Operation Optimization of Integrated Energy System considering Power-to-Gas Technology and Carbon Trading

Xin Sun, Yadi Zhang, Yuyun Zhang, Jingdong Xie, and Bo Sun

College of Electrical Engineering, Shanghai University of Electric Power, Shanghai, China

Correspondence should be addressed to Xin Sun; sunxin@shiep.edu.cn

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1. Introduction

With the rapid growth of global fossil energy demands and the increasing prominence of environmental issues, China actively promotes the development of clean and low-carbon power. Up to now, the total installed wind power capacity has reached 282.0 GW, whereas the total installed photovoltaic capacity is up to 253.8 GW [1]. During the development process, there are some problems that occurred, such as high rate of wind power and photovoltaic curtailment and low rate of comprehensive energy utilization. Therefore, the IES, which can implement multienergy complementary and accommodate renewable energy, has been received increasing interest in recent years [2, 3].

1.1. Review of the Literature. P2G technology, as one of the core links of IES, which contributes to strengthen electric-gas coupling, is an important way to reduce the rate of wind power and photovoltaic curtailment [4]. On this basis, introducing P2G equipment into IES can produce H2 and CH4 through consuming CO₂ [5, 6] to reduce carbon emissions and energy purchases. At present, scholars have studied a lot on P2G technology. The P2G technology provides a promising method to balance the electric grid as energy storage. Compared with the general P2G model, the refined P2G model, which considers the actual operating characteristics of electrolytic cell and methane reactor, is a reasonable way to represent the energy coupling mode of P2G technology [7]. Higher P2G operating costs have an impact on renewable energy accommodation and economic operating costs of IES to a certain extent [8]. Research in [9] that focused on the operating benefits and costs of P2G technology analyzed the economic value of P2G in several specified application scenarios. The cost-saving achieved by installing P2G is higher than that via optimal scheduling [10, 11]. Based on P2G equipment and traditional gas turbine, the P2G system proposed in [11] brings lower energy losses. However, the additional carbon dioxide emissions are also generated by the system. A low-carbon economic dispatch model proposed in [12] can properly achieve a balanced trade-off between economic benefits and carbon emission.
The carbon trading mechanism is an effective way to reduce carbon emissions and promote the development of clean and low-carbon power [13]. Considering the ladder-type carbon trading mechanism [14, 15], more low-carbon energy can be utilized to reduce carbon emissions with reduced economic benefits of IES. Based on the carbon emission flow (CEF) theory, the carbon pricing method introduced into the dispatching model charges consumers by tracing the embedded carbon emissions of energy production, transportation, and consumption [16], whereas the life-cycle assessment (LCA) method analyzes the carbon emissions generated by the energy conversion process of different energy chains (EC) [17]. A robust optimization model with carbon trading proposed in reference [18] has remarkable low-carbon benefits and strong robustness of the integrated electricity-gas system. Studies mentioned above focused on tracing carbon emissions of energy conversion process, but there is a lack of consideration of the effect of P2G technology.

1.2. Contributions of the Paper. Most of the studies pay little attention to the refined P2G model and its important role in carbon trading. To fill the gap, we intend to propose a low-carbon operation optimization model, which can reduce carbon emission and improve the comprehensive operating capability of IES with the purpose of the maximized total revenue of IES. The main contributions of this study are summarized as follows:

(1) A detailed IES model considering including electricity, gas, heat, and other forms of energy is proposed in this study. The refined P2G model is adopted in this model to improve energy conversion efficiency and reduce carbon emission. The carbon emission replacement coefficient of the P2G model is calculated in each energy conversion process.

(2) An optimal efficiency matching coefficient is estimated to modify the operating cost coefficient, increase the rate of the CHP unit utilization, and improve the resource allocation of the energy system.

(3) A multiaspect optimization model considering P2G technology and carbon trading is proposed, including energy selling benefits, operating cost, carbon emission cost, wind power and photovoltaic curtailment punishment cost, and so on.

(4) Case studies verify the advantages of the optimization model that are carried out. The results show that the P2G with gas tank mode has an obvious advantage in the comprehensive operating capability of IES.

2. IES Model Based on P2G Technology

2.1. IES Structure. IES is a multienergy coupling system connected by an energy supply network and load, including electricity, gas, heat, and other forms of energy. The schematic diagram of IES based on P2G technology in this study is shown in Figure 1.

2.2. P2G Model. The P2G technology can be divided into power to natural gas and power to hydrogen with the main producers as natural gas and hydrogen. According to the principle of water electrolysis, the power-to-hydrogen technology uses surplus energy of IES to produce hydrogen, which can be directly imported to the gas pipeline or hydrogen tank. The energy conversion efficiency of this process is about 75%–85%. The power-to-natural gas technology, based on power to hydrogen, produces methane through the reaction of hydrogen and carbon dioxide at high temperature and under high pressure, the conversion efficiency of which is about 75%–85%, whereas the conversion efficiency of power to natural gas is about 45%–60% [19]. The detailed technical process of P2G equipment is shown in Figure 2 [10].

The electrolytic cell (EC) is the core of P2G technology. Some of the hydrogen produced by EC enters the hydrogen storage tank through the compressor in order to supply hydrogen load, and the rest enters the methane reactor to produce methane, which is transported to the gas pipeline in order to supply the CHP unit or gas load. The model of EC can be formulated as follows:

\[
P_{EC,t} = \eta_{EC} P_{P2G,t},
\]

\[
\eta_{EC,t} = a_{EC} \left( \frac{P_{EC,t}}{P_{P2G,t}} \right)^2 + b_{EC} \left( \frac{P_{EC,t}}{P_{P2G,t}} \right) + c_{EC},
\]

\[
P_{P2G,\text{min}} \leq P_{P2G,t} \leq P_{P2G,\text{max}},
\]

\[
\Delta P_{EC,\text{min}} \leq P_{P2G,t+1} - P_{P2G,t} \leq \Delta P_{EC,\text{max}}.
\]

In equation (1), the output power of EC can be expressed by the conversion efficiency of EC multiplied by the input power of P2G.

Hydrogen storage involves several physical processes. This study considers the characteristics of hydrogen tank (HT) from the dispatch process for hydrogen storage calculation, which is described by a transfer station for hydrogen. The model of HT can be formulated as follows:

\[
0 \leq P_{H,\text{ch},t} \leq m_H P_{H,\text{ch},\text{max}},
\]

\[
0 \leq P_{H,\text{di},t} \leq (1 - m_H) P_{H,\text{di},\text{max}},
\]

\[
W_{H,\text{ch},t+1} = W_{H,\text{ch},t} + P_{H,\text{ch},t} \eta_{H,\text{ch}} - \frac{P_{H,\text{di},t}}{\eta_{H,\text{di}}},
\]

\[
W_{H,\text{ch},t} \leq W_{H,\text{ch},\text{max}},
\]

\[
W_{H,\text{di},t} \leq W_{H,\text{di},\text{max}},
\]

\[
W_{H,\text{ch},24} = W_{H,0}.
\]

In equation (2), \( m_H \) is a variable in the range of 0-1, which represents the ability of charging and discharging energy. The gas storage tank (GT) model, which is similar to the HT model, is not repeated.
Methane reactor (MR) can produce methane through the reaction of carbon dioxide captured from IES and hydrogen produced by EC in order to supply the CHP unit, which reduce the gas purchasing cost and realize bidirectional coupling between power network and gas network. The model of MR can be described as follows:

\[
\begin{align*}
\frac{1}{\eta_{MR}}P_{MR,t} & \leq P_{MR,t} \leq P_{MR,max} \\
PMR_{min} & \leq P_{MR,t} + 1 - P_{MR,t} \leq PMR_{max} \\
\end{align*}
\]

The hydrogen and natural gas produced by P2G technology can be separately stored in gas tanks. Energy storage technologies are shown in Table 1 [20], which shows that the energy charging rate and energy storage capacity of P2G technology are better than traditional energy storage technology.

### 2.3 Component Model

#### 2.3.1 Microturbine (MT) Model

MT is a low-power gas turbine, which has the advantages of quick start-up time,
The model of MT can be described as follows:

\[
\begin{align*}
0 & \leq P_{MT,t} \leq P_{MT.r}, \\
P_{MT.e,t} &= \eta_{MT.e} P_{MT,t}, \\
P_{MT.h,t} &= \eta_{MT.h} P_{MT,t}, \\
\Delta P_{MT.d,t} &\leq P_{MT,t+1} - P_{MT,t} \leq \Delta P_{MT.u,t}.
\end{align*}
\] (4)

The conversion efficiency of MT is related to the actual equipment load rate, which is difficult to obtain the characteristic alternated working condition of equipment under different scenarios [21, 22]. This study adopts the models of a typical device introduced in [25], which are formulated in equation (5):

\[
\begin{align*}
\eta_{MT.e} &= \eta_{MT.e.r} (2.745 f_{MT} - 2.861 f_{MT}^2 + 1.071 f_{MT}^3), \\
f_{MT} &= \frac{P_{MT,t}}{P_{MT.r}}, \\
\eta_{MT.h} &= \eta_{MT.h.r} (0.85 f_{MT} + 0.15).
\end{align*}
\] (5)

2.3.2. Gas Boiler (GB) Model. Compared with coal-fired boilers, GB is cleaner and more environmentally friendly. In the real IES, GB can accordingly support the heat supply in time to the supply of CHP units to the heat load, so as to achieve auxiliary heat production and improve the operating efficiency of IES. The model of GB can be described as follows:

\[
\begin{align*}
0 & \leq P_{GB,t} \leq P_{GB.r}, \\
P_{GB.h,t} &= \eta_{GB} P_{GB,t}, \\
\Delta P_{GB.d,t} &\leq P_{GB,t+1} - P_{GB,t} \leq \Delta P_{GB.u,t}.
\end{align*}
\] (6)

2.3.3. Renewable Energy Output Constraints. This study argues that the actual output of renewable energy should not be larger than the predicted maximum value. Wind power output constraint and photovoltaic power output constraint are shown in Constraint (7) and Constraint (8), respectively.

\[
\begin{align*}
0 & \leq P_{w,t} \leq P_{w.\text{max}}, \\
0 & \leq P_{pv,t} \leq P_{pv.\text{max}}.
\end{align*}
\] (7) (8)

2.4. Optimal Efficiency Matching Coefficient. In order to improve the matching performance of the thermoelectric ratio between the CHP unit and the load, this study proposes the optimal efficiency matching coefficient \( \theta \) to modify the operating cost coefficient and increase the rate of the CHP unit utilization. \( \theta \) represents the thermoelectric ratio of the CHP unit and load, formulated in equation (9).

When the thermoelectric ratio of the CHP unit is higher than the load \( \theta > 1 \), the operating cost coefficient of the CHP unit can increase operating cost and decrease the output power to a small extent to make thermoelectric ratios equal. When the thermoelectric ratio of the CHP unit is lower than the load \( \theta < 1 \), the operating cost coefficient of the CHP can decrease operating cost and increase the output power with a small extent to make thermoelectric ratios equal.

\[
\begin{align*}
\theta_t &= \frac{V_{P,t}}{V_{L,t}}, \\
V_{L,t} &= \frac{L_{b,t}}{L_{e,t}}, \\
V_{P,t} &= \frac{P_{MT.h,t}}{P_{MT.e,t}}.
\end{align*}
\] (9)

3. Carbon Trading Mechanism Model

The essence of the carbon trading market is to reduce carbon emissions and control the total quantity. The concrete measure is to allocate carbon emission credits toward different carbon-emitting sources. The buyer is paying for the part that exceeds the carbon emission cap, whereas the seller is being rewarded for the difference between actual emission and emission cap.

Carbon emission quotas of different energy devices in IES are given during the carbon trading process in order to control carbon emissions of IES, which contributes to improve the effect of energy-saving and emission reduction. The carbon trading cost of IES can be described as follows:

\[
\begin{align*}
C_E &= K_C (C_E - E_p), \\
E_p &= \alpha \sum_{t=1}^{T} \sum_{i=1}^{N} P_{i,C,t}.
\end{align*}
\] (10)

Considering that the carbon emission of energy devices is indicated in the three stages as energy production, transportation, and consumption, this study measures the carbon emission coefficient \( \lambda \) of energy devices based on the LCA energy chain analysis method [17]. The actual carbon emission can be described as follows:

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**Table 1: Comparison of energy storage technologies.**

<table>
<thead>
<tr>
<th>Types</th>
<th>Energy charging rate (h)</th>
<th>Energy storage capacity (MW·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flywheel energy storage</td>
<td>0.1–0.9</td>
<td>0.01–0.5</td>
</tr>
<tr>
<td>Battery energy storage</td>
<td>0.1–10</td>
<td>0.1–50</td>
</tr>
<tr>
<td>Compressed air energy storage</td>
<td>1–10</td>
<td>100–10¹</td>
</tr>
<tr>
<td>Pumped hydro storage</td>
<td>5–10³</td>
<td>100–10⁵</td>
</tr>
<tr>
<td>P2G energy storage</td>
<td>0.1–10⁴</td>
<td>10⁵–10¹⁴</td>
</tr>
</tbody>
</table>
In this study, the CHP unit in IES can capture carbon dioxide for P2G equipment to synthesize methane. The process of supplying hydrogen has contributed to reducing the carbon emissions of IES due to no carbon dioxide produced during the combustion of hydrogen. The reduction in carbon dioxide emissions by consuming hydrogen can be calculated with the amount of natural gas replacement. The carbon emission replacement coefficient $\lambda_{H2C}$ is 0.185 kg/kWh [23]. Therefore, in carbon trading, the amount of carbon dioxide consumed in the P2G process and the carbon dioxide equivalent emission reduction in hydrogen storage is included in the total carbon emissions of the system. The formulas can be described as follows:

$$E_{P2G} = \sum_{t=1}^{T} \left( \lambda_{P2G} P_{MR,t} + \lambda_{H2C} P_{H,cht,t} \right),$$

$$\lambda_{P2G} = \frac{M_{CO2}}{M_{CH4}} \times \frac{1}{H_{CH4}},$$

where $H_{CH}$ represents the high heat value of methane relative to mass, taken as 15.3 kW-h/kg.

### 4. Low Carbon Operation Optimization Model

#### 4.1. Objective Function.

The objective function is the maximized total revenue of IES, including sales benefits, operating cost, carbon trading cost, wind power, and photovoltaic curtailment punishments.

$$\text{max } E = S_{total} - C_{op} - C_{E} - C_{WS},$$

where $E$ represents the net revenue of IES, $S_{total}$ represents the energy sales benefits, $C_{op}$ is the operating cost of IES, and $C_{WS}$ represents wind power and photovoltaic curtailment punishments.

$$S_{total} = \sum_{t=1}^{T} \left( K_{s,t} I_{e,t} + K_{h,t} I_{h,t} + K_{g,t} I_{g,t} + K_{H,t} I_{H,t} \right),$$

$$C_{op} = C_{om} + C_{EN} + C_{G}.$$

In equation (15), $C_{op}$ represents the operating cost of IES, $C_{om}$ represents operation and maintenance cost of equipment, $C_{EN}$ represents the interaction cost between IES and power network, and $C_{G}$ represents gas purchase cost.

$$C_{om} = \sum_{t=1}^{T} \left( \theta \alpha_{CHP} P_{MT,t} + \alpha_{GB} P_{GB,t} + \alpha_{EC} P_{EC,t} + \alpha_{MR} P_{MR,t} 
\quad + \alpha_{H} P_{H,t} + \alpha_{G} P_{G,t} \right),$$

$$C_{EN} = \sum_{t=1}^{T} \left( K_{s,t} \max\{P_{ip,t} - P_{min}, 0\} + K_{s,t} \min\{P_{ip,t}, 0\} \right),$$

$$C_{G} = \sum_{t=1}^{T} (K_{g,t} P_{g,t}),$$

where $P_{ip,t}$ represents the power of the tie-line power between the IES and power grid at time $t$, with positive value means purchasing electricity from power network whereas negative value means selling electricity to the power network.

$$C_{WS} = \sum_{t=1}^{T} \left[ H_{w} \left( P_{w,f,t} - P_{w,t} \right) + H_{p} \left( P_{pv,f,t} - P_{pv,t} \right) \right].$$

#### 4.2. Constraints

##### 4.2.1. Energy Balance Constraints.

Equation (18) denotes the balancing constraints of electricity, natural gas, heat, and hydrogen in IES.

$$\begin{align*}
P_{ip,t} + P_{w,t} + P_{pv,t} - P_{P2G,t} + P_{PMT,t} &= L_{e,t}, \\
P_{g,t} + P_{NG,t} - P_{MT,t} - P_{GB,t} + P_{g,cht,t} - P_{g,dis,t} &= L_{g,t}, \\
P_{MT,h,t} + P_{GB,h,t} &= L_{h,t}, \\
P_{EC,t} - P_{MR,t} + P_{H,cht,t} - P_{H,dis,t} &= L_{H,t}. \end{align*}$$

##### 4.2.2. External Network Constraints.

External network constraints are presented in equations (19) and (20). Constraint (19) enforces the power of the tie-line power between the IES and power grid within their lower and upper bounds. Constraint (20) enforces the amount of purchased gas within lower and upper bounds.

$$P_{ip,t} \leq P_{ip,t} \leq P_{ip,max},$$

$$P_{g,t} \leq P_{g,t} \leq P_{g,max}.$$

#### 4.3. Particle Swarm Optimization Algorithm.

Particle swarm optimization with the advantages of simple algorithm structure and the rapid searching rate is widely used to solve nonlinear optimization problems. Considering equations (1), (5), and (9) are nonlinear constraints, the optimization model of IES is solved by particle swarm optimization as shown in Algorithm 1.
5. Case Study

5.1. Basic Configurations. In this section, the optimized results for the case study are based on the IES with P2G equipment and carbon trading, the parameters of which are shown in Table 2. Figures 3 and 4 show the load curve and the predicted curve of the output of the renewable energy. Time-of-use prices are given in Table 3. The carbon trading price and natural gas price are set as $40 \text{CNY/t}$ and $2.5 \text{CNY/m^3}$, respectively. The low heat value of natural gas is set as $9.7 \text{kW-h/m^3}$.

According to the measurement of carbon emissions introduced in Section 2, energy chain carbon emission coefficients are listed in Table 4 [17].

With reference to the allocation schemes of carbon emission quotas issued by the Development and Reform Commission of Shanghai, [24] and Guangdong Province [25] in China [24, 25], carbon emission quotas of energy devices are listed in Table 5 [17], which takes into account the actual situation of the IES.

In order to verify the effectiveness of the model established in this study, we consider three cases in Table 6. Case 1 is considered as a traditional IES, in which CHP unit, GB, and renewable energy unit are designed as the basic structure of IES. Case 2 is considered as a traditional IES with P2G equipment, in which the refined P2G model is considered in the IES model. Case 3 is considered as an IES with P2G equipment, in which optimal efficiency matching coefficient is considered in the optimization model on the basis of Case 2.

5.2. Analysis of Optimization Results in Different Cases.

The optimization results of electric power are shown in Figure 5. As shown in Figure 5, the load demand in the daytime is mainly supplied by renewable energy and CHP units, and the system can purchase electricity from the power network during peak hours. At night, with the characteristic of low load demand and high output of renewable energy, the system has to reduce the output of CHP units and sell the excessive wind power to the power network. With the help of P2G equipment, the excessive output of renewable energy is converted into natural gas and then stored into a gas storage tank or supplied to the system when wind power curtailment is serious between 23:00–24:00 and 0:00–4:00. The application of the optimal efficiency matching coefficient makes the output of CHP units gentler and increases the output of the P2G equipment at night, which has a positive effect on the accommodation of excessive wind power and carbon dioxide. Between 7:00 and 22:00, the thermoelectric ratio of load $(V_{LT})$ is less than 0.725, whereas the optimal efficiency matching coefficient is greater than 1.3. The excess power provides to P2G instead of being sold to the network. From 7:00 to 22:00, the thermoelectric ratio of load $(V_{LT})$ is less than 0.725 and the optimal efficiency matching factor $(\theta)$ is greater than 1.3. The excess power generated by the system is supplied to the P2G. The CHP unit and gas boiler use more natural gas generated by the P2G as fuel, which further reduces the amount of natural gas purchased from the IES. This indicates that the effect of the optimal matching factor not only improves the output of the CHP unit but also changes the source of natural gas used by the system, which in turn reduces the cost of carbon emissions and natural gas.

The optimization results of heat power and renewable energy accommodation are shown in Figures 6 and 7, respectively. The heat power and electric power of the CHP
unit are sensitive to electricity price. During the valley hours (23:00–24:00 and 1:00–4:00), the electricity price and the electric load demand are at a low level. Therefore, the output of the CHP unit has been reduced to make full use of wind power, whereas the output of GB has been increased to meet heat load demand. The P2G equipment further reduces the amount of wind power abandonment, maintains the balance of gas network, and strengthens the coupling between power network and gas network. From 9:00 to 21:00, renewable energy can be completely consumed. With the high demand of the electric load and heat load, the CHP unit at output peak hours has been reduced the marginal cost, further reducing the operating cost of the IES and improving the net benefit of the system. During the peak hours (19:00–22:00), the electricity price and the electric load demand are at a high level. The P2G produces large amounts of natural gas to further reduce the cost of purchasing electricity from the network, resulting in a further increase in CHP unit output to provide sufficient carbon dioxide to the P2G. Therefore, the amount of natural gas produced by the P2G is related to the price of electricity. The application of the optimal efficiency matching coefficient makes the output of the CHP unit gentler. The amount of natural gas produced by the P2G is related to the cost of operating the CHP.

The peak period of the load is exactly the low point of wind power and photovoltaic output at daytime. Renewable energy can be completely consumed. In order to keep power balance, the wind abandonment during 23:00–24:00 and 0:00–4:00 is serious as a result of the high output of wind power and low load demand, which restricts the output of the CHP unit. In case 1, the excessive wind power is fed to the grid in a traditional IES. However, due to the limitation of the tie-line power flow, renewable energy cannot be
Figure 5: IES electric power optimization results in different cases. (a) Case 1. (b) Case 2. (c) Case 3.

Figure 6: IES heat power optimization results in different cases. (a) Case 1. (b) Case 2. (c) Case 3.
completely absorbed. The amount of wind power and photovoltaic abandonment is 20.258 MW, and the rate of wind power and photovoltaic abandonment is 18.26%. P2G equipment has been introduced into case 2, to realize the conversion of electricity to hydrogen or natural gas, which can be supplied for load or stored in gas storage tanks. The amount of wind power and photovoltaic abandonment is reduced by 6.956 MW, and the rate of wind power and photovoltaic abandonment is 15.602%. The optimal efficiency matching coefficient has been adopted to case 3; thus, the matching of the thermoelectric ratio between CHP unit and load demand is improved. The amount of wind power and photovoltaic abandonment is further reduced, and the rate of wind power and photovoltaic abandonment is 5.3%. As a result, the application of the optimal efficiency matching coefficient and P2G technology could significantly reduce wind power and photovoltaic curtailment and improve the utilization rate of the IES.

5.3. Analysis of Benefits and Costs of IES in Different Cases.

The operating cost of IES in different cases is summarized in Table 7. The energy selling benefit in case 1 is 264740 CNY, whereas the values in case 2 and case 3 are both 285960 CNY. This is mainly due to the introduction of P2G equipment in cases 2 and 3, which converts excessive electricity into hydrogen or natural gas and then obtains additional hydrogen selling revenue. Due to the influence from the optimal efficiency matching coefficient on operating cost coefficient of devices, the operating cost of case 3 is 2.23% lower than that of case 2. Compared with case 1, the introduction of P2G technology in case 2 and case 3 reduces the amount of wind power and photovoltaic abandonment, which further reduces the rate of wind power and photovoltaic abandonment. As a result, the energy purchase costs in case 2 and case 3 are, respectively, 4.75% and 5.85% lower than that in case 1. In terms of carbon trading, the carbon emission costs in case 1 are 17790 CNY. The carbon emission costs in case 2 and case 3 are, respectively, 30.35% and 35.86% lower than that in case 1. IES with P2G could consume carbon dioxide to reduce carbon emissions and use the optimal efficiency matching coefficient to make CHP output gentler. The optional ideas of the system have significant advantages in improving the utilization of devices and reducing carbon emissions. In Section 5.3, the renewable energy accommodation of IES in different scenarios is already compared, which can be used to conclude that the rate of wind power and photovoltaic curtailment is gradually decreasing in different scenarios, and the cost of wind power and photovoltaic abandonment is also significantly reduced. The revenue in case 1 is 91680 CNY. The increase in energy selling benefits and decrease in total operating costs make the net benefit of case 2 increased by 24.83% in contrast to case 1. After optimizing the output power of CHP units and the price of electricity, the net income of Scenario 3 is increased by 10.4% in contrast to that in case 2. In general, the IES with P2G equipment and optimal efficiency matching coefficient has significant improvement in economic benefits and environmental benefits.

5.4. Alternative Analysis.

In order to analyze the advantages of IES with P2G over traditional IES, mode 1 is set as IES introduced in the electric boiler with electricity and heat storage devices. Mode 2 is set as IES introduced in P2G equipment with gas tanks. In these two modes, the comparison of renewable energy accommodation is shown in Figure 8, and the comparison of the operating economy is shown in Table 8.

From Figure 8 and Table 8, it can be seen that the renewable energy accommodation capacity of mode 2 is stronger than that of mode 1 during the period of 23:00–24:00 and 0:00–4:00. According to the optimization results of the whole period, the amount of wind power and photovoltaic abandonment and the rate of wind power and photovoltaic abandonment in mode 1 are 16.742 MW and 13.6%, whereas in mode 2 the values are 13.302 MW and 9.17%, respectively; consequently, the penalty cost in mode 2 is 14.28% lower than that in mode 1.

As shown in Table 8, compared with mode 1, the energy selling benefits of mode 2 are 8.02% higher, while the costs of energy purchase and carbon emission are 1.87% and 25% lower, respectively. This is because the system can gain additional energy selling benefits and reduce the amount of gas purchased from the gas network through the conversion of electricity to hydrogen or natural gas in mode 2. Although the P2G equipment can equivalently reduce the carbon
emissions through capturing carbon dioxide and producing hydrogen, the operating cost of P2G equipment, which is in the developmental stage, is higher in contrast to that of mode 1, that is, an increase of 35.08%. From the results, mode 2 has a great advantage in the environmental benefits, which leads to the result that the net income of mode 2 is 20580CNY higher than that of mode 1. With the development of P2G technology, P2G equipment with gas tank mode might have significant advantages in comprehensive benefits with the reduction in operating cost.

6. Conclusions

This study presents an optimization model for an IES considering P2G technology and carbon trading mechanism, which is solved by the particle swarm optimization algorithm. Case studies convey the following information:

(1) This study proposed a P2G carbon emission coefficient based on the refined P2G model. Considering the refined P2G model and carbon trading, the IES can significantly improve the capability of renewable energy accommodation, reduce the operating cost of carbon emissions, strengthen energy coupling, and effectively help P2G equipment to increase the economic benefits.

(2) Application of the optimal efficiency matching coefficient in the IES can modify the operating cost of the CHP unit, which has significant advantages in adjusting the amount of natural gas produced by the P2G, further reducing the amount of carbon dioxide. The adjustment of operating costs also changes the CHP unit output and greatly improves the efficiency of devices, thereby absorbing more renewable energy.

(3) P2G with gas tank mode has a great advantage in environmental benefits. With the development of technology, the comprehensive benefits of IES will be effectively improved.

Further studies still need to perform operation optimization of IES focused on uncertainties of distributed renewable energy and mutual interdependencies of energy conversion devices.

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net income (CNY)</td>
<td>91680</td>
<td>114440</td>
<td>126340</td>
</tr>
<tr>
<td>Energy selling benefits (CNY)</td>
<td>264740</td>
<td>285960</td>
<td>285960</td>
</tr>
<tr>
<td>Operating cost (CNY)</td>
<td>27510</td>
<td>43510</td>
<td>42540</td>
</tr>
<tr>
<td>Energy purchase cost (CNY)</td>
<td>90720</td>
<td>86410</td>
<td>85410</td>
</tr>
<tr>
<td>Carbon emission cost (CNY)</td>
<td>17790</td>
<td>12390</td>
<td>11410</td>
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<tr>
<td>Penalty cost relevant to wind and solar abandonment (CNY)</td>
<td>37040</td>
<td>29220</td>
<td>20260</td>
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</tbody>
</table>

Figure 8: Comparison of IES renewable energy accommodation in two modes.
Abbreviations

P2G: Power to gas
IES: Integrated energy system
EC: Electrolytic cell
CHP: Combined heat and power
HT: Hydrogen tank
GT: Gas storage tank
MR: Methane reactor
MT: Microturbine
GB: Gas boiler
P_{EC,t}: Output power of EC at time \( t \)
P_{P2G,t}: Input power of P2G at time \( t \)
\eta_{EC,t}: Conversion efficiency of EC at time \( t \)
P_{H.ch,t}/P_{H.dis,t}: Charging/ discharging energy of HT at time \( t \)
W_{H,t}: Hydrogen storage capacity in HT at time \( t \)
P_{NG,t}: The power of P2G equipment to produce methane at time \( t \)
P_{MR,t}: Input power of MR at time \( t \)
P_{MT,t}: Output power of MT at time \( t \)
P_{MT.h,t}: Electrical heat-generating power of MT at time \( t \)
\eta_{MT,h,t}: Efficiency of MT
P_{GB,h,t}: Heat-generating rate of GB at time \( t \)
P_{w,t}/P_{pv,t}: The actual output power of wind power/photovoltaic at time \( t \)
V_{p,t}: The thermodrastic ratio of CHP unit at time \( t \)
C_{EC}: The carbon trading cost of IES
E_{EC}: The total carbon emissions within the time of system optimization
E_{all,i}: The total carbon emissions of IES energy equipment
\lambda_{i}: The carbon emission coefficient of the energy equipment \( i \)
P_{i,c,t}: Output power of the energy equipment \( i \) at time \( t \)
E_{P2G}: Total carbon dioxide consumption in the P2G process
P_{ip,t}: The power of the tie-line power between the IES and power grid at time \( t \)
P_{g,t}: The amount of gas purchased at time \( t \)
\alpha_{EC}/\alpha_{EC}: The efficiency coefficients of EC
P_{P2G,min}/P_{P2G,max}: Upper/lower input power of P2G
\Delta P_{P2G,max}/\Delta P_{EC,min}: Upper/lower limit of the ramp power
\eta_{H.ch,h}/\eta_{H.dis,h}: The charging/discharging efficiency of HT
P_{H.ch,max}/P_{H.dis,max}: The upper charging/ discharging limit of HT at time \( t \)
W_{H,max}/W_{H,min}: The upper/lower capacity of HT
\eta_{MR}: Conversion efficiency of MR
P_{MR,min}/P_{MR.max}: The upper/lower input power of MR
\Delta P_{MR.max}/\Delta P_{MR.min}: The upper/lower ramp power of MR
P_{MT}: Rated output power of MT
\Delta P_{MT.d}/\Delta P_{MT.i}: The electricity/heat conversion efficiency of MT at rated power
\eta_{MT,hr}: Conversion efficiency of GB
P_{GB}: Rated output power of GB
\Delta P_{GB,i}/\Delta P_{GB.d}: The upper/lower ramp power of GB
P_{w,t}: The predictive upper output power of wind power at time \( t \)
P_{p,t}: The predictive upper output power of photovoltaic at time \( t \)
V_{L}: The thermodrastic ratio of load at time \( t \)
K_{c}: Load demand of electricity/heat/natural gas/hydrogen at time \( t \)
P_{p}: The carbon emission quota of energy devices in IES
N: The number of carbon emission equipment
\lambda_{i}: The carbon emission quota coefficient of the energy equipment \( i \)
K_{b}: The carbon emission coefficients in production/transportation/consumption
K_{s,i}/K_{k,h,i}/K_{H,i}: The carbon dioxide consumption coefficient for synthesis of methane
K_{i}: The high heat value of methane relative to mass
M_{CO}/M_{CH}_{4}: The molecular masses of carbon dioxide/methane
H_{all,i}: Electricity price purchased by power network
K_{s,i}/K_{k,h,i}/K_{H,i}: The price of electricity/heat/natural gas/hydrogen at time \( t \)
H_{w}/H_{pv}: The operating cost of CHP units/GB/EC/GT
P_{w,i}/P_{pw,i}: The penalty coefficients for wind power/photovoltaic curtailment
P_{ip,i}/P_{ip,p}: The predicted wind power at time \( t \)
P_{ip,i}/P_{ip,p}: The predicted photovoltaic at time \( t \)
P_{ip, max}/P_{ip, min}: The upper/lower tie-line power between the IES and power network
P_{p, max}/P_{p, min}: The upper/lower limit of the energy purchased by IES from natural gas network.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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References


