect emission coefficient of external power sources is determined by the power structure of the regional power grid and the emission coefficients of each power source type.

- **Scenario 3**: Incorporate carbon emissions/carbon transaction costs into the objective function of the optimal planning and design of the integrated energy system, where the carbon emissions of the system are considered from the perspective of the entire life cycle. Considering the full life cycle carbon emissions of energy and energy storage equipment during production, transportation and operation, it is also converted into carbon emission costs and calculated into the system cost. The relevant carbon emission coefficients are shown in Table 1.

### 5.3 Optimization Results

Taking economy and environmental protection (carbon emissions) as the target constraints, combined with local meteorological data, the integrated energy system constructed this time was simulated for 8760 hours, with a design life of 25 years, and the optimal configuration plan for the park's integrated energy system was obtained. The simulation results are as follows: the main equipment investment cost is 4,792,500 yuan, the annual maintenance cost is 148,900 yuan, the annual natural gas consumption is 1,028,700 yuan, the annual electricity consumption is 10.073 million kWh, and the annual power purchase cost is 6,389,600 yuan. The prediction curve is shown in Figure 8. The equipment design and installation capacity of the optimized plan is shown in Table 4.

#### Table 4. Design and installation capacity of equipment

| Equipment name                  | Design capacity (kW) |
|--------------------------------|----------------------|
| Photovoltaic power generation  | 179.2                |
| Wind turbine generator         | 420                  |
| Gas boiler                     | 1800                 |
| Electric refrigeration         | 750                  |
| Battery                        | 958.1                |

#### Fig. 8. Forecast curve of park daily load and wind output

**5.4 Analysis of the results of the program**

This article analyzes the cost of the optimal configuration plan according to three scenarios, and the specific results are shown below.

1) **Scenario 1** only considers the investment cost of the main equipment of 4,792 million yuan, the annual natural gas consumption of 1.0287 million yuan, the annual electricity purchase cost of 6,3896
million yuan, and the operation and maintenance cost of 148,900 yuan. Obtained the comprehensive cost of the park's integrated energy system scenario 1 is 7.7589 million yuan.

2) Scenario 2 calculates the carbon emissions from direct fuel emissions and indirect emissions from external power sources on the basis of comprehensive cost considerations, and uses 10.0723 million kilowatt-hours of purchased electricity annually. External power sources consider the energy structure of local power generation. Coal power generation accounted for 65.97%, natural gas power generation accounted for 13.24%, wind power generation accounted for 8.53%, photovoltaic power generation accounted for 12.25%, and its operating power generation carbon emission coefficient refers to Table 1, and the cost of each carbon source under scenario 2 is shown in Table 5. Combining the carbon emission coefficients of the operation/power generation link in Table 1, the carbon emission price combined with the local transaction average price is 28.49 yuan/ton, and the annual carbon emission price of the system operation/power generation link under Scenario 2 is 201,300 yuan, and the comprehensive cost is 7.9602 million yuan.

Table 5. Carbon emissions of each carbon source operating power generation link under Scenario 2

| Carbon source | External power purchase (kWh) | System internal load (kWh) | Carbon emissions (t) |
|---------------|-------------------------------|---------------------------|---------------------|
| Coal power    | 6746200                       | 5687.86                   |
| wind power    | 872300                        | 804000                    | 0                   |
| Photovoltaic  | 1252700                       | 292000                    | 1366.37             |
| natural gas   | 1353900                       | 2493800                   | 0                   |
| battery       | -                              | 562000                    | 11.63               |

3) Scenario 3, on the basis of scenario 2, considers the carbon emissions of each carbon source in the integrated energy system during the production and transportation process, including coal power, photovoltaic, wind power, consumed natural gas and energy storage equipment, according to the carbon emission coefficient in Table 1. Converted to the cost of the integrated energy system, it is obtained that under Scenario 3, the annual carbon emissions of each carbon source in the construction and transportation link total 1618.07 tons, as shown in Table 6. Combined with the comprehensive price of carbon trading, the annual carbon emission cost of each carbon source construction and transportation link under scenario 3 is 46,100 yuan.

Table 6. Emissions from carbon construction and transportation links of various carbon sources under Scenario 3

| Carbon source   | Carbon emissions (t) |
|-----------------|----------------------|
| Coal power      | 792.05               |
| wind power      | 15.80                |
| Photovoltaic    | 131.22               |
| natural gas     | 627.69               |
| battery         | 51.31                |
| total           | 1618.07              |

The comprehensive cost of the park's integrated energy system under the three scenarios is shown in Figure 9:
In Scenario 3, the comprehensive annual cost of the system is RMB 8.0063 million. The cost of carbon emissions during the entire life cycle is RMB 247,400, accounting for 3.1% of the total cost. This cost ratio will be compared with the cost of carbon emissions during the production, transportation and operation of power generation. Changes in carbon emissions prices are positively correlated.

6. Conclusion
This paper establishes a low-carbon operation optimization model of the integrated energy system. On the basis of satisfying the energy balance of supply and demand, proposes the optimal configuration and operation plan for the carbon emission of the integrated energy system of the park, and uses the carbon emission analysis method of the entire life cycle energy chain to calculate this time. The research park contains the comprehensive cost of carbon emissions throughout the life cycle.

1) The optimization scheme of the integrated energy system of the park proposed in this paper proposes a low-carbon configuration and operation scheme under the premise of meeting the balance of energy supply and demand in different seasons and periods. On the basis of ensuring the safe and stable operation of the system, the integrated energy system achieves high environmental benefits.

2) This article fully considers the full life cycle carbon emissions of the energy and equipment used in the park's integrated energy system during the production, transportation, and operation of power generation. The established low-carbon operation optimization model of the integrated energy system has strong applicability.

3) The minimum time scale of the model built in this paper is 1h, and the response capacity of the integrated energy system equipment can reach the minute or second level. How to optimize the park's integrated energy system in a smaller time scale will be a further step.

7. Reference
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