Dispatching Strategy for Low-Carbon Flexible Operation of Park-Level Integrated Energy System

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Abstract: In the face of the dual crisis of energy shortages and global warming, the vigorous development of renewable energy represented by wind-solar energy is a significant approach towards achieving energy transition, carbon peaking, and carbon neutrality goals. Targeting the park-level integrated energy system (PIES) with high penetration of wind-solar energy, we propose a day-ahead dispatching strategy that takes into account the flexible supply and the reward-punishment ladder-type carbon trading mechanism (RPLTCTM). Firstly, RPLTCTM and carbon capture equipment (CCE) are considered in the dispatching model, and the mechanism of coordinated operation of CCE and RPLTCTM is explored to further improve the system’s ability to restrain carbon emissions. Secondly, power-based flexibility indicators (PFIs) are adopted to quantitatively evaluate the flexibility supply, and based on the load demand response characteristics, the dispatchable resources on the load side are guided to improve the system’s operation flexibility. On this basis, a multi-objective optimal dispatching model that takes into account the carbon emission cost, energy cost, and flexibility supply are constructed, and the original problem is transformed into a mixed-integer single-objective linear problem through mathematical equivalence and flexibility cost. Finally, simulation examples validate that the economy, flexibility, and low-carbon level of the dispatching plan can be synergistically improved by the proposed strategy.

Keywords: park-level integrated energy system (PIES); reward-punishment ladder-type carbon trading mechanism (RPLTCTM); carbon capture equipment (CCE); power-based flexibility indicators (PFIs)

1. Introduction

Energy has been an essential material basis for the survival of human society. For the past few years, fossil energy has been recklessly exploited to drive economic development, resulting in not only resource depletion but also increasingly severe environmental pollution. A worldwide crisis of energy shortages and global warming is taking place [1–6]. In coping with this crisis and increasing the proportion of non-fossil energy in the energy system, renewable energy has received widespread attention. Compared with conventional power generation from fossil fuel, renewable energy technology meets the needs of the new energy system with its clean, environmentally friendly, and energy-recyclable characteristics. Meanwhile, integrated energy systems based on the synergistic optimization of multiple heterogeneous energy sources and multi-energy complementation are also attracting considerable attention as effective carriers of renewable energy [7–10].
The core of PIES is the holistic allocation and complementation of energy, which can fully facilitate the production and consumption of energy while improving the economic efficiency of the system. There has been growing research on the optimal dispatching of PIES in recent years. A dynamic model of natural gas flow characteristics and linearized natural gas models was proposed in [11] through the method of characteristics. Simulation results showed that this method can effectively improve the utilization rate of new energy. In [12], a two-stage robust optimization model for integrated energy systems was constructed based on an uncertain environment to reduce interaction fluctuations between the system and the main grid while improving integrated energy systems’ adaptability to renewable energy sources. In terms of low-carbon research, the development of carbon capture technology and the proposal of a carbon trading mechanism provided solutions for low-carbon operation of integrated energy systems, which have been extensively studied in the existing literature. A Stackelberg game model for integrated energy systems containing carbon capture devices verified such devices’ ability to reduce carbon emissions of the systems, which was proposed in [13]. In [14], an operation model of carbon capture plants with storage tanks was proposed to verify their advantages in promoting wind power consumption and reducing carbon emissions. In [15], a low-carbon economic model of integrated energy systems considering stepped carbon trading was proposed. Their analysis of simulation examples showed that the carbon emissions and operating costs of the system were significantly reduced under the ladder-type carbon trading mechanism. Based on the same mechanism, [16] constructed a reward-punishment carbon trading cost model to constrain the system’s carbon emissions. The simulation verified RPLTCTM’s ability to constrain the system’s carbon emissions. The aforementioned references demonstrate that both CCE and RPLTCTM can effectively reduce a system’s carbon emissions. Nevertheless, the inherent synergistic operation mechanism of CCE and RPLTCTM has been explored less in the existing literature.

The concept of system operation flexibility has been defined by institutions, such as the International Energy Agency. Many existing studies focus on the operation flexibility of energy systems. In [17], an integrated energy system optimal allocation method that considers the flexibility requirements was designed to strike a balance between operation economy and safety in system planning. In [18], a mathematical expression of the flexibility demand was derived, and a mathematical model of the operation flexibility of gas and heat supply networks was established. This analysis showed that the system operation cost can be effectively reduced by improving the operation flexibility. To mitigate the uncertainty in renewable energy and load, [19] proposed an integrated energy system optimization strategy considering multi-energy flexibility. This analysis validated that the proposed model can enhance the system’s operation flexibility and mitigate system power fluctuations by coordinating the unit output. A joint operation market mechanism with flexible regulation of resources was designed in [20], which showed that this method was highly effective in improving the level and flexibility of new energy consumption. The majority of existing studies have employed controllable devices to regulate system flexibility, with very few considering the introduction of load-side dispatchable resources for this task. Furthermore, the existing literature has seldom considered the synergistic optimization of low-carbon levels, economy, and flexibility in the dispatching objectives of PIES.

To address the above problems, this paper introduces CCE based on RPLTCTM to explore the synergistic operation mechanism of both, with the aim of further improving the system’s carbon control capability. In terms of flexibility, PFI is adopted to quantify the system flexibility, and the load-side dispatchable resources are introduced to enhance system operation flexibility based on the load demand response characteristics. In addition, an optimal dispatching model that takes into account the carbon emission cost, operation cost, and flexibility supply power is constructed to derive a rational day-ahead dispatching plan to accomplish the synergistic optimization of these three aspects.
2. Flexible Supply of PIES

There is no consensus on the definition of flexibility in power systems. According to a vast amount of the existing literature, the flexibility of system dispatching should be subject to the shortage of real-time system power due to the system’s adjustability and uncertainty factor [21]. In PIES, the system’s adjustability mainly comes from the available power of the flexibility resources, whereas the uncertainty factor is primarily manifested in the difficulty of accurately predicting the wind-solar access power. In this paper, the flexibility of the dispatching process is defined as the system’s ability to leave a flexibility margin during the period of day-ahead dispatching through rational planning of flexibly controllable resources, and to quickly adapt to fluctuating changes to guarantee balanced power in real-time in the event of wind-solar power fluctuations.

Flexibility resources include all means of coping with random variations in power. The access to flexibility resources allows PIES to promptly and accurately regulate energy [22]. In addition, the variation in the output power of the flexibility resources is directional, and so is the corresponding flexibility, which is divided into upward and downward flexibility, and is defined as Equation (1):

\[
\begin{align*}
 f_{\text{up},t} &= \min \left( \frac{P_{\text{max}}^m - P_{\text{m}}^t}{\Delta t}, \frac{\Delta P_{\text{up}}^m}{\Delta t} \right) \\
 f_{\text{down},t} &= \min \left( \frac{P_{\text{m}}^t - P_{\text{min}}^m}{\Delta t}, \Delta P_{\text{down}}^m \right)
\end{align*}
\]

where \( m \) is a collection of flexibility resources, \( P_{\text{m}}^t \) is the power of flexible resource, \( f_{\text{up},t} \) and \( f_{\text{down},t} \) are the upward and downward flexibility, \( \Delta P_{\text{up}}^m \) and \( \Delta P_{\text{down}}^m \) are the climbing upper and lower power of the flexibility resource, and \( \Delta t \) is the time interval for dispatching.

For a more concrete analysis of the flexibility of each controllable resource, PFI is adopted to evaluate the flexibility level of controllable resources. PFI refers to the ratio of the range of adjustable power output of the equipment to its rated power at a certain moment, which provides flexible resources with the ability to cope with power variations. In PIES, the adjustability of the system primarily comes from the micro-turbine (MT), energy storage system (ESS), load-side flexibility resources (LFRs), etc. The following indicator is used to evaluate the upward and downward flexibility supply of Equation (1) as Equation (2):

\[
\begin{align*}
 F_{\text{MTup},t} &= \left( \frac{P_{\text{max}}^e - P_{\text{max}}^t}{P_{\text{MT}}} \right) / P_{\text{MT}} \\
 F_{\text{MTdown},t} &= \left( \frac{P_{\text{min}}^t}{P_{\text{MT}}} \right) \\
 F_{\text{LFRup},t} &= \left( \frac{P_{\text{max}}^e + P_{\text{max}}^N}{P_{\text{max}}^e} - P_{\text{L}}^t \right) / \left( \frac{P_{\text{max}}^e}{P_{\text{max}}^e} + P_{\text{HIL}}^t \right) \\
 F_{\text{ESSup},t} &= \min \left( \frac{P_{\text{ESSup}}^t}{P_{\text{ESSch}}^t}, \frac{P_{\text{ESSch}}^t}{P_{\text{ESSup}}^t} \right) \\
 F_{\text{ESSdown},t} &= \min \left( \frac{P_{\text{ESSch}}^t}{P_{\text{ESSup}}^t}, \frac{P_{\text{ESSup}}^t}{P_{\text{ESSch}}^t} \right)
\end{align*}
\]

where in period \( t \), \( F_{\text{MTup},t} \), \( F_{\text{LFRup},t} \), and \( F_{\text{ESSup},t} \) are the upward PFI of MT, LFR, and ESS; \( F_{\text{ESSdown},t} \) and \( F_{\text{MTdown},t} \) are the downward PFI of ESS and MT; \( P_{\text{max}}^e \) and \( P_{\text{min}}^e \) are the maximum and minimum electrical power of MT; \( P_{\text{max}}^N \) and \( P_{\text{min}}^N \) are the rated capacity of MT and ESS; \( P_{\text{max}}^{\text{ESSch}} \) and \( P_{\text{max}}^{\text{ESSdc}} \) are the maximum charging and discharge electric power of ESS; \( S_{\text{ESS}}^\text{max} \) and \( S_{\text{ESS}}^\text{min} \) are the maximum and minimum capacities of ESS, respectively; \( \eta_{\text{ESSch}} \) and \( \eta_{\text{ESSdc}} \) are the charging and discharging efficiencies of ESS; \( S_{\text{ESS}}^\text{HIL} \) is the storage energy of ESS; and \( P_{\text{max}}^\text{HIL} \) and \( P_{\text{max}}^\text{HIL} \) are the maximum values of the interrupted electrical load and heat load.

3. Modeling of PIES

In this paper, a conventional integrated energy system with wind turbines (WTs) and photovoltaic (PV) units is employed into which CCE and RPLTCTM are introduced. The power consumption and electric load demand of CCE in the system are supplied by power sales from the grid, WT, PV units, and MT. The heat load demand is supplied by electric boilers (EBs) and gas boilers (GBs). The gas sales from the grid are supplied partly to
MT and partly to GB. The load side considers the time-shiftable and interruptible integrated demand response. The ESS and heat storage devices (HSDs) form the energy buffering part of the system. The load side considers the time-shiftable and interruptible integrated demand response. The energy coupling state is detailed in Figure 1.

![Internal structure diagram of PIES](image)

**Figure 1.** Internal structure diagram of PIES.

### 3.1. Renewable Generation Models

The constraint in Equation (3) guarantees that the power output of the WT system at a certain time obeys the Weber distribution with two parameters [23]:

$$f_{FG}(P_{WT}) = \begin{cases} \frac{C_{1}}{\Gamma(\alpha + \beta)} \left\{ \left( 1 + \frac{h_{WT}}{P_{N}} \right) V_{c} \right\}^{C-1} \times \exp \left\{ - \left( 1 + \frac{h_{WT}}{P_{N}} \right) V_{c} \right\}^{C} & 0 \leq P_{WT} \leq P_{N} \\ 0 & \text{else} \end{cases} \quad (3)$$

where $v$ is the actual wind speed of the fan, $v_{ci}$ is the cut-in wind speed, $v_{co}$ is the cut-out wind speed, $v_{N}$ is the rated air speed of the fan, $P_{WT}$ and $P_{N}$ are the output power and rated capacity of WT, and $C$ and $K$ are the shape and scale parameters of the Weber distribution, $h = v_{N}/v_{ci} - 1$.

The constraint in Equation (4) guarantees that the output of the PV system in a day obeys a two-parameter beta distribution [24]:

$$f_{GG}(P_{PV}) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \left( \frac{P_{PV}}{P_{PV_{max}}} \right)^{\alpha-1} \left( 1 - \frac{P_{PV}}{P_{PV_{max}}} \right)^{\beta-1} \quad (4)$$

where $\Gamma$ is the incomplete gamma function, $\alpha$ and $\beta$ are the shape factor, and $P_{PV}$ and $P_{PV_{max}}$ are the output electric power of $PV$ and its maximum.

### 3.2. Energy Conversion Equipment Models

#### 3.2.1. Micro Gas Turbine

$MT$ is a small thermal generator characterized by a flexible configuration, small investment cost, and low pollution. The corresponding mathematical model is presented in Equation (5):

$$\begin{cases} p_{c,t}^{MT} = p_{c,t}^{MT} \leq p_{c,t}^{MT_{max,e}} \\ p_{min,e}^{MT} \leq p_{c,t}^{MT} \leq p_{max,e}^{MT} \end{cases} \quad (5)$$

where in period $t$, $p_{c,t}^{MT}$ and $p_{c,t}^{MT_{max,e}}$ are the electric power and gas power of $MT$, $p_{min,e}^{MT}$ and $p_{max,e}^{MT}$ are the maximum and minimum limits of the electric power, and $\eta^{MT}_{c,t} \leq g_{2e}$ is the electrical efficiency of $MT$. 
3.2.2. Gas Boiler

GB expands in the boiler by burning natural gas, and the generated heat causes the walls of the boiler to absorb and heat up. The model is shown in Equation (6):

\[
\begin{align*}
P_{GB}^{h,t} &= P_{GB}^{g,t} \zeta_{GB}^2 h \\
P_{GB}^{min,h} &\leq P_{GB}^{h,t} \leq P_{GB}^{max,h}
\end{align*}
\]

where in period \( t \), \( P_{GB}^{h,t} \) and \( P_{GB}^{g,t} \) are the heating power and gas power of GB, \( P_{GB}^{min,h} \) and \( P_{GB}^{max,h} \) are the maximum and minimum limits of the electric power, and \( \zeta_{GB}^2 h \) is the thermal efficiency of GB.

3.2.3. Electric Boiler

EB heats up water to high-pressure steam by consuming electrical energy, and is characterized by low pollution, a small footprint, and high operating efficiency. The corresponding mathematical model is shown in Equation (7):

\[
\begin{align*}
P_{EB}^{h,t} &= P_{EB}^{e,t} \zeta_{EB}^2 h \\
P_{EB}^{min,e} &\leq P_{EB}^{h,t} \leq P_{EB}^{max,e}
\end{align*}
\]

where in period \( t \), \( P_{EB}^{h,t} \) and \( P_{EB}^{e,t} \) are the heating power and electric power of EB, \( P_{EB}^{min,e} \) and \( P_{EB}^{max,e} \) are the maximum and minimum limits of the heating power, and \( \zeta_{EB}^2 h \) is the thermal efficiency of EB.

3.2.4. Energy Storage Equipment

Based on the similar modeling form of ESS and HSD, the model is defined by Equation (8):

\[
S_{CN}^{t} = S_{CN}^{t-1} + \left( P_{CN ch}^{t} \eta_{CN ch} - P_{CN dc}^{t} / \eta_{CN dc} \right) \Delta t
\]

The above ESS and HSD are included in CN.

3.3. Integrated Demand Response (IDR)

Flexible loads can be divided into shiftable loads (SLs) and interruptible loads (ILs) according to their operating characteristics.

IL refers to a load that can be interrupted to relieve the pressure of energy system operations during periods of energy supply shortages or high prices [25]. The interruptible electrical loads are expressed as Equation (9):

\[
\begin{align*}
P_{IL}^{t} \min &\leq P_{IL}^{t} \leq P_{IL}^{t} \max \\
24 \sum_{t=1}^{N_{max}} U_{t,cut} \leq N_{cut} \max
\end{align*}
\]

where in period \( t \), \( P_{IL}^{t} \) is the interruption power of the load, \( P_{IL}^{t} \max \) and \( P_{IL}^{t} \min \) are the maximum and minimum limits of the interrupting load, \( U_{t,cut} \) is the binary variable for whether the load is interrupted or not, and \( N_{cut} \max \) is the number of interruptions allowed in the dispatching cycle.

SL implies that the equipment has a flexible start-up time, and the overall energy usage is unchanged when scheduling the equipment time [26]. SL is given as Equation (10):

\[
\begin{align*}
P_{SL}^{t} \min &\leq P_{SL}^{t} \leq P_{SL}^{t} \max \\
24 \sum_{t=1}^{N_{max}} p_{SL}^{t} \ &= 0
\end{align*}
\]

where in period \( t \), \( P_{SL}^{t} \) is a time-shiftable load and \( P_{SL}^{t} \max \) and \( P_{SL}^{t} \min \) are the maximum and minimum limits of the interrupted load.
3.4. CCE

Carbon capture and storage (CCS) has been a popular low-carbon technology. CCS separates and compresses the CO\(_2\) component from the gas produced by the emission source, before transporting it to a proper storage site. CCS can be divided into pre-combustion capture, post-combustion capture, and oxygen-enriched combustion [27]. According to [28], post-combustion capture only requires placement of the capture equipment downstream of the gas emission without altering the original system operation process. With simple principles, convenient cooperation with the unit, and mature technology, post-combustion capture has been widely used in practice. The power consumption of carbon capture comes from two sources, namely fixed power consumption and operating power consumption. The fixed power consumption is independent of the operating state of the equipment and can be considered as a constant. The operating power consumption is due to CCE performing solvent regeneration and compression in the process of capturing CO\(_2\) [29]; yet, the amount of CO\(_2\) treated does not exceed the total CO\(_2\) emissions [30]. The above process is shown in Equation (11):

\[
\begin{align*}
P_{\text{CCS}}^e, t &= P_{\text{CCS}, GD}^e, t + P_{\text{CCS}, YX}^e, t \\
P_{\text{CCS}, YX}^e &= \zeta_{\text{CCS}} Q_{\text{LX}, \text{CO}_2}^e, t \\
0 &\leq Q_{\text{LX}, \text{CO}_2}^e, t \leq Q_{\text{CO}_2}^e \\
Q_{j, \text{CO}_2}^{\text{CO}_2} &\leq Q_{j, \text{CO}_2}^{\text{CO}_2} \mu_{\text{CCS}}
\end{align*}
\]

where in period \(t\), \(P_{\text{CCS}}^e\) is the total electric power consumption in CCE, consisting of fixed power consumption \(P_{\text{CCS}, GD}^e\) and operation power consumption \(P_{\text{CCS}, YX}^e\); \(Q_{\text{LX}, \text{CO}_2}^e\) is the ideal value of captured CO\(_2\) at CCE; \(\zeta_{\text{CCS}}\) is the power consumption factor for ideal capture; \(Q_{\text{CO}_2}^e\) is the total carbon emission in the system; \(Q_{j, \text{CO}_2}^{\text{CO}_2}\) is the final captured CO\(_2\) at CCE; and \(\mu_{\text{CCS}}\) is the capture rate of CCE.

3.5. RPLTCTM

If the carbon emission exceeds the benchmark, a quota must be purchased; otherwise, the financial penalty must be applied. If the enterprise has an abundant emission quota, it is sold to make a profit. RPLTCTM sets different prices for different carbon emission intervals, which further constrains the number of carbon emissions. Its mechanism model is as follows:

1. Ideal quota model

Considering PIES in this paper, carbon emissions stemming from GB and MT, which are defined by Equation (12), and quota are taken in the form of unpaid quota:

\[
\begin{align*}
E_{\text{PIES}} &= E_{\text{MT}} + E_{\text{GB}} \\
E_{\text{MT}} &= \rho_e \sum_{i=1}^{24} p_{MT}^{i, e} \\
E_{\text{GB}} &= \rho_h \sum_{i=1}^{24} p_{GB}^{i, h}
\end{align*}
\]

where \(E_{\text{PIES}}, E_{\text{MT}},\) and \(E_{\text{GB}}\) are the carbon emission allowances of PIES, MT, and GB; and \(\rho_e\) and \(\rho_h\) are the carbon quota of the electricity and heat equipment.

2. RPLTCTM model

\(F_{\text{CO}_2}^{\text{cost}}\) is the cost of carbon trading. A positive \(F_{\text{CO}_2}^{\text{cost}}\) means that the actual carbon emission exceeds the carbon quota value and carbon quota must be purchased; the higher the carbon emission value, the higher the cost of the transaction. A negative \(F_{\text{CO}_2}^{\text{cost}}\) suggests that the carbon quota value is higher than the actual carbon emission, and the enterprise can sell the carbon quota for profit. Equations (13) and (14) describe the total amount of carbon
captured by CCE and the actual value of carbon trading, respectively. The RPLTCTM model is defined by Equation (15):

\[
F_{\text{CO}_2}^\text{cost} = \sum_{i=1}^{24} Q_{t}^{S/J,\text{CO}_2}
\]

\[
E_{\text{PJES}}^{S/J} = E_{\text{PJES}}^{S/J} - E_{\text{CO}_2}^{S/J}
\]

\[
E_{\text{PJES}}^{S/J,E} = E_{\text{PJES}}^{S/J} - E_{\text{CO}_2}^{S/J}
\]

\[
F_{\text{CO}_2}^\text{cost} = \left\{ \begin{array}{ll}
-k(1+2\lambda)(E_{\text{PJES}} - E_{\text{PJES}}^{S/J}) & \text{if } E_{\text{PJES}} \leq E_{\text{PJES}}^{S/J} - 1 \\
-k(1+2\lambda)l - k(1+\lambda)(E_{\text{PJES}} - E_{\text{PJES}}^{S/J}) & \text{if } 1 < E_{\text{PJES}}^{S/J} \leq E_{\text{PJES}} - 1 \\
k(E_{\text{PJES}}^{S/J} - E_{\text{PJES}}), E_{\text{PJES}} < E_{\text{PJES}}^{S/J} \leq E_{\text{PJES}} + l & \text{if } E_{\text{PJES}} + l < E_{\text{PJES}}^{S/J} \leq E_{\text{PJES}} + 2l \\
k(2+\mu)l + k(1+2\mu)(E_{\text{PJES}} - E_{\text{PJES}}^{S/J} - 2l) & \text{if } E_{\text{PJES}} + 2l < E_{\text{PJES}}^{S/J}
\end{array} \right.
\]

where \(E_{\text{PJES}}^{S/J}\) is the actual amount of carbon emissions from PIES, \(E_{\text{PJES}}^{S/J}\) is the total amount of carbon captured by CCE, \(E_{\text{PJES}}^{S/J,E}\) is the amount of carbon emissions from the PIES system captured by CCE, \(l\) is the carbon trading interval step, \(k\) is the price of carbon emissions trading, and \(\mu\) and \(\lambda\) are the penalty and reward coefficient, respectively.

4. Problem Formulation

4.1. Objective Function

The economic objective \(F_1\) is:

\[
F_1 = \sum_{t=1}^{24} \omega_{P_{\text{ PJES}}}^{buy}(P_{\text{ PJES}}^{buy} - P_{\text{ PJES}}^{sell}) + \sum_{i=1}^{T} \omega_{Q_{\text{ PJES}}}^{buy} + F_{\text{CO}_2}^\text{cost} + \sum_{i=1}^{24} (\omega_{\text{ PJES}}^{E_{\text{ PJES}}} + \omega_{\text{ PJES}}^{H_{\text{ PJES}}} + \omega_{\text{ PJES}}^{\text{ECC}} + k_{\text{MT}}^\text{SJ} S_{\text{MT}}^\text{SJ})
\]

where in period \(t\), \(P_{\text{ PJES}}^{buy}, P_{\text{ PJES}}^{sell}, P_{\text{ PJES}}^{buy}\) are the purchased electricity in PIES, sold electricity, and purchased gas, respectively; \(P_{\text{ PJES}}^{E_{\text{ PJES}}}\) and \(P_{\text{ PJES}}^{H_{\text{ PJES}}}\) are the interrupted electric and heating power; \(\omega_{\text{ PJES}}^{E_{\text{ PJES}}}\) and \(\omega_{\text{ PJES}}^{H_{\text{ PJES}}}\) are the price of electricity and gas; \(\omega_{\text{ PJES}}^{\text{ECC}}\) is the power consumption price for CCE; and \(k_{\text{MT}}^\text{SJ}\) and \(S_{\text{MT}}^\text{SJ}\) are the start-up cost and start-up variables for MT.

The flexibility objective is \(F_2\).

As the flexibility resources are continuously tapped, the decision makers of the system are faced with the dilemma of how to allow full adjustability of the flexibility resources to meet the flexibility demand at a smaller cost while ensuring the real-time power balance. In this paper, the flexibility power is optimized in the dispatching objective such that the controllable resources, which can leave a certain flexibility margin, fulfill and meet the flexibility demand of the succeeding period maximally:

\[
F_2 = \sum_{t=1}^{24} (f_{\text{ESSup},t} + f_{\text{ESSdown},t}) + \sum_{t=1}^{24} (f_{\text{LFRup},t} + f_{\text{MTup},t})
\]
4.2. Constraint Conditions

(1) Power supply system constraint:
\[
P_t^{buy} + E_{VRE,t} + P_{ESSdc,t} - P_{ESSch,t} + P_{MT,t} + P_{ESL,t} = P_{EB,t} + P_{CS,t} + P_{EIL,t} + P_{HSL,t}, \forall t
\]  
(18)

where in period \( t \), \( P_{ESSdc,t} \) and \( P_{ESSch,t} \) are the output charge and discharge electric power of ESS; and \( P_{EIL,t} \) is the PIES electrical load demand.

(2) Heating system constraint:
\[
P_t^{HSDdc} - P_t^{HSDch} + P_t^{GB} + P_{HL,t} = P_t^{HL} - P_t^{HSDl}, \forall t
\]  
(19)

where in period \( t \), \( P_t^{HSDdc} \) and \( P_t^{HSDch} \) are the output charge and discharge heating power of HSD; \( P_t^{HL} \) is the PIES heat load demand.

(3) Gas supply system constraint:
\[
P_{g,t}^{buy} = P_{g,t}^{GB} + (P_{e,t} + R_{e,t}) / e_{g2e}, \forall t
\]  
(20)

(4) Power constraint:
\[
\begin{align*}
P_{min,g,t}^{buy} & \leq P_{g,t}^{buy} \leq P_{max,g,t}^{buy} \\
u_{buy,e,t} P_{min,e,t}^{buy} & \leq P_{e,t} \leq u_{buy,e,t} P_{max,e,t} \\
u_{sell,e,t} P_{sell} & \leq P_{e,t} \leq u_{sell,e,t} P_{sell} \\
u_{sell,e,t} + u_{buy,e,t} & \leq 1
\end{align*}
\]  
(21)

where \( P_{max,g,t}^{buy} \) and \( P_{min,g,t}^{buy} \) are the maximum and minimum limitation of gas purchase; \( P_{max,e,t}^{buy} \) and \( P_{min,e,t}^{buy} \) are the maximum and minimum limitation of electric power purchase; \( P_{max,e,t}^{sell} \) and \( P_{min,e,t}^{sell} \) are the maximum and minimum limitation of electric power sales; and \( u_{buy,e,t} \) and \( u_{sell,e,t} \) are a binary variable for the state of power purchase and sale.

(5) ESS and HSD constraint:
\[
\begin{align*}
S_{CN}^t = \beta_{CN_{Nch}}^{t} + \beta_{CN_{Ndc}}^{t} = 1 \\
0 & \leq P_{CN_{Nch}}^{t} \leq \beta_{CN_{Nch}}^{t} P_{CN_{Nch}}^{max,t} \\
0 & \leq P_{CN_{Ndc}}^{t} \leq \beta_{CN_{Ndc}}^{t} P_{CN_{Ndc}}^{max,t} \\
S_{min}^{CN} & \leq S_{CN}^t \leq S_{max}^{CN} \\
\sum_{t=1}^{24} P_{CN_{Nch}}^{t} - \beta_{CN_{Nch}}^{t} P_{CN_{Nch}}^{max,t} & \leq N_{CN-c} \\
\sum_{t=1}^{24} P_{CN_{Ndc}}^{t} - \beta_{CN_{Ndc}}^{t} P_{CN_{Ndc}}^{max,t} & \leq N_{CN-d}
\end{align*}
\]  
(22)

where in period \( t \), \( S_{CN}^t \) is the capacity of the energy storage device, \( \beta_{CN_{Nch}}^{t} \) and \( \beta_{CN_{Ndc}}^{t} \) is the charge-discharge state binary variable; and \( N_{CN-c} \) and \( N_{CN-d} \) are the maximum numbers of charging and discharging.

4.3. Solution Process

In summary, this paper establishes the PIES optimal dispatching model through a holistic consideration of the synergy between CCE and RPLTCTM, quantitative analysis of the flexibility supply, and LFR guidance. In the dispatching model, the aforementioned flexibility objective is incorporated into the economic objectives in terms of cost, where the cost coefficients are selected with reference to the standby service prices in the electricity
market [31]. The overall model is a mixed integer linear programming (MILP) model that can be solved stably using a Cplex online solver. The solution process is shown in Figure 2.

![Solution Process Diagram](image)

**Figure 2.** The solution process.

### 5. Case Study

#### 5.1. Parameter Settings

To verify the feasibility of the proposed optimal dispatching strategy, PIES in certain areas is adopted as a simulation example. The system is the coupling of a six-node distribution grid, a six-node gas grid, and a four-node heat grid. The grid structure is illustrated in Figure 3, where MT is connected to the electrical grid’s fourth node and the gas grid’s second node; GB is connected to the gas grid’s third node and the heat grid’s third node; CCE is connected to the electrical grid’s third node; and EB is connected to the electrical grid’s sixth node and the heat grid’s fourth node.

![Test System Diagram](image)

**Figure 3.** The PIES test system.

PIES’s equipment operating parameters are shown in Table 1.
Table 1. Equipment Parameters.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Parameters</th>
<th>Values</th>
<th>Equipment</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESS</td>
<td>Charge/Discharge efficiency</td>
<td>0.9</td>
<td>GB</td>
<td>thermal efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>lower/upper limit of capacity</td>
<td>40/360 kW</td>
<td></td>
<td>Installed capacity</td>
<td>300 kW</td>
</tr>
<tr>
<td></td>
<td>Installed capacity</td>
<td>400 kW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The upper limit of output of storage</td>
<td>120 kW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSD</td>
<td>Charge/Discharge efficiency</td>
<td>0.9</td>
<td>EB</td>
<td>thermal efficiency</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>lower/upper limit of capacity</td>
<td>30/270 kW</td>
<td></td>
<td>Installed capacity</td>
<td>300 kW</td>
</tr>
<tr>
<td></td>
<td>Installed capacity</td>
<td>300 kW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The upper limit of output of storage</td>
<td>80 kW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MT</td>
<td>electrical efficiency</td>
<td>0.83</td>
<td>Purchase electricity</td>
<td>upper limit</td>
<td>1000 kW</td>
</tr>
<tr>
<td></td>
<td>Installed capacity</td>
<td>500 kW</td>
<td>Selling electricity</td>
<td>upper limit</td>
<td>1000 kW</td>
</tr>
</tbody>
</table>

The time-sharing tariff for PIES’ electric power is shown in Table 2.

Table 2. TOU ELECTRICITY PRICES.

<table>
<thead>
<tr>
<th>Periods</th>
<th>Specific Time Period</th>
<th>Electricity Prices (¥/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak period</td>
<td>8:00–11:00, 18:00–21:00</td>
<td>0.804</td>
</tr>
<tr>
<td>Flat period</td>
<td>6:00–7:00, 12:00–17:00</td>
<td>0.550</td>
</tr>
<tr>
<td>Valley period</td>
<td>1:00–5:00, 22:00–24:00</td>
<td>0.295</td>
</tr>
</tbody>
</table>

Flexible load parameters: the electric and heat loads have both SL and IL characteristics, accounting for 15% of the total load; Stepped carbon trading parameters in [11]; CCE parameters: \( u_{CCS} = 0.9, \xi_{CCS} = 1.5 \) kW/kg; Interruption compensation parameters: \( \omega_{el} = 0.8 \) \$/kW-h, \( \omega_{hl} = 0.6 \) \$/kW-h.

Wind-Solar expected output values and load data are shown in Figure 4:

Figure 4. WT and PV power output and electricity and heat load demands.

5.2. Optimal Operating Scheme

Figure 5 demonstrates the optimal operation strategy of the PIES electric power supply system. It shows that the system reduces PIES’ power purchase from the grid by increasing the MT output and reducing the carbon capture power in the event of high time-of-use electricity prices of the grid, thereby improving the PIES operation economy. Moreover,
the controllable load variable indicates the unconsumed power of new energy in PIES. It is evident in Figure 5 that the controllable load power remains at 0 throughout the dispatching cycle, which implies that the renewable energy is 100% consumed by the PIES system with no curtailment of wind or solar generation.

Figure 5. PIES optimal electrical power supply plan.

Figure 6 shows the optimal operation strategy of the heating equipment within PIES. It can be observed that, as an electrical energy replacement device, EB bears most of the heat load during the period of 1:00–4:00, which reduces the heating power of GB in this duration while bringing down the consumption of gas in PIES. In contrast, during the peak hours of the electricity price, gas is consumed by GB to supply most of the heat load, reducing the heating power of EB while lowering the consumption of electric power. This analysis shows that GB and EB have complementary characteristics in meeting the heat demand of PIES while further reducing the operating cost of PIES by improving the utilization of electric energy during low-load hours.

Figure 6. PIES optimal heating plan.

5.3. Multidimensional Demand Response Characterization

Figure 7 illustrates that the electric load curve after the demand response has a significant peak-shaving effect. During 12:00–15:00, there is more renewable energy power,
and the electrical load shifts the load from other periods to this period by the nature of the time shifting, with load spikes after the demand response. The interruptible load is subject to the impact of the compensation price, which further improves the PIES system operation economy by reducing the load demand through interruptions in times of high energy generation cost.

![Figure 7. Comparison of the PIES electric load operation plans before and after IDR.](image)

Figure 7. Comparison of the PIES electric load operation plans before and after IDR.

Figure 8 depicts the heat load operation scheme of PIES before and after the demand response. After the demand response, the heat load moves into the intermediate periods so that it operates in coordination with the energy supply characteristics. This analysis shows that the electric and heat loads have coupling characteristics. In the energy supply period, the heat load reduces the load demand in other periods by moving in and distributing energy rationally. In contrast, in the event of an energy shortage, the heat load further reduces the heat load demand in that period by interrupting part of the heat load based on moving out, which ensures balance between the supply and demand while reducing the system’s cost of purchasing electricity and heating.

![Figure 8. Comparison of the PIES thermal load operation schedule before and after IDR.](image)

Figure 8. Comparison of the PIES thermal load operation schedule before and after IDR.
5.4. Low-Carbon Analysis

Figure 9 suggests that under the constraint of RPLTCTM, PIES simultaneously generates carbon emissions in both ladder 1 and ladder 2 only when the outputs of MT and GB are high while the carbon emissions of PIES in ladder 3 during the dispatching cycle are zero. In addition, PIES reasonably allocates carbon quota in periods of high carbon emissions by the system. This analysis shows that RPLTCTM effectively limits the carbon emissions of PIES.

![Figure 9. PIES optimal carbon emission plan.](image)

To verify the low-carbon nature of the collaborative carbon control strategy, this section sets up four scenarios based on the constructed model to further investigate the effects of factors such as the carbon trading mechanism, carbon capture device, and carbon quota mechanism on the operation of PIES. The specific scenarios are set up as follows:

- **Scenario I**: Stepped carbon trading mechanism considered; carbon capture and carbon quota not considered.
- **Scenario II**: Stepped carbon trading mechanism considered, carbon capture considered, and carbon quota not considered.
- **Scenario III**: Stepped carbon trading mechanism considered, carbon capture not considered, and carbon quota considered.
- **Scenario IV**: Stepped carbon trading mechanism considered; carbon capture and carbon quota both considered.

It can be seen in Table 3 that scenario IV can better realize low-carbon economic operation of PIES by jointly considering the stepped carbon trading mechanism, carbon capture, and carbon quota mechanism. Most significantly, compared with Scenario I, which only considers the stepped carbon trading mechanism, Scenario IV can reduce PIES carbon emissions and operating costs by 45% and 3%, respectively. Meanwhile, compared with Scenario II and Scenario III, it can be noticed that the carbon capture equipment can dramatically reduce the system carbon emissions by 31.8%.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Operating Costs/¥</th>
<th>Carbon Emission/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario I</td>
<td>5479.63</td>
<td>3926.35</td>
</tr>
<tr>
<td>Scenario II</td>
<td>5444.77</td>
<td>2471.82</td>
</tr>
<tr>
<td>Scenario III</td>
<td>5329.63</td>
<td>3626.35</td>
</tr>
<tr>
<td>Scenario IV</td>
<td>5294.77</td>
<td>2171.82</td>
</tr>
</tbody>
</table>

Table 3. Analysis of the low-carbon characteristics of PIES.
5.5. Flexibility Analysis

PFI is the combined result of the adjustability of multi-equipment participation. It can be seen in Figure 10 that PFI is zero in the period of 11:00–18:00 when the electricity price is off-peak and the MT utilization is high. The presence of load-side demand response capability partially contributes to the flexibility margin of the system and enhances the flexibility of the system operation. This analysis shows that multiple resources have complementary characteristics in terms of system operation flexibility indexes and the participation of multiple resources gives rise to improved system operation flexibility compared to the conventional practice of only considering controllable units.

![Figure 10. PIES flexibility index of each equipment.](image)

As a load-side dispatchable resource, the load demand response characteristic effectively improves PFI. Meanwhile, it impacts the system economics. To further evaluate the impact of the degree of the integrated demand response on PIES operation, the test shown in Figure 11 was conducted.

![Figure 11. Impact of the comprehensive demand response ratio on PIES.](image)
As illustrated in Figure 11, as the integrated demand share increases, the PIES system operating cost first gradually decreases, and then slowly increases when the share exceeds 25%. In contrast, the flexibility of the demand response operation consistently increases. As far as the operating cost is concerned, the integrated demand response changes the power consumption plan of the original load, which makes the load distribution more consistent with the power supply characteristics while lowering the PIES operating cost. Nevertheless, as the demand response grows further, the load that the system is free to allocate increases. The final power consumption plan is no longer changed, and the operating cost does not decrease. In addition, the increase in the demand response share further enhances the flexibility of the system, and the cost incurred from simultaneously maintaining system flexibility and performing system optimization increases the total operating cost.

5.6. Renewable Energy Penetration Analysis

Figure 12 demonstrates the impact of renewable energy penetration on the PIES operating cost. It is evident that with the increase in penetration, the PIES operating cost shows a gradual decline. This occurs because as the renewable energy increases, the output of the controllable units gradually decreases. Meanwhile, the carbon emission and the amount of purchased power drop, resulting in a gradual decrease in the PIES operating cost.

![Figure 12](image_url)

**Figure 12.** Influence of renewable energy penetration on PIES operation.

Furthermore, this figure also highlights the effect of renewable energy penetration on the PIES carbon emissions. It is observed that with increasing penetration, the PIES carbon emissions exhibit a fluctuating downward trend. This is due to the high percentage of renewable energy, which reduces the output of MT and provides a clean source of power supply to CCE, resulting in a rapid decrease in carbon emissions as the carbon trading mechanism works in tandem with CCE. It is worth mentioning that the spike in carbon emissions is due to the increased power output of GB and thus meets the heat load demand.

6. Conclusions

In this paper, we constructed a PIES day-ahead dispatching model to effectively achieve the synergistic optimization of PIES flexibility, low carbon levels, and economy by devising the optimal dispatching strategy. The model proposed in this paper is applicable to integrated energy systems with a high proportion of renewable energy. Compared with the current study, the carbon control strategy of RPLTCTM in cooperation with CCE proposed in this paper can reduce carbon emissions and operation costs by 45% and 3%, respectively, compared with only RPLTCTM. Meanwhile, a comparison between setting
CCE and carbon quota scenarios verified that CCE has a decent low-carbon operation effect. Furthermore, PFI established in this paper can be coupled with the dispatching objective and involved in the analysis of the dispatching process. Moreover, the influence of the integrated load-side demand response on the flexibility and economy of the system was analyzed, and a more ideal economy and flexibility were found to occur at around a proportion of 25%.

**Author Contributions:** Conceptualization, Q.M.; methodology, L.G.; software, G.Z.; validation, S.L.; formal analysis, G.Z.; investigation, L.X.; resources, R.W.; data curation, K.H.; writing—original draft preparation, Q.M. and G.Z.; writing—review and editing, L.G.; visualization, S.J.; supervision, L.G.; project administration, Q.M.; funding acquisition, G.Z., K.H. and S.J. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work is supported by National Natural Science Foundation of China (No.52007130), Science and Technology Project of SGCC (No.5400-20211257A-0-5-SF).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Some or all data, models or code that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**