Design analysis of distributed energy systems with different energy storage devices under a flexible scheduling strategy

Zhichao Liu¹, Yiqun Pan¹, Baohong Jin²
¹School of Mechanical Engineering, Tongji University, Shanghai 201804, China
²College of Civil Engineering, Hunan University, Changsha, Hunan 410082, China
*Correspondence: Yiqun Pan, yiqunpan@tongji.edu.cn. Tel: 13301856961

Abstract
With the widespread application of distributed energy, distributed energy systems (DESs) equipped with energy storage devices are showing superior scheduling and energy-saving effects. To quantitatively analyze the impact of energy storage devices on the design of DESs, three DESs with different configurations of energy storage devices are established. This study also adopts a bi-level dynamic optimization model to optimize the design of three DESs. The optimized design results show that energy storage devices can significantly increase the design capacity of combined heating and power units and absorption chillers while reducing the design capacity of ground source heat pumps and gas boilers, particularly the thermal energy storage (TES) device. And both the TES device and the electricity energy storage (EES) device can reduce the operating cost, carbon tax and total cost of the DESs to varying degrees, but the EES device’s influence on carbon tax and total cost is less apparent than that of the TES device. To some extent, this study illustrates the influence of TES and EES devices on the optimal design of DESs and provides a few useful references for the configuration of energy storage devices.

Highlights
- Different energy storage devices are equipped in different systems.
- A dynamic optimization model is adopted instead of a static equipment model.
- A bi-level optimization model is used to optimize the design of distributed energy system.
- Intelligent optimization algorithm combined with classical mathematical programming theory is used to solve this model.

Introduction
Distributed energy systems (DESs) with high flexibility are expected to become an important way to solve the sustainable development of energy. However, with the maturity of renewable energy application technologies and the application of plug-in hybrid electric vehicles, the supply and demand of energy in DESs has increased greatly uncertainty (Andervazh et al., 2020). The development of DESs equipped with energy storage devices can effectively solve the fluctuation of energy supply and realize the stable and efficient operation of the DESs. Due to the coupling relationship of a variety of heterogeneous energy sources in DESs, the modeling idea of an Energy Hub (EH) was proposed in order to more clearly describe energy conversion and supply-demand balance relationship (Wei et al., 2021). Meanwhile, in order to improve the extensibility of the DESs and the portability of the model, an EH modeling method based on graph theory was proposed (T. Ma et al., 2019). On the basis of the above modeling ideas, T. Ma et al. (2018) adopted the static equipment model to establish a coupled system optimization model with the total system cost as the optimization objective. Since the static model cannot reflect the off-design characteristics of the equipment, a dynamic system optimization model was established by Deng et al. (2022). Based on the work proposed above, Mansouri et al. (2022) established a dynamic multi-objective optimization model for the optimization design of power-gas (P-G) technology. At the same time, in order to realize the decoupling of design and operation, following electric load (FEL), following heat load (FTL) and following hybrid electric-heat load (FHL) strategies based on the role of the combined heating and power (CHP) units are proposed (Mago et al., 2010; Mago & Chamra, 2009). Wang et al. (2022) explored the influence of different energy storage devices on DESs optimization results based on above strategies. Since it is difficult to realize flexible scheduling of DESs with relatively fixed operation strategies, X. Luo et al. (2021) formulated the operation strategies of DESs with the method of decision tree. To avoid the problem of machine learning methods relying on historical load data, a bi-level optimization model is proposed. X. Luo et al. (2018), based on this model, optimized the independent renewable energy system with the total system cost as the optimization goal, and found that the energy storage device could improve the penetration rate of renewable energy in the DESs. Although the bi-level optimization model is widely used in the optimization design and operation analysis of DESs equipped with energy storage devices, it is rarely used to explore the influence of different energy storage devices on the DESs optimization design and operation scheduling.

Therefore, this paper takes a public building in Changsha City as an example to establish three distributed energy systems with different energy storage devices, and carries out optimization design and operation scheduling analysis.
Distributed energy system modeling

Basic structure of DESs

The DESs can not only make full use of renewable energy, but also meet the heating, cooling, and electricity needs of users. In the DESs shown in Figure 1, the input energy includes: regional renewable energy (solar energy, geothermal energy), grid electricity, and municipal gas. The energy conversion equipment in the system converts the above input energy into output energy required by the user side, mainly including the transformer, photovoltaic (PV) arrays, CHP unit, gas boiler, ground source heat pump (GSHP), and absorption chiller (ABC).

Figure 1. The basic structure of DESs.

At the same time, the power, heating, and cooling hubs are introduced for energy balance with the concept of EH. In addition, in order to explore the influence of different types of energy storage devices on the optimal design and operation performance of the system, three DESs with different storage devices are designed, and the configurations are shown in Table 1.

Table 1. DESs with different energy storage devices.

<table>
<thead>
<tr>
<th>System name</th>
<th>TES device</th>
<th>EES device</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>System 2</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>System 3</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

Equipment Mathematical Model

The operation of energy conversion equipment in DESs is affected by many parameters. In order to simplify the mathematical model of the equipment, the commonly used black box model based on energy efficiency is adopted in this study. Meanwhile, the dynamic device model is adopted to describe the operating performance of the device more accurately. Different from the energy conversion equipment, the source-load duality of energy storage devices allows it to achieve the time-series transfer of energy to meet the supply-demand balance of DESs. Therefore, the mathematical model of energy storage devices can be expressed by the charging and discharging states and power. The specific expressions are shown in Table 2.

Table 2. DESs Equipment dynamic model.

<table>
<thead>
<tr>
<th>Items</th>
<th>Mathematical models</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>[ P_{pe} = A_{pe} \cdot \eta_{pe} \cdot 1 \cdot (1 - 0.005 \times (t_a - 25)) ]</td>
</tr>
<tr>
<td>CHP</td>
<td>[ \begin{align*} P_{\text{chp},e} &amp;= \text{COP}<em>{\text{chp}} \cdot \eta</em>{\text{chp},e} \ P_{\text{chp},h} &amp;= \text{COP}<em>{\text{chp}} \cdot (1 - \eta</em>{\text{chp},e} - \eta_{\text{loss}}) \end{align*} ]</td>
</tr>
<tr>
<td>CHP</td>
<td>[ \eta_{\text{chp},e} = \begin{cases} 0 &amp; \text{PLR}<em>{\text{chp}} &lt; 0.2 \ a_0 + a_1 \cdot \text{PLR}</em>{\text{chp}} + a_2 \cdot \text{PLR}<em>{\text{chp}}^2 &amp; \text{PLR}</em>{\text{chp}} \geq 0.2 \end{cases} \eta_{\text{loss}} = 0.08 ]</td>
</tr>
<tr>
<td>CHP</td>
<td>[ \text{PLR}<em>{\text{chp}} = P</em>{\text{chp},e}/P_{\text{chp},e} \cdot a_0=0.1, a_1=0.4, a_2=-0.2 ]</td>
</tr>
<tr>
<td>GB</td>
<td>[ \begin{align*} P_{gb} &amp;= g_b + \eta_{gb} \ \text{PLR}<em>{gb} &amp;= \text{Pou}</em>{gb}/P_{gb},\text{PLF} = \eta_{gb}/\eta_{gb,r} \end{align*} ]</td>
</tr>
<tr>
<td>GSHP</td>
<td>[ \begin{align*} \text{PLR}<em>{\text{gsfh}} &amp;= \text{COP}</em>{\text{gsfh}} \cdot \text{PLF}<em>{\text{gsfh}} \quad \text{PLF}</em>{\text{gsfh}} = \text{COP}<em>{\text{gsfh}} \cdot \eta</em>{\text{gsfh,r}} \ \text{COP}<em>{\text{gsfh,r}} &amp;= 4.5 \ \text{PLR}</em>{\text{gsfh}} &amp;= P_{\text{gsfh}}/(0.2137 \cdot \text{PLR}<em>{\text{gsfh}}^2 + 1.119 \cdot \text{PLR}</em>{\text{gsfh}} + 0.1007) \end{align*} ]</td>
</tr>
<tr>
<td>ABC</td>
<td>[ \begin{align*} \text{PLF}<em>{\text{abc}} &amp;= \text{PLR}</em>{\text{abc}}/(0.75 \cdot \text{PLR}<em>{\text{abc}}^2 + 0.0195 \cdot \text{PLR}</em>{\text{abc}} + 0.213) \ \eta_{\text{abc,r}} &amp;= 0.9 \ 0.2 \leq \text{PLR}_{\text{abc}} \leq 1 \end{align*} ]</td>
</tr>
</tbody>
</table>

Bi-level optimization model

Energy storage devices will affect the equipment cost and operational performance of the system. In this paper, a bi-level dynamic optimization model is established to analyze the influence of energy storage devices on the optimal design and operation of DESs. The upper-level optimized configuration model takes the system’s total cost as the optimization objective to determine the equipment capacity of DESs. The lower-level optimal scheduling model takes the operating cost as the optimization objective to determine the reasonable scheduling scheme. As shown in Figure 2, based on outdoor design parameters, this paper firstly calculates the design load of the building by Energy Plus. Then the constraints of the upper-level and lower-level optimization models are established according to the design loads and the EH model. The constraints of the upper-level model include the maximum equipment capacity constraint and the design load in winter. And the constraints of the lower model include energy conservation and equipment operating power. Finally, the design load, outdoor parameters and economic parameters are imported into the bi-level optimization model for solving to obtain the equipment capacity of three DESs under the optimization scenarios.
Carbon tax compensation is one of the main means to limit greenhouse gas emissions. In the DESs of this paper, CO\(_2\) emissions mainly come from grid electricity and gas.

\[
C_{\text{tax}} = \theta_{\text{tax}} \sum_{t=1}^{24} (P_{\text{grid}}(t) \cdot \lambda_{\text{CO}_2,\text{grid}} + G_{\text{gas}}(t) \cdot \lambda_{\text{CO}_2,\text{gas}}) \tag{3}
\]

Where \(\theta_{\text{tax}}\) is the carbon tax price; \(\lambda_{\text{CO}_2,\text{grid}}\) and \(\lambda_{\text{CO}_2,\text{gas}}\) are the equivalent CO\(_2\) emissions of coal power and gas, which are 0.968 kg/kWh and 0.220 kg/kWh, respectively (Zhang et al., 2020); \(P_{\text{grid}}(t)\) and \(G_{\text{gas}}(t)\) are the consumption of grid power and gas at time \(t\), which can be obtained from the lower-level scheduling model.

**Optimization variables and constraints**

In the optimal configuration model, the optimization variable is the capacity of the candidate equipment. Considering the equipment installation conditions and building loads, the design capacity of the equipment needs to meet the following constraints.

\[
0 \leq C_{\text{cap}} \leq C_{\text{max}} \tag{4}
\]

Where \(C_{\text{max}}\) is the maximum design capacity of equipment \(k\), whose value is usually the maximum value of the corresponding load.

In addition, considering that the design daily load in summer is taken as the design parameter in this study, in order to meet the winter load demand at the same time, it is necessary to ensure that the maximum heat production of the system is greater than the maximum heat load.

\[
P_{\text{max}}_{\text{grid,h}} + P_{\text{max}}_{\text{chp,h}} + P_{\text{max}}_{\text{ghb,h}} \geq L_{\text{user,h}} \tag{5}
\]

Where \(P_{\text{max}}_{\text{grid,h}}\) is the maximum heat production of the GSHP; \(P_{\text{max}}_{\text{chp,h}}\) is the maximum heat production of the CHP unit; \(P_{\text{max}}_{\text{ghb,h}}\) is the maximum heat production of the gas boiler; and \(L_{\text{max}}_{\text{user,h}}\) is the maximum heating load in winter.

**Lower-level optimal scheduling model**

**Optimization objective**

The lower-level optimization scheduling model takes the minimum system operating cost as the optimization objective, which mainly comes from the electricity purchase cost of the grid and gas cost:

\[
\min C_{\text{op}} = \sum_{t=1}^{24} (P_{\text{grid}}(t) \cdot \vartheta_{\text{grid}}(t) + G_{\text{gas}}(t) \cdot \vartheta_{\text{gas}}) \tag{6}
\]

Where \(\vartheta_{\text{grid}}\) is the time-of-use (TOU) electricity price; and \(\vartheta_{\text{gas}}\) is the gas price.

**Optimization variables and constraints**

In the optimal scheduling model, the operating power of the equipment is taken as the variable to optimize. The operating power of the equipment should not only meet the constraints of the upper-level equipment capacity, but also meet the constraints of the supply and demand balance of the EH.

1. Equipment operating power constraints

(1) Energy conversion devices
The operating power of the energy conversion equipment is affected by the capacity constraints of the upper-level equipment and the start-up and shutdown of the equipment which is in the following ranges:

\[
\begin{align*}
0 & \leq P_{\text{grid}}(t) = \text{Load} + \text{Discharge} - \text{Generation} \\
0 & \leq P_{\text{ch},k}(t) = \underbrace{u_k \cdot \gamma_{\text{ch},k} \cdot S_k}^\text{Minimum} \\
0 & \leq P_{\text{dis},k}(t) = \underbrace{1 - u_k \cdot \gamma_{\text{dis},k} \cdot S_k}^\text{Maximum} \\
\alpha_k \cdot S_k & \leq S_k(t) \leq \alpha_k \cdot S_k \\
\end{align*}
\]  
(7)

Where \( P_{\text{grid}} \) is the part-load ratio of equipment \( k \); \( P_{\text{ch},k} \) is the minimum part-load ratio for the start-up of equipment \( k \); and \( P_{\text{dis},k} \) and \( P_{\text{ch},k} \) are the minimum and maximum output power of equipment \( k \) in the operating state.

2. Energy balance constraint

The three energy hubs of power, heating, and cooling established in this paper must ensure the balance of energy supply and demand.

\[
\begin{align*}
P_{\text{grid}}(t) + P_{\text{ch},k}(t) + P_{\text{dis},k}(t) & = L_{\text{user},k}(t) + P_{\text{gs},k}(t) + P_{\text{abc},k}(t) \\
P_{\text{gs},k}(t) & = L_{\text{user},k}(t) + P_{\text{abc},k}(t) + P_{\text{ch},k}(t) \\
\end{align*}
\]  
(8)

Where \( P_{\text{gs},k} \) is the use electricity consumption of GSHP; \( P_{\text{gs},k} \) is the cooling power of GSHP; \( P_{\text{abc},k} \) is the cooling power of ABC; \( P_{\text{abc},k} \) is the heat consumption of ABC; and \( P_{\text{abc},k} \) is the heat production of the gas boiler.

Model Solving

Classical mathematical programming theory, intelligent optimization algorithm and their combination are commonly used to solve the bi-level optimization model (Guo et al., 2022; Ju et al., 2022). Since the off-design characteristics of the equipment are considered in the lower-level scheduling model, the non-convex and nonlinear characteristics of the model are enhanced, which makes it difficult to apply the classical mathematical programming theory to solve. As shown in Figure 3, a classical mathematical programming theory is used in this study to solve the lower-level scheduling model, and a genetic algorithm is used to solve the upper-level optimization model. In the solution process of the lower-level model, this study first carries out piecewise linearization on the performance curve of the equipment, and then calls the Gurobi’s non-convex solver to solve it. The minimum operation cost and operation energy consumption obtained from the lower-level model will be uploaded to the upper-level model to calculate the total system cost, and the upper-level model will transfer the optimized equipment capacity to the lower-level model to constrain its scheduling. Through multiple iterations, the optimal configuration and scheduling schemes of three DESs can be obtained.

Case studies

Design parameters

In the optimization process of DESs, outdoor meteorological parameters, design load, energy price and carbon tax price need to be input. Therefore, this paper takes a public building in Changsha as an example for analysis. After determining the outdoor design parameters shown in Table 5 and Figure 4(a), Energy Plus is used to calculate the design load of the building and the results are shown in Figure 4(b). Meanwhile, as shown in Table 6, the equipment capacity optimization range can be determined according to the calculated design load. Finally, this paper determined the energy and carbon tax prices shown in Table 7 according to relevant literature.

Table 5. Air conditioning outdoor design temperature and groundwater temperature (Jin et al., 2023)

<table>
<thead>
<tr>
<th>Design conditions</th>
<th>design dry-bulb temperature</th>
<th>Groundwater temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>36°C</td>
<td>17°C</td>
</tr>
<tr>
<td>Winter</td>
<td>−1°C</td>
<td>11°C</td>
</tr>
</tbody>
</table>

Figure 3. Solution flow chart of the bi-level optimization model.
found that the TES device can significantly increase the capacity of CHP unit and ABC in the DESs, and reduce the capacity of the GSHP and boiler. The impact of the EES device on the DESs is similar to that of the TES device, but its effect is less than that of the TES device.

Table 8. System equipment capacity.

<table>
<thead>
<tr>
<th>System name</th>
<th>Cap_{chp}</th>
<th>Cap_{gb}</th>
<th>Cap_{gs}</th>
<th>Cap_{abs}</th>
<th>Cap_{tes}</th>
<th>Cap_{ees}</th>
<th>A_{pv}</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>1122</td>
<td>205</td>
<td>1780</td>
<td>520</td>
<td>0</td>
<td>0</td>
<td>1500</td>
</tr>
<tr>
<td>System 2</td>
<td>1265</td>
<td>0</td>
<td>1682</td>
<td>618</td>
<td>961</td>
<td>0</td>
<td>1500</td>
</tr>
<tr>
<td>System 3</td>
<td>1272</td>
<td>0</td>
<td>1678</td>
<td>622</td>
<td>947</td>
<td>0</td>
<td>1500</td>
</tr>
</tbody>
</table>

As can be seen from Figure 5, equipment capacity affects both equipment cost and operational performance of the DESs. Due to the difference in equipment capacity, the equipment cost of System 2 and System 3 is higher than that of System 1, with increase rates of 5.7% and 17.8%, respectively. Contrary to the change of equipment cost, the operating cost, carbon tax and total cost of System 2 and System 3 are all less than those of System 1. The operating cost, carbon tax and total cost reduction rates of System 2 compared with System 1 are 2.9%, 5.5% and 1.5% respectively, and the operating cost reduction rates of System 3 compared with System 1 is as high as 5.7%. However, due to the high equipment cost, the total cost reduction rates of System 3 compared with System 1 is only 1.75%. It can be seen that both the TES and EES devices can reduce the operating cost, carbon tax and total cost of the DESs to varying degrees, but the effect of the EES device on the carbon tax and total cost is not as excellent as that of the TES device.

Table 7. Energy price and carbon tax.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit price (CNY/kWh)</th>
<th>Time period</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>0.3275</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1.224</td>
<td>20:00-23:00</td>
<td>Peak periods</td>
</tr>
<tr>
<td></td>
<td>0.911</td>
<td>9:00-12:00, 16:00-20:00</td>
<td>High periods</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.68</td>
<td>8:00-9:00, 12:00-16:00</td>
<td>Flat periods</td>
</tr>
<tr>
<td></td>
<td>0.306</td>
<td>0:00-8:00, 23:00-24:00</td>
<td>Valley periods</td>
</tr>
<tr>
<td>Carbon tax</td>
<td>0.3 (CNY/kgCO2)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Optimization results

Based on the above inputs, this paper optimizes the DESs under three scenarios, and the optimization results are shown in Table 8. Compared with system 1, it can be

Figure 5. Cost differences between the three systems.

Analysis of results

Since the scheduling results of the system are directly affected by the utilization costs of different types of energy, this paper firstly calculates the electric load scheduling process of System 1 and the part-load rate of the CHP unit. It can be seen from Figure 6 that, in the low period of electricity prices, the power purchased from the grid is much higher than the power generated by the CHP unit, and the CHP unit is in the lowest load state. In other periods, the CHP unit is basically operating at full load. It can be seen that the power cost from the grid in the low period of electricity prices is less than the power generation cost of the CHP unit, and the other periods are the opposite.
After determining the utilization costs of different types of energy, this paper compares the scheduling processes of cooling, heating and electric loads of System 1 and System 2 under design conditions, and the results are shown in Figure 7. As can be seen from the cooling load scheduling process in Figure 7(a), the cooling load of the two systems is met by the GSHP in the low period of electricity prices, while it is met by the GSHP and ABC in other periods. As shown the heat load scheduling process in Figure 7(b), the heating load of System 1 cannot be fully met by the CHP unit, so gas boiler is used for assist. In System 2, due to the scheduling of the TES device, it can ensure that the CHP unit undertakes all the heating load, which can make more efficient use of gas and avoid the use of gas boiler. Combined with the electrical load scheduling process in Figure 7(c), it can be seen that the electrical load of the GSHP in System 2 is less than that in system 1. There are two main reasons: In the cooling load scheduling process of Figure 7(a), the cooling power of the GSHP in System 2 is less than in System 1 because of the equipment capacity difference; Meanwhile, as seen in Figure 8, the operating efficiency of the GSHP in System 2 is higher than that in System 1. Due to the lower cooling power and higher operating efficiency of the GSHP, the electrical load of System 2 is less than that of System 1. Under the dual influence of lower electric load of the GSHP and larger capacity of the CHP unit, the power purchased from the grid in other periods of electricity price for System 2 is significantly less than that for System 1. It can be determined that the TES device can improve the operating efficiency of the GSHP and reduce the power load. At the same time, combined with higher power generation of the CHP unit, it will reduce the electricity purchased from the grid during other periods of electricity prices, and ultimately reduce the carbon tax and operating cost of the DESs.

Figure 6. Electric load supply–demand relationship and part-load rate of CHP unit in System 1.

Figure 7. Scheduling process of System 1 and System 2 in design conditions.

Figure 8. The efficiency of GSHP in System 1 and System 2.
design conditions to analyze the effect of the EES device. Combined with the design capacity of the two DESs, it can be found that the smaller GSHP capacity makes the electric load of System 3 slightly less than that in System 2; And the larger capacity of the CHP unit makes the power generation of the CHP unit in System 3 slightly larger than that in System 2. Under the above influence, the carbon tax of System 3 is finally slightly less than that of System 2. In addition, by comparing the power purchased from the grid in the two DESs during different periods, it can be observed that the power purchased from the grid in the peak and high periods of the System 3 is obviously less than that of the System 2 due to the scheduling of the EES device, which also directly reduces the operating cost of the System 3.

Both the TES device and the EES device can increase the capacity of the CHP unit and ABC in DESs, reduce the capacity of GSHP, and avoid the use of gas boilers, especially the TES device. Due to the difference in equipment capacity, the equipment cost of System 2 and System 3 is higher than that of System 1, with an increased rate of 5.7% and 17.8%, respectively. It can be seen that the EES device can significantly increase the equipment cost of the DESs.

With the lower capacity of GSHP and the scheduling of the TES device, the operation efficiency of the GSHP in System 2 is improved, and the power purchased from the grid of the DESs is lower. Therefore, the operating cost, carbon tax and total cost of System 2 are all less than that of System 1, with a reduction rate of 2.9%, 5.5% and 1.5% respectively.

The scheduling function of the EES device reduces the power purchased from the grid in the peak and high periods of electricity price for System 3, which makes the operating cost of System 3 significantly less than that of System 2, with a reduction rate of 2.8%.

Figure 9. Electricity scheduling process of system 2 and system 3.

Conclusion

The purpose of this study is to investigate the impact of energy storage devices on the optimal design of DESs. Therefore, a bi-level dynamic optimization model is used to optimize three DESs with different energy storage devices. Based on the optimization results, the effects of different energy storage devices are analyzed, and the main conclusions are summarized as follows:

Both the TES device and the EES device can increase the capacity of the CHP unit and ABC in DESs, reduce the capacity of GSHP, and avoid the use of gas boilers, especially the TES device. Due to the difference in equipment capacity, the equipment cost of System 2 and System 3 is higher than that of System 1, with an increased rate of 5.7% and 17.8%, respectively. It can be seen that the EES device can significantly increase the equipment cost of the DESs.

With the lower capacity of GSHP and the scheduling of the TES device, the operation efficiency of the GSHP in System 2 is improved, and the power purchased from the grid of the DESs is lower. Therefore, the operating cost, carbon tax and total cost of System 2 are all less than that of System 1, with a reduction rate of 2.9%, 5.5% and 1.5% respectively.

The scheduling function of the EES device reduces the power purchased from the grid in the peak and high periods of electricity price for System 3, which makes the operating cost of System 3 significantly less than that of System 2, with a reduction rate of 2.8%.

References


