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Multi-Time-Scale Low-Carbon Economic Dispatch Method for Virtual Power Plants Considering Pumped Storage Coordination

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Abstract: Low carbon operation of power systems is a key way to achieve the goal of energy power carbon peaking and carbon neutrality. In order to promote the low carbon transition of energy and power and the coordinated and optimized operation of distributed energy sources in virtual power plants (VPP), this paper proposes a framework for collaborative utilization of pumped storage–carbon capture–power-to-gas (P2G) technologies. It also constructs a multi-time scale low carbon economic dispatch model for VPP to minimize the internal resource operation cost of VPP in each time period. During the intraday scheduling stage, the day-ahead scheduling results as the planned output and the energy flow is then dynamically corrected at a short-term resolution in the framework. This allows for the exploration of the low-carbon potential of each aggregation unit within the virtual power plant. The results of the simulation indicate that the strategy and model proposed in this paper can effectively encourage the consumption of renewable energy sources, promote the low-carbon operation of power system power, and serve as a valuable reference for the low-carbon economic operation of the power system.

Keywords: virtual power plant; pumped storage; carbon capture; multi-timescale optimization

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1. Introduction

According to the State Council of China, it is crucial to focus on the implementation of the key work division outlined in the 'Government Work Report'. Specifically, there is a need to prioritize the work of carbon peaking and carbon neutralization in many application areas such as industrial and transportation fields [1,2] To achieve this, an action plan for carbon emission peaking should be formulated before 2030. Currently, fossil fuels remain the primary source of power globally. However, there is a growing consensus to promote low-carbon electricity and increase the use of renewable clean energy sources to create a more sustainable energy network in Ref. [3]. Distributed renewable energy sources are geographically dispersed and operate independently, which can result in inefficient resource allocation due to a lack of coordination and unity. However, the virtual power plant also presents an opportunity for innovative solutions to address these challenges in Ref. [4].

The transition from fossil fuel power generation to cleaner and low-carbon power generation requires a significant amount of time. As a result, the carbon emissions produced by fossil fuel power generation have become the primary obstacle in achieving the 'dual carbon' goal. According to 'China's Carbon Neutrality Research Report Before 2060', the development of new energy sources and carbon capture and storage (CCS) technology is the key to achieving carbon neutrality in Ref. [5]. The utilization of CCS technology in fossil fuel power plants can significantly reduce their carbon emissions and improve their flexibility in operation, thus facilitating the consumption of wind power in Refs. [6,7]. However, the storage cost associated with carbon dioxide is high and there is a risk of leakage. To effectively mitigate these issues, reusing the captured CO_2 is the most effective method in Ref. [8]. P2G technology provides a promising solution for the reuse of CO_2, while also enabling energy conversion and load time-space translation. The stored natural gas can be utilized to consume renewable clean energy and manage peak-shaving and valley-filling of electric load.

Currently, research on carbon emission reduction often focuses on two independent methods: CCS and P2G in Refs. [9–12]. Studies on carbon capture units typically examine capital gains, operation decisions, and optimal control in Refs. [13–15]. The recent literature has analyzed the advantages of carbon capture power plants participating in peak regulation and suggests that these plants can serve as an ideal supporting power source for wind power in Refs. [16,17]. Additionally, wind and photovoltaic power generation can also power the CO_2 capture system, ultimately reducing the cost of generating electricity for carbon capture plants. In the previous literature, carbon capture units were introduced as a means of reducing carbon emissions. A multi-regional VPP optimal scheduling model under the energy market was proposed in Ref. [18]. Ref. [19] presented a low-carbon economic dispatch model for electric–gas systems that included carbon capture systems and wind power. This model also factored in the emission cost based on carbon tax into the objective function. Both of these studies confirm that carbon capture units are a more environmentally friendly and flexible alternative to traditional coal-fired power plants.

P2G devices have been extensively researched as coupling elements between power grids and gas networks, as well as controllable energy-consuming response devices. The working principle and performance of P2G, along with its economic evaluation, have been introduced in Refs. [20,21]. Additionally, Refs. [22,23] have constructed a carbon capture power plant and P2G system framework, which use CO_2 captured by the carbon capture power plant as a raw material for the production of natural gas to reuse CO_2. The fast response of P2G energy conversion and transmission also enhances the flexibility of the system. It has been suggested in Ref. [24] that P2G can be used to transfer power from peak hours to off-peak hours, thereby easing the pressure on the power supply. These studies confirm that P2G plays a positive role in clean energy consumption, relief of environmental pressure, and economic improvement.

As the penetration of renewable energy generation in VPP increases, it also provides a new direction for solving the problem of energy consumption in the operation of carbon capture-P2G systems. However, the variability in wind and photovoltaic power generation can affect the reliability of the VPP power supply and reduce the low-carbon economic benefits of the carbon capture-P2G system in Refs. [25–27]. Currently, there are two solutions to this problem. The first approach is to implement a multi-time scale rolling optimization strategy to compensate for forecast errors and increase the consumption of renewable energy generation. The second solution involves using fast adjustment devices like energy storage power plants and carbon capture power plants to manage fluctuations in renewable energy. Since the prediction accuracy of renewable energy generation and load improves with shorter time scales in Ref. [28], it is relevant to study multi-timescale dispatching strategies in order to correct the deviation of dispatching plans with long time scales from more accurate prediction conditions. In addition, pumped storage (PS) units are becoming increasingly important for peak regulation in power systems due to their rapid output response, flexible adjustment methods, and environmental benefits. Current research focuses on the joint operation mode of wind power and pumped storage in Refs. [29–31]; there is a need to consider the coordinated operation of pumped storage units and carbon capture-power-to-gas systems on multiple time scales.

In summary, based on existing research, this paper proposes a framework for collaborative utilization of pumped storage—carbon capture—P2G technologies. It also constructs a multi-time scale low carbon economic dispatch model for VPP to minimize the internal resource operation cost of VPP in each time period. During the intraday scheduling stage, the day-ahead scheduling results as the planned output and the energy flow is then dynamically corrected at a short-term resolution in the framework. This allows for the exploration of the low-carbon potential of each aggregation unit within the virtual power plant. Finally, the validity of the proposed method is verified by example analysis.

2. Pumped Storage—Carbon Capture—P2G VPP Multi-Timescale Low Carbon Operation Framework

2.1. VPP System Architecture

The carbon capture-to-gas synergistic operation framework extends the flexibility of the carbon capture plant by regulating the energy consumption of the carbon capture system and by supplying the captured CO_2 to the P2G plant for methane production. However, the ability of this mechanism to generate greater benefits is limited by the level of load demand at the current moment. It is difficult to support the increasing load peak-to-valley difference from year to year and the regulation demand caused by the anti-peaking characteristic of scaled renewable energy. On this basis, this paper introduces pumped storage units with the characteristics of flexible conversion of operating conditions and fast adjustment of output, with the starting point of improving the flexible adjustment capability of VPP. This paper proposes a pumped storage-carbon capture-electricity-to-gas synergistic utilization framework, as shown in Figure 1.

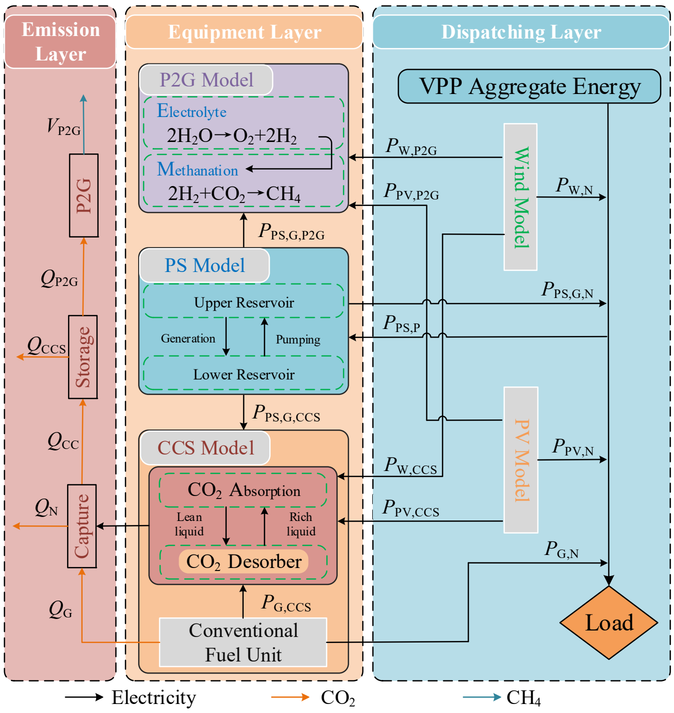

Figure 1. VPP system architecture.

In the emission layer, the only source of carbon emissions from the VPP system is the carbon capture plant. A portion of the CO_2 is captured by the carbon capture system and another portion of the CO_2 is emitted into the atmosphere. The captured CO_2 can be used as a feedstock for the production of methane in the P2G plant and the excess can be disposed of by carbon sequestration. Where Q_G is the amount of CO_2 directly generated by the carbon capture unit for power generation. Q_N is the amount of CO_2 emitted directly into the atmosphere. Q_{CC} is the amount of CO_2 captured by the carbon capture system.

Q_{CCS} is the amount of CO_2 sequestered. Q_{P2G} is the amount of CO_2 consumed by the P2G unit. V_{P2G} is the volume of methane produced by the P2G unit.

At the equipment level, wind power, photovoltaic power generation, and pumped storage units can provide energy consumption for carbon capture systems and P2G equipment. Pumped storage units, as auxiliary regulation resources, can take advantage of the spatial and temporal complementarity of different energy resources in terms of power and energy consumption.

At the dispatch level, the VPP aggregation energy is supplied by wind power, photovoltaic power, pumped storage unit power, and carbon capture plant output. When the pumped storage unit is in pumping mode, the energy consumption is supplied by the VPP aggregation energy. Where $P_{W,N}$ and $P_{PV,N}$ are the feed-in power for wind and PV, respectively; $P_{W,P2G}$ and $P_{PV,P2G}$ are the energy consumption provided by wind and PV for P2G, respectively; $P_{W,CCS}$, $P_{PV,CCS}$, and $P_{G,CCS}$ are the energy consumption provided by wind power, photovoltaic power, and carbon capture plant for the carbon capture system, respectively; $P_{PS,G,P2G}$, $P_{PS,G,CCS}$, and $P_{PS,G,N}$ are the energy consumption and feed-in power provided by the pumped storage units to the P2G and carbon capture system. $P_{PS,P}$ is the pumping power of the pumped storage unit as an energy consuming device.

The energy flow based on the framework of synergistic utilization is more flexible to match the change in renewable energy output, the energy consumption of the carbon capture system, and the energy consumption of the P2G equipment, so as to improve the carbon emission reduction and renewable energy consumption level of the VPP.

2.2. VPP Multi-Timescale Coordinated Optimization Strategy

The conventional day-ahead dispatching method can scarcely fulfill the system safety and economic criteria owing to the unpredictability brought by the grid connection of large-scale renewable energy. The multi-timescale rolling optimization theory relies on the principle that the prediction accuracy of renewable energy output and load demand increases as the timescale is shortened and rolling correction of controllable power output in a short timescale to match the fluctuation in renewable energy output, so as to meet the safety and economic requirements of the system. The multi-timescale rolling optimization strategy is shown in Figure 2.

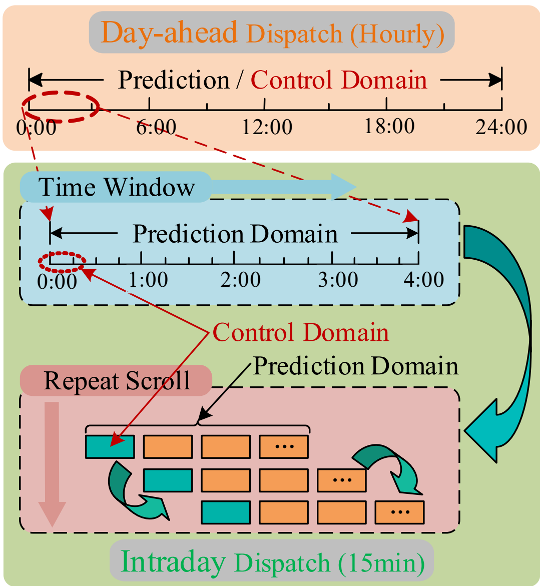

Figure 2. Multi-timescale rolling optimization strategy.

This paper proposes a multi-timescale rolling optimization strategy for virtual power plants considering a framework for collaborative utilization of pumped storage—carbon capture—P2G technologies based on the multi-timescale optimization theory to modify the energy flow under the framework for collaborative utilization on short timescales to further exploit the fine-grained scheduling advantages of the framework for collaborative utilization.

The prediction and control domains in the day-ahead scheduling are both 24 h with a time resolution of 1 h. The prediction domain in the day-ahead scheduling is the ultra-short-term prediction time scale for uncertain resources, i.e., 4 h with a time resolution of 15 min and the control domain is 15 min. The day-ahead scheduling plan with a time resolution of 1 h is expanded to 96 time periods with a resolution of 15 min. The intraday scheduling time window is rolled back every 15 min, each time rolling to solve the intraday scheduling plan for the 4 h in the prediction domain and execute the 15-min intraday scheduling plan in the control domain. The process is repeated until the intraday scheduling plan is completed.

3. VPP Multi-Time Scale Low Carbon Economic Dispatch Model

Based on the above multi-timescale rolling optimization strategy for virtual power plants considering the pumped storage—carbon capture—P2G synergistic utilization framework, optimal scheduling models are developed for the day-ahead and intraday scheduling phases based on the predicted power of wind power, photovoltaic power, and load at different timescales, respectively.

3.1. Source and Load Uncertainty Treatment

At present, the prediction models for wind power, photovoltaic power generation, and load have been studied in depth, including the historical data method and probabilistic model method and the predicted power of each unit is obtained based on the Monte Carlo simulation method and deep learning algorithm. The focus of this paper is on the optimal scheduling of VPP. So, we assume that the prediction errors of wind and PV power generation and load are inscribed by a normal distribution with zero mean and independent of each other [32], as shown in the following equation:

$$\begin{cases} \delta_t^{\mathrm{W}} \sim N(0, \sigma_{\mathrm{W},t}^2) \\ \delta_t^{\mathrm{PV}} \sim N(0, \sigma_{\mathrm{PV},t}^2) \\ \delta_t^{\mathrm{EL}} \sim N(0, \sigma_{\mathrm{EL},t}^2) \end{cases} \tag{1}$$

where δ_t^{W}, δ_t^{PV}, and δ_t^{EL} are the forecast variances for wind power, PV power, and load at time t, respectively. $\sigma_{\mathrm{W},t}^2$, $\sigma_{\mathrm{PV},t}^2$, and $\sigma_{\mathrm{EL},t}^2$ are the variances of the forecast deviations at time t for wind power, PV power, and load, respectively.

3.2. Day-Ahead Scheduling Model

In the day-ahead dispatching phase, the VPP day-ahead 24 h dispatching plan is formulated based on the short-term predicted power of wind power, PV power, and load with a time resolution of 1 h and one day cycle.

3.2.1. Objective Function

The day-ahead scheduling model takes the total operating cost of VPP in the scheduling cycle as the objective function to minimize.

$$min f_1 = \sum_{t=1}^{24} (C_t^{\mathrm{G}} + C_t^{\mathrm{P2G}} + C_t^{\mathrm{PS}} + C_t^{\mathrm{CO_2}} - C_t^{\mathrm{Gre}} + C_t^{\mathrm{W}} + C_t^{\mathrm{PV}} + C_t^{\mathrm{Pun}} + C_t^{\mathrm{Grid}}) \tag{2}$$

where C_t^{G} is the fuel cost of the carbon capture plant at time t. C_t^{P2G} is the operating cost of the P2G device at time t. C_t^{PS} is the cost of switching the operating conditions of the pumped storage unit at moment t. $C_t^{\mathrm{CO_2}}$ is the CO_2-related cost of the VPP at time t. C_t^{Gre} is the gain from VPP's participation in the green certificate transaction at time t. C_t^{W} and C_t^{PV} are the operation and maintenance costs of wind power and photovoltaic power generation at time

t, respectively. C_t^{Pun} is the penalty costs for wind power abandonment and photovoltaic power abandonment at time t. C_t^{Grid} is the cost of electricity purchased from the grid by VPP at time t.

(1) Carbon capture plant fuel costs.

$$C_t^{\text{G}} = \text{a}\left(P_t^{\text{G}}\right)^2 + \text{b}P_t^{\text{G}} + \text{c} \quad (3)$$

where a, b, and c are the operating cost factors of the carbon capture unit, respectively. P_t^{G} is the equivalent output of the carbon capture unit at time t.

(2) P2G equipment operating costs.

$$C_t^{\text{P2G}} = k^{\text{Buy}} Q_t^{\text{Buy}} + k^{\text{P2G}} P_t^{\text{P2G}} - k^{\text{CH}_4} V_t^{\text{P2G}} \quad (4)$$

where k^{Buy} is the purchase price of CO_2 for the production of methane for the P2G equipment, CNY/t, (CNY: China Yuan). k^{P2G} is the operating cost factor for P2G equipment, CNY/(MW·h). P_t^{P2G} is the energy consumption of the P2G equipment at time t, MW. Q_t^{Buy} is the amount of CO_2 to be purchased at time t when the P2G equipment consumes more energy and the amount of CO_2 captured is less, t. k^{CH_4} is the fixed price per unit volume of methane in the methane market, CNY/m^3. V_t^{P2G} is the volume of methane generated by the P2G device at time t, m^3.

(3) Pumped storage unit operating conditions switching costs.

$$C_t^{\text{PS}} = k^{\text{PS,G}} \delta_t^{\text{PS,G}} (\delta_t^{\text{PS,G}} - \delta_{t-1}^{\text{PS,G}}) + k^{\text{PS,P}} \delta_t^{\text{PS,P}} (\delta_t^{\text{PS,P}} - \delta_{t-1}^{\text{PS,P}}) \quad (5)$$

where $k^{\text{PS,G}}$ is the cost of a single start-up of a pumped storage unit under power generation condition, CNY. $k^{\text{PS,P}}$ is the cost of a single start-up of a pumped storage unit under power pumping condition, CNY. $\delta_t^{\text{PS,G}}$ and $\delta_t^{\text{PS,P}}$ are the Boolean variables for the state of the pumped storage unit generating and pumping water, respectively.

(4) CO_2-related costs.

CO_2-related costs include the cost of carbon sequestration and the cost of VPP participation in carbon trading.

$$C_t^{\text{CO}_2} = k^{\text{CS}} Q_t^{\text{CS}} - k^{\text{CO}_2} (Q_t^{\text{N}} - Q_t^{\text{Buy}} - Q_t^{\text{Q}}) \quad (6)$$

$$Q_t^{\text{Q}} = \gamma^{\text{C}} P_t^{\text{G}} \quad (7)$$

where k^{CS} is the fixed price for a unit mass of CO_2 sequestered, CNY/t. k^{CO_2} is the unit carbon price in the carbon trading market, CNY/t. Q_t^{CS} is the amount of carbon sequestered at time t, t. Q_t^{N} is the net carbon emission of VPP at time t, t. Q_t^{Q} is the carbon emission allowance allocated to VPP in time period t, t. γ^{C} is the carbon emission benchmark credit per unit of electricity, t/(MW·h).

(5) Green certificate trading revenue.

$$C_t^{\text{Gre}} = k^{\text{Gre}} (P_t^{\text{gre}} - P_t^{\text{re}}) \Delta t \quad (8)$$

where k^{Gre} is the unit price of green certificate, CNY/book (green certificate power conversion is 1 green certificate = 1 MW·h). P_t^{gre} is the amount of renewable energy generation consumed by VPP in time period t, MW·h. P_t^{re} is the weight of renewable energy consumption of VPP in time period t, MW·h. Δt is the length of the period when VPP is currently involved in green certificate trading.

(6) Operation and maintenance costs of wind and photovoltaic power generation.

$$C_t^{\mathrm{W}} = k^{\mathrm{W}}(P_t^{\mathrm{W,C}} + P_t^{\mathrm{W,P2G}} + P_t^{\mathrm{W,N}}) \tag{9}$$

$$C_t^{\mathrm{PV}} = k^{\mathrm{PV}}(P_t^{\mathrm{PV,C}} + P_t^{\mathrm{PV,P2G}} + P_t^{\mathrm{PV,N}}) \tag{10}$$

where k^{W} and k^{PV} are the unit operation and maintenance cost coefficients for wind power and photovoltaic power generation, respectively, CNY/(MW·h). $P_t^{\mathrm{W,C}}$ and $P_t^{\mathrm{PV,C}}$ are the energy captured by wind power and photovoltaic power for the carbon capture system, respectively, MW. $P_t^{\mathrm{W,P2G}}$ and $P_t^{\mathrm{PV,P2G}}$ are the energy consumption provided by wind power and photovoltaic power for power-to-gas equipment, respectively, MW. $P_t^{\mathrm{W,N}}$ and $P_t^{\mathrm{PV,N}}$ are the grid-connected power for wind power and photovoltaic power, respectively, MW.

(7) Penalty cost for wind and photovoltaic power generation.

$$C_t^{\mathrm{Pun}} = k_{\mathrm{Pun}}^{\mathrm{W}}(P_t^{\mathrm{W,pre}} - P_t^{\mathrm{W}}) + k_{\mathrm{Pun}}^{\mathrm{PV}}(P_t^{\mathrm{PV,pre}} - P_t^{\mathrm{PV}}) \tag{11}$$

where $k_{\mathrm{Pun}}^{\mathrm{W}}$ and $k_{\mathrm{Pun}}^{\mathrm{PV}}$ are the penalty cost per unit of wind power abandonment and the penalty cost per unit of photovoltaic power abandonment, respectively, CNY/(MW·h). $P_t^{\mathrm{W,pre}}$ and $P_t^{\mathrm{PV,pre}}$ are the predicted power of wind power and photovoltaic power generation at time t, respectively, MW. P_t^{W} and P_t^{PV} are the grid-connected power of wind power and photovoltaic power respectively, MW.

(8) Cost of VPP to purchase electricity from the main network.

When power is in short supply, VPP can purchase power to meet internal power load demand.

$$C_t^{\mathrm{Grid}} = k_t^{\mathrm{P}} P_t^{\mathrm{Grid}} \tag{12}$$

where k^{P2G} is the purchased electricity price for time period t, CNY/(MW·h). P_t^{Grid} is the amount of electricity purchased from the grid by VPP in time period t, MW·h.

3.2.2. Constraints

The key of the VPP optimal dispatch model is to optimize the output of each piece of equipment within the permissible range under the premise of ensuring the balance between the VPP aggregation energy and load demand with the goal of economy. The most complicated part of the model is the operating constraints of the equipment.

(1) System power balance constraint.

First of all, it is necessary to ensure that the VPP aggregation energy is equal to the load demand, i.e., the power is conserved.

$$P_t^{\mathrm{EL}} + P_t^{\mathrm{PS,P}} = P_t^{\mathrm{G,N}} + P_t^{\mathrm{W,N}} + P_t^{\mathrm{PV,N}} + P_t^{\mathrm{PS,G,N}} + P_t^{\mathrm{Grid}} \tag{13}$$

where P_t^{EL} is the load demand of VPP at time t, MW.

(2) Carbon capture unit operating constraint.

The operation of a carbon capture plant includes two parts of constraints: the carbon capture unit and the carbon capture system. Among them, the operation constraints of the carbon capture unit are the same as those of the conventional unit, including the output range, the climb limit, and the internal power balance of the carbon capture plant. This is shown in the following equation:

$$P^{\mathrm{G,min}} \le P_t^{\mathrm{G}} \le P^{\mathrm{G,max}} \tag{14}$$

$$P_t^{\mathrm{G}} = P_t^{\mathrm{G,C}} + P_t^{\mathrm{G,N}} \tag{15}$$

$$\left| P_t^{G} - P_{t-1}^{G} \right| \leq \Delta P^{G} \tag{16}$$

where $P^{G,\min}$ and $P^{G,\max}$ are the lower and upper limits of carbon capture unit output, respectively, MW. $P_t^{G,C}$ and $P_t^{G,N}$ are the energy consumption provided by the carbon capture unit to the carbon capture system at time t and the net output of the carbon capture unit at time t, respectively, MW.

The carbon capture unit is converted from a fuel unit so its operating upper and lower limit constraints and climbing constraints are similar to those of the fuel unit. The difference is that a carbon capture system is added to the fuel unit and the energy consumption constraint and operation constraint of the carbon capture system need to be considered.

$$P_t^{CC} = P^{A} + P_t^{OP} \tag{17}$$

$$P^{A} \leq P_t^{CC} \leq P_t^{CC,\max} \tag{18}$$

$$P_t^{CC,\max} = k^{CC} E^{G} P_t^{G} \tag{19}$$

$$P_t^{CC} = P_t^{G,C} + P_t^{W,C} + P_t^{PV,C} + P_t^{PS,G,C} \tag{20}$$

$$\left| P_t^{CC} - P_{t-1}^{CC} \right| \leq \Delta P^{CC} \tag{21}$$

$$Q_t^{CC} = P_t^{OP} / k^{CC} \tag{22}$$

$$0 \leq Q_t^{CC} \leq E^{G} P_t^{G} \tag{23}$$

where P_{t-1}^{G} is the equivalent output of the carbon capture unit at time $t-1$, MW. ΔP^{G} is the climbing rate constraint of carbon capture unit output, MW. P^{A} and P_t^{OP} are the fixed and operational energy consumption of the carbon capture system, respectively, MW. P_t^{CC} is the total energy consumption of the carbon capture system at time t, MW. $P_t^{CC,\max}$ is the maximum energy consumption of the carbon capture system at time t, MW. k^{CC} is the energy required to capture a unit of CO_2 by the carbon capture system, MW/t. E^{G} is the unit carbon emission intensity of the carbon capture unit, t/MW. $P_t^{PS,G,C}$ is the energy consumption provided to the carbon capture system by the pumped storage unit in the power generation condition at time t, MW. ΔP^{CC} is the rate of climbing constraint on the energy consumption of the carbon capture system, MW. Q_t^{CC} is the amount of CO_2 captured by the carbon capture system at time t, t.

(3) Power-to-gas equipment operating constraint.

CO_2 captured by carbon capture systems can be avoided by carbon sequestration technology but the sequestration technology not only bears the high cost of long-distance transportation but also faces the risk of explosion and environmental hazards due to sequestration leakage. The use of P2G equipment to produce methane requires the consumption of CO_2, a low-carbon emission reduction method that not only reduces CO_2 emissions but also makes full use of renewable energy to provide energy for P2G equipment.

The relationship between the CO_2 consumed by the P2G equipment to produce methane at time t and its operational energy consumption is as follows:

$$Q_t^{P2G} = \lambda^{CO_2} \eta^{P2G} P_t^{P2G} \tag{24}$$

$$P_t^{P2G} = P_t^{W,P2G} + P_t^{PV,P2G} + P_t^{PS,G,P2G} \tag{25}$$

where Q_t^{P2G} is the amount of CO_2 consumed by the P2G equipment at time t, t. λ^{CO_2} is the amount of CO_2 required to generate methane per unit power for the P2G equipment. η^{P2G} is the conversion efficiency of P2G equipment. P_t^{P2G} is the energy consumption of the P2G equipment at time t, MW.

The volume of methane generated by the P2G plant at time t is as follows:

$$V_t^{\mathrm{P2G}} = 3.6\eta^{\mathrm{P2G}} P_t^{\mathrm{P2G}} / H^{\mathrm{g}} \tag{26}$$

where H^{g} is the calorific value of natural gas, taken as 39 $\mathrm{MJ/m^3}$ [19].

(4) Wind and photovoltaic power generation operational constraint.

$$P_t^{\mathrm{W}} = P_t^{\mathrm{W,C}} + P_t^{\mathrm{W,P2G}} + P_t^{\mathrm{W,N}} \tag{27}$$

$$P_t^{\mathrm{PV}} = P_t^{\mathrm{PV,C}} + P_t^{\mathrm{PV,P2G}} + P_t^{\mathrm{PV,N}} \tag{28}$$

$$0 \le P_t^{\mathrm{W}} \le P_t^{\mathrm{W,pre}} \tag{29}$$

$$0 \le P_t^{\mathrm{PV}} \le P_t^{\mathrm{PV,pre}} \tag{30}$$

where $P_t^{\mathrm{W,pre}}$ and $P_t^{\mathrm{PV,pre}}$ are the predicted power of wind power and PV power at time t, respectively, MW. P_t^{W} and P_t^{PV} are the grid-connected power of wind power and photovoltaic power, respectively, MW. The grid-connected power is required to develop an optimal grid-connected plan under the premise of ensuring energy balance. Therefore, the grid-connected power of renewable energy sources at a given moment is less than the predicted power.

(5) Operational constraints for pumped storage.

The power limitations of pumped storage units in power generation and pumping conditions and the mutually exclusive relationship between the operating conditions of pumped storage units are expressed as follows:

$$P_t^{\mathrm{PS}} = \delta_t^{\mathrm{PS,G}} P_t^{\mathrm{PS,G}} + \delta_t^{\mathrm{PS,P}} P_t^{\mathrm{PS,P}} \tag{31}$$

$$P_t^{\mathrm{PS,G}} = P_t^{\mathrm{PS,G,C}} + P_t^{\mathrm{PS,G,P2G}} + P_t^{\mathrm{PS,G,N}} \tag{32}$$

$$0 \le \delta_t^{\mathrm{PS,G}} + \delta_t^{\mathrm{PS,P}} \le 1 \tag{33}$$

$$W_t^{\mathrm{PS}} = W_{t-1}^{\mathrm{PS}}(1-\eta^{\mathrm{c}}) + \Delta T \eta^{\mathrm{P}} P_t^{\mathrm{PS,P}} - \Delta T \eta^{\mathrm{G}} P_t^{\mathrm{PS,G}} \tag{34}$$

$$W_{\min}^{\mathrm{PS}} \le W_t^{\mathrm{PS}} \le W_{\max}^{\mathrm{PS}} \tag{35}$$

$$W_{t=0}^{\mathrm{PS}} = W_{t=T}^{\mathrm{PS}} \tag{36}$$

where P_t^{PS} is the equivalent output of the pumped storage unit at time t, MW. $P_t^{\mathrm{PS,G}}$ and $P_t^{\mathrm{PS,P}}$ are the power generation and pumping power of pumped storage units at time t, MW. Due to the abundant storage capacity of the lower water reservoir in pumped storage power plant, this article only restricts the storage capacity of the upper reservoir. W_t^{PS} is the capacity of the upper reservoir for pumped storage power plant at time t, $\mathrm{m^3}$. $W_{\min}^{\mathrm{PS}}$ and $W_{\max}^{\mathrm{PS}}$ are the lower and upper limits of the upper reservoir capacity of pumped storage power plant, respectively. The initial storage capacity of the upper reservoir is $W_{t=0}^{\mathrm{PS}} = (W_{\min}^{\mathrm{PS}} + W_{\max}^{\mathrm{PS}})/2$. η^{c} is the water loss rate. η^{P} and η^{G} are the average water volume and electricity conversion coefficient of pumped storage units under pumping and power generation conditions, respectively. ΔT and T are the time interval and total number of time periods within the operation cycle optimized for pumped storage unit, respectively.

3.3. Intraday Scheduling Model

The intraday scheduling model takes the day ahead scheduling plan as a reference. Rolling correction of the output of carbon capture units, energy consumption of carbon capture systems, pumping energy consumption and power generation of wind power, photovoltaic power generation, and pumped storage based on the 15 min–4 h ultra-short term prediction of wind power, photovoltaic power generation, and load, thus forming the intraday scheduling plan.

3.3.1. Objective Function

The daily scheduling model ignores the switching cost of pumped storage units. Each run solves a 4-h scheduling plan, with an execution time resolution of 15 min and a total cycle of 96 time periods. The objective function is as follows:

$$minf_2 = \sum_{t=1}^{96} (C_t^{G'} + C_t^{P2G'} + C_t^{CO_2'} - C_t^{Gre'} + C_t^{W'} + C_t^{PV'} + C_t^{Pun'} + C_t^{Grid'}) \tag{37}$$

where $C_t^{G'}$ is the fuel cost for carbon capture plants at time t. $C_t^{P2G'}$ is the operating cost of the P2G device at time t. $C_t^{CO_2'}$ is the CO_2-related cost of the VPP at time t. $C_t^{Gre'}$ is the gain from VPP's participation in the green certificate transaction at time t. $C_t^{W'}$ and $C_t^{PV'}$ are the operation and maintenance costs of wind power and photovoltaic power generation at time t, respectively. $C_t^{Pun'}$ is the penalty costs for wind power abandonment and photovoltaic power abandonment at time t. $C_t^{Grid'}$ is the cost of electricity purchased from the grid by VPP at time t.

3.3.2. Constraints

The difference between the constraints of the intraday scheduling model and the day ahead scheduling model is that the optimal time resolution is changed from 1 h to 15 min. The constraints that need to be changed in the intraday scheduling model are as follows:

$$P_t^{EL'} + P_t^{PS,P'} = P_t^{G,N'} + P_t^{W,N'} + P_t^{PV,N'} + P_t^{PS,G,N'} + P_t^{Grid'} \tag{38}$$

$$P_t^{EL'} = P_t^{EL} + \delta_t^{EL} \tag{39}$$

$$P_t^{W'} = P_t^{W} + \delta_t^{W} \tag{40}$$

$$P_t^{PV'} = P_t^{PV} + \delta_t^{PV} \tag{41}$$

where $P_t^{EL'}$, $P_t^{W'}$, and $P_t^{PV'}$, respectively, represent the load demand, predicted power of wind, and photovoltaic power generation during the intraday scheduling phase during time period t. The physical meaning of other variables is the same as that of the day ahead scheduling phase.

In addition, due to the change in scheduling resolution from 1 h to 15 min during the intraday phase, the output of the carbon capture plant, the energy consumption climbing constraints of the carbon capture system, and the calculation method of the capacity of the pumped storage upper reservoir also need to be adjusted accordingly.

$$\left| P_t^{G} - P_{t-1}^{G} \right| \le \Delta P^{G}/4 \tag{42}$$

$$\left|P_t^{\mathrm{CC}} - P_{t-1}^{\mathrm{CC}}\right| \leq \Delta P^{\mathrm{CC}}/4 \tag{43}$$

$$W_t^{\mathrm{PS}} = W_{t-1}^{\mathrm{PS}}(1-\eta^{\mathrm{c}}) + \Delta T' \eta^{\mathrm{P}} P_t^{\mathrm{PS,P}}/4 - \Delta T' \eta^{\mathrm{G}} P_t^{\mathrm{PS,G}}/4 \tag{44}$$

$$W_{t=0}^{\mathrm{PS}} = W_{t=T'}^{\mathrm{PS}} \tag{45}$$

In the formula, due to the different time resolutions between the day ahead and intraday scheduling stages, the energy consumption ramp response ability of the carbon capture unit and the carbon capture system cannot be significantly adjusted in a short period of time. In addition, the upper reservoir capacity and capacity constraints of pumped storage also need to be calculated at a time resolution of 15 min. Other constraints are the same as those in the day ahead scheduling phase, so they will not be repeated here.

3.4. Solving Process

The solution process of the low-carbon economic dispatch model for virtual power plants based on the collaborative utilization framework of pumped storage–carbon capture–power-to-gas proposed in this article is shown in Figure 3. The model developed includes a nonlinear objective function, real numbers, and Boolean solution variables, which belong to the mixed-integer nonlinear programming problem that is linearized and optimized by the Cplex solver (Version is 12.8).

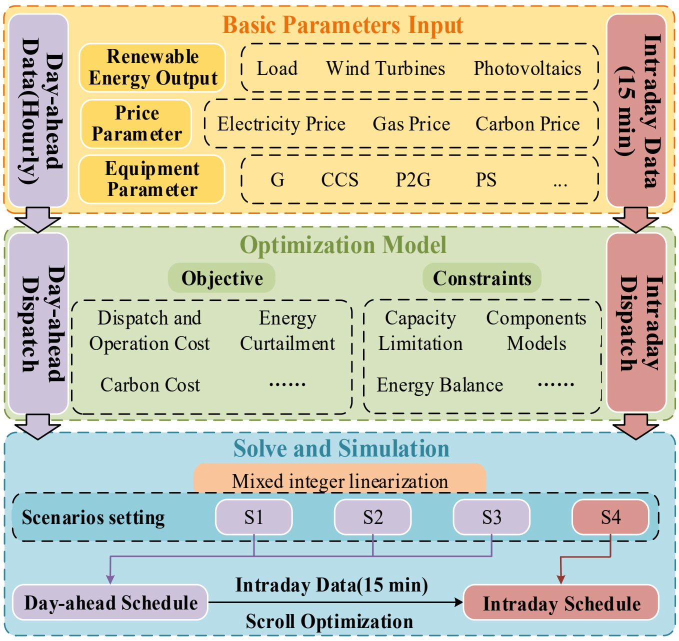

Figure 3. Solution flowchart.

To analyze the collaborative utilization framework of the pumped storage–carbon capture–power-to-gas proposal in this article and the impact of multi-time scale scheduling strategies on the scheduling results of virtual power plants, the following four operating schemes are set:

S1: A low-carbon economic scheduling model for a virtual power plant with carbon capture and power-to-gas conversion, as the basic operating scenario;

S2: Introduce pumped storage units on the basis of S1 and establish a low-carbon economic dispatch model for a virtual power plant that includes pumped storage, carbon capture, and power-to-gas conversion, to study the impact of pumped storage on the dispatch results of virtual power plants;

S3: Low carbon economic dispatch of a virtual power plant based on the collaborative operation framework of pumped storage–carbon capture–power-to-gas, to study the linkage effect of various equipment under the collaborative operation strategy;

S4: Multi-time scale low-carbon economic scheduling of virtual power plant based on the collaborative operation framework of pumped storage–carbon capture–power-to-gas and the introduction of 50 MW·h energy storage power plant coordination in the intraday stage to study the impact of multi-time scale rolling optimization strategies on the short-term scheduling results of a virtual power plant.

4. Case Study

The virtual power plant constructed in this chapter includes a 500 MW carbon capture plant, 150 MW P2G equipment, a 100 MW pumped storage power plant, a 350 MW wind power plant, and a 200 MW photovoltaic power plant. The operating parameters of each aggregation unit are shown in Table 1 and the electricity purchase price is shown in Table 2. The daily and intraday predicted fluctuation variance in wind and photovoltaic power generation output is 0.05 and the load-predicted fluctuation variance is 0.005 [32]. The predicted curves of renewable energy generation and load in the day ahead and intraday stages are shown in Figure 4 [33].

Table 1. Equipment operating parameters.

a (CNY/MW^2) 0.0033	b (CNY/MW) 111.78	c (CNY) 6900
$P^{G,min}$ (MW) 150	$P^{G,max}$ (MW) 500	P^A (MW) 15
ΔP^G (MW) 50	ΔP^{CC} (MW) 65	k^{Buy} (CNY/t) 835.39
k^{P2G} (CNY/MW·h) 139.23	$k^{CH}{}_4$ (CNY/m^3) 2.92	$k^{PS,G}$ (CNY) 750
$k^{PS,P}$ (CNY) 1000	k^{CS} (CNY/t) 128	k^{CO2} (CNY/t) 150
γ^C (MW·h) 0.76	k^W (CNY/t) 344.5	k^{PV} (CNY/t) 442
K^{CC} (MW·h) 0.269	E^G (t/MW·h) 0.9	λ^{CO2} (t/MW·h) 0.2
η^{P2G} 0.6	η^c 0.001	η^P (m^3/MW·h) 749
η^G (m^3/MW·h) 998	$W^{PS,min}$ (m^3) 145,582.13	$W^{PS,max}$ (m^3) 767,366.49

Table 2. Time-sharing electricity purchase price.

Time Slot		**Electricity Price (CNY/MW·h)**
Valley period	1:00–4:00 24:00–24:00	430
Peacetime period	5:00–6:00 11:00–15:00 20:00	650
Peak period	7:00–10:00 16:00–19:00	790

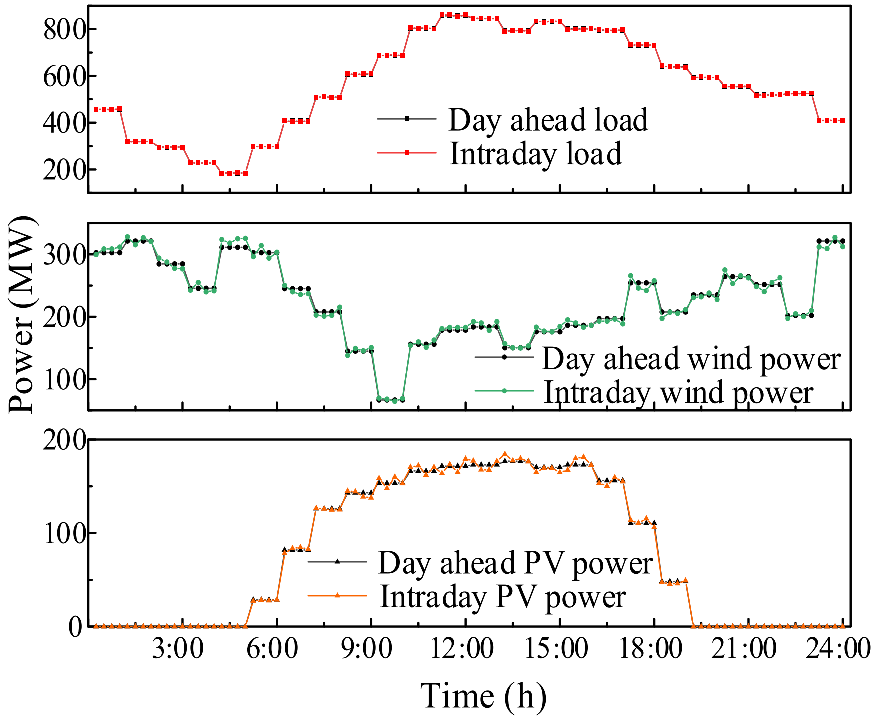

Figure 4. Wind power, photovoltaic power generation, and load forecasting power.

4.1. Day Ahead Scheduling Plan

4.1.1. Comparison of Scheduling Plan

The scheduling plan of the virtual power plant under three day-ahead operation schemes is shown in Figure 5 and the operating costs and benefits of the virtual power plant are shown in Table 3.

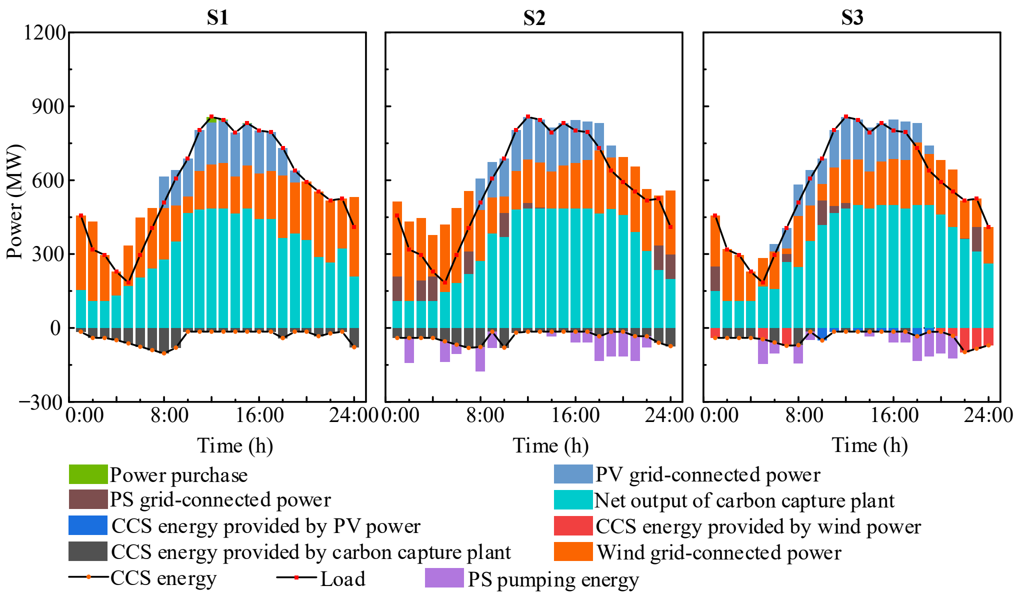

Figure 5. VPP scheduling plans under different operating schemes.

Table 3. Benefits and costs of a virtual power plant (10^4 CNY).

	S1	S2	S3	S4
Net cost	373.53	369.83	360.90	358.31
Operation and maintenance cost	378.61	388.53	391.79	391.31
Carbon trading revenue	11.51	15.01	13.54	21.31
Green certificate trading revenue	28.81	30.03	31.63	31.68
Natural gas sales revenue	12.06	15.69	17.72	17.41
P2G operating cost	10.39	13.52	15.27	15.01
Switching cost of pumped storage conditions	-	0.78	0.60	0.35
Carbon storage cost	19.48	18.21	16.13	22.04
Electricity purchasing cost	1.58	0	0	0
Penalty cost	15.85	9.53	0	0

According to the three scheduling schemes, the carbon capture system under S1, S2, and S3 all play a flexible regulating role. The carbon capture plant under Scenario S1 serves as the only regulating resource of the virtual power plant and flexibly adjusts the carbon capture energy consumption and the net output of the carbon capture plant to meet the load demand on the basis of consuming renewable energy as much as possible.

However, due to the constraints of the carbon capture plant output and the climbing constraint of carbon capture energy consumption, VPP made a power purchase from the main grid during the 12:00–13:00 h period and the cost of the power purchase was 15,800 CNY. With the low load demand during the 3:00–7:00 h period, even though the net output of the carbon capture plant operates at a lower level, the abandoned power from wind and PV reaches 567.46 MW·h, with a penalty cost of 158,500 CNY. This ultimately results in a net operating cost of 3,735,300 CNY for the virtual plant under Scenario S1.

The introduction of pumped storage units in Scenario S2 increases the regulation capacity of the virtual power plant, which can meet the system load without purchasing power from the main grid. However, due to the high wind power output during the 4:00–6:00 h, the load demand is at a low level during this period. Compared to Scenario S1, the amount of wind and PV power abandonment under Scenario S2 is reduced to 320.45 MW·h and the penalty cost for wind and PV power abandonment is 95,300 CNY. The net operating cost of the virtual power plant under Scenario S2 is 3,698,300 CNY, which is 37,000 CNY lower than that of Scenario S1.

Scenario 3, due to the introduction of the pumped storage–carbon capture–power-to-gas synergistic utilization framework, can flexibly coordinate carbon capture energy consumption with power-to gas energy consumption on the basis of meeting load demand. The cost of power purchase and the penalty cost of wind and PV power abandonment are not incurred under Scenario 3 and the final net operating cost of the virtual power plant is 3.609 million CNY, which is 126,300 CNY and 89,300 CNY lower compared to Scenarios S1 and S2, respectively.

In summary, the introduction of pumped storage units improves the flexibility of the virtual power plant to a certain extent. Although it increases the operation and maintenance cost, it reduces the cost of power purchase and the cost of wind and PV power abandonment penalties and can fully compensate for the increased operation and maintenance cost due to the introduction of pumped storage units. In addition, the flexible regulation of the pumped storage–carbon capture–power-to-gas synergy framework further improves the level of renewable energy consumption and reduces the operating costs of the virtual power plant.

4.1.2. Consumption of Renewable Energy

The renewable energy consumption under the three scenarios is shown in Figures 6 and 7. Due to the low load demand during the 2:00–7:00 h, wind power generation is higher during this period. In Scenario S1 and Scenario S2, although the carbon capture plant and pumped storage units play the role of flexible regulation resources, not all of the renewable energy generation is consumed. In Scenario S3, thanks to the flexible allocation effect of the pumped storage–carbon capture–power-to-gas synergistic utilization framework, wind power provides more energy consumption for P2G equipment during the 23:00–8:00 h, thus relieving the pressure on energy consumption reserved for P2G equipment by the virtual power plant.

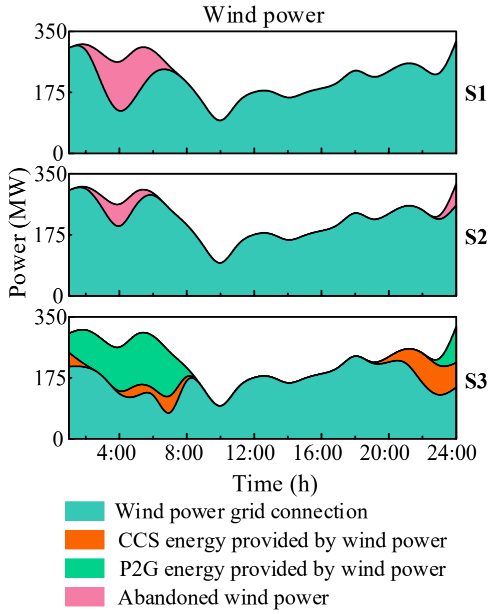

Figure 6. Wind power consumption under different operation scenarios.

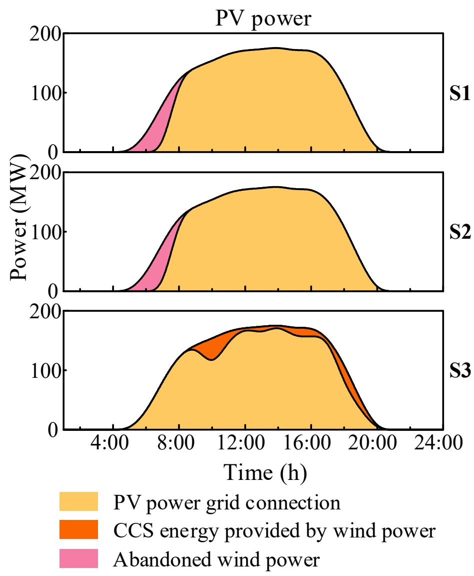

Figure 7. PV power consumption under different operation scenarios.

Wind power provides part of the energy consumption for the carbon capture system during the 20:00–1:00 and 4:00–8:00 h and photovoltaic power from 9:00–19:00, relieving the pressure on the carbon capture plant to provide energy for the carbon capture system and allowing full consumption of wind power and photovoltaic power.

4.1.3. VPP Carbon Emissions

The energy consumption of the carbon capture system and the P2G plant under the three operation scenarios are shown in Figure 8 and the carbon emissions of the virtual plant are shown in Figure 9.

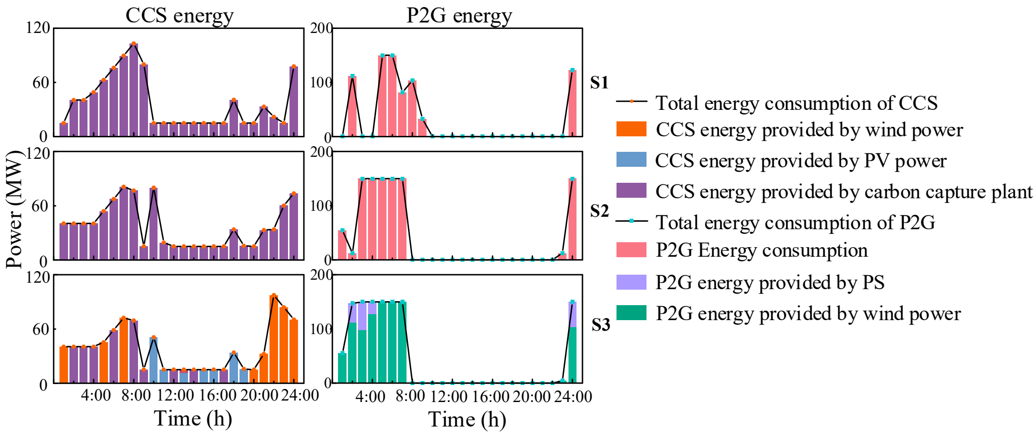

Figure 8. Energy consumption of carbon capture and P2G under different operation scenarios.

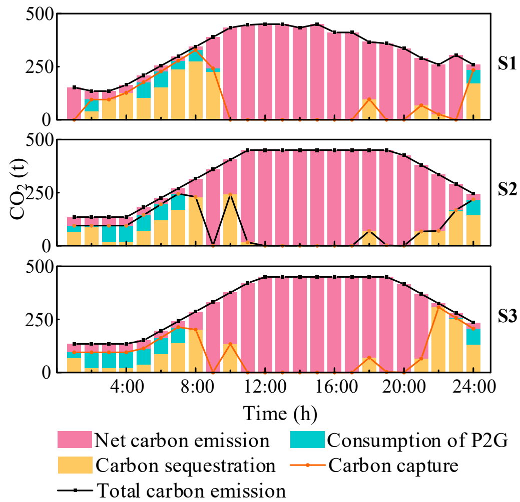

Figure 9. CO_2 emissions under different operating scenarios.

Under Scenario S1, the carbon capture system needs to reduce energy consumption to increase the net output of the carbon capture plant due to the lack of regulation resources in the virtual power plant and the P2G equipment also reduces energy consumption to relieve the pressure on the system power balance. The low levels of carbon capture energy consumption and P2G energy consumption during the 22:00–1:00 h period resulted in a total carbon capture of 1989.7 t and P2G consumption of 376.6 t of CO_2 under Scenario S1. This ultimately resulted in a net carbon emission of 5749.7 t from the VPP.

Under Scheme S2, the energy consumption of the carbon capture system increases at 10:00 and 22:00–23:00 h because the pumped storage unit relieves the regulation pressure of the carbon capture plant. The total carbon capture amount reaches 2048.9 t, which is 59.2 t higher compared to that of Scenario S1. The energy consumption of P2G equipment increases during the 3:00–4:00 h, 7:00, and 23:00–1:00 h, resulting in a 489.9 t of CO_2 consumed by the P2G equipment, which is 113.3 t higher compared to the P2G consumption of Scenario S1. The net carbon emissions of the virtual power plant under Scenario S2 are 5703.6 t, which is 46.1 t lower compared to Scenario S1.

Under Scenario S3, the energy consumption of the carbon capture system and the energy consumption of the P2G equipment can both be provided by wind power, photovoltaic power, and pumped storage units, thus reducing the pressure on the carbon capture plant to provide energy for the carbon capture system and the pressure on the energy demand of the P2G equipment. The total carbon capture capacity under Scenario S3 is 2111.3 t, which is 121.6 t and 62.4 t higher than that of Scenarios S1 and S2, respectively. The amount of CO_2 consumed by P2G under Scenario S3 is 553.24 t, which is 176.64 t and

63.34 t higher compared to the consumption of Scenario S1 and Scenario S2, respectively. The net carbon emission of the virtual power plant under Scenario S3 is 5657.0 t, which is 92.7 t and 46.6 t lower compared to that of Scenarios S1 and S2, respectively.

In summary, although the introduction of pumped storage units meets the electric energy balance demand of the virtual power plant to a certain extent, it fails to fully exploit the flexible and low-carbon operating characteristics of pumped storage, carbon capture plant, and P2G equipment. The pumped storage—carbon capture—P2G synergistic utilization framework proposed in this paper can make full use of the spatial and temporal complementarity of different power generation equipment to achieve the effective utilization of resources within the virtual power plant and efficient optimization of the energy structure. It can effectively exploit the carbon reduction potential of the virtual power plant and improve the level of renewable energy consumption while ensuring the economic operation of the virtual power plant.

4.2. Intraday Scheduling Plan

The use of only renewable energy output and load forecast data in the day-ahead phase can result in deviations between the output plan declared by the virtual power plant and the dispatch plan executed in the intraday phase, due to the uncertainty of renewable energy output and load demand. This can result in virtual power plants bearing the risk of supply and demand imbalance, as well as economic losses from wind and light abandonment penalties. In order to improve the accuracy of the dispatching plan of the virtual power plant under ultra-short-term forecast conditions, a multi-timescale rolling optimization strategy based on scheme S3 from the day-ahead phase is introduced. Additionally, a 50 MW·h energy storage plant is added to aid in the rolling revision process. The intraday scheduling plan of the virtual power plant is shown in Figure 10.

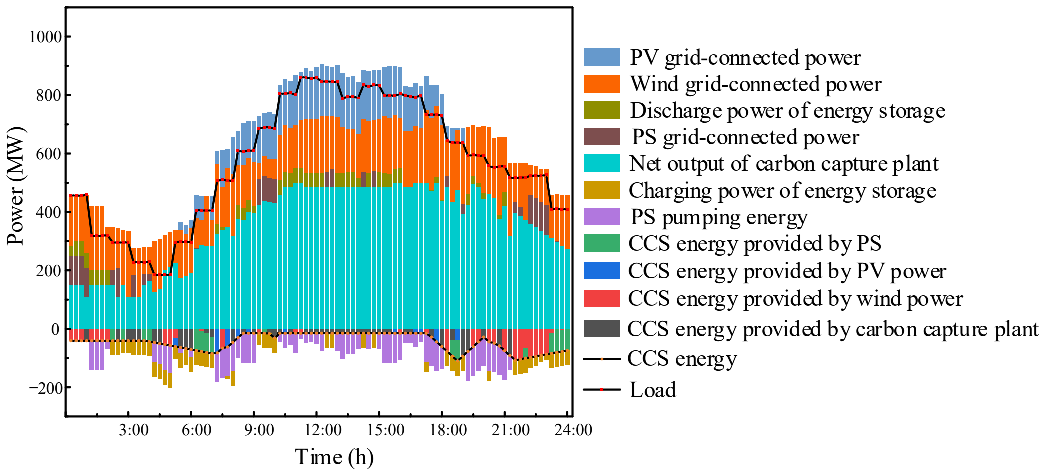

Figure 10. Intraday scheduling plan.

4.2.1. Intraday Scheduling Plan Analysis

In all three day-ahead dispatch plans, the flexible operating characteristic of the cooperation between the carbon capture plant and the carbon capture system is evident. Option S2 reduces the output of the carbon capture plant to some extent as pumped storage units are introduced, while Option S3 benefits from the coordination of the synergistic utilization framework, resulting in improved energy consumption of the carbon capture system compared to the other two options. The intraday dispatch plan has lower net carbon emissions by 282.1 t compared to the day-ahead dispatch plan. This results in an increase of 77,700,000 RMB for the virtual power plant to participate in carbon trading. The total renewable energy generation during the intraday phase is 7288.49 MW·h, while the day-ahead phase has a total renewable energy generation of 7276.46 MW·h. Both the day-ahead and intraday dispatch phases achieved full consumption of renewable energy, resulting in a 0.05 million CNY increase in revenue for the virtual power plant's participation in green certificate trading, ultimately resulting in a 0.0259 million CNY reduction in the net operating cost of the virtual power plant.

4.2.2. Energy Consumption Correction Analysis of Carbon Capture System

The total energy consumption of the carbon capture system and the energy consumption provided by the carbon capture plant, wind power, PV power, and pumped storage unit for the carbon capture system in the intraday phase of the correction are shown in Figure 11. The energy consumption of the carbon capture plant for the carbon capture system was 309.64 MW·h and 404.73 MW·h in the day-ahead and intraday phases, respectively. The energy consumption of wind power for the carbon capture system was 457.82 MW·h and 397.47 MW·h in the day-ahead and intraday phases, respectively. The energy consumption of photovoltaic power generation for carbon capture systems was 157.18 MW·h and 90.02 MW·h in the day-ahead and intraday phases, respectively. The energy consumption of pumped storage units for the carbon capture system was 3.293 MW·h and 233.86 MW·h in the day-ahead and intraday phases, respectively.

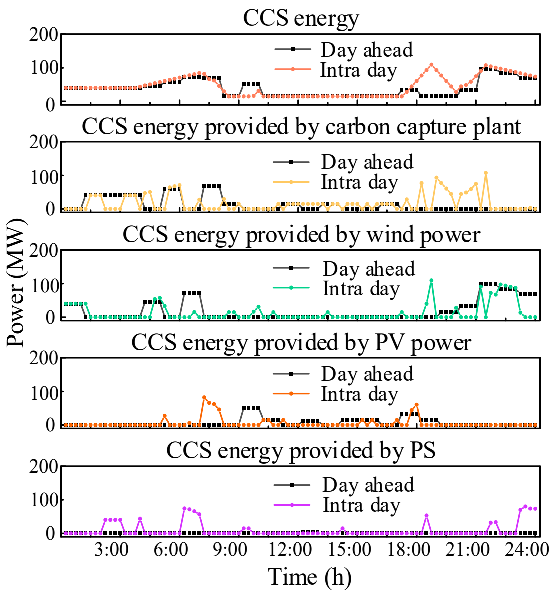

Figure 11. Energy consumption correction of the carbon capture system.

Due to the reduced load demand in the 18:00–20:00 period, wind power output is higher in this period. The carbon capture plant reduces the net output by increasing the energy consumption of the carbon capture system to meet the load demand of the system while keeping the equivalent output constant. The total energy consumption of the carbon capture system in the day-ahead and intraday phases is 927.96 MW·h and 1078.98 MW·h, respectively, which is 151.02 MW·h higher than the total energy consumption in the day-ahead phase. The amount of CO_2 captured by the carbon capture system was 2111.3 t and 2672.8 t, respectively, an increase of 561.5 t compared to the amount of CO_2 captured in the day-ahead phase.

4.2.3. Energy Consumption Correction Analysis of P2G Equipment

The total energy consumption of the P2G equipment and the energy consumption provided by wind power, PV power, and pumped storage units for the P2G equipment in the intraday phase are corrected as shown in Figure 12. The total energy consumption of the P2G equipment in the day-ahead phase is 1106.48 MW·h and the amount of CO_2 consumed is 553.24 t. The total energy consumption of the P2G plant in the intraday phase is 1087.45 MW·h and the amount of CO_2 consumed is 543.74 t. Compared with the day-ahead phase, the intraday phase has fluctuations in the energy consumption provided by wind power to the P2G equipment due to the large fluctuations in wind power during the period 23:00–4:00. As of the 2:00 h, the pumped storage units and wind power together provide the maximum energy consumption of 150 MW for the P2G equipment. In this period, each aggregation unit can coordinate with the wind power output to achieve the full consumption of wind power.

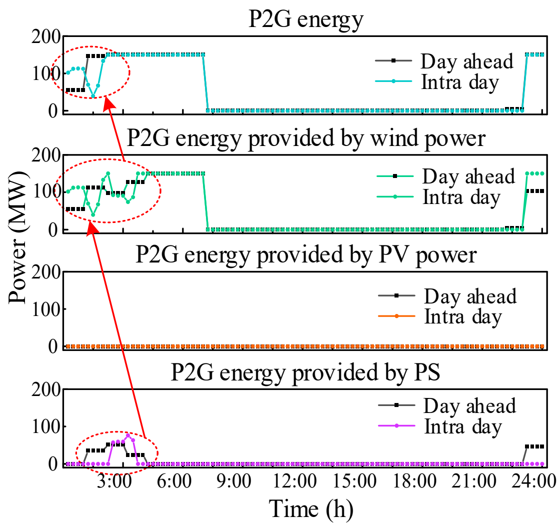

Figure 12. Energy consumption correction of P2G equipment.

The energy consumption provided by wind power for P2G equipment during the day-ahead and intraday phases is 950.0 MW·h and 1004.68 MW·h, respectively. The energy consumption of photovoltaic power generation for P2G equipment in the day-ahead and intraday phases is 0 MW·h and 21.19 MW·h, respectively. The energy consumption provided by pumped storage units for P2G equipment in the day-ahead and intraday phases is 156.48 MW·h and 78.96 MW·h, respectively. The total energy consumption of the P2G plant and the amount of CO_2 consumed by the P2G plant in the day-ahead and intraday phases are not significantly different, while the amount of carbon capture is increased by 561.5 t compared to the day-ahead phase. As a result, the net carbon emissions of the virtual power plant decreased from 5657 t in the intraday phase to 5374.9 t, a reduction of 282.1 t in net carbon emissions.

4.2.4. Energy Consumption and Power Generation Correction Analysis of Pumped Storage

The corrections of the pumped storage unit's pumping energy consumption, generation power, and feed-in power in the intraday phase are shown in Figure 13. The total pumping energy consumption of pumped storage units in the day-ahead and intraday phases was 733.97 MW·h and 1008.65 MW·h, respectively, an increase of 274.68 MW·h in the intraday phase compared to the day-ahead phase. The total power generation of pumped storage units in the day-ahead and intraday phases is 545.6 MW·h and 735.98 MW·h, respectively, with an increase of 190.38 MW·h in the intraday phase compared to the day-ahead phase. The total feed-in tariff was 385.83 MW·h and 423.17 MW·h in the day-ahead and intraday phases, respectively, an increase of 37.34 MW·h in the intraday phase compared to the day-ahead phase. In summary, the multi-timescale rolling optimization strategy in the intraday phase further exploits the flexible regulation potential of pumped storage and the fine-grained regulation advantages of the pumped storage–carbon capture–power-to-gas synergistic utilization framework compared to the day-ahead phase.

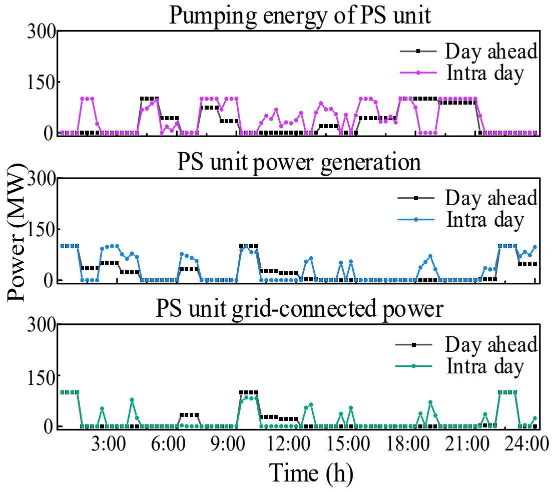

Figure 13. Pumping energy correction and power generation correction of pumped storage unit.

In summary, the multi-timescale rolling optimization strategy can adjust the cooperation scheme of the aggregation unit within the virtual power plant according to the fluctuation in renewable energy and load at the short time resolution, also at the short time resolution. The modification of energy flow in the pumped storage–carbon capture–power-to-gas co-operating framework can further exploit the refined scheduling advantages of the co-operating framework.

5. Conclusions

In this paper, the pumped storage–carbon capture–power-to-gas synergistic operation framework is proposed to address the lack of flexible regulation in the joint operation mode of carbon capture plant and P2G equipment. Aiming at the volatility problem of uncertain resources, a multi-timescale low-carbon economic dispatch model for virtual power plants is established based on a multi-timescale rolling optimization strategy. The advantages of the proposed strategy and model are verified through arithmetic simulation and the following conclusions are drawn:

The pumped storage–carbon capture–power-to-gas synergistic operation framework realizes the synergistic complementarity of different aggregation units and the low-carbon economic operation of the VPP. Compared with the carbon capture-electricity-to-gas joint operation mode, the net cost of the virtual power plant is reduced by 126,300 CNY, the amount of renewable energy consumed is increased by 567.46 MW·h, and the net carbon emission from the system is reduced by 92.7 t. It effectively improves the flexible regulation capability of the virtual power plant and promotes the low-carbon economic operation of the virtual power plant.

The multi-timescale rolling optimization strategy leverages the ability of CCS and P2G equipment energy consumption to track fluctuations in renewable energy. Compared with the day-ahead scheduling plan, the CO_2 captured by the carbon capture system increased by 561.5 t and the net carbon emissions from the VPP decreased by 282.1 tons. In addition, the regulation depth of the PS was also tapped. Compared with the previous day's scheduling plan, the total pumping energy consumption increases by 274.68 MW·h and the total power generation increases by 190.38 MW·h. The multi-timescale rolling optimization strategy is capable of correcting the energy flow in the framework of the synergistic operation of pumped storage–carbon capture–power-to-gas with a shorter temporal resolution based on renewable energy sources and the uncertainty of loads. The multi-timescale rolling optimization strategy can further take advantage of the refined scheduling of the pumped storage–carbon capture–power-to-gas synergistic operation framework.

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Data Availability Statement: The data that support the findings of this study are not openly available due to sensitivity but are available from the corresponding author upon reasonable request.

Conflicts of Interest: Author Junwei Zhang was employed by the company SPIC Green Energy Science & Technology Development Co., Ltd.; Author Dongyuan Liu was employed by the State Grid Jibei Electric Power Co., Ltd. Chengde Power Supply Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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