Robust Optimization of a CCS-P2G Virtual Power Plant Accounting for Penalized Carbon Price

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November 8, 2023

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***Abstract*—The virtual power plant (VPP) consisting of power to gas (P2G) and carbon capture system (CCS) can reduce the system carbon emissions and effectively respond to the low-carbon electricity market. However, the fluctuation of carbon price in the carbon trading market affects the carbon capture rate and carbon trading cost of the VPP system, and the uncertainty of renewable energy output in the VPP also affects the optimal scheduling. Therefore, this paper constructs a robust optimal scheduling model of CCS-P2G virtual power plant taking into account the punitive carbon price. In the model, the penalty carbon price increases the price of excessive carbon emission; the volatility of renewable energy output is included in the robust optimization. The simulation results show that compared with the traditional carbon price, the penalty carbon price has a better carbon reduction effect on VPP; the smaller the robustness index in the robust optimization, the more conservative the system is, and the larger the VPP gain is, and vice versa. The model proposed in this paper can efficiently participate in the competition of power market and carbon trading market, and the formulation of reasonable penalty carbon price and robustness index can realize the synergy of economy and low carbon of VPP system.**

Keywords—Wind-scenic uncertainty, electricity-to-gas conversion, virtual power plant, robust optimization, carbon trading

I. INTRODUCTION

Virtual Power Plant (VPP) provides a platform for the aggregation and coordinated optimization of Distributed Energy Resources (DREs) through advanced communication technologies and software systems[1].VPP needs to face the uncertainty of high penetration of new energy sources into the grid and their output, and urgently seeks for ways to make VPP operation economical and low-carbon while taking into account the fluctuation and consumption capacity of new energy sources[2].

Reference [1] considers an integrated electricity-gas-heat energy system with carbon capture, utilization and storage, which realizes the combination of low carbon and economy. Reference [2] utilizes CO_2 captured by carbon capture power plant to give P2G plant as electricity-to-gas feedstock, which can build P2G-CCS virtual power plant.

VPPs face renewable energy (wind or solar) output uncertainty, and traditional deterministic optimization is difficult to cope with optimal scheduling of VPPs considering multiple uncertainties. Stochastic programming, fuzzy optimization, and robust optimization are commonly used. Among them, robust optimization requires only the range of uncertainties and does not require subjective selection of fuzzy affiliation functions or probability distribution functions that generate errors.

II. VPP STRUCTURE FOR CARBON CAPTURE AND WASTE INCINERATION CONSIDERING P2GSELECTING A TEMPLATE

A. VPP Basic Structure

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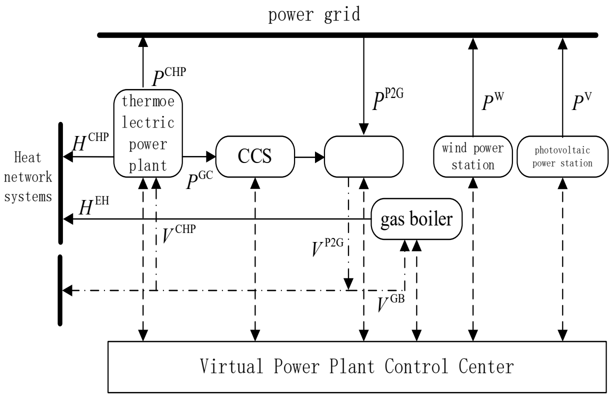

Fig. 1. VPP system architecture.

B. *Operating Characteristics of Cogeneration Units*

There is a certain coupling relationship between the electrical output and thermal output of CHP units. Compared to the back pressure type CHP unit, which can only operate in the "heat to electricity" operating state, the extraction type CHP unit can adjust its power generation within a certain range when the heating is determined. For example, under the thermal output, the electrical output can be adjusted within a certain range. However, as the thermal output increases, the adjustable range of electrical output decreases, as shown in Figure 2.

The thermoelectric operation area of CHP units can be represented as:

$$\begin{cases} H_{\min}^{\mathrm{chp}} \le H_t^{\mathrm{chp}} \le H_{\mathrm{med}}^{\mathrm{chp}}: \\ P_{\min}^{\mathrm{chp}} - c_{\mathrm{v1}} H_t^{\mathrm{chp}} \le P_t^{\mathrm{chp}} \le P_{\max}^{\mathrm{chp}} - c_{\mathrm{v2}} H_t^{\mathrm{chp}} \\ H_{\mathrm{med}}^{\mathrm{chp}} \le H_t^{\mathrm{chp}} \le H_{\max}^{\mathrm{chp}}: \\ c_{\mathrm{m}} \left(H_t^{\mathrm{chp}} - H_{\mathrm{med}}^{\mathrm{chp}} \right) + P_{\min}^{\mathrm{chp}} \le P_t^{\mathrm{chp}} \le P_{\max}^{\mathrm{chp}} - c_{\mathrm{v2}} H_t^{\mathrm{chp}} \end{cases} \tag{1}$$

In the formula: $H_{\max}^{\mathrm{CHP}}$ 、 $H_{\min}^{\mathrm{CHP}}$ 、 $H_{\mathrm{med}}^{\mathrm{CHP}}$ are the upper and lower limits of the thermal output of the condensing CHP unit, as well as the heating power of the steam turbine with the lowest generating power of the unit; $P_{\max}^{\mathrm{CHP}}$ 、 $P_{\min}^{\mathrm{CHP}}$ represents the upper and lower limits of electrical output, respectivel; P_t^{CHP} 、 H_t^{CHP} represents the electrical and thermal output of the CHP unit at time t; c_{v1} 、 c_{v2} is the c_{v} value corresponding to the minimum and maximum intake volume of the steam turbine, respectively, Among them, c_{v} is the reduction in power generation under the condition of extracting more unit heating heat when the inlet steam volume of the steam turbine remains constant; c_{m} is the electric heat conversion coefficient of the CHP unit, which can be considered as a constant.

C. *Carbon Capture Energy Consumption and Carbon Utilization In The CCS-P2G System*

The energy consumption of the carbon capture system is provided by the cogeneration unit, and its expression is [12]:

$$P_t^{\mathrm{GC}} = P_t^{\mathrm{B}} + P_t^{\mathrm{OP}} \tag{2}$$

In the formula: P_t^{GC} 、 P_t^{B} and P_t^{OP} are the total energy consumption, fixed energy consumption, and operating energy consumption of the carbon capture system at time t. Among them, fixed energy consumption can be regarded as a constant.

The expression for the relationship between the amount of CO_2 captured by a carbon capture system (Q_t^{CC}) and operating energy consumption:

$$P_t^{\mathrm{OP}} = w^{\mathrm{C}} Q_t^{\mathrm{CC}} \tag{3}$$

In the formula: w^{C} is the operating energy consumption per unit of CO_2 processed by a carbon capture power plant.

The expression for the carbon content Q^{P2G} sent to the P2G device using the captured CO_2 amount is [13]:

$$Q^{\mathrm{P2G}} = \rho_{\mathrm{CO_2}} V_t^{\mathrm{P2G}} \tag{4}$$

$$V_t^{\mathrm{P2G}} = \frac{3.6 \eta^{\mathrm{P2G}} P_t^{\mathrm{P2G}}}{H^{\mathrm{g}}} \tag{5}$$

In the formula: $\rho_{\mathrm{CO_2}}$ is the density of CO_2; V_t^{P2G} s the volume of methane produced at time t; η^{P2G} is the conversion efficiency of P2G electricity to gas; H^{g} is the calorific value of natural gas, taken as $\begin{cases} e_{\mathrm{air}}^t = e_1^t + e_2^t \\ e_2^t = (1 - \eta_{\mathrm{c}}) E_1^t \end{cases}$.

III. OPTIMAL SCHEDULING MODEL FOR VIRTUAL POWER PLANTS

A. *Objective Function*

The objective function VPP is based on a 24-hour scheduling cycle, with the optimization objective of maximizing economic benefits. Taking into account various benefits and costs, the objective function expression is:

$$f = \max \sum_{t=1}^{\mathrm{T}} \left(I_t^{\mathrm{SE}} - I_t^{\mathrm{C}} - F_t^{\mathrm{H}} - F_t^{\mathrm{STO}} \right) \tag{6}$$

1）VPP electricity and heat sales revenue I_t^{SE}:

$$\begin{aligned} I_t^{\mathrm{SE}} = M^{\mathrm{s}} \left(P_t^{\mathrm{W}} + P_t^{\mathrm{V}} + \sum_{i \in \theta} P_{i,t}^{\mathrm{CHP}} - P_t^{\mathrm{GC}} \right) + \\ M^{\mathrm{h}} \left(H_t^{\mathrm{CHP}} + H_t^{\mathrm{GB}} \right) - M^{\mathrm{b}} P_t^{\mathrm{EM}} \end{aligned} \tag{7}$$

In the formula:i is the serial number of the cogeneration unit; θ is the number of cogeneration units in the virtual power plant; M^{s} 、 M^{h} 、 M^{b} are the electricity selling price, heat selling price, and electricity purchasing price from the power grid of the virtual power plant; P_t^{W} 、 P_t^{V} 、 P_t^{GC} 、 P_t^{EM} are the wind power, photovoltaic output, total energy consumption of carbon capture, and purchasing power at time t; H_t^{GB} is the thermal power output of the gas boiler at time t.

2）VPP carbon trading cost

Calculate the actual carbon emission rights involved in carbon trading market transactions based on unpaid carbon emission quotas and the actual carbon emissions of the system Q_t^{jy} :

$$Q_t^{\mathrm{jy}} = Q_t^{\mathrm{N}} - Q_t^{\mathrm{A}} \tag{8}$$

$$Q_t^{\mathrm{N}} = e^{\mathrm{g}} P_t^{\mathrm{CHP}} - Q_t^{\mathrm{CC}} \tag{9}$$

$$Q_t^{\mathrm{A}} = \gamma^{\mathrm{C}} P_t^{\mathrm{CHP}} \tag{10}$$

In the formula: Q_t^{N} is the actual $\mathrm{CO_2}$ emissions at the time; Q_t^{A} is the free carbon emission quota allocated by the time control center,When the actual carbon emissions Q_t^{N} and free carbon emissions quota Q_t^{A} of the system are equal at time t, the actual carbon emissions rights participating in the carbon trading market are zero, and the carbon trading cost is also zero; e^{g} is the carbon emission intensity per unit of electricity; γ^{C} is the carbon emission quota per unit of electricity.

In order to impose stronger penalties on high carbon emissions, the carbon trading penalty coefficient will increase with the increase of actual carbon emission rights. Considering this growth characteristic, this article uses an exponential function to construct a penalty coefficient and carbon trading cost model.

When the difference between carbon emissions and carbon quotas exceeds the given range, the excess will increase the price of carbon trading; When the carbon emissions are lower than the carbon quota, the excess carbon emissions rights will be sold to obtain profits, and a penalty carbon trading function will be introduced to increase the punishment of carbon emissions. The calculation model of penalty carbon price is as follows:

$$x_t^{\mathrm{C\_p}} = \frac{x_t\left(e^{Q_t^{\mathrm{jy}}}-1\right)}{Q_t^{\mathrm{jy}}} \tag{11}$$

The carbon trading cost for considering punitive carbon prices is:

$$I_t^{\mathrm{C}} = x_t^{\mathrm{C\_p}} \cdot Q_t^{\mathrm{jy}} = x_t\left(e^{Q_t^{\mathrm{jy}}}-1\right) \tag{11}$$

In the formula: x_t is the carbon trading price at that time; $e^{Q_t^{\mathrm{jy}}}$ is the penalty coefficient for carbon trading; I_t^{C} is the penalty coefficient for carbon trading; At time t, the carbon trading cost of the system is represented by a positive value representing purchase and a negative value representing sale.When the carbon emission rights $Q_t^{\mathrm{jy}}=0$ actually participate in the carbon trading market, the carbon trading penalty coefficient $e^{Q_t^{\mathrm{jy}}}=1$ and the carbon trading cost are 0. In the formula: $a_i\left(i=0,\cdots,5\right)$ is the cost function coefficient.

3）The cost of purchasing natural gas for the CHP unit and gas boiler is expressed as:

$$F_t^{\mathrm{H}} = k^{\mathrm{CH_4}} V_t^{\mathrm{BUY}} \tag{12}$$

$$V_t^{\mathrm{BUY}} = V_t^{\mathrm{GB}} + V_t^{\mathrm{CHP}} - V_t^{\mathrm{P2G}} \tag{13}$$

$$V_t^{\mathrm{CHP}} = \frac{P_t^{\mathrm{CHP}}}{H^{\mathrm{g}}\eta^{\mathrm{CHP,e}}} + \frac{H_t^{\mathrm{CHP}}}{H^{\mathrm{g}}\eta^{\mathrm{CHP,h}}} \tag{14}$$

In the formula: $k^{\mathrm{CH_4}}$ is the unit price of natural gas in the natural gas market; V_t^{GB} 、 V_t^{CHP} represents the natural gas consumed by gas boilers and CHP units, respectively; $\eta^{\mathrm{CHP,e}}$ 、 $\eta^{\mathrm{CHP,h}}$ represents the power generation and heating efficiency of the CHP unit.

4）Carbon storage costs

The expression for using carbon storage equipment to store $\mathrm{CO_2}$ is as follows:

$$F_t^{\mathrm{STO}} = k^{\mathrm{STO}}\left(Q_t^{\mathrm{CC}} - Q_t^{\mathrm{P2G}}\right) \tag{15}$$

In the formula: k^{STO} is the cost coefficient of carbon sequestration.

B. Constraint Condition

1）CCS equipment carbon capture capacity constraints

Because all the $\mathrm{CO_2}$ captured by CCS equipment is discharged by the cogeneration unit, the carbon constraint is:

$$0 \le Q_t^{\mathrm{CC}} \le Q_t^{\mathrm{l}} \tag{16}$$

$$Q_t^{\mathrm{l}} = e^{\mathrm{g}}\eta_{\max}^{\mathrm{CC}} P_t^{\mathrm{CHP}} \tag{17}$$

$$0 \le P_t^{\mathrm{OP}} \le P_{\max}^{\mathrm{OP}} \tag{18}$$

In the formula: $\eta_{\max}^{\mathrm{CC}}$ is the maximum carbon capture rate of CCS equipment; $P_{\max}^{\mathrm{OP}}$ is the upper limit of energy consumption and output for carbon capture operation.

2）Operational constraints of condensing cogeneration units

$$P_{\min}^{\mathrm{CHP}} \le P_t^{\mathrm{CHP}} \le P_{\max}^{\mathrm{CHP}} \tag{19}$$

3）P2G operation constraints

$$0 \le P_t^{\mathrm{P2G}} \le P_{\max}^{\mathrm{P2G}} \tag{20}$$

In the formula: $P_{\max}^{\mathrm{P2G}}$ is the maximum operating power of the P2G device.

4）Thermal balance constraint

$$P_t^{\mathrm{k}} + P_t^{\mathrm{GC}} + P_t^{\mathrm{P2G}} = P_t^{\mathrm{CHP}} + P_t^{\mathrm{W}} + P_t^{\mathrm{V}} + P_t^{\mathrm{EM}} \tag{21}$$

$$H_t^{\mathrm{k}} = H_t^{\mathrm{GB}} + H_t^{\mathrm{CHP}} \tag{22}$$

In the formula: H_t^{k} represents the planned thermal load power demand of VPP at time *t*.

IV. ADJUSTABLE ROBUST OPTIMIZATION MODEL CONSIDERING UNCERTAINTY IN SCENIC OUTPUTS

For this model, considering the volatility of wind power output, the worst case of the system is considered here to be the worst economy of the system when the wind and light fluctuations are the largest, and the worst case under the established renewable energy power balance is expressed as follows:

$$P_t^{\mathrm{k}} + P_t^{\mathrm{GC}} + P_t^{\mathrm{P2G}} - P_t^{\mathrm{EM}} - P_t^{\mathrm{CHP}} = \max\left(P_t^{\mathrm{W}} + P_t^{\mathrm{V}}\right) \tag{23}$$

$$\begin{aligned} &\max\left(P_t^{\mathrm{W}} + P_t^{\mathrm{V}}\right) = \bar{P}_t^{\mathrm{W}} + \bar{P}_t^{\mathrm{V}} + \\ &\max\left\{\eta^{\mathrm{Wd}}P_t^{\mathrm{Wd}} + \eta^{\mathrm{Wu}}P_t^{\mathrm{Wu}} + \eta^{\mathrm{Vd}}P_t^{\mathrm{Vd}} + \eta^{\mathrm{Vu}}P_t^{\mathrm{Vu}}\right\} \end{aligned} \tag{24}$$

$$\eta^{\mathrm{Wd}} + \eta^{\mathrm{Wu}} + \eta^{\mathrm{Vd}} + \eta^{\mathrm{Vu}} \le \Gamma_t \tag{25}$$

$$0 \le \eta^{\mathrm{Wd}}, \eta^{\mathrm{Wu}}, \eta^{\mathrm{Vd}}, \eta^{\mathrm{Vu}} \le 1 \tag{26}$$

In the formula: $\bar{P}_t^{\mathrm{W}}$ and $\bar{P}_t^{\mathrm{V}}$ are the predicted values of scenery, respectively; P_t^{Wd}, P_t^{Wu}, P_t^{Vd}, and P_t^{Vu} are the upper and lower limits of wind PV power fluctuations, respectively; η^{Wd}, η^{Wu}, η^{Vd}, and η^{Vu} are the lower limit as well as the upper limit of the fluctuation ratio of wind PV, respectively; Γ_t is a robustness metric that indicates the strength of robustness at various times of the virtual power plant's operating cycle.

By introducing the dyadic variables λ_1, π_1, π_2, π_3, and π_4, the $\max\{\bullet\}$ in Eq. (26) as well as Eqs. (27) and (36) can be equated to facilitate the solution of the dyadic problem as follows:

$$\min\left(\lambda_1\Gamma_t + \pi_1 + \pi_2 + \pi_3 + \pi_4\right) \tag{27}$$

$$\lambda_1 + \pi_1 \ge P_t^{\mathrm{Wd}},\quad \lambda_1 + \pi_2 \ge P_t^{\mathrm{Wu}} \tag{28}$$

$$\lambda_1 + \pi_3 \ge P_t^{\mathrm{Vd}},\quad \lambda_1 + \pi_4 \ge P_t^{\mathrm{Vu}} \tag{29}$$

$$\lambda_1, \pi_1, \pi_2, \pi_3, \pi_4 \ge 0 \tag{30}$$

V. CASE ANALYSIS

A. VPP System Vomponents and Parameters

The VPP power sales plan for the area where the virtual power plant is located is shown in Figures 2 and 3, along with the thermal load and the forecasted output of wind and PV.

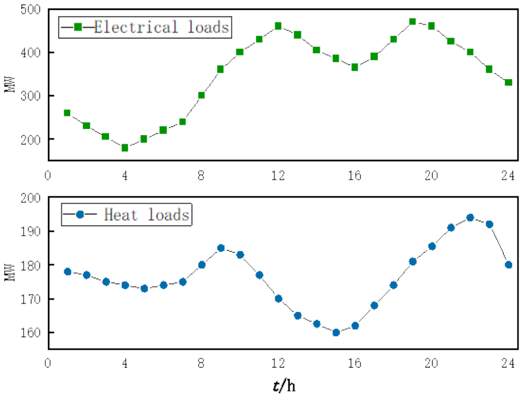

Fig. 2. VPP power sales program and heat loade.

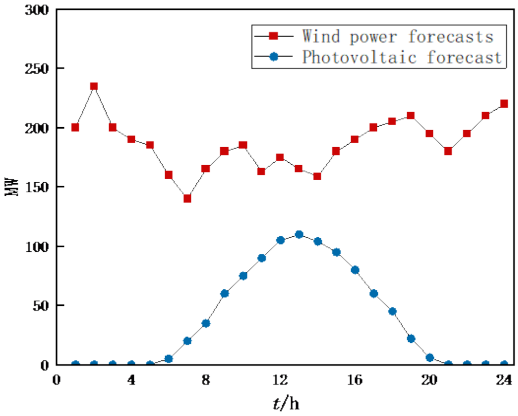

Fig. 3. Wind and photovoltaic forecast output.

To verify the correctness and validity of the model proposed in this paper, the parameters of each unit of VPP are shown in Table I.

TABLE I. PARAMETERS OF THE EQUIPMENT OF THE VPP

Equipment Name	Quantity (units)	Maximum Output/Minimum Output (MW)
Thermal power plants	1	350/100
Wind power plant	1	250/50
Photovoltaic power plants	1	150/0
Carbon Capture	1	50/10
P2G	1	60/0

B. Comparison Scenarios and Analysis of Results

In order to compare and analyze the impact of carbon capture and electric-to-gas equipment introduced in the VPP on the total revenue of the VPP as well as to verify the correctness of the robust linear optimization method, four comparison scenarios are set up, as shown in Table II.

TABLE II. FOUR DIFFERENT VPP BUILD SCENARIOS

Scenario	Condensate CHP	CCS-P2G	Robust linear optimization method	Punitive carbon price
1	√	×	×	×
2	√	√	×	×
3	√	√	√	×
4	√	√	√	√

According to the four scenarios constructed, the comparison of the total gain and the abandoned wind power and CO2 emission scenarios obtained from the optimization are shown in Table III, Fig. 4 and Fig. 5, respectively.

TABLE III. TOTAL BENEFITS IN EACH SCENARIO

Scenario	Robustness metrics	VPP total return/RMB
1	/	2337100
2	/	2497240
3	$\Gamma_t=0$	2497650
4	$\Gamma_t=0$	2498340

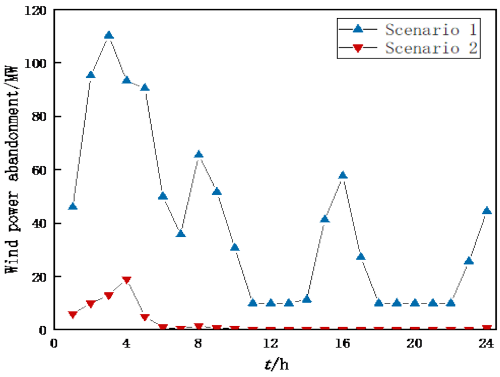

Fig. 4. Wind abandonment power for Scenario 1 and Scenario 2.

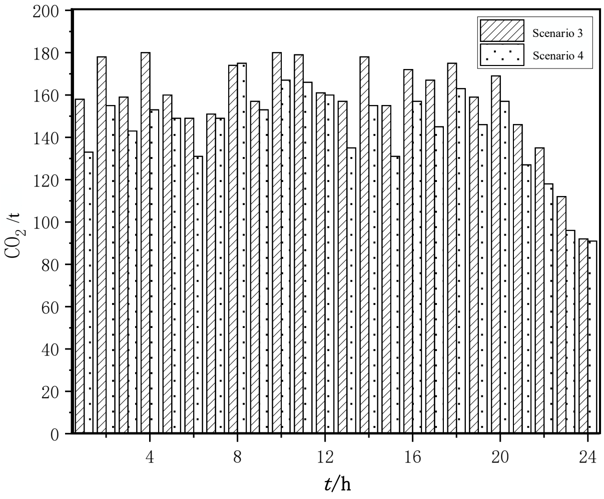

Fig. 5. CO_2 emissions for Scenario 3 and Scenario 4.

Based on the optimization results, Scenario 2 realizes the synergistic operation of CCS-P2G and the virtual power plant compared with Scenario 1, and a total of 19.78t of captured CO2 is supplied to the P2G equipment as raw material, which saves the cost of purchasing CO2 and carbon sequestration, and leads to a reduction in the cost of purchasing natural gas in Scenario 2.After joining the CCS-P2G equipment, the equipment converts electricity into natural gas, which is supplied to CHP units, gas boilers for power generation and heat generation or sold in the natural gas market, and links the electricity market with the natural gas market through the electricity-to-gas equipment, so that wind power can be consumed in the low load moment (23:00-7:00) and the normal load moment (8:00-10:00, 15:00-17:00) to satisfy the CCS-P2G requirements.), wind power consumption meets the operation of the CCS-P2G equipment, in the load peak moments due to the sale of power revenue is much larger than the CCS-P2G equipment to bring revenue, the gas turbine, as well as wind power generation, photovoltaic power generation power all to the by the network sale, P2G equipment power is 0.

In Scenario 3 the robustness index $\Gamma_t=0$ is taken and compared with Scenario 2, both of them have the same total benefit, which shows the correctness of the robust optimization algorithm; Scenario 4 introduces a punitive carbon price, since the carbon trading cost is directly proportional to the size of the actual carbon emission right, a high carbon price will limit the carbon emission of VPP, which leads to the reduction of the carbon trading cost and the increase of the total benefit.

C. *Impact of Uncertainty on Optimization Runs*

In order to observe the effect of different robustness indexes on the operating output of the unit, the CHP unit and purchased power adjustments were set at robustness indexes of 0.5, 1.0, and 1.5, respectively.

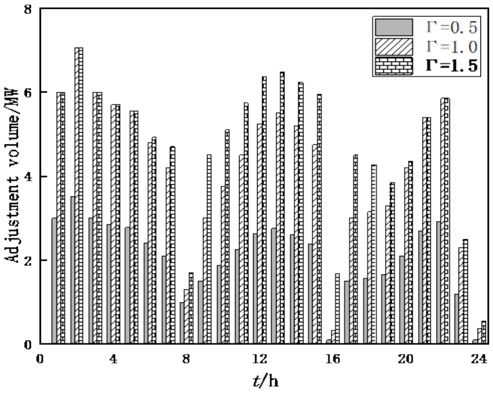

Fig. 6. Impact of different robustness metrics on the amount of unit adjustmen.

From Fig. 6, it can be seen that when the system operates in the worst case to cope with the downward fluctuation of the wind power output, the CHP unit needs to increase its output in order to guarantee the balance of electric power, and the purchased power should be increased appropriately. When the robustness index is 0.5, 1.0, and 1.5, the total amount of adjustments that need to be increased for the three is 50.5 MW, 100.5 MW, and 115 MW, respectively. As the robustness metric Γ_t increases, the range of the wind-scenery power uncertainty set becomes larger, and it can be seen that the VPP's benefits under a multi-cooperative market gradually decrease. That is, the greater the system conservatism, the greater the downward fluctuation of wind and light, and the greater the amount of power that needs to be adjusted in real time by the CHP units and the purchased power in order to satisfy the electric power balance. The total returns of VPP under different robustness indicators are shown in Table IV.

TABLE IV. IMPACT OF DIFFERENT ROBUSTNESS METRICS ON TOTAL VPP RETURNS

Robustness metrics	VPP total return/RMB
0.5	2497300
1.0	2479900
1.5	2473200

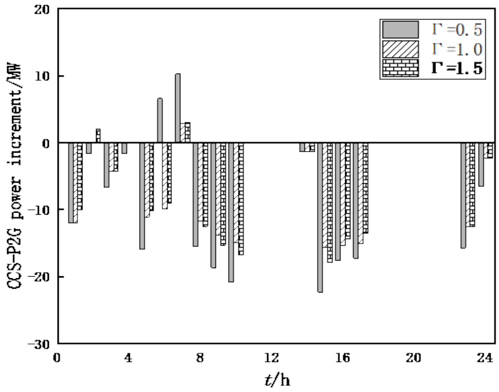

Fig. 7. Power increment of CCS-P2G with different robustness metrics.

From the above Table IV and Fig. 7, it can be seen that increasing the robustness index Γ_t makes the system become conservative, and at the same time makes the VPP revenue decrease, and the power of CCS-P2G increases, and its power decreases by 156 MW, 136 MW, and 134 MW for robustness indexes of 0.5, 1.0, and 1.5, respectively, compared to deterministic optimization.This is due to the fact that the wind PV output fluctuates downwards, and the CHP unit needs to increase its output and the purchased power also increases, but since the increased power will first meet the load demand, the power of CCS-P2G decreases, but increasing the robustness index makes the power of CCS-P2G increase despite the increase in the incremental power. It should be noted that the appropriate value can be selected by the scheduler's risk preference in the actual scheduling.

VI. CONCLUSION

1) In the proposed electricity-gas-heat virtual power plant with CCS-P2G under the penalized carbon price, P2G provides a pathway for reuse of captured CO2, while the conversion energy required for P2G and energy consumption for capture can fully utilize the abandoned wind power. Compared with the traditional carbon price, the carbon reduction effect and economy are better, and it can efficiently participate in the competition of the power market and carbon trading market.

2) The correctness of the robust linear optimization in this paper is verified by adjusting the robustness index to describe the conservativeness of the system, where the higher the conservativeness, the more additional power and purchased power is generated by the CHP units in the corresponding system, and the economic efficiency will decrease.

3) Different robustness indexes are selected, and the power of CCS-P2G increases gradually with the increase of robustness indexes, which achieves the balance of power

decarbonization, robustness and system economic returns to some extent.

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