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Low-Carbon Economic Planning of Integrated Electricity-Gas Energy Systems

Yue Xiang [a], Yongtao Guo [a*], Gang Wu [b], Junyong Liu [a], Wei Sun [c], Yutian Lei [d], Pingliang Zeng [e]

[a] College of Electrical Engineering, Sichuan University, Chengdu 610065, China

[b] State Grid Sichuan Economic Research Institute, Chengdu 610041, China

[c] School of Engineering, Institute for Energy Systems, The University of Edinburgh, EH93DW, United Kingdom

[d] Energy Development Research Institute, China Southern Power Grid, Guangzhou 510663, China

[e] School of Automation, Hangzhou Dianzi University, Hangzhou 310018, China

Correspondence

Yongtao Guo, Email: yongtao_guo@outlook.com

Abstract

The energy system carbon reduction is an inevitable trend to deal with the global warming problem. The power industry, being a vital part of energy system, faces severe challenges. To decarbonize the power sectors, the implementation of low-carbon technologies and integration of high penetrated renewable power generation would be an effective solution. Therefore, given the existence of multi-type low-carbon technologies including the flexibility reformation of coal-fired units, construction of gas-fired units and installation of energy storage systems, a low-carbon economic planning model of integrated electricity-gas systems with high penetration of wind generation is proposed. The carbon tax and carbon capture technology are integrated to accelerate carbon reductions. In particular, the strategic planning cases contributed by different scenarios are formulated. The simulation results on an electricity-gas test system demonstrate the feasibility and effectiveness of the proposed model in carbon reduction as well as wind curtailment. Compared with the initial state, the implementations of the proposed three planning strategies can reduce carbon emissions by 9.8%, 32.5% and 9.3%, respectively. Meanwhile, the wind power curtailment ratio is decreased by 63.2%, 38.9%, and 63.7%, respectively. Moreover, a sensitivity analysis of carbon tax price and wind power penetration level are performed to investigate the low-carbon transition of the integrated electricity-gas systems.

Keywords: Electricity-gas systems; Economic planning; High penetrated wind generation; Carbon tax and carbon capture; Flexibility

NOMENCLATURE

Indices and sets

z Indices of planning strategy

m Indices of representative scenario

j Indices of energy supply devices

i / g Indices of coal-fired/gas-fired power plant

w Indices of wind farm

s Indices of energy storage system

c Indices of carbon capture and storage system

gw Indices of gas well

$\Omega_{strategy}$ Set of planning strategy

Ω_{N} Set of representative scenarios

Ω_{device} Set of all energy supply devices

Ω_{cf} / Ω_{gf} / Ω_{wf} / Ω_{es} Set of coal-fired/gas-fired power plant/wind farm/ energy storage system

Ω_{ccs} Set of carbon capture and storage system

Ω_{gw} / Ω_{gn} Set of gas well/gas node

Ω_{el} / Ω_{gl} Set of electrical load/gas load

Constants

μ_i / μ_g Carbon emission intensity of coal-fired power plant *i* /gas-fired power plant *g*

c_i / c_w Unit cost of coal-fired power plant generation *i* /wind power generation *w*

c_{gw} Unit gas production cost of gas well *gw*

c_s Unit cost of energy storage system *s* operation

c_i^{up} / c_i^{dn} Unit cost of upward/downward reserve capacity provided by coal-fired power plant *i*

c_g^{up} / c_g^{dn} Unit cost of upward/downward reserve capacity provided by gas-fired power plant *g*

c_s^{up} / c_s^{dn} Unit cost of upward/downward reserve capacity provided by energy storage system *s*

c_{ab} Unit wind power curtailment penalty

θ_c / γ_c Unit power consumption for carbon capture and maximum capture rate of carbon capture and storage system *c*

T Power transfer distribution factor (PTDF) matrix of the system

Φ_g Power to gas conversion coefficient of gas-fired power plant *g*

Variables

$P_{i,t}$ / $P_{g,t}$ / $P_{w,t}$ / $P_{s,t}$ Dispatched power of coal-fired power plant *i*/ gas-fired power plant *g*/ wind farm *w*/ energy storage system *s* at time *t*

$G_{g,t}^{gw}$ Gas supply by gas well *gw* at time *t*.

$R_{i,t}^{up}$ / $R_{i,t}^{dn}$ Upward/downward reserve capacity supplied by coal-fired power plant *i* at time *t*

$R_{g,t}^{up}$ / $R_{g,t}^{dn}$ Upward/downward reserve capacity supplied by gas-fired power plant *g* at time *t*

$R_{s,t}^{up}$ / $R_{s,t}^{dn}$ Upward/downward reserve capacity supplied by energy storage system *s* at time *t*

$\pi_{m,t}$ Gas pressure of gas node *m* at time *t*

$F_{g,t}^{gf}$ Gas consumption of gas-fired power plant *g* at time *t*

Acronyms

CFPP coal-fired power plant

CCS carbon capture and storage

ESS energy storage system

GFPP gas-fired power plant

1. Introduction

Global warming has brought severe challenges to the human society. The greenhouse gases (GHG) emissions, mainly consists of carbon dioxide (CO_2), are aggravating the process of global warming. Carbon reduction has become a global consensus in a way to transit into a low-carbon economy and sustainable society. In 2015, the Paris Agreement had put forward clear targets to limit global average temperature well below 2 °C and keep pursuing efforts to 1.5 °C [1]. The electricity sector contributes 35% of global GHG emissions, leading far ahead of any other sectors as the primary carbon emitter [2]. With an increasing number of countries considering or having officially announced their goals of carbon neutrality [3], the global electricity sector urgently needs to take actions and plays its part in this low-carbon transition within the energy systems. In fact, according to the "Energy Technology Perspectives 2017" released by the International Energy Agency (IEA), at least 50% of the carbon reduction potentials can be tapped from the electricity sector [4]. Thus, decarbonization in the global electricity sector is technologically practicable and practically necessary [5].

There are two main approaches to realize large-scale decarbonization in electricity sector: 1) the rapid deployment of low-carbon technologies and projects, and 2) the integration of extremely high penetrated renewable energy [6],[7]. The advantages of these two approaches can be achieved through effective low-carbon planning, so the power system can minimize carbon emissions with low economic costs and in the meantime accommodate the high penetrated renewable energy. However, the rise of renewable generation (such as wind generation) has limited future development capacity for coal-fired power plants and even urges the early retirement of existing ones [8],[9]. Still, due to the volatility and intermittency of wind generation, it is unrealistic to completely replace the coal-fired generation by wind generation in a short period of time. To tackle the emergency of carbon reduction, the carbon capture and storage (CCS) technology is considered as one of the most potential options to realize a deep reduction in carbon emissions [10]. With CCS retrofitting to coal-fired power plants, at least 14% of carbon reduction would benefit from it by 2060 in the 2 ℃ scenario (2DS) [11].

Another available and promising alternative is gas-fired power plants owing to their higher energy efficiency and lower carbon emission intensity (emit about 50%–60% less carbon dioxide than coal-fired power plants [12]). The operating energy of gas-fired power plants is provided by natural gas pipelines, hence the interdependence of the electricity and natural gas systems is strengthened. Many research studies have been carried out focusing on low-carbon economic planning and scheduling for integrated electricity-gas energy systems considering CCS retrofit or gas-fired power plants' construction. In [13], an expansion co-planning framework for electricity system and gas system towards low-carbon economy is proposed. This framework contains components of gas pipelines, gas-fired power plants and power transmission lines. In [14], to verify the future availability of gas network in low-carbon oriented planning for the power system, a combined gas and electricity network planning model is established to discuss impacts of various low-carbon strategies on the Great Britain's gas network expansions, where the investment cost is also analyzed. An optimal low-carbon planning model of multiple energy systems (MES) is described in [15], in which various forms of energy sources including electricity and natural gas are jointly exploited, and the final results show that carbon reduction target can be achieved with a reasonable low economic cost. In [16] and [17], the CCS optimal planning and deployment is evaluated in the context of large-scale carbon reduction in China's power sector. Suggestions are drawn that CCS retrofitting is economically feasible in the current carbon reduction scenario. In addition to low-carbon planning studies, the low-carbon economic scheduling of electricity-gas energy systems has also been widely studied in [18]-[21], where CCS retrofit, gas-fired power plants and some other low-carbon factors (e.g., carbon tax, carbon emission trading, power-to-gas technology) are investigated in detail.

Generally, greater carbon reduction and larger renewable generation integration generally work in tandem. This indicates that the accommodation capacity for renewable generation within energy systems should be constantly concerned about when to look for the low-carbon substitutions. Restrained by regions, resources, technology maturity and policies factors, although gas-fired power plants are superior in start-up time, ramping speed and minimum output stability, which makes it the best technical means to accommodate renewable generation, large-scale deployment or complete replacement of coal-fired power plants would require much higher security guarantee as the interdependence of electricity and natural gas systems might intense as never before. Thus, it's hard to ensure the operation stability of the two energy systems only by gas-fired power plants when uncertainty occurs. In this situation, the flexibility reformation of coal-fired power plants has become the most economical and practical solution to cope with the renewable generation accommodation during the low-carbon transition stage. Technically, flexibility reformation of coal-fired power plants is to improve the ramping speed and reduce the lower limit of output [22],[23]. Throughout the flexibility reformation, the improvement of renewable generation accommodation is well realized, which is mainly reflected in the reduction of renewable generation curtailment [23]-[25]. It provides an important technical basis for low-carbon planning with high penetrated renewable generation.

In recent studies, the economic planning towards low-carbon is tackled with the application of generation expansion planning model combined with the detailed system's operation simulation that incorporates unit commitment (UC) constraints. That framework enables both investment decisions and representative operation scenarios to be taken into account and makes final planning schemes to be more reliable and adaptive [26]-[28]. In addition, the siting and sizing energy storages is a popular option to handle the intermittency of the renewable generation for flexibility enhancement in planning [29], [30]. However, a more direct solution should not be ignored, which is to technically improve the ramp rate and reserve capacity of the existing power plants. Furthermore, economic, low-carbon and flexible are three important factors but are rarely considered in tandem in the traditional planning towards low-carbon. Thus, how to achieve the goal of flexibility enhancement while realizing carbon reduction in the economic planning should be investigated.

To solve the above problem, a low-carbon economic planning model of high-penetration wind power for integrated electricity-gas systems incorporated the operation simulation is proposed. Main contributions of this paper are summarized as follow:

(1) Considering the integration of carbon elements (i.e., carbon tax and carbon capture and storage cost) into the planning cost items, a low-carbon oriented economic cost model is proposed.

(2) Three strategies towards low carbon involving the flexibility reformation of coal-fired power plants, expansion of gas-fired power plants and energy storage systems [31] are modeled in the economic planning to reduce carbon emissions and enhance the flexibility of the integrated electricity-gas systems with high penetrated wind power.

(3) Case studies demonstrate the sensitivity of carbon tax and wind power penetration level with different planning strategies, and the economic results of carbon emissions and wind curtailments are further analyzed.

The remainder of this paper is organized as follows. Section 2 introduces the mathematical modeling of low-carbon technologies and low-emission strategies for planning. Section 3 presents the low-carbon economic planning model of integrated electricity-gas systems. Case studies for different planning strategies are illustrated in Section 4. Results and extended discussions are conducted in Section 5. The last Section 6 summarizes the conclusions.

2. Modeling of low-carbon technologies and strategies

2.1. Low-carbon technologies

For the purpose of carbon reduction, a most common approach is to retrofit carbon capture systems into fossil-fuel power plants at present. Based on [20], the post-combustion carbon capture and storage system is deployed and the power plants with the CCS retrofitting can be mathematical formulated as follows.

The CFPP and GFPP generation is regarded as the major source of carbon emissions. The volume of carbon emissions is determined by the power output, which can be connected by the carbon emission intensity μ_{cf} and μ_{gf}, as shown in Eq. (1).

$$\begin{cases} Q_{i,t}^{carbon} = \mu_i P_{i,t} \\ Q_{g,t}^{carbon} = \mu_g P_{g,t} \end{cases}, \quad \forall i \in \Omega_{cf}, \forall g \in \Omega_{gf}, \forall t \in \mathrm{T} \tag{1}$$

The CCS retrofitting to CFPPs needs power supply to operate. The power consumption of CCS contains two parts: the unit power consumption θ_c for capturing carbon volume $Q_{c,t}^{ccs}$ and the fixed power consumption $P_{c,t}^{0}$ for regular operation, as shown in Eq. (2).

$$P_{c,t}^{ccs} = \theta_c Q_{c,t}^{ccs} + P_{c,t}^{0}, \quad \forall c \in \Omega_{ccs}, \forall t \in \mathrm{T} \tag{2}$$

Moreover, CCS captured carbon must not exceed its max value $Q^{ccs,\max}$, which is determined by the maximum capture rate γ_c (usually reaches to 80%-90%) of CCS and the carbon emissions $Q_{i,t}^{carbon}$ produced by CFPPs generation, as shown below.

$$\begin{cases} 0 \le Q_{c,t}^{ccs} \le Q^{ccs,\max} \\ Q^{ccs,\max} = \gamma_c Q_{i,t}^{carbon} \end{cases}, \quad \forall c \in \Omega_{ccs}, \forall i \in \Omega_{cf}, \forall t \in \mathrm{T} \tag{3}$$

The final net power output of the CCS retrofitted CFPPs is expressed as

$$P_{i,t}^{net} = P_{i,t} - P_{i,t}^{ccs}, \quad \forall i \in [\Omega_{cf} \cap \Omega_{ccs}], \forall t \in \mathrm{T} \quad . \tag{4}$$

2.2. Strategies for planning towards low carbon

The Low-emission describes a technical strategy with less carbon emissions during the system’s operation, while the flexibility can be defined as the ability to react fast to the fluctuations from renewable energy generation. The greater its speed of reaction, the higher the flexibility is. In the following strategies, flexibility reformation of CFPP is seen as the flexibility enhancement one, and GFPP combined is considered as low-emission as well as high-flexibility one. The ESS can be both low-emission and operationally flexible, since its energy storage function rather than being power generation sources can alleviate the fluctuation of high penetrated renewable energy generation.

1) Flexibility reformation of CFPP

After the flexibility reformation of CFPP, the minimum stable output is decreased hence the effective output range is expanded. The power output limits as well as the ramp limits are donated in Eq. (5).

$$\cdot\begin{cases}(1-x_i)P_i^{\min}+x_iP_i^{\min}\le P_{i,t}-R_{i,t}^{dn}, \quad P_{i,t}+R_{i,t}^{up}\le P_i^{\max} \\ P_{i,t-1}-(1-x_i)r_i^{\max}-x_i\,r_i^{\max}\le P_{i,t}\le P_{i,t-1}+(1-x_i)r_i^{\max}+x_i\,r_i^{\max} \\ 0\le R_{i,t}^{dn}\le T_i[(1-x_i)r_i^{\max}+x_i\,r_i^{\max}], \quad 0\le R_{i,t}^{up}\le T_i[(1-x_i)r_i^{\max}+x_i\,r_i^{\max}]\end{cases}, \quad \forall i\in\Omega_{cf},\forall t\in \mathrm{T} \tag{5}$$

where x_i is the binary variable and once the flexibility reformation of CFPP accomplished, it will be set to one. $P_i^{\min}$ and $r_i^{\max}$ donate the minimum stable output and maximum ramp rate of CFPP after flexibility reformation.

2) Construction of GFPP

The construction of GFPP means adding new power sources with higher ramping speed and lower minimum stable output, whose final effect is similar to the flexible reformation of CFPP, as expressed in Eq. (6).

$$\begin{cases}x_gP_g^{\min}\le P_{g,t}-R_{g,t}^{dn}, \quad P_{g,t}+R_{g,t}^{up}\le x_gP_g^{\max} \\ P_{g,t-1}-r_g^{\max}\le P_{g,t}\le P_{g,t-1}+r_g^{\max} \\ 0\le R_{g,t}^{dn}\le T_gr_g^{\max}, \quad 0\le R_{g,t}^{up}\le T_gr_g^{\max}\end{cases}, \quad \forall g\in\Omega_{gf},\forall t\in T \tag{6}$$

where x_g is the binary variable represents the construction statement of GFPP.

3) Installation of ESS

The ESS plays an important role in wind power accommodation. Moreover, the operation of ESS hardly produce carbon emissions. Thus, it is essential for low-carbon energy transition in a period of time. The model of ESS' installation, along with the charge and discharge process can be established in (7)—(10). Eq. (7) describes the relationship between charge and discharge state of ESS, but only available when installation state x_s is set to one. Eq. (8) describes the charge and discharge rate limits of ESS. The state-of-charge (SOC) of ESS is limited by (8). Moreover, the ESS also participates in the upward and downward reserve provision (10).

$$\begin{cases}I_{s,t}^{ch}+I_{s,t}^{ds}\le 1 \\ x_s\ge I_{s,t}^{ch}, \quad x_s\ge I_{s,t}^{ds}\end{cases}, \quad \forall s\in\Omega_{es},\forall t\in \mathrm{T} \tag{7}$$

$$0\le P_{s,t}^{ch}\le I_{s,t}^{ch}\overline{P_s^{ch}}, \quad 0\le P_{s,t}^{ds}\le I_{s,t}^{ds}\overline{P_s^{ds}}, \quad \forall s\in\Omega_{es},\forall t\in \mathrm{T} \tag{8}$$

$$\begin{cases} SoC_{s,t}^{es} = SoC_{s,t-1}^{es} + (\eta_e^{ch} P_{s,t}^{ch} - P_{s,t}^{ds} / \eta_e^{dc}) \Delta t \\ \underline{SoC_s^{es}} \le SoC_{s,t}^{es} \le \overline{SoC_s^{es}} \\ SoC_{s,0}^{es} = SoC_{s,T}^{es} \end{cases}, \quad \forall s \in \Omega_{es}, \forall t \in \mathrm{T} \tag{9}$$

$$\begin{cases} 0 \le R_{s,t}^{up} \le \min((SoC_{s,t} - x_s \underline{SoC_s^{es}}) \eta_e^{dc}, x_s \overline{P_{s,t}^{dc}} - P_{s,t}^{dc}) \\ 0 \le R_{s,t}^{dn} \le \min((x_s \overline{SoC_s^{es}} - SoC_{s,t}) / \eta_e^{ch}, x_s \overline{P_{s,t}^{ch}} - P_{s,t}^{ch}) \end{cases}, \quad \forall s \in \Omega_{es}, \forall t \in \mathrm{T} \tag{10}$$

3. Low-carbon economic planning model

3.1. Scenario generation

The planning strategy will affect the economy and carbon emissions during the whole operation period, so it is necessary to ensure the consistency between the investment cost and the total operation cost, i.e., a whole year's operation cost needs to be calculated to match the annual investment cost in the same time scale. The K-means method is adopted to obtain the annual representative scenarios from the time series data of wind power, electricity load and gas load. Then, the operation cost of every representative scenario is optimized. Finally, the annual total operation cost is calculated by multiplying operation cost of representative scenarios by the number of days and added together. To make the low-carbon economic planning problem tractable, representative days generated with cluster method [32] are integrated into the model.

3.2. Planning Objective

The objective of the planning model is to minimize the summation of annual investment cost and operation cost, which can be formulated as (11).

$$\min TC = C_{\mathrm{inv}} + C_{\mathrm{op}} \tag{11}$$

where C_{inv} is the annual investment cost corresponding to each planning strategy, as shown in Eq. (12). The binary variable ω_z is set to one if the corresponding planning strategy $\# z$ is chosen. $X_i^{z,i}$. is another binary variable for the investment statement of facility i with the strategy $\# z$. $C_i^{z,i}$ donates the capital cost of the facility i with the strategy $\# z$. r is the discount rate, and Y is the lifetime of the planning project. They are set to be 5% and 20 years in this paper, respectively.

$$C_{\mathrm{inv}} = \omega_z \sum_{i \in \Omega_{device}} X_i^{z,i} C_i^{z,i} \frac{r(1+r)^Y}{(1+r)^Y - 1}, \quad z \in \Omega_{strategy} \tag{12}$$

The second item C_{op} represents the operation cost in a representative day, which contains the energy supply cost, reserve capacity cost, wind power curtailment penalty, and carbon emission & storage cost. As shown in (13)—(18).

$$C_{\mathrm{op}} = C_{es1} + C_{es2} + C_{re} + C_{ab} + C_{co_2} \tag{13}$$

$$C_{es1}=\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\left[\sum_{i\in\Omega_{cf}}c_iP_{i,t}^{cf}+\sum_{w\in\Omega_{wf}}c_w(P_{w,t}^{wf}-P_{w,t}^{ab})\right] \tag{14}$$

$$C_{es2}=\begin{cases}0 & z=1\\ \omega_z\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\sum_{g\in\Omega_{gf}}c_{gw}G_{g,t}^{gw} & z=2\\ \omega_z\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\sum_{s\in\Omega_{es}}c_s\left|P_{s,t}^{es}\right| & z=3\end{cases} \tag{15}$$

$$C_{re}=\begin{cases}\omega_z\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\sum_{i\in\Omega_{cf}}(c_i^{up}R_{i,t}^{up}+c_i^{dn}R_{i,t}^{dn}) & z=1\\ \omega_z\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\left[\sum_{i\in\Omega_{cf}}(c_i^{up}R_{i,t}^{up}+c_i^{dn}R_{i,t}^{dn})+\sum_{g\in\Omega_{gf}}(c_g^{up}R_{g,t}^{up}+c_g^{dn}R_{g,t}^{dn})\right] & z=2\\ \omega_z\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\left[\sum_{i\in\Omega_{cf}}(c_i^{up}R_{i,t}^{up}+c_i^{dn}R_{i,t}^{dn})+\sum_{s\in\Omega_{es}}(c_s^{up}R_{s,t}^{up}+c_s^{dn}R_{s,t}^{dn})\right] & z=3\end{cases} \tag{16}$$

$$C_{ab}=\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\sum_{w\in\Omega_{wf}}c_{ab}P_{w,t}^{ab} \tag{17}$$

$$C_{co_2}=\sum_{m\in\Omega_N}D_m\sum_{t=1}^{T}\left[\rho_{ct}(\sum_{i\in\Omega_{cf}}\mu_iP_{i,t}^{cf}+\sum_{g\in\Omega_{gf}}\mu_gP_{g,t}^{gf})+\rho_{cs}\sum_{c\in\Omega_{ccs}}Q_{c,t}^{ccs}\right] \tag{18}$$

There are two parts of the energy supply cost, as shown in (14) and (15). Generally, the basic energy supply cost C_{es1} is included in each planning strategy, which consists of generation cost of CFPPs and wind power. Since different planning strategies will be considered, an extra energy supply cost C_{es2} is included to take into account of gas production cost of gas wells and ESS charging and discharging cost, depending on which strategy is adopted.

Similarly, the reserve capacity cost is different from each other in different strategies. The upward and downward reserve capacity can be provided by CFPPs, GFPPs and ESS. Thus, the total reserve capacity cost can be formed as (16).

In order to develop the wind power accommodation along with reducing carbon emissions, wind power curtailment penalty C_{ab} and carbon emission & storage cost C_{co_2} are both taken into account in (17) and (18). The carbon emission & storage cost is incorporated into the total operation cost by introducing the carbon tax price ρ_{ct} and unit carbon capture and storage cost ρ_{cs}. Note that Ω_N is the set of representative days and D_m denotes the number of days in a cluster.

3.3. Constraints

3.3.1. Common constraints

A set of common constraints exist in every strategy, which are mainly the power system constraints including power output, reserve capacity and minimum on/off time limits. In addition, the limits on node power balance and transmission line capacity are also considered.

1) Power output limits and reserve capacity constraints

$$P_i^{\min} \le P_{i,t} - R_{i,t}^{dn},\ \ P_{i,t} + R_{i,t}^{up} \le P_i^{\max},\quad \forall i \in \Omega_{cf}, \forall t \in \mathrm{T} \tag{19}$$

$$P_{i,t-1} - r_i^{\max} \le P_{i,t} \le P_{i,t-1} + r_i^{\max},\quad \forall i \in \Omega_{cf}, \forall t \in \mathrm{T} \tag{20}$$

$$0 \le R_{i,t}^{dn} \le T_i r_i^{\max}, 0 \le R_{i,t}^{up} \le T_i r_i^{\max},\ \ \forall i \in \Omega_{cf}, \forall t \in \mathrm{T} \tag{21}$$

$$0 \le P_{w,t} \le P_{w,t}^{f},\quad \forall w \in \Omega_{wf}, \forall t \in \mathrm{T} \tag{22}$$

The ramping speed of CFPP is limited by (19), while (20) and (21) represents the reserve capacity limit and the reserve response time constraints. Eq. (22) donates the power output limit of wind power generation.

2) Spinning reserve constraints

$$\sum_{j \in \Omega_{\text{device}}} R_{j,t}^{up} \ge \beta_{\text{d}} \sum_{d \in \Omega_{el}} L_{d,t}^{e} + \beta_{\text{w}} \sum_{w \in \Omega_{wf}} P_{w,t},\ \ \forall j \in \Omega_{\text{device}}, \forall t \in \mathrm{T} \tag{23}$$

$$\sum_{j \in \Omega_{\text{device}}} R_{j,t}^{dn} \ge \beta_{\text{d}} \sum_{d \in \Omega_{el}} L_{d,t}^{e} + \beta_{\text{w}} \sum_{w \in \Omega_{wf}} P_{w,t},\ \ \forall j \in \Omega_{\text{device}}, \forall t \in \mathrm{T} \tag{24}$$

Spinning reserve would cope with the fluctuations caused by wind power and load forecast errors. Where β_{d} and β_{w} represent the reserve demand coefficient of load and wind power.

3) Minimum on/off time constraints

$$\begin{cases} \left(X_{i,t-1}^{on} - T_i^{\text{on}}\right)\left(I_{i,t-1} - I_{i,t}\right) \geqslant 0 \\ \left(X_{i,t-1}^{off} - T_i^{\text{off}}\right)\left(I_{i,t} - I_{i,t-1}\right) \geqslant 0 \end{cases},\quad \forall i \in [\Omega_{cf} \cup \Omega_{gf}], \forall t \in T \tag{25}$$

The start-up and shut-down time of the CFPP and GFPP should meet the minimum ON/OFF time in (25).

4) Nodal power balance and transmission line capacity constraints

$$\sum_{j \in \Omega_{\text{device}}} P_{j,t} = \sum_{d \in \Omega_{\text{el}}} L_{d,t}^{e},\ \ \forall j \in \Omega_{\text{device}}, \forall t \in \mathrm{T} \tag{26}$$

$$-ef_l^{\max} \le \sum_{j \in \Omega_{\text{device}}} T_{l,j} P_{j,t} - \sum_{d \in \Omega_{el}} T_{l,d} L_{d,t}^{e} \le ef_l^{\max},\ \ \forall j \in \Omega_{\text{device}}, \forall t \in \mathrm{T} \tag{27}$$

Eq.(26) represents the relationship between power supply by energy source devices and electricity demand at each node. The transmission line capacity is limited by (27), where T_l donates the power transfer distribution factor (PTDF) matrix based on DC power flow. $ef_l^{\max}$ is the transmission capacity limit of line *l*.

3.3.2. Strategy constraints

Some extra constraints would be added in terms of different strategies.

1) Flexibility reformation of CFPP

Same as the constraint (5) in Section 2.2.

2) Construction of GFPP

Same as the constraint (6) in Section 2.2. Also, the conversion of electricity and gas should be taken into account at the same time (28).

$$F_{g,t}^{gf} = \Phi_g P_{g,t}, \quad \forall g \in \Omega_{gf}, \forall t \in \mathrm{T} \tag{28}$$

The electricity system and natural gas system are linked by GFPPs, and the natural gas consumption of GFPP generation is formulated as (28), where Φ_g is the power to gas conversion coefficient.

Due to the introduction of GFPPs, the natural gas system constraints (29)—(33) are added simultaneously.

$$F_{gw}^{\min} \le F_{gw,t} \le F_{gw}^{\max}, \ \forall gw \in \Omega_{\mathrm{gw}}, \forall t \in T \tag{29}$$

$$\pi_m^{\min} \le \pi_{m,t} \le \pi_m^{\max}, \ \forall m \in \Omega_{\mathrm{gn}}, \forall t \in T \tag{30}$$

$$\pi_{m,t} \le k_c \pi_{n,t}, \ \forall m,n \in \Omega_{\mathrm{gn}}, \forall t \in T \tag{31}$$

$$\begin{cases} F_{mn} = \mathrm{sgn}(\pi_m, \pi_n) C_{mn} \sqrt{\left| \pi_m^2 - \pi_n^2 \right|} \\ \mathrm{sgn}(\pi_m, \pi_n) = \begin{cases} +1 & \pi_m \ge \pi_n \\ -1 & \pi_m < \pi_n \end{cases} \end{cases} \tag{32}$$

$$\sum_{gw \in \Omega_{gw}} F_{gw,t} = \sum_{d \in \Omega_{gl}} L_{d,t}^g + \sum_{mn \in \Omega_{pl}} F_{mn,t} + \sum_{g \in \Omega_{gf}} F_{g,t}^{gf}, \quad \forall t \in T \tag{33}$$

Eq. (29)—(33) are formulated based on the Weymouth theory with steady-state gas flow. The gas output $F_{gw,t}$ is limited by the minimum and maximum values of gas wells, as shown in (29). The pressure of each node should be limited by the lower and upper bounds (30), while compressors equipping can step up the nodal pressure to compensate the pressure loss in transmission (31). Eq. (32) represents the relationship between the gas flow in pipelines and nodal gas pressure, including gas flow directions and conversion method. $L_{d,t}^g$ is the gas load demand at time t. $F_{mn,t}$ represents the gas flow from node m to node n at time t. $F_{g,t}^{gf}$ donates the gas consumption of GFPP g at time t. Eq. (33) shows the nodal gas balance in natural gas network, where the gas injection should be equal to withdrawn at each node.

3) Installation of ESS

Same as the constraints (7)—(10) in Section 2.2.

4. Case study

4.1. Integrated electricity-gas system description

A modified 24-bus power system and 12-node natural gas system are depicted in Fig.2. The 24-bus power system has ten coal-fired power plants G1-G10 and four wind farms W1-W4. Three of these coal-fired power plants (i.e., G3, G4 and G10) are retrofitted with CSS. The 12-node natural gas system contains three gas wells N1-N3, ten pipelines, two compressors and four natural gas loads. The relevant parameters can be found in [33], [34].

Assuming that the target of carbon reduction along with the flexibility enhancement is set for the system, however, it cannot be achieved with the existing power supply infrastructure (i.e., only coal-fired generation and wind power generation as energy suppliers). Therefore, to improve the operational flexibility of the system and mitigate the carbon emission, implementing new low-carbon economic planning strategies is of great necessity.

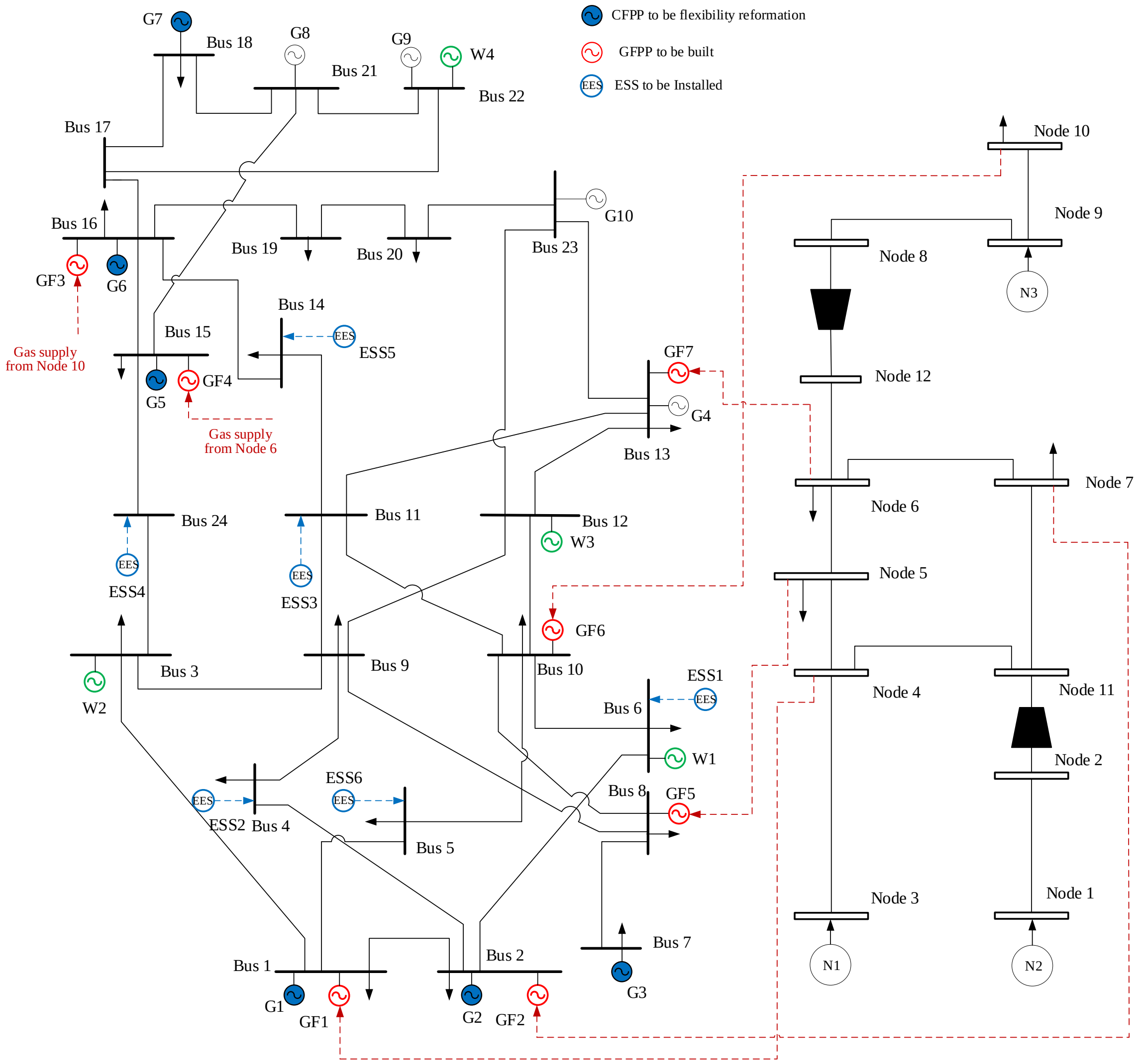

Fig. 1 Topology of the test system.

4.2. Load and wind power cluster result

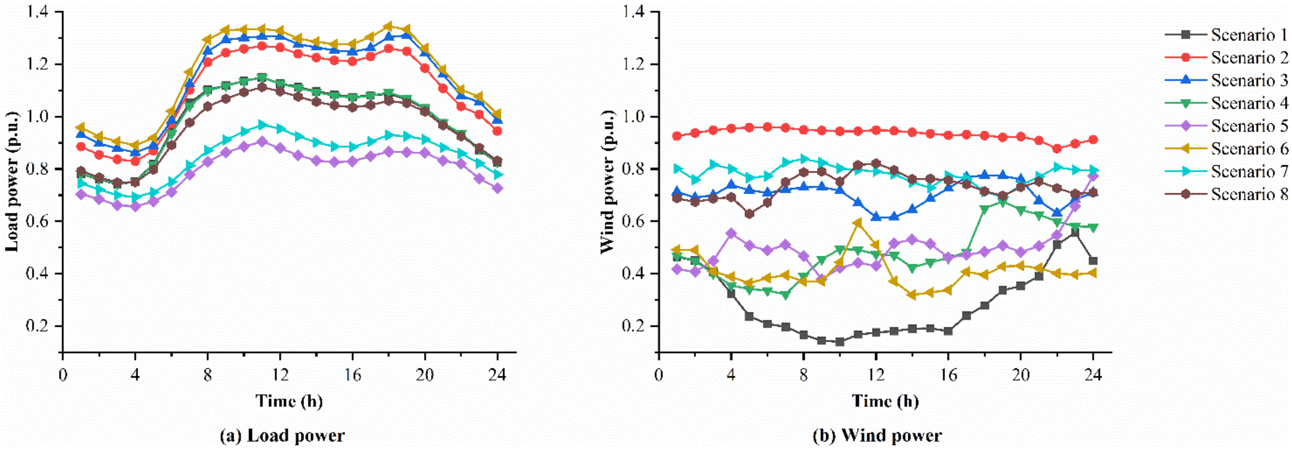

Fig. 2. Representative scenario of electricity load and wind generation.

The electricity and natural gas demand are described in this section. Using the scenario generation method in section 3.1, according to the historical time series data [32] and the gas load time series data [35] with seasonal characteristics, eight representative load and wind power generation profiles are shown in Fig. 2, after clustering 366 days in the whole year by k-means method. There are eight typical scenarios in total, and the hourly variability of wind power generation is shown in Fig. 2(b). The strong diversity can be observed among these scenarios. Taking scenario 1 as example, during the period of 8: 00-16:00, the wind power output is flatter in a low level, and gradually rises in 17:00-23:00, but when it comes to scenario 2, the wind power output is flatter in a high level during the whole day. There are ramping events taking place between adjacent hours frequently and sometimes the wind power difference in three or five continuous intervals reaches to 30% of the capacity, and that's when the demand for system flexibility arises.

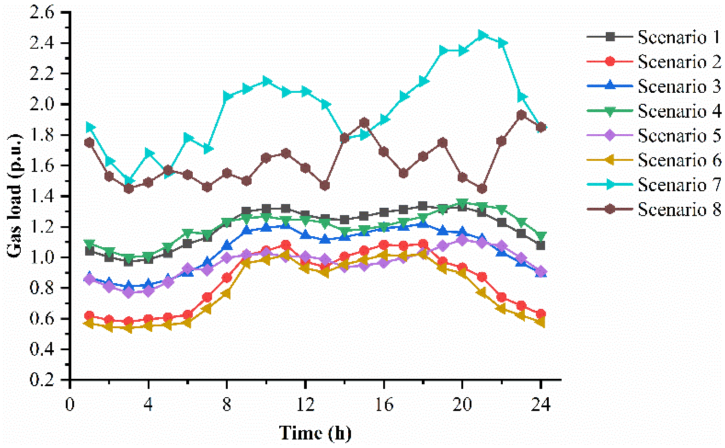

Fig. 3. Representative scenario of natural gas load.

When introducing the GFPPs in Strategy #2, the natural gas system is jointly operated with the electricity system. The gas load profile is shown in Fig. 3. There are six scenarios (Scenario 1-Scenario 6) being generated according to the four seasonal natural gas consumption characteristics in the whole year. More specifically, Scenario 1 and 5 represent the two representative diurnal natural gas consumption patterns in winter, which with the almost same consumption trend but different values, indicating the peaks and regular gas consumption patterns in this season. Similarly, Scenario 2 and 6 show the two gas consumption patterns in summer, respectively. It is assumed that just one gas consumption pattern is considered in autumn and spring in this paper. In addition, two scenarios (Scenario 7 and Scenario 8) with larger fluctuation of gas consumption are also included.

4.3. *Options for planning strategy*

There are three low-carbon economic planning strategies with options as follows:

Strategy #1: Six coal-fired power plants (G1, G2, G3, G5, G6, and G7, they have lower ramping speed in common and more likely to be phased out in the near future) to be flexibility reformed.

Strategy #2: Seven gas-fired power plants (GF1-GF7) candidate connecting the power system with natural gas system. The investment rule is to add the new ones at the position where coal-fired power plants with low flexibility are located at or directly at new spare nodes.

Strategy #3: Six energy storage systems (ESS1-ESS6) to be installed.

The device parameters of the three strategies are given in Table 1, 2 and 3.

Table 1

Parameters of the candidate GFPPs (Note that the generation cost of GFPPs is included in the gas production cost).

Devices	Installation location	Capacity (MW)	Min stable Output (MW)	Ramp speed (MW/h)	Min on/off time (h)	Operation cost (CNY/MW)		Capital cost (10^4 CNY/MW)
						Power	Reserve	
GF #1	Bus 1	110	11	100	2			
GF #2	Bus 2	100	10	95	3			
GF #3	Bus 16	120	12	100	3			
GF #4	Bus 15	100	10	110	2	—	1.6	182
GF #5	Bus 8	300	30	300	2			
GF #6	Bus 10	300	30	300	2			
GF #7	Bus 13	300	30	300	2			

Table 2

Parameters of the candidate ESS.

Devices	Installation location	$\eta_e^{ch} / \eta_e^{dc}$	$SoC_s^{\max}$ (Capacity) (MWh)	$SoC_s^{\min}$ (MWh)	SoC_s^0 (MWh)	$P_{dc}^{\max} / P_{ch}^{\max}$ (MW)	Operation cost (CNY/MW)		Capital cost (10^4 CNY/MW)
							Power	Reserve	
ESS #1	Bus 6		120	24	48	108			
ESS #2	Bus 4		100	20	40	90			
ESS #3	Bus 11		100	20	40	90			
ESS #4	Bus 24	0.9	150	30	60	135	12	5.5	140
ESS #5	Bus 14		110	22	44	99			
ESS #6	Bus 5		120	24	48	108			

Table 3

Options for flexibility reformation of CFPPs.

Devices	Installation location	Capacity (MW)	Before		After		Capital cost (10^4 CNY/MW)
			Min stable Output (MW)	Ramp speed (MW/min)	Min stable Output (MW)	Ramp speed (MW/min)	
G1	Bus 1	238	107.10	2.38	83.30	7.14	105
G2	Bus 2	224	100.80	2.24	78.40	6.72	
G3	Bus 7	225	101.25	2.25	78.75	6.75	
G5	Bus 15	255	114.75	2.55	89.25	7.65	
G6	Bus 16	278	125.10	2.78	97.30	8.34	
G7	Bus 18	310	139.50	3.10	108.50	9.30	

4.4. Other parameters

In this case study, the installed capacity of each wind farm is set to 1800MW, and the proportion of this capacity to the peak load in each scenario exceeds 52%, which can be classified as high level of wind power penetration. The natural gas load reference value is 975kcf. The cost of wind power generation and curtailment are 15 CNY/MW and 150 CNY/MW, respectively. The carbon tax price is 20 CNY/ton and the carbon emission storage & transmission of CCS cost is 3 CNY/ton. The forecast error is set to be the sum of 5% electricity load and 15% wind power in each scenario.

4.5. Solution method

The proposed model is converted into a mixed integer linear programming (MILP) by linearization of the non-convex gas flow constraint (32) with the incremental linear method [36]. All case studies are optimized and solved by the Gurobi 9.1.1 solver on the MATLAB R2018b platform.

5. Results and discussion

5.1. Low-carbon economic planning results

This section shows the planning results in each strategy, as well as the optimal operation results of the initial state, as shown in Table 4. It can be seen that in the initial state, the goal of carbon reduction and wind power accommodation is not well satisfied, which is reflected in the large carbon emissions (2.5613×10^5 ton) and the high wind power curtailment (21.36%) of a year. In order to mitigate the severe situation, three low-carbon economic planning strategies are adopted, and the carbon emission reduced by 9.8%, 32.5% and 9.3%, respectively. Moreover, the system flexibility is enhanced due to the significantly decrease of wind power curtailment after applying each strategy. Among them, the strategy #3 is the most flexible one, as the wind power curtailment dropped to 7.74%. In fact, less carbon emission cost and wind power penalty make strategies more economical, which can be seen from Table 5. To meet the energy demand, there should be adequate energy supply, no matter what kind of energy sources is utilized. In all three strategies, the wind power generation has been fully utilized for energy supply to varying degrees and leads to the decrement of CFPPs generation (Fig. 4), thus, the carbon emission only produced by CFPPs generation eventually reduced. The collateral effect is that the overall annual cost evidently drops.

The mechanisms of the carbon reduction and flexibility enhancement in the three strategies are not exactly the same. The main idea of strategy #1 in carbon reduction and flexibility enhancement is to improve the utilization level of wind power generation. Flexibility reformation of CFPPs can increase the ramping rate and also decrease the required minimum stable output. Therefore, when encountering ramping up events of increasing wind power, the down-regulation capacity can be lowered even smaller to make more operational space for accommodating the high wind power generation effectively. At the same time, there might not be any excess downward reserve capacity provided but can also meet the downward spinning reserve requirement, so the reserve supply cost is reduced. Strategy #3 take the advantages of ESS in peak load shifting, which can reduce the energy supply burden during peak load periods and increase the utilization of wind power generation. Therefore, the goals of carbon reduction and flexibility enhancement are both achieved. New built GFPPs with higher ramping speed and lower minimum stable output are considered in strategy #2. Not exactly like the retrofitted CFPPs in strategy #1, these GFPPs have new low-carbon emitters that results in much more carbon reducing while flexibility improving. In Table 4, it can be observed that the total carbon emission of strategy #2 is less than that in the other two strategies, but when it comes to the flexibility enhancement, the final effect is not as good as the other two strategies. This is because the existing coal-fired units can almost meet the electricity demand, so it is not necessary to construct too many gas-fired units (only two of the seven candidates have been put into construction) as the extra energy supply and flexibility options, on the premise of gas well supply sufficiency for natural gas loads.

Table 4

Planning results of different strategies.

Planning strategy	**Results**	**Overall annual cost (10^8 CNY)**	**Annual operation cost (10^8 CNY)**	**Investment cost (10^8 CNY)**	**Carbon emission (10^5 t)**	**Annual wind power curtailment (%)**
Initial state	-	9.1318	9.1318	-	2.5613	21.36
#1	G1 (1), G2 (2), G3 (7), G5 (15), G6 (16)	7.8926	6.8647	1.0279	2.3123	7.87
#2	GF #5 (8), GF #7 (13)	8.0575	7.1813	0.8762	1.7313	13.03
#3	ESS #1 (6), ESS #2 (4), ESS #3 (11), ESS #5(14)	7.3805	6.8974	0.4831	2.3232	7.74

Table 5

Annual operation cost compositions comparison of different strategies.

Planning strategy	Annual energy supply cost* (10^8 CNY)	Annual reserve supply cost (10^8 CNY)	Annual wind curtailment penalty (10^8 CNY)	Annual carbon emission & storage cost (10^8 CNY)	Annual operation cost (10^8 CNY)
Initial State	3.5831	0.2489	2.8725	2.4273	9.1318
#1	3.4070	0.2192	1.0152	2.2233	6.8647
#2	3.3584	0.1290	1.7118	1.9821	7.1813
#3	3.4259	0.2473	0.9936	2.2306	6.8974

* Note that the energy supply cost also includes the gas supply cost or ESS operation cost in #2 or #3.

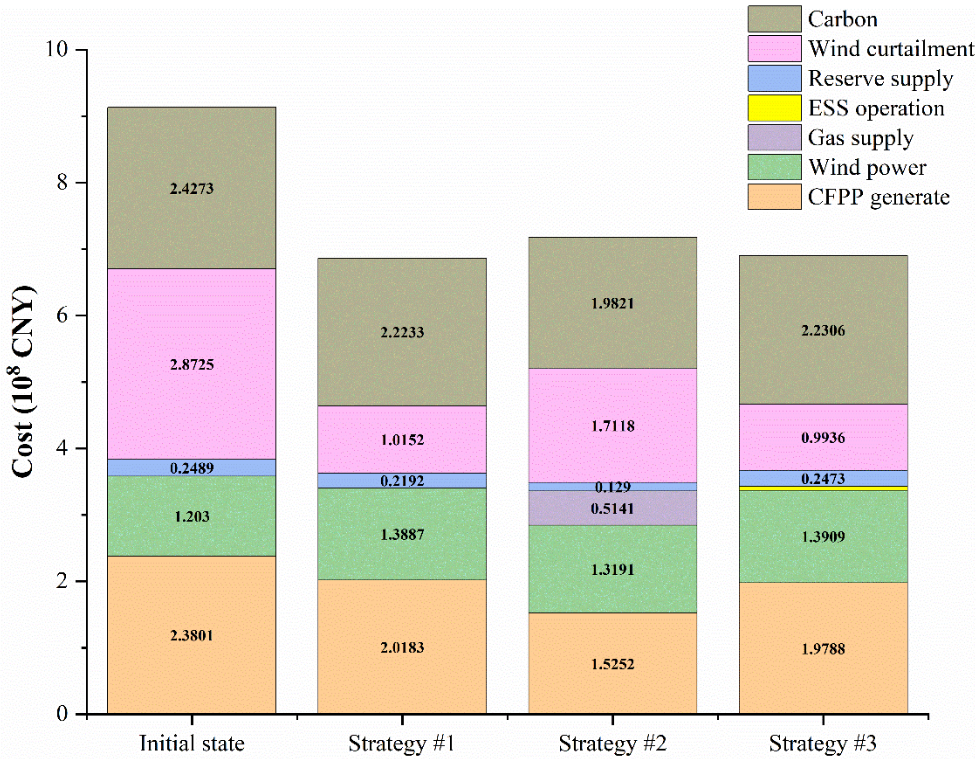

Fig. 4. Cost breakdown of annual operation cost in initial state and in each strategy.

5.2. Impacts of key parameters

5.2.1. Carbon tax price

To illustrate the impact of different carbon tax prices on carbon reduction and flexibility enhancement in the three strategies, the sensitivity analysis of different strategies with different carbon tax price is depicted in Fig. 5. Note that the carbon related parameters involved in this paper are carbon tax price and carbon emission capture and storage & transmission cost. To eliminate the influence of the latter, it is fixed as 1000 CNY/ton here. As seen, the total cost in every planning strategy raises with the increase of carbon tax price. However, in the strategy #1, the carbon emission almost stays constant regardless of carbon tax price variation. This is because the electricity supply should be able to correspond and follow the electricity demand changes in every scenario, which means the output characteristics of CFPPs cannot be widely replaced by the wind power generation. However, strategy #1 still maximizes the utilization rate of wind power by reforming the flexibility of CFPPs as many as possible, and almost all the candidate CFPPs (1530MW capacity in total) are flexibility reformed when the carbon tax price exceeds 50 CNY/ton, as shown in Fig. 6. Anyway, as the carbon emission barely changes, the total cost of this planning strategy would increase with the increase of carbon tax price.

The role of the strategy #3 is different in that it accommodates more wind power than strategy #1 to improve flexibility of the system. With the installation of ESS, a part of the excessive wind power can be stored and utilized later, so the total cost is reduced compared to strategy #1. Besides, it is indicated that the wind power curtailment of the strategy #3 is always the lowest among all three from Fig. 6, and indicates it a better option for flexibility enhancement. However, the flexibility has reached its limit because the ESS capacity to be planned reaches summit (700MW capacity in total). Meanwhile, it also suffers from the dominant of the power generation from the CFPPs and carbon emission still remains high.

With the planning strategy #2, the total cost continues to decline and carbon emission remains lower in the comparison with the strategy #1 and #3, mainly because of the reduction in electricity supply of CFPPs. The high carbon tax price forces the CFPPs with high carbon pollution to reduce the power generation, and shifts the power source to the low-emission GFPPs to generate the electricity. Therefore, the advantages of natural gas system are obtained, which results in the cheaper and cleaner gas supply gradually increasing. The higher the carbon tax price, the more superior in economy and carbon reduction of the planning strategy #2, especially when the carbon tax price is over 80 CNY/ton. But the wind power curtailment remains high and flexibility of the system hardly improves, as depicted in Fig. 6. This is because the installed capacity of GFPPs with high operational flexibility is unable to occupy a dominant position in the total electricity supply, their effect on flexibility enhancement is not obvious. This can be learned that when the carbon tax price is over 60 CNY/ton, the total capacity of GFPPs available to investment has almost reached the candidate's top limits (1330MW capacity in total), and the wind power curtailment maintains at the relatively high level of around 13%.

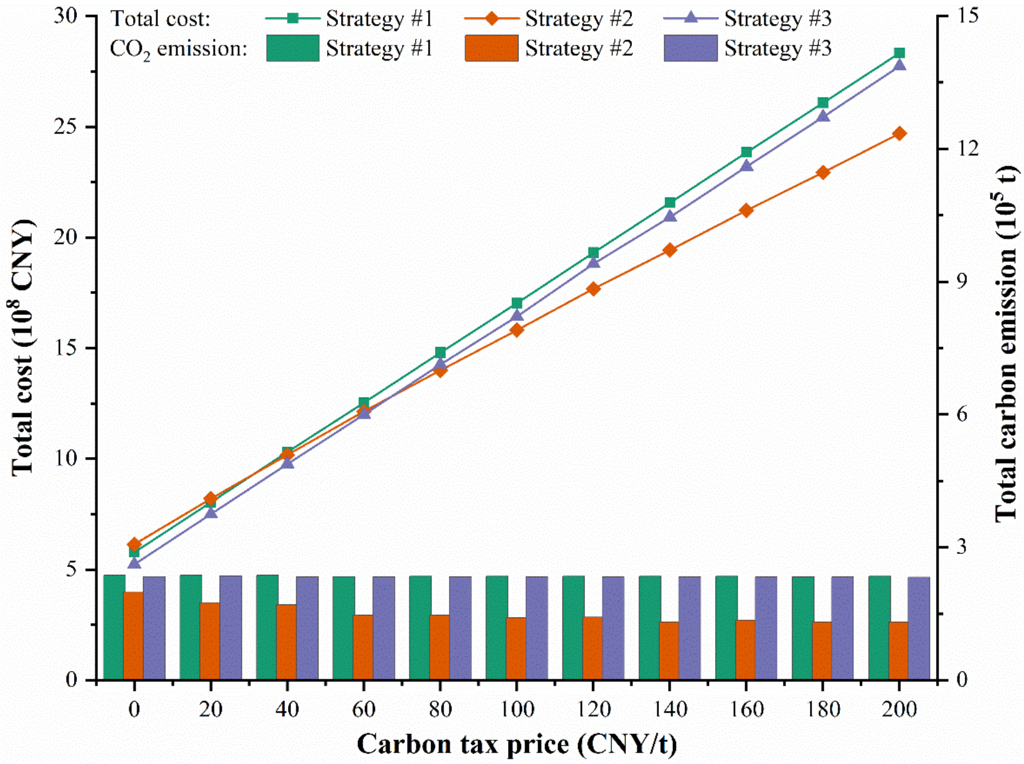

Fig. 5. Total cost and carbon emission in different carbon tax price of three strategies.

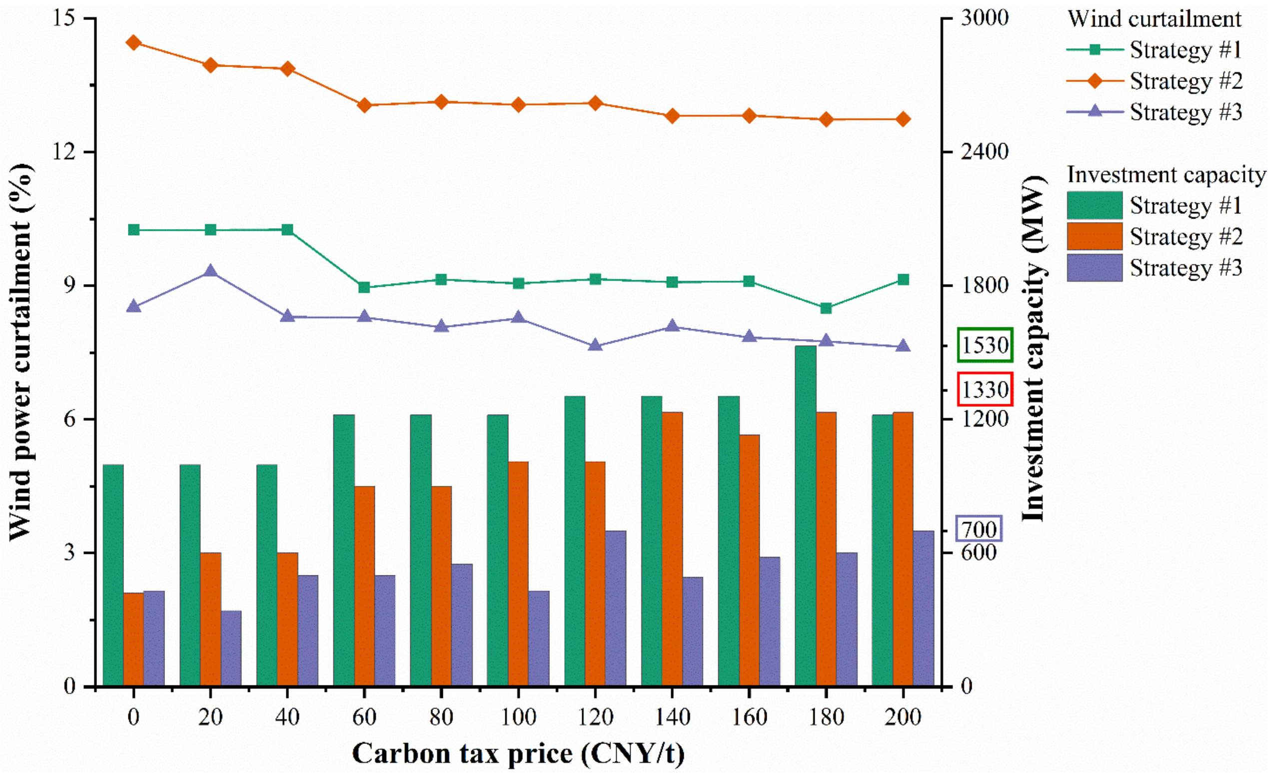

Fig. 6. Wind power curtailment and investment capacity of each strategy in different carbon tax price. The values 1530, 1330 and 700 in the boxes of the right Y-axis represent the total investment capacity of the corresponding technologies in strategy #1, strategy #2 and strategy #3, respectively.

5.2.2. *Wind penetration level*

The planning results changes with the increase of wind power penetration level in each planning strategy. Fig. 7 and Fig. 8 show the total cost, total carbon emission, wind power curtailment and final investment capacity in each strategy with the different wind power penetration levels. High wind power integration would increase the total cost mainly because of the wind curtailment penalty rises caused by the limited investment capacity of flexible technologies in each strategy. However, the carbon emissions keep reducing moderately in strategy #1 and #3 even though the high-emission facility (i.e., CFPP) exits. This is due to the retrofitted CCS facility works to capture more carbon emissions. On the other hand, although the wind power curtailment remains increasing, driven by the target of carbon reduction, most of the wind power is well utilized with the increase of the wind farm installed capacity.

The wind power curtailment level of strategy #2 is much higher than the other two strategies when the penetration rate is above 56.57%. Despite that, it is highlighted that the total investment capacity of GFPPs with higher flexibility remains at around 600MW. It suggests that the carbon reduction target is given higher priority when considering retrofitting new GFPPs in strategy #2 for planning, but it's unwilling to add too many new carbon emission sources even at the expense of the overall system's flexibility. Thus, it can be conducted that the higher the wind power penetration is, the less benefits can be obtained from strategy #2 in the condition of loose carbon emission restriction policies.

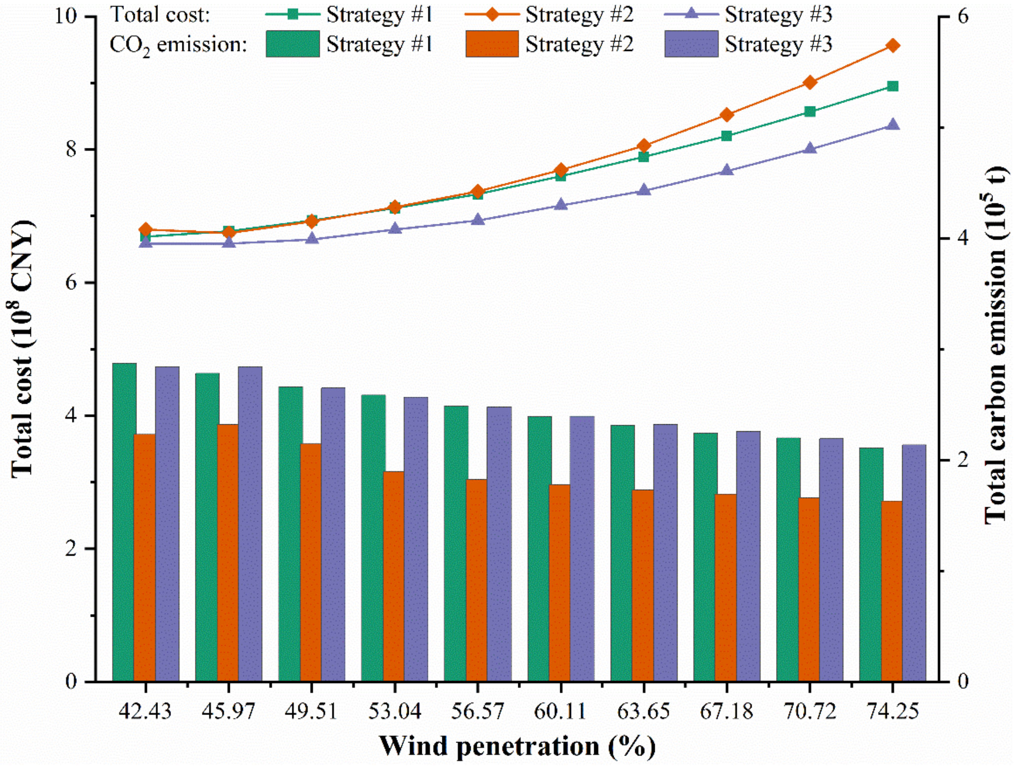

Fig. 7. Total cost and carbon emission in different wind penetration levels of three strategies.

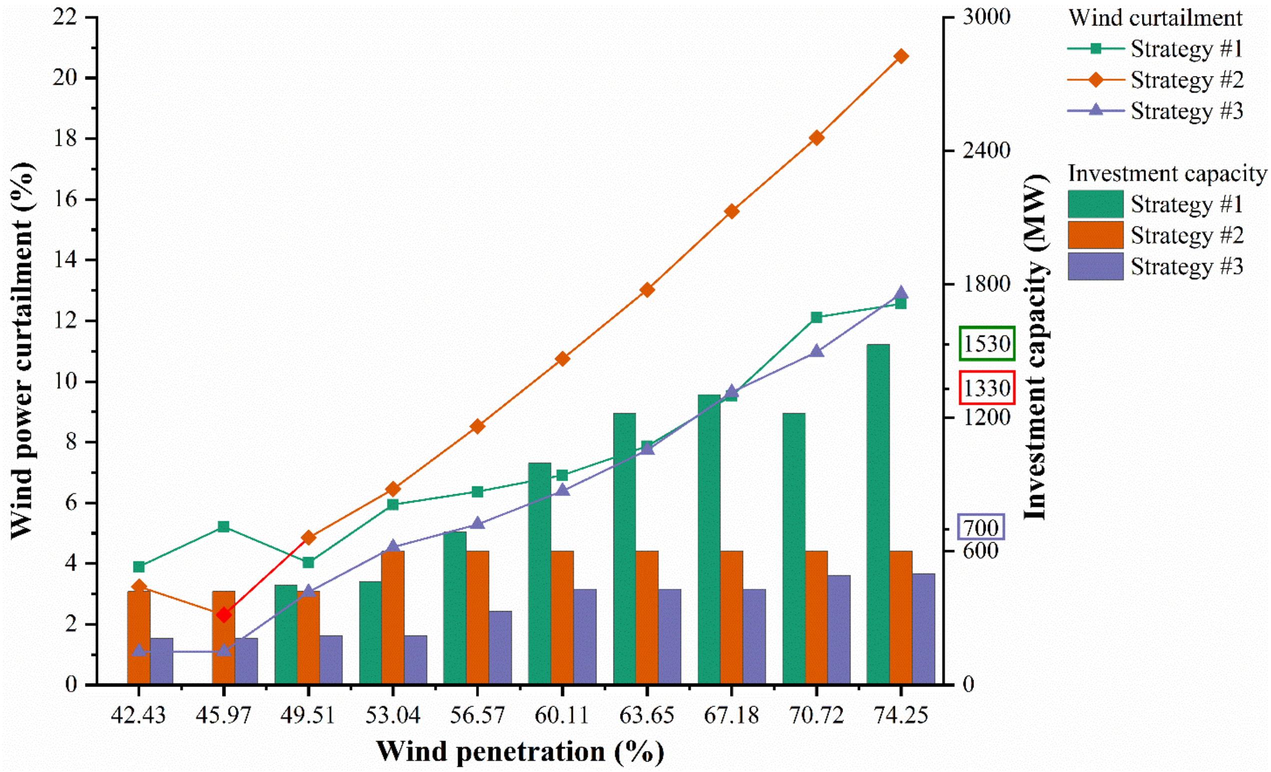

Fig. 8. Wind power curtailment and investment capacity of each strategy in different wind penetration levels. The values 1530, 1330 and 700 in the boxes of the right Y-axis represent the total investment capacity of the corresponding technologies in strategy #1, strategy #2 and strategy #3, respectively.

5.3. *Discussions*

Based on the results and sensitivity analysis conducted above, it is worth noticing that the new construction of GFPPs has been a better option for deep carbon reduction in the low-carbon planning, since they own a lower carbon emission intensity. However, although the GFPP is more operational flexible one when encountering the high variability event of renewable generation, the overall flexibility enhancement result is not very satisfied because the investment cost of constructing new GFPPs is relatively too expansive to large-scale deploy for practical consideration. Thus, when planning for both carbon reduction and flexibility enhancement purposes of integrated energy system on the premise of a limited budget, the new GFPP construction strategy may not be able to fully show its advantages.

In contrast, when implementing ESS installation and flexibility reformation of CFPPs strategies for the same goals, the carbon emission remains high and the carbon tax restriction can hardly work from the test results. This is mainly due to there is lack of new low-carbon power generation sources for replacement to meet the existing load demand. However, owing to the low capital cost and high technical convenience of flexibility reformation of CFPPs, they can be carried out in large-scale nowadays so the flexibility enhancement effect is usually well achieved when confronting high renewable energy penetration. For ESS installation, despite of its higher investment cost for technology advances, the flexibility enhancement still remains obvious with only small capacity investment since its unique superiority of excess renewable energy storage. Therefore, it can also be regard as a great flexibility enhancement option but still struggled in deep carbon reduction for the same reason as CFPPs flexibility reformation reflected.

6. Conclusions

This paper has proposed a low-carbon economic planning model of integrated electricity-gas systems with high penetrated wind power generation. Carbon tax are included as low-carbon stimulation means and carbon capture and storage are also considered to mitigate the carbon emissions. Three strategies for planning towards low carbon (i.e., flexibility reformation of CFPP, construction of GFPP and installation of ESS) are integrated to effectively support the carbon reduction and flexibility enhancement. In addition, the scenario generation method is adopted to enable the operation process into the planning model, so that the profile characteristics of load and wind power are taken into account. The main conclusions are summarized as follows:

(1) Three low-carbon planning strategies are to be alternative solutions for carbon reduction and flexibility enhancement, with carbon emissions reduction by 9.8%, 32.5% and 9.3%, along with wind power curtailment decreasing by 63.2%, 38.9%, and 63.7%, respectively.

(2) After adopting three planning strategies, although the investment cost is newly added in the early stage, the operation process shows that the annual operation cost would be significantly reduced, which makes the investment of the proposed planning strategies much more economic.

(3) Sensitivity analysis of carbon tax prices and wind power penetration levels reveals the advantages and applicability of different planning strategies in reducing carbon emission while improving system flexibility. When the carbon tax price is higher than 80 CNY/ton, the introduction of GFPPs can greatly reduce carbon emissions, but the effect of flexibility enhancement is not very satisfactory. With the increase of wind power penetration, the GFPP construction only reduces carbon emissions marginally but the wind power curtailment level rises sharply. On the contrary, installing ESS and implementing flexibility reformation of CFPPs can ensure much lower wind power curtailment while the carbon emissions reduction is less significant, which are better choices for flexibility enhancement with looser carbon reduction management.

It noted that the uncertainty of renewable generation and load has not been fully studied, which would be further investigated and integrated into the low-carbon economic planning model to improve its robustness in the future.

CRediT authorship contribution statement

Yue Xiang, Yongtao Guo: Conceptualization, Methodology; Yongtao Guo, Yue Xiang: Writing- Original draft preparation; Junyong Liu, Pingliang Zeng: Supervision; Yue Xiang, Yongtao Guo, Gang Wu, Wei Sun, Yutian Lei: Writing-Reviewing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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