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Decarbonization Scheduling Strategy Optimization for Electricity-Gas System Considering Electric Vehicles and Refined Operation Model of Power-to-Gas

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ABSTRACT As the global warming crisis becomes increasingly serious, decarbonized integrated electricity-gas system (IEGS) which can reduce CO_2 emissions are gradually developed. However, with high proportion of renewable energy access, the inherent randomness and volatility bring great difficulties to energy scheduling optimization of decarbonized IEGS. In this article, for reducing CO_2 emissions, meanwhile improving the utilization efficiency of wind power, a novel IEGS architecture with collaborative operation of power-to-gas (P2G), carbon capture system (CCS) and electric vehicles (EVs) is constructed. P2G is operated in a refined model combined with H_2 storage and captured CO_2 by CCS can be further consumed in reaction of P2G. Besides, EVs are innovatively adopted in IEGS as flexible energy resource to reduce the impact of wind power fluctuations. Additionally, a multi-step day ahead-intraday collaborative optimization framework is proposed to handle with the uncertainty of wind power, more accurate predicted wind power can be adopted under this framework. The objective function of constructed IEGS is minimize the total operating costs, which takes the CO_2 processing costs and penalty costs of wind power deviations into consideration. Numerical studies are conducted with different cases, with the constructed structure and proposed multi-step optimization framework, the emissions of CO_2 can be efficiently reduced and wind power utilization can be significantly improved, the total operating costs of IEGS can be reduced more than 20% compared with other cases, which demonstrates that the research of this article has better economic benefits and environmental friendliness.

INDEX TERMS CO_2 emissions reduction, carbon capture system, decarbonized integrated electricity-gas system, power-to-gas, uncertainty of wind power.

I. INTRODUCTION

In recent years, the problem of global warming caused by greenhouse gas emissions has become increasingly serious. The world is committed to holding global warming below 2.0 °C and to pursuing the goal of limiting it to 1.5 °C [1]. As one of the most common greenhouse gases, CO_2 is the main cause of global warming [2]. Therefore, how to reduce CO_2 emissions while optimizing the scheduling strategy of energy system has become an issue of extensive research, especially in integrated electricity-gas system (IEGS) which is increasingly widely used [3].

With the conversion and integration of multiple energy sources, natural gas-fired unit (NGU) has become one of the most widely used approach to reduce greenhouse gas emissions of system [4]. Compared with conventional fossil fuel-fired power generation unit, NGU has higher production efficiency, faster ramp speed, and especially less CO_2

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emissions [5]. Besides using of environment-friendly NGU, the rapidly developing carbon capture system (CCS) is also widely applied to reduce the emissions of CO_2 in the production process of fossil fuel-fired power generation units [6]. Through dealing with flue gas by CCS, large amount of CO_2 can be captured. In addition to the above technologies, renewable energy, which is a kind of sustainable, efficient and CO_2 emissions free resource, is widely accessed into power systems to reduce greenhouse gas emissions [7]. However, due to the inherent randomness and volatility of renewable energy, a large amount of renewable energy cannot be effectively scheduled and utilized [8]. To solve this problem, one of the latest and rapidly developing approaches is power-to-gas (P2G) technology, which can efficiently convert surplus power caused by fluctuations of renewable energy into hydrogen (H_2) or synthetic natural gas (SNG) and store it in gas network [9]. The application of this technology can not only significantly improve the utilization of renewable energy, but also consume CO_2 in the SNG production process of P2G, which is perfect for reducing greenhouse gas emissions during dispatching of energy system. On the other hand, electric vehicles (EVs) have been widely used in power systems due to their low carbon emissions, but few articles have considered their energy scheduling effect in IEGS [10]. In this article, in order to improve utilization of wind power and reduce CO_2 emissions in IEGS, not only the P2G and CCS are adopted in energy scheduling, the flexibility provided by EVs is also utilized. Furthermore, new optimization framework is proposed to reduce effect of wind power uncertainty.

A. RELATED WORK

In IEGS, through the widely application of NGU and P2G, a bi-directional energy conversion architecture was constructed between power system and natural gas network, the coupling relationship between power system and gas network would have deeper impact on the energy scheduling in energy system [11], [12]. Moreover, for low carbon intensity target based on an established emissions trading scheme in China, CCS was increasingly utilized to reduce greenhouse gas emissions, which has influence on energy dispatching mode of power system [13]. Also, as a kind of dynamic energy resource, EVs were widely integrated in economic dispatch optimization of power system due to their flexibility and carbon reduction characteristics, which provided multiple ways for energy scheduling [14], [15]. Considering these, it is necessary and desirable to construct novel models and search efficient dispatch strategies for IEGS with P2G, CCS and flexible resources contained.

A considerable amount of researches on the energy dispatching of IEGS have been done previously. In order to obtain the optimal energy dispatching strategy of IEGS, novel stochastic model was proposed and piecewise linearization method was adopted to convert the constraints of gas network in [16], however optimization was only conducted under day-ahead time scale, the accuracy of obtained strategies cannot be ensured. A distributed optimization framework of IEGS was proposed in [17], which took demand side response and uncertainties into consideration. The uncertainties of distributed generation was dealt with robust uncertain set, which may lead to excessive convergence. An IEGS model contained the supply constraint of natural gas and the uncertainty gas price was proposed in [18], two-stage stochastic unit commitment problem of IEGS was solved in it, but flexible energy resource such as EVs, DRP were not contained in the optimization, economic dispatch problem was not considered. According to these, this article considers adopting multi-step optimization to improve the accuracy of energy strategies and handle uncertainty of wind power with scenario method, also EVs are incorporated into operation of IEGS.

Furthermore, with the rapid development of P2G technology, it has become an important linkage that deepened the coupling relationship between power grid and gas network, which increases the flexibility of energy conversion and the difficulty of optimizing energy scheduling strategies in IEGS. Some researches have studied the energy dispatching of IEGS with P2G contained. Considering NGU and P2G simultaneously, bi-directional energy dispatching structure was constructed to optimize IEGS under steady-state condition [19]. In [20], an IEGS containing NGU and P2G was constructed to optimize the energy dispatching of renewable energy generation. Except for these researches above, as the P2G technology developed and matures gradually, it can not only be used to convert electricity directly to SNG, but also alternatively can be used to produce intermediate product H_2 for maximum economic benefit. In [21], P2G was used to convert exceeded electricity into H_2 which can be stored in H_2 storage system, once energy was needed in the future, it can be used to refurnish electricity with fuel cells. In [22], P2G was adopted to create H_2 through electrolysis when exceeded electricity was generated due to fluctuations of renewable energy or price of electricity is low, which can effectively pursue the best operation benefit. In addition to generating H_2, methanation process during operation of P2G can consume large amounts of CO_2, which can be optimized coordinately with CCS to reduce greenhouse gas emissions of IEGS. CO_2 is converted to generate SNG in P2G, and CCS can capture the needed CO_2 for P2G [23]. According to this, through joint optimization of P2G and CCS, decarbonized energy dispatch of IEGS can be achieved for less greenhouse gas emissions and better economic benefits. However, researches above have only considered the effect of P2G, most of them have not utilized the flexibility of EVs in the optimization of IEGS. As a promising and developing approach to provide flexibility in demand side of multi-energy systems, EVs play an increasingly important role in the process of energy scheduling, which is necessary to incorporated into the optimization.

With rapid development of vehicle-to-grid (V2G) technology, the utilization of EVs has been gradually improved due to their high flexibility and low carbonization [24]. Large number of dispatchable EVs can provide sufficient flexibility to adjust the supply-demand balance of energy system, how to utilize them to optimize the energy flow considering uncertainties is also the key to energy system optimization. In [25], the scheduling strategies of distributed generators, EVs charging demand were optimized, the number of participated EVs and usage time of them were taken into account. However, although mobility of EVs was considered, the uncertainty of renewable energy has not been dealt with. In [26], the optimal size and location of EVs charging stations were analyzed, to increase the proportion of EVs accessed in energy systems. But energy scheduling strategies of other parts in energy systems have not been researched in depth. In [27], the utilization of charging stations and the travel behavior of users were considered to optimize the distribution and expansion of EVs in energy network. But the conversion of multiple energy resources has not been considered. As can be seen, although with the gradual maturity of rapid charge technology, the dispatching of EVs was studied mostly in power systems, few of researches has concentrated on the regulating effect of EVs on energy scheduling in IEGS under clean renewable energy uncertainty. With the flexibility provided by EVs, system can achieve better ability to balance supply and demand, as well as reducing peak load when renewable energy supply fluctuates. Besides, without the burning of fossil fuels, EVs are playing an important role in the decarbonisation of IEGS. Therefore, energy scheduling with EVs participating need to be further studied.

Except for all those above, as the scale of renewable energy accessed to IEGS gradually increased, the impact of renewable energy uncertainty on energy dispatching become non-negligible [28]. In [29], uncertainty of renewable resources was handled with a non-probabilistic information gap method in virtual energy hub. It is worthy of reference, but the method is more suitable for providing system operators with alternative scheduling strategies. In [30], [31], robust optimization was adopted to optimal dispatch reserve capacity and gas storage system, for reducing the impact of renewable energy uncertainty. But over convergent results are easily obtained. On the other hand, although efforts have been made in analysing the optimization of IEGS under uncertain conditions in above researches, most of them just simply consider the optimization under day-ahead time scale, which apply day-ahead predicted renewable energy as dispatchable resource. Characteristic of renewable energy, which is the prediction error of generation would decrease if the prediction interval is near real-time [32], [33], has not taken into consideration during the optimization. This characteristic can be utilized to further reduce the impact of renewable energy uncertainty on energy scheduling of IEGS [34]. Besides this, when renewable energy generation fluctuates, demand response program (DRP) are also efficient approaches to dispatch energy. In [35], for enhancing the flexibility of energy scheduling, DRP based optimization framework was proposed. The operator can decide to supply exceeded energy to non-critical loads currently or to store it for future using. According to these above, to achieve the decarbonized energy scheduling strategies of IEGS under renewable energy uncertainty, not only EVs and DRP are considered in this article, but also a multi-step day ahead-intraday collaborative optimization framework is proposed for energy dispatch of IEGS.

B. CONTRIBUTIONS

Taking the above descriptions into consideration, this article aims at constructing an EVs contained decarbonized energy scheduling model for IEGS, which coordinately optimizes the CCS and P2G under wind power uncertainty. EVs and DRP in power grid are considered as dispatchable energy resources to enhance the flexibility of IEGS. Dynamic time window mechanism based multi-step day ahead-intraday collaborative optimization framework is adopted to apply more accurate predicted wind power in energy dispatching. The Objective of optimization is to minimize total operating costs in IEGS, which takes the costs of CO_2 emissions and the penalty costs of wind power deviations into consideration, for pursuing higher utilization of wind power and less greenhouse gas emissions. In general, the major contributions of this article can be summarized as follows.

1) Aiming at decarbonizing the operation of IEGS and pursuing the best operating costs, multi-step day ahead-intraday collaborative optimization framework is proposed to optimize energy scheduling strategies of IEGS under uncertain condition of wind power, flexibility provided by EVs and DRP is utilized to reduce effect of wind power uncertainty. In first step optimization, IEGS are optimized for their day-ahead energy scheduling strategies. In second step, energy scheduling strategies in power grid are further adjusted based on rolling horizon mechanism, EVs and DRP are optimized as flexible energy resources in this process.
2) For reducing the greenhouse gas emissions and improving the utilization of wind power during the operation of IEGS, CCS and P2G are jointly operated in the optimization. CCS captures CO_2 generated during the operation of fossil fuel-fired generation unit and delivers it to P2G, then P2G consumes CO_2 in the process of producing SNG. Besides this, refined operation models of P2G are adopted in the optimization, it can convert exceeded electricity to SNG directly, on the other hand, combining with H_2 storage system, it is enabled to store electricity at lower price and refurnish power grid at higher price, for the best economic benefits of IEGS.
3) In the optimization, the amount of wind power deviations and consumed CO_2 are considered as factors affecting operating costs, so as to pursue higher renewable energy utilization and less greenhouse gas emissions. Moreover, different penetration levels of wind power are compared to analyse the variation of total operating costs in different cases.

The rest of this article is organized as follows. Section II constructs the multi-step day ahead-intraday collaborative optimization framework for IEGS. Section III formulates the mathematical models of IEGS. Relaxation of gas network

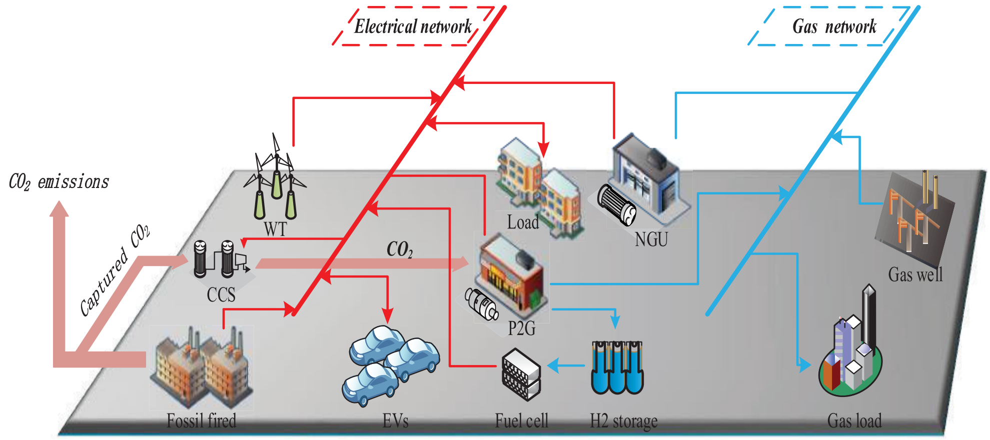

FIGURE 1. Architecture of EVs contained decarbonized IEGS.

constraint are described in Section IV. Finally, the case studies and conclusions are given in Section V and Section VI, respectively.

II. MULTI-STEP DAY AHEAD-INTRADAY COLLABORATIVE OPTIMIZATION FRAMEWORK

With the large-scale access of wind power generation, the stochasticity and volatility of it makes the optimal operation of IEGS facing great challenge. Rolling horizon optimization is one of the most useful approaches to reduce the impact of renewable energy uncertainty [36]. With the dynamics of optimization time window, it can constantly modulate the obtained dispatching strategies to satisfy the change of conditions or update available data. Considering that the errors of wind power generation increases with the extension of time horizon, the closer to real-time, the more accurate predicted results are. Taking advantage of this, multi-step day ahead-intraday collaborative optimization framework based on rolling horizon mechanism is proposed, more accurate predicted wind power generation can be utilized to better reduce the influence of uncertainty.

Different components in IEGS are optimized in different steps, which mainly considers their differential response speeds. The specific dispatching components and architecture of IEGS is presented in Fig. 1. In day-ahead step, the optimization is carried out for the whole IEGS for day-ahead energy scheduling strategies. P2G is coordinated with CCS to reduce the emissions of CO_2 and improve the utilization of wind power, meanwhile, it can use the generated H_2 to refurnish power grid through fuel cells. Day-ahead predicted wind power generation is applied in this step.

As described in the previous section, due to the relatively large errors of day ahead wind power prediction, there may be a fluctuation between predicted and actual wind power generation. Thus, in the second step, more accurate intraday predicted wind power generation is utilized to reduce the impact of uncertainty. On the other hand, considering the slow adjustment speed of the gas network, it can not be guaranteed that the condition of the network can be restored to steady-state after the change of scheduling strategies. Therefore, in this optimization step, only power grid which has fast response speed is adjusted, EVs and DRP are further adjusted in this step as flexible energy resources to balance supply-demand in power grid when wind power fluctuates. According to the above, the intuitive instruction of multi-step day ahead-intraday collaborative optimization framework is shown in Fig. 2.

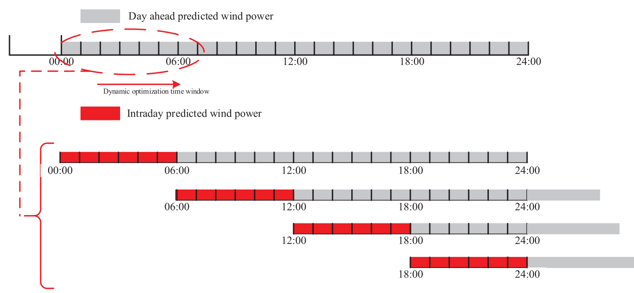

FIGURE 2. Framework of multi-step day ahead-intraday collaborative optimization.

III. MATHEMATICAL MODELING OF EVs CONTAINED DECARBONIZED IEGS

A. OBJECTIVE FUNCTION OF DAY-AHEAD OPTIMIZATION

In this step, the target is to pursue the minimum operating costs of the whole IEGS, which contains the costs of operation C_{op}^{st}, the costs of dealing with CO_2 $C_{CO_2^{st}}$ and the penalty costs of wind power deviations C_{wt}^{st}. The specific expression of total operating costs is presented as follows.

$$minC_{total}^{st} = C_{op}^{st} + C_{CO_2}^{st} + C_{wt}^{st} \tag{1}$$

Operation costs C_{op}^{st} mainly contains the generation of fossil fuel-fired generators and NGU, the costs of gas well production. Meanwhile, in this paper stochastic scenarios are generated to simulate the uncertainty of wind power. Therefore, the probability of different scenarios are considered in the objective function. The specific formula is shown as (2).

$$C_{op}^{st} = \sum_{s=1}^{N_s} \rho_s \sum_{t=1}^{N_T} \{ \sum_{n=1}^{N_g} c_n I_n(s,t)[G(P_n(s,t)) + Su_n(s,t) + Sd_n(s,t)] + \sum_{\omega=1}^{N_{GW}} c_{gas} Q_\omega(s,t) \} \quad (2)$$

in which, ρ_s represents the probability of each uncertain scenario; N_T is the optimization period which is 24 hours in this optimization step; N_g is the amount of generators in IEGS, which contains fossil fuel-fired generator and NGU; c_n means the fuel costs of each generator; I_n is binary auxiliary variable which present the unit combination state of generators; $G(P_n(s,t))$, $Su_n(s,t)$ and $Sd_n(s,t)$ represent the amount of consumed fuel caused by produce power, start and stop operation, respectively; N_{GW} means the number of gas well in gas network; c_{gas} is the gas price in IEGS; at last, $Q_\omega(s,t)$ means the amount of purchased gas from gas wells.

The costs of processing CO_2 mainly includes the costs of carbon emissions caused by fossil fuel-fired generator, the payment of CO_2 transmission and storage and the costs of capturing CO_2 from atmosphere which is used in P2G conversion process. This part of total costs is presented as follows.

$$C_{CO_2}^{st} = \sum_{s=1}^{N_s} \rho_s \sum_{t=1}^{N_T} \{ c_{CO_2} [\sum_{a=1}^{N_{fossil}} \mu_a P_a(s,t) - \sum_{c=1}^{N_{CCS}} Q_c^{CO_2}(s,t) - \sum_{m=1}^{N_{CS}} Q_m^{CO_2,air}(s,t)] + c_{ts} [\sum_{c=1}^{N_{CCS}} Q_c^{CO_2}(s,t) - \sum_{m=1}^{N_{CS}} Q_m^{CO_2,CCS}(s,t)] + c_{air} \sum_{m=1}^{N_{CS}} Q_m^{CO_2,air}(s,t) \} \quad (3)$$

in which, c_{CO_2} is the carbon tax price of greenhouse gas emissions; N_{fossil} represents the amount of fossil fuel-fired generator in IEGS, $P_a(s,t)$ is the generation of fossil fuel-fired generator and μ_a means the production rate of CO_2, this term presents the total generated CO_2 from the operation of fossil fuel-fired generator; N_{CCS} is the number of CCS, which used to capture CO_2, $Q_c^{CO_2}(s,t)$ is the total amount of CO_2 captured by CCS; N_{CS} is the number of CO_2 storage, which is combined with P2G facility for CO_2 conversion reaction. $Q_m^{CO_2,air}(s,t)$ means the stored CO_2 from atmosphere for the using of P2G. The first three terms represent the total costs of carbon emissions in IEGS. c_{ts} means the transmission costs of captured CO_2, part of the total captured CO_2 is stored into CO_2 storage for P2G conversion process, but the remaining CO_2 needs to be transferred to other places for future use. $Q_m^{CO_2,CCS}(s,t)$ represents the amount of stored CO_2 from the total captured CO_2 of CCS. c_{air} means the price of capturing CO_2 from atmosphere and $Q_m^{CO_2,air}(s,t)$ is the amount of captured CO_2 from atmosphere which used in P2G conversion process.

The penalty costs of wind power deviations is presented in (4), which is related to the gap of dispatched wind power generation obtained after the optimization and actual wind power generation.

$$C_{wt}^{st} = \sum_{s=1}^{N_s} \rho_s \sum_{t=1}^{N_T} \sum_{w=1}^{N_w} c_{wt} [P_w^f(s,t) - P_w(s,t)] \quad (4)$$

in which, N_w is the number of wind power generator in IEGS; c_{wt} represents the penalty price of wind power deviations; $P_w^f(s,t)$ and $P_w(s,t)$ means the scheduled wind power in optimization and actual wind power generation, respectively. The deviation between them is considered as the fluctuations caused by uncertainty.

B. OBJECTIVE FUNCTION OF INTRADAY OPTIMIZATION

In this step, rolling horizon mechanism is adopted to optimize the energy dispatching strategy with more accurate predicted wind power generation. The time interval of optimization is 1 hour in this stage, power grid is further adjusted in this step. The dispatching strategies related to the natural gas network are maintained as the results obtained in first step. In addition, as described previously, EVs and DRP are considered as regulation means to reduce the impact of wind power uncertainty on the IEGS. The specific objective function is shown as follows.

$$C_{total}^{nd} = C^{st} + \sum_{s=1}^{N_s} \rho_s \sum_{t=1}^{N_T} \{ \sum_{w=1}^{N_w} c_{wt} [P_w^{f,nd}(s,t) - P_w^{nd}(s,t)] + \sum_{d=1}^{N_{DR}} c_{DR} P_d^{DR}(s,t)] \} \quad (5)$$

in which, C^{st} means the costs that kept unchanged in this step, which is obtained in previous optimization. For instance, the costs related to natural gas network, the processing costs of CO_2 and the generation costs of fossil fuel-fired generator. The second term in (5) represents the penalty costs of wind power deviations in intraday optimization, the deviations are the amount between intraday predicted wind power which is more accurate and the actual wind power. The last terms are the compensation costs of DRP.

C. CONSTRAINTS OF POWER GRID

In order to ensure the safe and stable operation of IEGS, the constraints of power grid must be obeyed during the optimization process. The balance of supply and demand energy is presented as (6).

$$\sum_{a=1}^{N_{fossil}} P_a(s,t) + \sum_{b=1}^{N_{ngu}} P_b(s,t) + \sum_{w=1}^{N_w} P_w(s,t) + \sum_{p=1}^{N_{p2g}} P_p^{out}(s,t) + \sum_{u=1}^{N_{EVs}} P_u^{out}(s,t) + \sum_{d=1}^{N_{DR}} P_d^{DR}(s,t) = \sum_{c=1}^{N_{CCS}} P_c(s,t) + \sum_{p=1}^{N_{p2g}} P_p^{in}(s,t) + \sum_{u=1}^{N_{EVs}} P_u^{in}(s,t) + \sum_{k=1}^{N_L} P_k(s,t) \quad (6)$$

in which, $P_a(s,t)$ and $P_b(s,t)$ are the generation of fossil fuel-fired generator and NGU, respectively; $P_w(s,t)$ is the scheduled wind power generation; $P_p^{out}(s,t)$ and $P_p^{in}(s,t)$ represent the scheduling strategies of P2G, which are the produced power and consumed power in the optimization. Through jointly operating with H_2 storage, P2G is able to produce power from H_2 at time of high economic returns. $P_d^{DR}(s,t)$ are the dispatched energy of DRP and $P_u^{out}(s,t)$, $P_u^{in}(s,t)$ are the charging and discharging strategies of EVs. At last, $P_c(s,t)$ means the energy needed for the operation of CCS and $P_k(s,t)$ represent the electrical load demand in IEGS.

The limitations of fossil fuel-fired generator, NGU and wind power generator are shown as (7) to (9).

$$P_a^{min} I_a(s,t) \le P_a(s,t) \le P_a^{max} I_a(s,t) \quad a \in N_{fossil} \tag{7}$$
$$P_b^{min} I_b(s,t) \le P_b(s,t) \le P_b^{max} I_b(s,t) \quad b \in N_{ngu} \tag{8}$$
$$0 \le P_w(s,t) \le P_w^f(s,t) \tag{9}$$

in which, (7) is the generation capacity limitation of fossil fuel-fired generator, and (8) is the limitation of NGU. Total amount of available wind power is limited in (9).

Considering generators, the constraints of ramping up and down, the costs of starting up and shutting down and the minimum on or off time are limited with (10) to (13).

$$\begin{cases} P_n(s,t) - P_n(s,t-1) \le R_n^{up} I_n(t) + P_n^{max}[1 - I_n(t)] \\ \qquad + P_n^{min}[I_n(t) - I_n(t-1)] \\ P_n(s,t-1) - P_n(s,t) \le R_n^{down} I_n(t) + P_n^{max}[1 - I_n(t)] \\ \qquad + P_n^{min}[I_n(t-1) - I_n(t)] \end{cases} \tag{10}$$

$$\begin{cases} Su_n(s,t) \ge su_n[I_n(t) - I_n(t-1)] \\ Su_n(s,t) \ge 0 \end{cases} \tag{11}$$

$$\begin{cases} Sd_n(s,t) \ge sd_n[I_n(t-1) - I_n(t)] \\ Sd_n(s,t) \ge 0 \end{cases} \tag{12}$$

$$\begin{cases} [T_n^{on}(t-1) - T_n^{on,min}][I_n(t-1) - I_n(t)] \ge 0 \\ [T_n^{off}(t-1) - T_n^{off,min}][I_n(t-1) - I_n(t)] \ge 0 \end{cases} \tag{13}$$

in which, R_n^{up} and R_n^{down} represent the rate of ramping up and down, which describe the characteristic of generators. su_n and sd_n are the costs of start up and shut down of each generator, which are constants in this article. $T_n^{on,min}$ and $T_n^{off,min}$ in (13) are the minimum on and off time limitation of generators.

Storage capacity, charging and discharging rate limitation of EVs are presented as (14) to (19).

$$E_u^{EVs}(s,t) = E_u^{EVs}(s,t-1) - [I_u^{out}(s,t) P_u^{out}(s,t) - I_u^{in}(s,t) P_u^{in}(s,t)]\Delta t \tag{14}$$
$$I_u^{out}(s,t) + I_u^{in}(s,t) \le 1 \tag{15}$$
$$E_u^{min,EVs} \le E_u^{EVs}(s,t) \le E_u^{max,EVs} \tag{16}$$
$$0 \le P_u^{out}(s,t) \le P_u^{max,out} \tag{17}$$
$$0 \le P_u^{in}(s,t) \le P_u^{max,in} \tag{18}$$
$$E_u^{EVs}(s,t_0) = E_u^{EVs}(s,N_T) \tag{19}$$

in which, (14) presents the relationship between current capacity and previous capacity of EVs. The constraint (15) of binary auxiliary variables limits that EVs can not charging and discharging at the same time. The limitation of total stored energy in EVs is shown as (16). $P_u^{max,out}$ and $P_u^{max,in}$ are the discharging and charging rate of EVs, respectively. (19) means that the capacity of EVs at the end of optimization must be the same with the beginning.

DC power flow is adopted to represent the limitation of power transmission, which is shown below:

$$\begin{aligned} &\Big|\sum_{l=1}^{N_L} H_{ij-l}\Big[\sum_{a=1}^{N_{fossil}} \Gamma_{la} P_a(s,t) + \sum_{b=1}^{N_{ngu}} \Gamma_{lb} P_b(s,t) \\ &+ \sum_{w=1}^{N_w} \Gamma_{lw} P_w(s,t) + \sum_{p=1}^{N_{p2g}} \Gamma_{lp}[P_p^{out}(s,t) - P_p^{in}(s,t)] \\ &+ \sum_{u=1}^{N_{EVs}} \Gamma_{lu}[P_u^{out}(s,t) - P_u^{in}(s,t)] + \sum_{d=1}^{N_{DR}} \Gamma_{ld} P_d^{DR}(s,t) \\ &- \sum_{k=1}^{N_L} \Gamma_{lk} P_k(s,t)\Big]\Big| \le P_{ij}^{max} \end{aligned} \tag{20}$$

in which, H_{ij-l} means the power transfer distribution factor of transmission lines. Γ_{la}, Γ_{lw}, Γ_{lp}, Γ_{lu}, Γ_{ld} and Γ_{lk} represent the node incidence matrix at row l of fossil fuel-fired generator a, NGU b, wind power generator w, P2G p, EVs u, DRP d and electrical load demand k. P_{ij}^{max} means maximum power flow limitation of transmission line ij.

D. CONSTRAINTS OF GAS NETWORK

Due to the increasing coupling between the power grid and the gas network, the constraints related to the natural gas network need to be considered. The supply of natural gas should match the demand as shown in (21).

$$\begin{aligned} &\sum_{\omega=1}^{N_{GW}} Q_\omega(s,t) + \sum_{p=1}^{N_{p2g}} Q_p(s,t) \\ &\quad = \sum_{gl=1}^{N_{GL}} Q_{gl}(s,t) + \sum_{a=1}^{N_{fossil}} Q_a(s,t) + \sum_{mn=1}^{N_{pipe}} Q_{mn}(s,t) \end{aligned} \tag{21}$$

in which, $Q_\omega(s,t)$ represents the amount of gas required from the gas wells. $Q_p(s,t)$ is the gas generated from P2G facility. $Q_{gl}(s,t)$ and $Q_a(s,t)$ are gas load demand in gas network and the consumed natural gas of NGU, respectively. The last term of (21) means the gas flow in each gas pipeline, which is often described by Weymouth equation (22).

$$Q_{mn}(s,t) = \mathrm{sgn}[\pi_m(s,t), \pi_n(s,t)] C_{mn} \sqrt{|\pi_m^2(s,t) - \pi_n^2(s,t)|}$$
$$\mathrm{sgn} = \begin{cases} 1 & \pi_m(s,t) \ge \pi_n(s,t) \\ -1 & \pi_m(s,t) < \pi_n(s,t) \end{cases} \tag{22}$$

where mn is the index of gas pipelines, m and n are the nodes of natural gas network. sgn is a symbolic function that determined according to the pressure of nodes at the end of pipeline. C_{mn} is the Weymouth constant which depends on the characteristics of pipeline. $\pi_m(s,t)$ and $\pi_n(s,t)$ are the pressures of node m and n, respectively.

$$-Q_{mn}^{max} \leq Q_{mn}(s,t) \leq Q_{mn}^{max} \tag{23}$$
$$\pi_m^{min} \leq \pi_m(s,t) \leq \pi_m^{max} \tag{24}$$

The limitations of gas flow in each pipeline and pressure of each node are presented as (23) and (24). Q_{mn}^{max} limits the allowable range of gas flow in pipeline mn, and π_m^{min}, π_m^{max} are the safe pressure of each node.

E. CONSTRAINTS OF NGU

In this article, the consumed natural gas of NGU can be modeled as (25).

$$Q_b(s,t) = \frac{[G(P_b(s,t))I_b(s,t) + Su_b(s,t) + Sd_b(s,t)]}{HHV_{CH_4}} \tag{25}$$

in which, $G(P_b(s,t))$ represents the consumed fuel of NGU for producing power, which commonly presented as a quadratic function. HHV_{CH_4} is the higher heat value of natural gas, which usually be considered as 1.026 MBtu/kcf.

F. CONSTRAINTS OF P2G

In this article, P2G facility can be used to convert electricity to H_2 or SNG which can be stored in natural gas network. Excess wind power can be consumed with the utilization of P2G, besides this, the generated H_2 from P2G can be stored in H_2 storage facility in this article. By this way, P2G can not only convert excess power to natural gas, but also can convert electricity to H_2 when price of power is low, and consume H_2 to refurnish power grid through fuel cell when electricity price is high. The specific architecture of P2G is shown as Fig. 3.

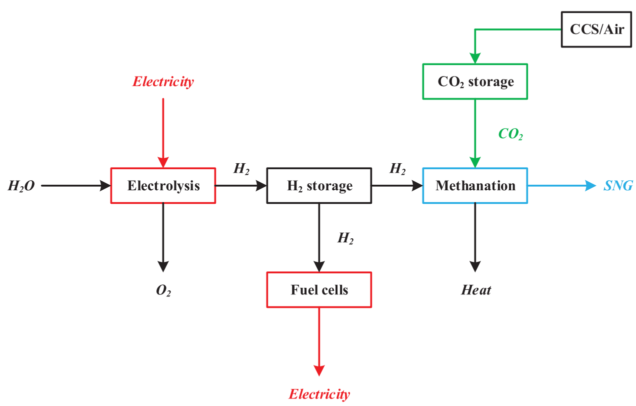

FIGURE 3. Architecture of P2G facility.

The operation process of P2G involves two steps, which are water electrolysis and methanation. In water electrolysis step, electricity is converted into H_2 as follow.

$$H_2O \xrightarrow{\text{Electricity}} H_2 + \frac{1}{2}O_2 \quad \Delta H = +285\text{kj/mol} \tag{26}$$

during this reaction, the generated H_2 can be calculated with (27).

$$Q_p^{H_2}(s,t) = \frac{P_p^{in}(s,t)\eta_p^{H_2}}{HHV_{H_2}} \tag{27}$$

in which, $Q_p^{H_2}(s,t)$ is the amount of generated H_2. $P_p^{in}(s,t)$ represents the consumed power by P2G and $\eta_p^{H_2}$ is the conversion efficiency of converting electricity energy to H_2, which is commonly considered as about 60%. HHV_{H_2} is the high heat value of H_2.

In methanation step, the generated H_2 can be used to synthesize SNG as follows.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \Delta H = -165\text{kj/mol} \tag{28}$$

CO_2 would be consumed in this reaction, which reduces the gas emissions of IEGS. The consumed CO_2 and generated CH_4 can be modeled as follows.

$$Q_p^{CO_2}(s,t) = Q_p^{H_2}(s,t)\varepsilon_{H_2\rightarrow CO_2} \tag{29}$$
$$Q_p^{CH_4}(s,t) = Q_p^{H_2}(s,t)\varepsilon_{H_2\rightarrow CH_4} \tag{30}$$

where $\varepsilon_{H_2\rightarrow CO_2}$ and $\varepsilon_{H_2\rightarrow CH_4}$ represents the conversion coefficients of H_2 to CO_2 and CH_4, respectively.

The input power of P2G is limited as (31), in order to maintain safety during the operation of P2G.

$$P_p^{min,in} \leq P_p^{in}(s,t) \leq P_p^{max,in} \tag{31}$$

in which, $P_p^{min,in}$ and $P_p^{max,in}$ are the limitations of power consumption rate.

H_2 storage facility and fuel cell are cooperated with P2G facility in this article, so as to enable P2G to refurnish power grid through consuming H_2. All the generated H_2 in electrolysis reaction is stored in the H_2 storage system.

$$Q_{HS}^{H_2,in}(s,t) = Q_p^{H_2}(s,t) \tag{32}$$

The capacity and operation constraints of H_2 storage are presented as (33) to (37).

$$E_{HS}^{H_2}(s,t) = E_{HS}^{H_2}(s,t-1) - [Q_{HS}^{H_2,out}(s,t) - Q_{HS}^{H_2,in}(s,t)]\Delta t \tag{33}$$
$$E_{HS}^{min,H_2} \leq E_{HS}^{H_2}(s,t) \leq E_{HS}^{max,H_2} \tag{34}$$
$$0 \leq Q_{HS}^{H_2,out}(s,t) \leq Q_{HS}^{max,H_2,out} \tag{35}$$
$$0 \leq Q_{HS}^{H_2,in}(s,t) \leq Q_{HS}^{max,H_2,in} \tag{36}$$
$$E_{HS}^{H_2}(s,t_0) = E_{HS}^{H_2}(s,N_T) \tag{37}$$

in which, $E_{HS}^{H_2}(s,t)$ represents the capacity state of H_2 storage system. $Q_{HS}^{H_2,out}(s,t)$ and $Q_{HS}^{H_2,in}(s,t)$ are the amount of H_2 injected and withdrawn by storage system, the maximum values are limited as (35) and (36). To ensure sustainable operation, the capacity of H_2 storage at the end of optimization is set to be the same as the beginning, which is described as (37).

Besides this, the released H_2 can be used for two purposes: synthesizing CH_4 and generating electricity. It can be described as follow.

$$Q_{HS}^{H_2,out}(s,t) = Q_{HS}^{H_2,out,CH_4} + Q_{HS}^{H_2,out,FC} \tag{38}$$

where $Q_{HS}^{H_2,out,CH_4}$ represents the amount of H_2 which utilized to produce SNG, the other term means the H_2 consumed to refurnish power grid through fuel cell.

The electricity generated by fuel cell is depend on the consumed H_2 [37], which can be represented as follow.

$$P_p^{out}(s,t) = \eta_{FC} Q_{HS}^{H_2,out,FC}(s,t) \tag{39}$$

in which, η_{FC} is the efficiency of fuel cell system, which is commonly considered as 55%. $Q_{HS}^{H_2,out,FC}(s,t)$ is the consumed H_2 from H_2 storage system to refurnish power grid.

G. CONSTRAINTS OF CCS

During the generation process of fossil fuel-fired generator, flue gas would be generated and vented. CCS can capture large amount of CO_2 from flue gas, for reducing the greenhouse gas emissions and saving total operating costs. The specific architecture of CCS mainly consists of absorber, stripper and CO_2 storage system. The captured CO_2 can be transported for further utilization, or stored in the storage to synthesize SNG in this article.

Because of the joint operation of fossil fuel-fired generator and CCS, part of the energy generated by fossil fuel-fired generator is used to meet the demand of load, while another part is used to supply CCS. The generated power can be presented as follow.

$$P_a(s,t) = P_a^{total}(s,t) - P_c^{CCS}(s,t) \tag{40}$$

where $P_a(s,t)$ is the energy injected into power grid. $P_c^{CCS}(s,t)$ is the energy consumed by CCS.

The amount of CO_2 contained in the flue gas can be calculated with (41), which is depended on the total generated power and the CO_2 emission intensity of producer.

$$Q_{CO_2}(s,t) = \mu_{CO_2} P_a^{total}(s,t) \tag{41}$$

The energy consumption of CCS is related to the amount of treated CO_2, which can be expressed as:

$$P_c^{CCS}(s,t) = \phi_c Q_{CO_2}^{tre}(s,t) + C \tag{42}$$

$$0 \le Q_{CO_2}^{tre}(s,t) \le Q_{CO_2}(s,t) \tag{43}$$

in which, ϕ_c is the efficiency of CCS in consuming energy to deal with CO_2. $Q_{CO_2}^{tre}(s,t)$ is the amount of treated CO_2, which is limited in (43). C is a constant which represents the fixed energy consumption during the operation.

At last, the captured CO_2 of CCS can be calculated as follows.

$$Q_{CO_2}^{CCS}(s,t) = \beta_{CCS} Q_{CO_2}^{tre}(s,t) \tag{44}$$

where β_{CCS} represents the CO_2 capture rate of CCS, which is less than 90 %.

With the utilization of CO_2 storage system, the captured CO_2 can be stored for synthesizing SNG. The injected CO_2 of storage could come from CCS and atomosphere, which is presented as follow.

$$Q_{CS}^{CO_2,in}(s,t) = Q_{CS}^{CO_2,in,CCS}(s,t) + Q_{CS}^{CO_2,in,a} \tag{45}$$

IV. SECOND-ORDER CONE RELAXATION OF GAS NETWORK CONSTRAINTS

Natural gas network is one of the most complex nonlinear systems in this world. Due to high nonlinearity of constraints in gas network, such as (22) and (25), the optimization of IEGS becomes nonconvex and hard to solve with available commercial solvers. Second-order con (SOC) relaxation is one of the most effective and widely used methods for convexification. In this article, SOC relaxation is used to convert the optimization into a mixed integer nonlinear programming (MINLP) problem for solving with commercial solver.

Specifically, (25) can be converted to SOC form directly as (46), the tightness of relaxation can be ensured because that in the process of minimizing objective, unnecessary natural gas consumption of NGU would be eliminated to reduce the total costs.

$$Q_b(s,t) \ge \frac{[G(P_b(s,t))I_b(s,t) + Su_b(s,t) + Sd_b(s,t)]}{HHV_{CH_4}} \tag{46}$$

For constraint (22), by introducing binary auxiliary variables I_{mn}^+ and I_{mn}^- to represent the direction of gas flow in the pipeline, this highly nonlinear constraint can be reformulated as a MINLP form as (47) to (48), where p_m is the squared node pressure.

$$[I_{mn}^+(s,t) - I_{mn}^-(s,t)][p_m(s,t) - p_n(s,t)] = [\frac{Q_{mn}(s,t)}{C_{mn}}]^2 \tag{47}$$

$$I_{mn}^+(s,t) + I_{mn}^-(s,t) = 1 \tag{48}$$

Furthermore, (47) can be replaced with (49) to (53), so that the constraint can be further relaxed into an mixed integer second order cone programming (MISOCP) form [38].

$$\psi_{mn}(s,t) \ge [\frac{Q_{mn}}{C_{mn}}]^2 \tag{49}$$

$$\psi_{mn}(s,t) \ge p_n(s,t) - p_m(s,t) + [I_{mn}^+(s,t) - I_{mn}^-(s,t) + 1] \times (p_m^{min} - p_n^{max}) \tag{50}$$

$$\psi_{mn}(s,t) \ge p_m(s,t) - p_n(s,t) + [I_{mn}^+(s,t) - I_{mn}^-(s,t) - 1] \times (p_m^{max} - p_n^{min}) \tag{51}$$

$$\psi_{mn}(s,t) \le p_n(s,t) - p_m(s,t) + [I_{mn}^+(s,t) - I_{mn}^-(s,t) + 1] \times (p_m^{max} - p_n^{min}) \tag{52}$$

$$\psi_{mn}(s,t) \ge p_m(s,t) - p_n(s,t) + [I_{mn}^+(s,t) - I_{mn}^-(s,t) - 1] \times (p_m^{min} - p_n^{max}) \tag{53}$$

Equation (49) to (53) are McCormick envelope [39]–[41] used to bound ψ_{mn}. When (49) is tight, SOC constraints (49) to (53) can be used to replace constraint (47). By this way, gas flow constraint in gas network would be converted to MISOCP form which can be solved with commercial solver such as CPLEX.

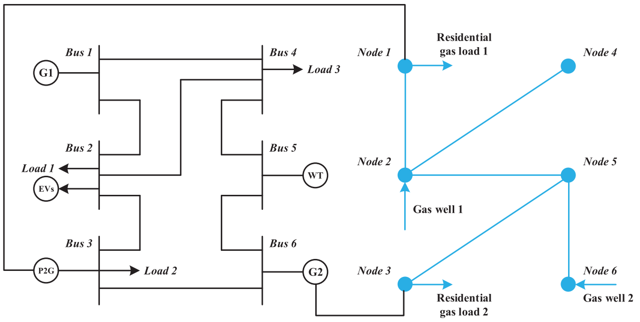

FIGURE 4. Structure of IEGS.

TABLE 1. Prices adopted in the optimization.

Price	Value
Electricity (Peak)	728 RMB/MWh
Electricity (Regular)	532 RMB/MWh
Electricity (Valley)	336 RMB/MWh
DRP compensation	60 RMB/MWh
Wind power penalty	350 RMB/MWh
Carbon tax	120 RMB/ton
Carbon delivering	30 RMB/ton
Capture carbon from atmosphere	500 RMB/ton

V. CASE STUDIES

A modified IEEE 6-bus power system combined with 6-node natural gas system is utilized in this article to verify the validity of the proposed multi-step day ahead-intraday collaborative optimization framework. Refined operation model of P2G is applied to reduce greenhouse gas emissions, EVs and DRP are further considered to provide flexibility to IEGS. Several different cases are analyzed to demonstrate the effect of optimization, all these cases are implemented on Matlab R2016b platform with a Core I7-6700, 3.40GHz, 16GB RAM personal computer, MISOCP problem is solved by Yalmip and CPLEX solvers.

The modified IEGS is shown in Fig. 4. The power grid contains two generators, which are fossil fuel-fired generator G1 and NGU G2. G1 is located at bus 1 and G2 is connected at bus 6. One wind farm WT is located at bus 5. P2G is connected at bus 3 for energy conversion. Seven transmission lines connect each bus in power grid. CCS is operated with fossil fuel-fired generator G1 for greenhouse gas capturing. H_2 storage system is combined with P2G for refined operating of it. Three electrical loads are located at bus 2, bus 3 and bus 4, respectively. DRP are considered in these buses, which account for 30%, 40% and 40% of total load in buses. EVs are considered as the model of aggregator for energy dispatching, and they are connected at bus 2 to provide flexibility for IEGS. Some prices adopted in the optimization is listed as Table 1, the carbon tax price, payment for delivering CO_2 and price for capturing CO_2 form atmosphere are set as 120 RMB/ton [42], 30 RMB/ton [43] and 500 RMB/ton [44], respectively. The compensation costs of DRP is set as 60 RMB/MW and the penalty cost for wind power deviation is considered as 350 RMB/MW.

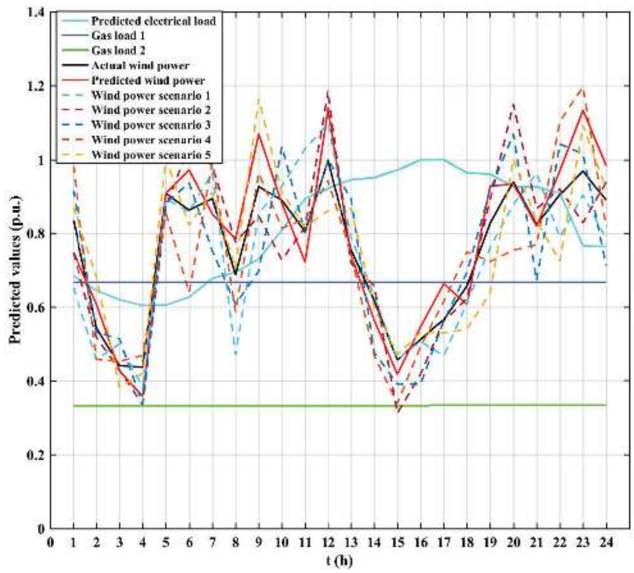

FIGURE 5. Predicted wind power and electrical demand in IEGS.

With consideration the uncertainty of wind power, different generation scenarios of wind power are considered in the optimization, scenario generation method based on Monte-Carlo simulation and scenario reduction method are utilized to simulate the fluctuations of wind power. 1000 scenarios are generated and then scenario reduction is adopted until 5 scenarios are remained [45]–[47]. Except for wind power scenarios, the predicted electrical load of power grid, gas load of gas network are presented in Fig. 5, also the actual wind power generation in the period of optimization is considered as known, which is utilized to reflect the wind power deviation after each optimization cases. In Fig. 5, the peak values of electrical load, wind power generation, gas load are 256 MW, 128.4 MW and 6000 kcf, respectively.

EVs are dispatched as an aggregator to further accommodate the energy scheduling strategy in IEGS. According to literature [48], the maximum amount of dispatchable number of EVs is 6000, and in each time interval, the total operated EVs are different, besides, based on the total demand of EVs, the percentage of dispatchable EVs can change within a range, 80%-95% of total demand is considered as the fluctuations of dispatchable EVs in this paper. The minimum and maximum capacity provided by EVs are 5 MWh and 100 MWh, minimum and maximum rate of charge and discharge are 1 MWh and 80 MWh, respectively. Fig 6 shows the total dispatchable load of EVs in each time interval.

The optimization of IEGS under five cases are analyzed, for demonstrating the effect of proposed multi-step day ahead-intraday collaborative optimization framework on reducing the influence of wind power uncertainty, and role of P2G on improving the utilization of wind power.

TABLE 2. UC strategies of generators in case 1 to case 3.

Unit	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h	24h
G1	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
G2	○	○	○	○	○	○	○	○	○	○	●	○	●	●	●	●	●	●	○	○	○	○	○	○

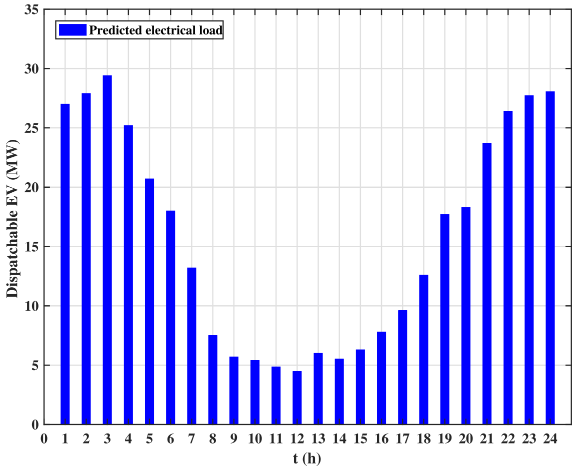

FIGURE 6. Dispatchable load of EVs.

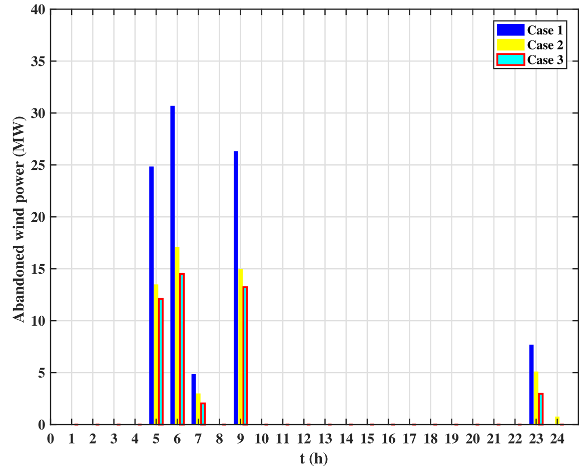

FIGURE 7. Abandoned wind power.

1) Case 1: Single-step day ahead optimization of IEGS without P2G and CCS.
2) Case 2: Single-step day ahead optimization of IEGS plus P2G.
3) Case 3: Single-step day ahead optimization of IEGS plus P2G and CCS.
4) Case 4: Multi-step day ahead-intraday optimization of IEGS plus P2G and CCS.
5) Case 5: Multi-step day ahead-intraday optimization under different penetration levels of wind power.

A. EFFECT ANALYSES OF CCS AND P2G

In this article, CCS is jointly operated with fossil fuel-fired generator to reduce greenhouse gas emissions, and P2G facility is utilized to improve the utilization of wind energy. The optimization results of case 1 to case 3 are compared to demonstrate the effect of CCS and P2G. In these cases, the optimization is conducted under day-ahead time scale, predicted wind power generation and demand in Fig. 5 is utilized during the accommodation. Besides, EVs and DRP are operated as flexible energy resources.

After day-ahead optimization for three cases, the hourly unit commitment (UC) strategies of generators can be obtained and are listed in Table 2. It can be seen that the strategies of the three cases are the same. Analysing from the obtained UC strategies, it can be known that fossil fuel-fired generator G1 is kept on working during the optimization period due to lower fuel costs, while natural gas generator G2 with higher generation costs is used as complement, for balancing the supply and demand when the energy supply in IEGS can not meet the demand in some periods, such as 11h and 13h-18h. In these periods, wind power generation is relatively reduced, however the energy demand in whole IEGS is increased, thus G2 is started to compensate for the deficiency of electricity.

In these three cases, P2G and CCS are added successively to verify the effectiveness of them in improving the utilization of wind power and reducing CO_2 emissions, therefore after the optimization of each case is completed, the abandoned wind power and released CO_2 in three cases are compared. Taking advantage the scenarios of wind power generation in Fig. 5 in the optimization, Fig. 7 presents the abandoned wind power in each case. It can be seen clearly from this figure that, in three cases, wind curtailment occurs when the predicted capacity of wind power is larger than the electrical demand, such as 5h and 23h. Further analysing the comparison results of three cases, conclusions can be obtained as follow:

1) In case 1, P2G and CCS are not considered, power grid and gas network are coupled with NGU. Under this system structure, the excess wind power can not be converted to natural gas and injected into the gas network for future use, therefore the abandoned wind power in this case is the largest as presented in Fig. 7, the specific value of it is 94.28 MW.

2) In case 2, P2G facility is utilized to in IEGS, bi-directional energy conversion structure is constructed between two energy networks. Under this structure, wind power can be further used by converting it to gas and stored in gas network, which can consume part of wind power when it is abundant. Consequently, it can be seen that the abandoned

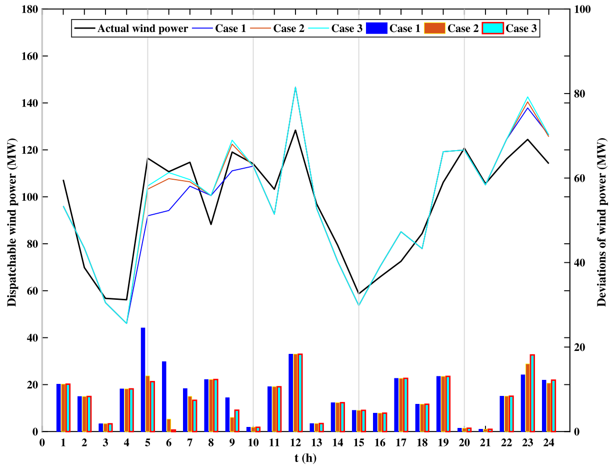

FIGURE 8. Deviation of wind power.

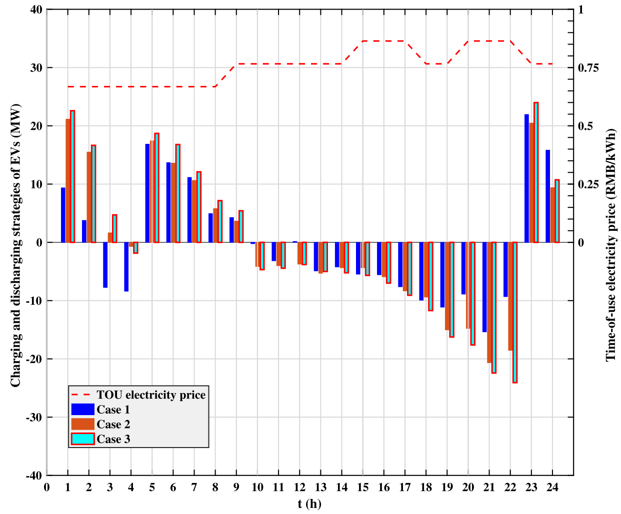

FIGURE 9. Charging and discharging strategies of EVs.

wind power in case 2 is relatively reduced compared to case 1, the specific value in this case is 54.29 MW.

3) In case 3, the structure of IEGS is further improved, both P2G and CCS are contained and operated jointly, which presented as that the captured CO_2 by CCS can be delivered and used by P2G facility. Moreover, P2G is operated in a more refined model combined with H_2 storage, it can convert electricity into H_2 and stored in the storage temporarily after the demand of electrical load is satisfied, when the power supply is insufficient or the trade price of electricity rises, the stored H_2 would be converted into electricity by fuel cells to refurnish the IEGS. Under this mode of collaborative operation, CCS provided the needed CO_2 for P2G with lower costs, while reduce the costs of carbon tax by consuming CO_2. Through this way, the conversion of excess wind energy from P2G can be further facilitated to pursue higher overall system revenue. As seen from the obtained results in Fig. 7, with the collaborative operation of P2G and CCS, the abandoned wind power in case 3 is the smallest in these cases, the specific value is 44.84 MW.

Compared with the results of case 1 and case 2, the abandoned wind power in case 3 is reduced by 52.4% and 17.4%, respectively. From this comparison, it can be intuitively seen that, with utilization of energy conversion effect of P2G and CCS, the abandoned wind power during the operation of IEGS can be significantly reduced, which effectively saving the total operating costs of system.

According to the amount of abandoned wind power in Fig. 7, the scheduled wind power in each case can be obtained as Fig. 8. Due to different system structure in three cases, the utilization of wind power is different. In case 1 with no P2G and CCS, large amount of wind power can not be converted, the deviations between dispatched wind power and actual wind power is relatively big, as can be intuitively concluded from the comparison of wind power deviations in Fig. 8. It can be seen that in time period 5h, the deviation in case 1 has reached a peak of 24.53 MW. By contrast, with the utilization of P2G and CCS in case 3, less wind power is abandoned due to energy conversion between two energy networks, the dispatched wind power is much closer to actual wind power situation. As shown in Fig. 8, the deviations in this case is the smallest in most time periods compared with that of the other two cases, especially in 6h, the deviation is reduced to 0.37 MW. In this article, larger deviations of wind power would cause more penalty costs, which increases the total operating costs of IEGS. Therefore, it can be concluded from the comparison above that, considering P2G and CCS in IEGS can efficiently improve the utilization of wind power, so as to save the total operating costs of IEGS.

In addition to P2G's regulatory role, EVs, as a promising dispatchable resource in integrated energy system, is further adopted to adjust the energy scheduling strategies of IEGS under the fluctuations of wind power. Combined with DRP regulation, EVs and DRP provide IEGS with a high degree of flexibility in energy scheduling. Through the excitation effect of electricity price during the optimization period, the optimal charging and discharging strategies of EVs and the planning strategies of DR in three cases can be obtained, which are compared in Fig. 9 and Fig. 10.

Under the incentive effect of time-of-use (TOU) electricity price, EVs in IEGS would dispatch stored energy for pursuing lower system operating costs. In time periods with valley electricity price, EVs would charge their batteries from energy network, as in the time periods before 8h in Fig. 9. While in other time periods with peak valley electricity price, EVs would participate to the dispatching and release energy for saving total operating costs in IEGS, it can be seen from Fig. 9, in time periods 10h to 22h, the amount of released electricity from EVs is clearly increased. Furthermore, in these periods, the discharging electricity of EVs in case 3 is relatively more than the other two cases. It can be concluded that the IEGS with structure in case 3 can better save total operating costs in an uncertainty environment. Similar with dispatching strategies of EVs, the optimal scheduling strategies

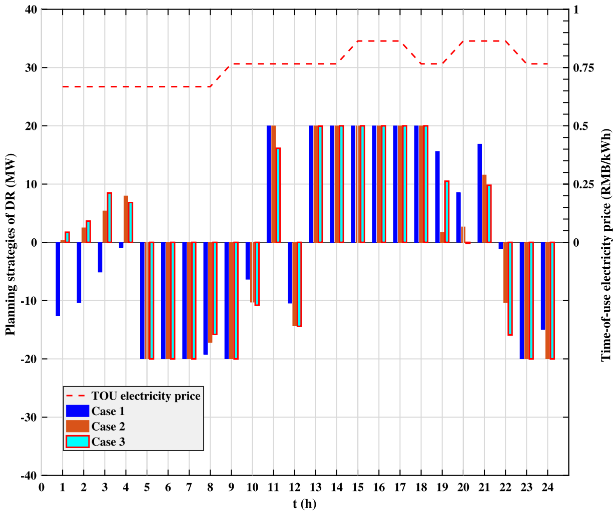

FIGURE 10. Planning strategies of DR.

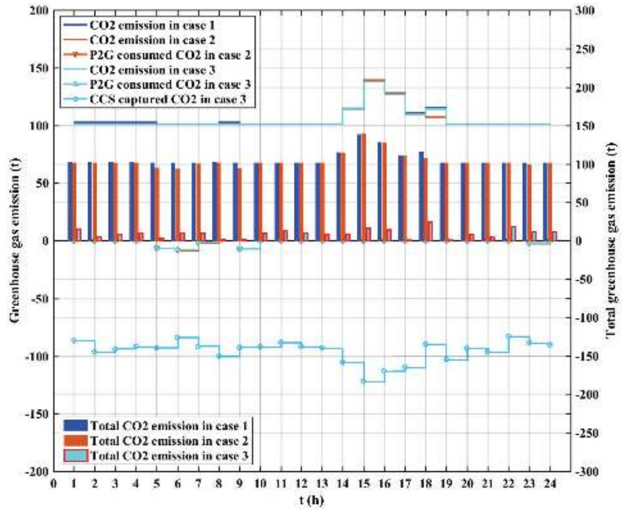

FIGURE 11. Comparison of CO_2 emission.

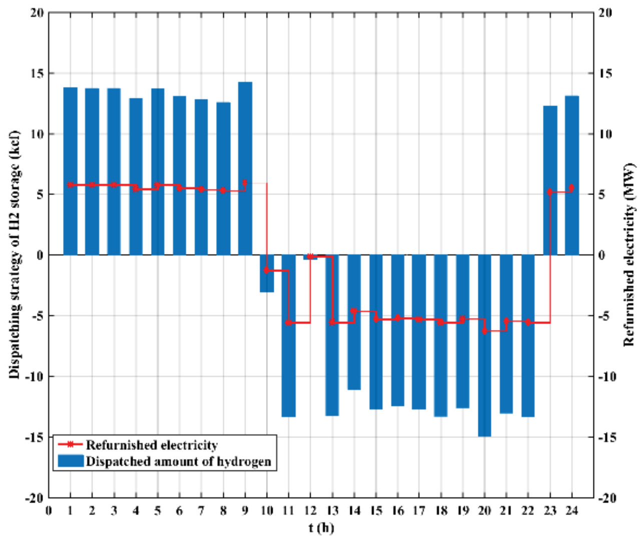

FIGURE 12. Dispatching strategies of H_2 storage system.

of DR presents the same energy scheduling trend as shown in Fig. 10, due to different electricity price. In time periods with high price as 14h to 21h, DR loads would be shifted to the other time periods such as 5h to 9h and 23h to 24h, for reducing total energy demand in peak electricity price. Through the flexible energy scheduling of EVs and DRP, during the operation of IEGS, not only the balance of supply and demand can be ensured, but also the total operating costs can be effectively reduced. It demonstrates that considering the scheduling effect of EVs and DRP reasonably in IEGS is of great significance.

The other focus of this article is the environmental friendliness of IEGS, which mainly considers the greenhouse gas emissions during operation. Due to the increasingly serious environmental crisis, this has gradually become a matter of great significance and must be paid attention to. As the main components of greenhouse gas, CO_2 mainly produced because of the operation of fossil fuel-fired generator. In order to prove that case 3 with P2G and CCS in this article is more friendly to environment, total generated total generated CO_2 in three cases are compared in Fig. 11. In case 1 without P2G and CCS, the produced CO_2 from fossil fuel-fired generator can not be consumed, which would be released and punished. It can be seen clearly that the amount of emitted CO_2 in this case is the largest. In case 2, P2G is utilized to convert excess electricity into natural gas, during this process, part of CO_2 can be consumed in methanation reaction as presented in figure, however the amount of consumed CO_2 is relatively small, because P2G can only work when electricity is sufficient in case 2. Therefore, CO_2 emissions should be less than that of case 1, which can also be known from this figure. By contrast, in case 3 with P2G and CCS, most CO_2 from the flue gas produced by fossil fuel-fired generator can be directly captured, delivered and stored, which can effectively reduce the emission of CO_2. As seen in Fig. 11, the amount of CO_2 emission is the least of three cases. Although it takes costs to deliver and store captured CO_2 for future use, the curtailed CO_2 emission reduces the total operating costs caused by greenhouse gas emission.

On the other hand, refined operation model of P2G is considered in case 3, reaction of power to hydrogen and methanation reaction are separated. P2G is combined with H_2 storage system, which makes it can convert electricity in those period without excess wind power. Under this operation model, the dispatching strategies of H_2 storage mainly incited by TOU electricity price. Using the flexibility provided by H_2 storage, P2G can convert electricity into gas for future use in period with low electricity purchasing costs, and use stored energy with fuel cells in period with high electricity price. As shown in period 15h to 22h with peak electricity price, the storage system mainly releases stored H_2 to refurnish IEGS for pursuing lower total operating costs. Fig. 12 presents the withdrew and released hydrogen amount

TABLE 3. Comparison of operating costs in case 1 to case 3.

IEGS	Generation	Gas supply	Wind power deviations penalty	DRP	CO_2 emissions	CO_2 transfer	H_2 generation	Saved costs by P2G	Total costs
Case 1	373326.02	296117.78	76454.05	21721.05	306459.60	-	-	-	1074078.51
Case 2	379929.89	297310.15	66100.52	20653.80	301605.47	-	-	3068.94	1065599.81
Case 3	372640.70	296150.27	65991.01	21252.06	30323.15	68678.89	-15246.87	2891.09	839349.77

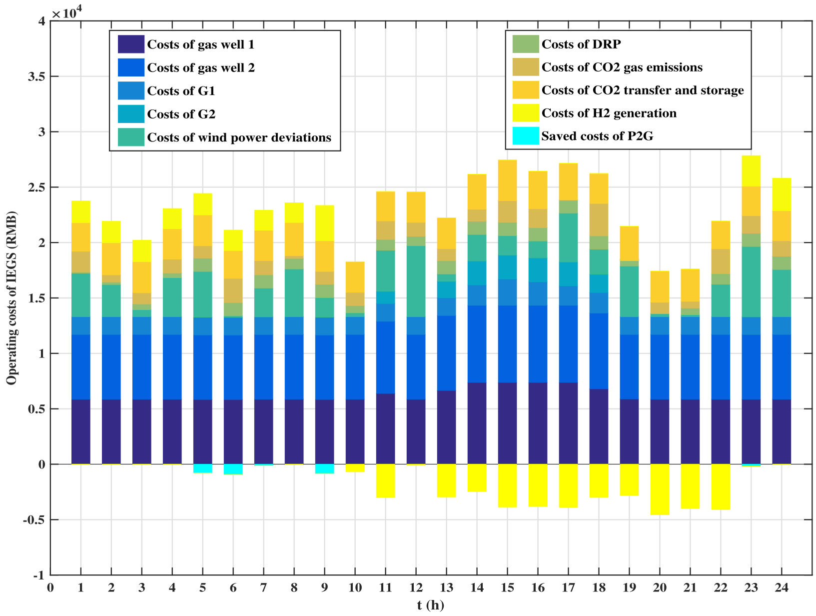

FIGURE 13. Total operating costs of IEGS in case 3.

of H_2 storage in case 3, as well as the obtained electricity under this operation model. According to this, it can be calculated that the total revenue produced by this part of energy is 15246.87 RMB, which proves that considering refined operation model of P2G is of great significance to the operation of IEGS.

From above comparisons of case 1 to case 3, it can be naturally concluded that, with the collaborative operation of P2G and CCS, and flexibility provided by EVs and DRP, the utilization of wind power can be effectively improved, also CO_2 emissions can be significantly reduced. All of these advantages can be reflected in the economic benefits of the total operating costs, as shown in Fig. 13. Total operating costs mainly contains gas supply costs of gas wells, generating costs of generators, punishment costs of wind power deviations, dispatching costs of DRP, CO_2 gas emission costs, CO_2 transfer and storage costs, H_2 generation costs and saved costs by P2G conversion. It can be seen that, except for needed costs to meet energy demand in both networks, the other main costs is the penalty of wind power deviation, this also proves that using P2G and CCS to improve utilization of wind power is necessary.

In order to present the costs of each part more intuitively and compare the total costs of each case, Table 3 lists the total costs of three cases and components of each case. It can be seen clearly from this table that, less wind power is abandoned in case 3 due to the collaborative operation of P2G and CCS, the penalty costs of wind power deviations is the least. CCS effectively captures CO_2 produced by generator, although it takes costs to transfer and store captured CO_2 for future use, still the saved costs of CO_2 gas emissions is less than that in other two cases. Furthermore, flexible operating models of hydrogen storage in case 3 also effectively pursue better overall operating costs for IEGS. With total costs of 839349.77 RMB, the operating costs of case 3 is saved more than 21.9% compared with that of case 1, and more than 21.2% compared with costs of case 2. It is further demonstrated that with considering P2G, CCS and EVs in IEGS can significantly reduce total operating costs for integrated energy system.

B. EFFECTIVENESS OF MULTI-STEP DAY AHEAD-INTRADAY COLLABORATIVE OPTIMIZATION FRAMEWORK

According to analyses above, IEGS with P2G and CCS in case 3 can better optimal energy scheduling strategies, the utilization of wind power can be improved and the environmental costs can be saved. However, although scenario method is adopted to simulate the uncertainty of wind power in case 3, with utilization of day ahead predicted wind power generation, still there are relatively large prediction errors which leads to a large gap between scheduled and actual wind power, the accuracy of obtained energy scheduling strategies can

TABLE 4. UC strategies of generators in case 4.

Unit	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h	24h
G1	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
G2	○	○	●	●	○	○	○	○	○	○	○	○	●	●	●	●	●	●	○	○	○	○	○	○

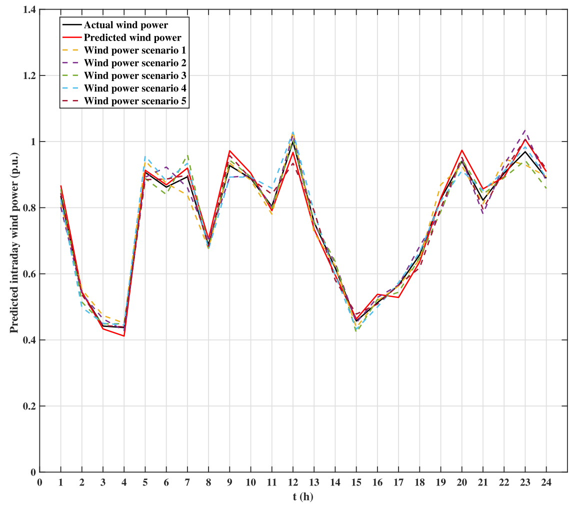

FIGURE 14. Predicted wind power of multi-step day ahead-intraday collaborative optimization framework.

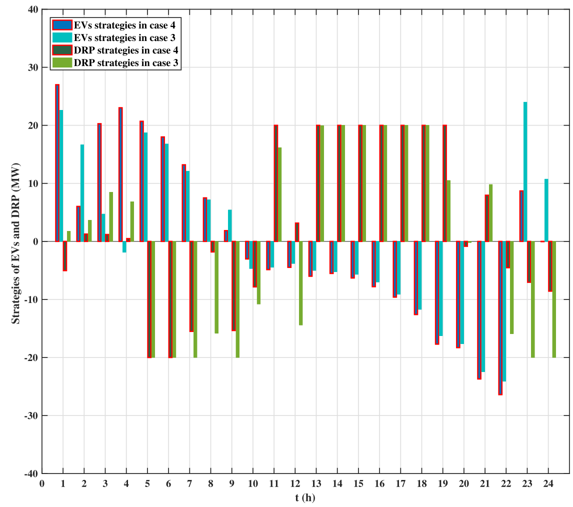

FIGURE 15. Strategies of EVs and DRP.

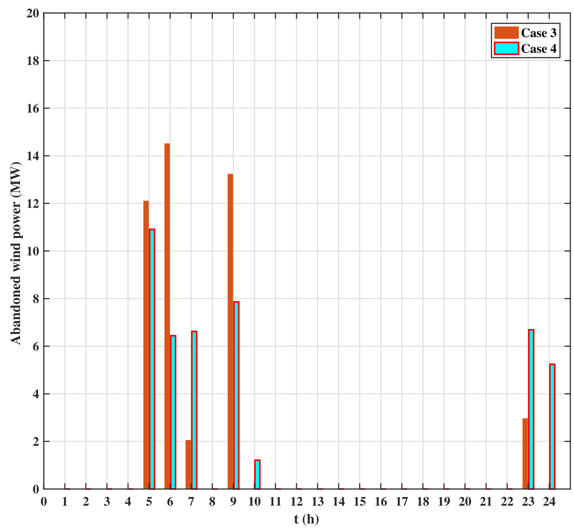

FIGURE 16. Abandoned wind power in case 4.

not be guaranteed. To this end, for obtaining more accuracy predicted wind power to reduce the effect of uncertainty, a dynamic multi-step day ahead-intraday collaborative optimization framework is proposed in this article. With dynamic optimization time window, predicted wind power under intraday time scales which has smaller prediction errors can be utilized in the optimization. The predicted wind power and generated wind power scenarios under intraday time scale are presented in Fig. 14. Compared with predicted wind power under day ahead time scale in Fig. 5, it can be seen clearly that predicted wind power in proposed optimization framework is much more accuracy. For making better comparison with single-step optimization, the proposed optimization framework is conducted in case 4, and the optimal results of case 4 is compared with that of case 3.

First of all, in Table 4, the obtained hourly UC strategies of generators in case 4 are presented. For fossil fuel-fired generator G1, in order to keep balance of supply and demand in IEGS, its still operated in all the periods, however for NGU G2, states in some periods are changed compared with that in case 3. This is mainly due to the difference of predicted wind power in two cases. Also because of this, in case 4, optimal strategies of EVs and DRP, abandoned wind power and wind power deviations also different with that of case 3, as can be seen in Fig. 15, Fig. 16 and Fig. 17.

In Fig. 15, the dispatching strategies of EVs and DRP in case 4 is compared with that obtained in case 3. From the figure it can be seen that, in case 4, with the utilization of multi-step day ahead-intraday optimization framework, the adopted predicted wind power which has less errors makes the obtained energy scheduling strategies more accuracy, as seen in this figure, the electricity released from EVs and loads curtailed from DRP in periods 13h to 22h in case 4 are relatively more than that in case 3, as the electricity price is at peak point in these periods, more released electricity of EVs and curtailed loads of DRP would significantly reduce the operating costs of system. It proves that the flexi-

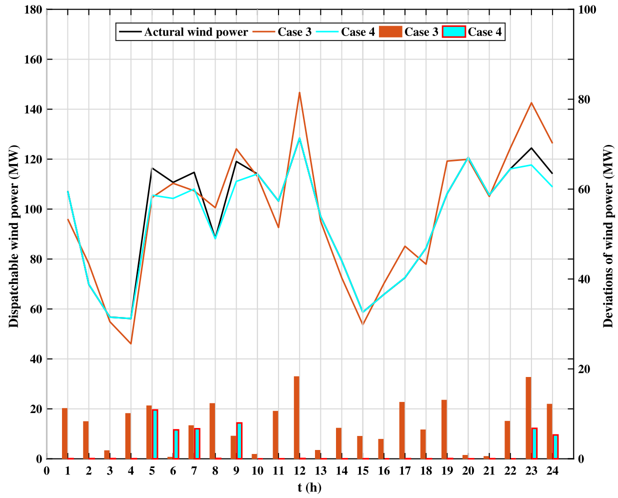

FIGURE 17. Deviations of wind power in case 4.

bility provided by EVs and DRP can better reduce the effect of wind power uncertainty on operating costs.

In Fig. 16, the abandoned wind power in case 4 is presented and compared with that in case 3. It is clearly that in those periods which wind power generation is larger than electrical demand, such as 5h to 10h, the amount of wind power curtailment in case 4 is effectively reduced. On the other hand, in Fig. 17, the amount of scheduled wind power obtained with the proposed optimization framework is also compared with the results of single-step day-ahead optimization, due to that more accuracy intraday predicted wind power is adopted in case 4, thus optimization process can accommodate energy scheduling strategies more reasonable, the utilization of wind power can be improved which results to less wind power deviations, as seen in this figure. With this advantage, the penalty costs of wind power can be significantly reduced, which proves that proposed optimization framework is more economical for IEGS.

In Fig. 18, the operating costs of each component in case 4 is presented, with proposed multi-step day ahead-intraday optimization framework, the utilization of wind power is further improved, and the dispatching strategies of flexible resources such as EVs and DRP are more accuracy, as a consequence, the economic benefits of these improvements result in a reduction in IEGS operating costs in Case 4. It is obvious in this figure that costs of wind power deviations is significantly reduced compared with case 3 in Fig. 13, which efficiently saves the total operating costs of IEGS.

For an intuitive comparison, the total operating costs of case 3 and case 4 are listed in the Table 5. It can be seen clearly that, due to improvement of wind power utilization and accurate operating of flexible energy resources, the costs of each component in case 4 is reduced compared with that of case 3, the total operating costs in case 4 is 667358.43 RMB, which is about 20% reduced than costs of case 3. It is demonstrated that the proposed multi-step optimization framework can save the operating costs of IEGS to a considerable extent.

According to the description and comparison in this section, with utilization of dynamic optimization time window, the proposed multi-step day ahead-intraday framework can effectively reduce the waste of renewable energy compared with single-step optimization, more accuracy predicted wind power generation adopted in the optimization makes the scheduling strategies of flexible energy resources more economically rational, which demonstrates that the proposed optimization framework is much more suitable for the energy scheduling of IEGS.

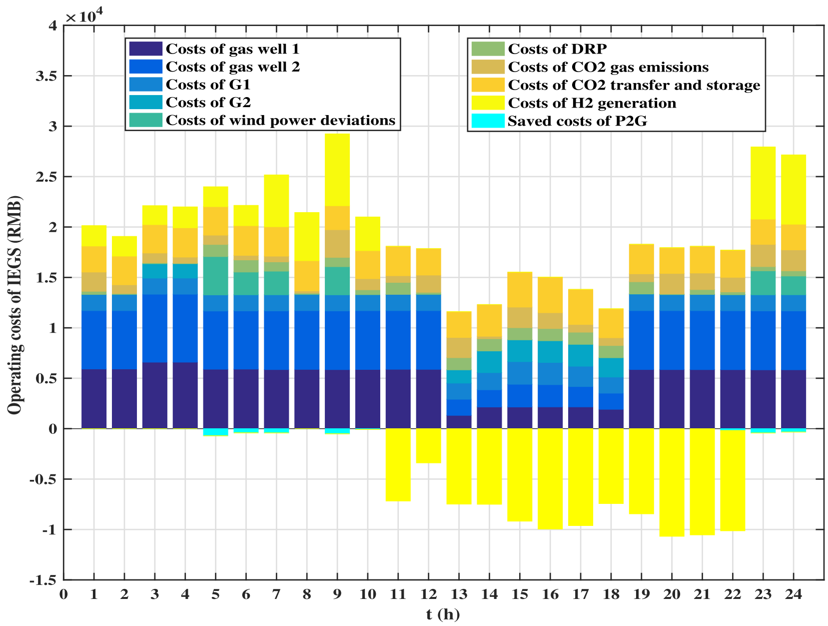

FIGURE 18. Total operating costs of IEGS in case 4.

TABLE 5. Comparison of operating costs in case 3 and case 4.

IEGS	Generation	Gas supply	Wind power deviations penalty	DRP	CO_2 emissions	CO_2 transfer	H_2 generation	Saved costs by P2G	Total costs
Case 3	372640.70	296150.27	65991.01	21252.06	30323.15	68678.89	-15246.87	2891.09	839349.77
Case 4	357161.63	237063.71	15594.78	16834.61	30312.97	68475.91	-55005.62	3079.56	667358.43

TABLE 6. Comparison in case 5 under different wind power penetration levels.

IEGS	Generation	Gas supply	Wind power deviations penalty	DRP	CO_2 emissions	CO_2 transfer	H_2 generation	Saved costs by P2G	Total costs
45 % wind power	357161.63	237063.71	15594.78	16834.61	30312.97	68475.91	-8698.04	3079.56	667358.43
50 % wind power	331095.94	293945.32	41072.43	18592.46	28136.65	68356.58	-16107.39	6872.91	758219.08
55 % wind power	319604.84	291935.07	65965.46	16836.53	29146.35	67710.79	-15743.92	12335.69	763119.42

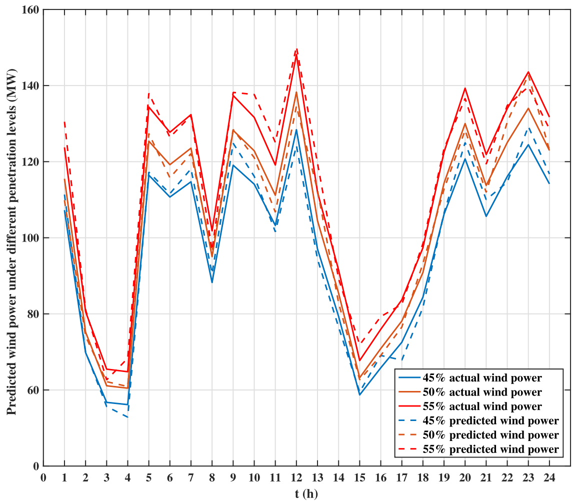

FIGURE 19. Predicted wind power with different penetration levels.

C. ANALYSES OF ENERGY STRATEGIES UNDER DIFFERENT WIND ENERGY PENETRATION LEVELS

Although it is demonstrated that the proposed optimization framework is effective in improving the utilization of wind power, with the continuous expansion of wind power scale, its optimization performance under different penetration levels of wind power still needs to be analyzed. In this section, the optimizations under 45%, 50% and 55% wind power penetration level are conducted and compared. Predicted generation conditions of different levels of wind power are shown in Fig. 19. With larger penetration level, more wind power is adopted in the optimization.

With proposed optimization framework, similar dispatching strategies of each components in IEGS can be obtained and listed in Table 6, as presented in previous sections, total operating costs is utilized to evaluate the optimality of the obtained energy scheduling strategies. As shown in this table, the specific operating costs under different wind power penetration levels are compared, in which, the results corresponding to 45% wind power is obtained in the optimization of case 4 above. From the comparison in this table, it can be concluded that, with the increase of wind power penetration level, the costs of generation and gas supply can be reduced. This is mainly because the more wind power is utilized to supply the demand in IEGS. However, more wind power is abandoned because of the expanded scale of wind power. It can be seen that the penalty of wind power deviations of 55% wind power case is almost 6 times more than that of 45% wind power case, as shown in the table. On the other hand, in IEGS with higher wind power penetration level, the costs of CO_2 gas emissions and CO_2 transfer are relatively reduced, which makes the energy network more environmental friendly.

From the analyses above, it can be concluded that, although the proposed optimization framework can effectively improve the utilization of wind power, the scale of accessed wind power still needs to be researched. A reasonable amount of wind power should be used in IEGS, so that to reduce the operating costs of the system, while maintaining the environmental friendliness.

VI. CONCLUSION

In this paper, for improving utilization of wind power under uncertain conditions, meanwhile achieving transformation to decarbonization of environment friendly integrated energy system by reducing CO_2 emissions, the optimization of energy scheduling strategies in IEGS is studied.

With consideration of penalty costs of abandoning wind power and emitting CO_2, P2G, CCS and EVs are synergistically optimized in IEGS, to improve the wind energy efficiency and reduce the greenhouse gas emissions. P2G is operated in a refined model, which can not only convert excess electricity into natural gas, but also can stored electricity with H_2 storage for higher revenue. CCS is also combined with P2G to effectively reduce the CO_2 gas emissions during the operation. EVs are dispatched as flexible energy resources for saving total system operating costs. Simulation results demonstrate that, with consideration of P2G, CCS and EVs in IEGS, the system operating costs can be reduced more than 17.4%.

On the other hand, considering the effect of wind power uncertainty, a multi-step day ahead-intraday collaborative optimization framework is proposed and adopted in the optimization of IEGS. With the mechanism of dynamic optimization time window, more accuracy predicted wind power can be used to make the dispatching strategies of each components more reasonable and economical. From the simulation comparisons in 5 cases, it can be concluded that the collaborative optimization of P2G, CCS and EVs and the adoption of proposed optimization framework can effectively improve the utilization of wind power, meanwhile significantly reduce the CO_2 gas emissions in IEGS. Reflected in the economic benefits, with more reasonable dispatching strategies of each part in IEGS, the total operating costs can be reduced about 20% than the single-step optimization framework, which further demonstrates the effectiveness of the proposed optimization framework in the article.

As future research, integration of multiple kinds of renewable energy resources in IEGS, such as wind power, photovoltaic energy and biomass energy, is considered as the aiming of further work. Meanwhile, promising flexible energy resource such as hydrogen fuel cell vehicles and optimization of multiple IEGSs are also planned to be contained in future research, for more economical and practical energy dispatching strategies of integrated energy systems.

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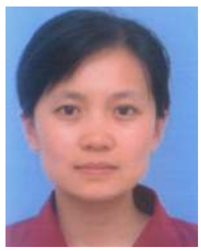

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