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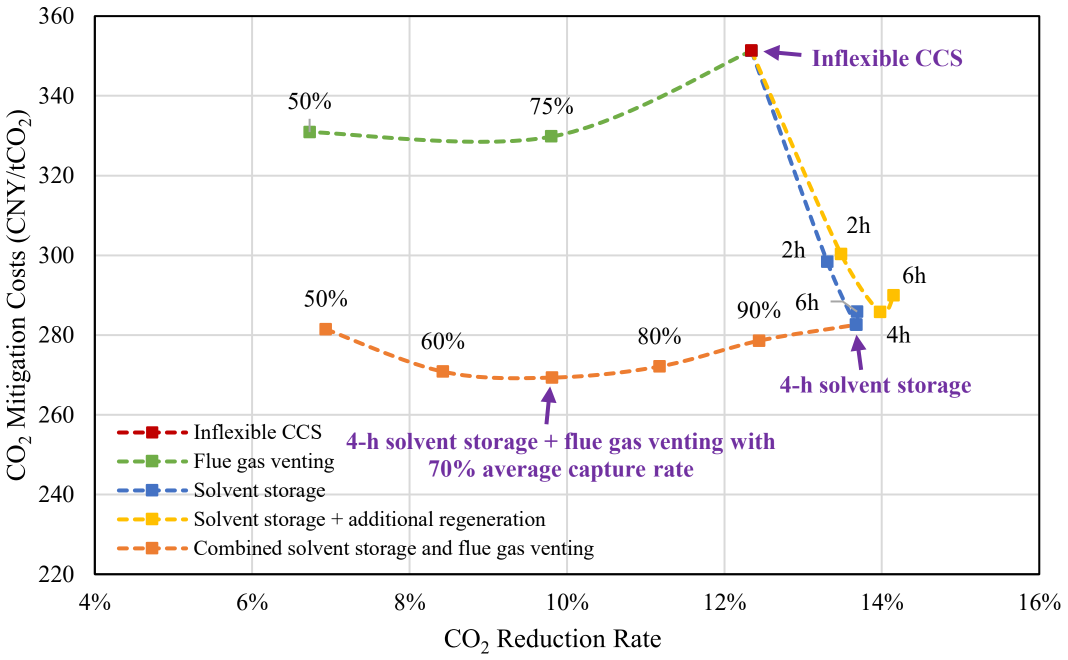
Abstract

Electrical power systems account for over 40% of China's total CO_2 emissions, with 56% of electricity generated by thermal power plants as of 2022. Flexibly-operated carbon capture and storage (CCS) has been proposed as an effective measure for decarbonizing coal-fired power plants, offering lower capture costs and energy penalties than those of conventional CCS. This study characterizes the operation of flexible carbon capture power plants (CCPPs) in largescale power system with variable renewable energy and quantifies the system-level environmental and economic benefits of the synergies between flexible CCPPs and variable renewable energy. Hourly analysis suggests that flexible CCS would reduce energy consumption during peak demand periods and operate at full load during off-peak periods to utilize otherwise curtailed renewable electricity. Across a broad search space for flexible CCS installations and capture configurations, we found a complex interaction between mitigation costs and total carbon reductions. Under a 10% CCS installation rate on coal-fired plants, the lowest mitigation cost is 269 CNY/t (37 USD/t, as of 2024) when installing flexible CCS with 4 h of solvent storage and a 70% carbon capture rate, resulting in a 9.8% reduction in power system carbon emissions. To fully realize the benefits of flexible CCPPs in future power systems, both policy incentives and optimal operations are required. Concerning the practical deployment of CCS, we further assessed the opportunities for near-term CCS deployment with the flexibility to increase carbon stringency over time.

Keywords: flexibly-operated carbon capture and storage, carbon capture power plants, variable renewable energy, power system decarbonization

Graphic Abstract



CCS, carbon capture and storage

Highlights

Modeling and optimization of flexible carbon capture and storage operation with different configurations

Characterization of the interplay between flexible carbon capture power plants and variable renewable energy in largescale power system

Quantitative evaluation of the environmental and economic benefits of flexible carbon capture power plants

Exploration of opportunities for the future development and deployment of flexible carbon capture and storage

1 Introduction

China is the world's largest CO_2 emitter, projecting 12.1 Gt of CO_2 emissions by 2022[1]. To address global climate change, China has set targets to peak its CO_2 emissions by 2030 and achieve carbon neutrality by 2060[2]. Electric power systems account for over 40% of China's total CO_2 emissions[3] and are driven by thermal power, which accounts for 66.5% of total power generation[4]. With expanding investments in clean energy resources, the installation capacity of renewable power plants has exceeded that of thermal power plants in 2022[5]. However, thermal power plants will remain the dominant power source in the next decade owing to their crucial role in maintaining the stability of power systems. According to a projection by the State Grid Energy Research Institute, the installation of coal-fired power plants will reach 1290 GW by 2030, increasing by 17.8% from 2020[6]. Decarbonizing coal-fired power plants is necessary for China to achieve its carbon mitigation targets in the coming decades.

Carbon capture and storage (CCS) is an effective measure for the decarbonization of coal-fired power plants[7]. Post-combustion capture using amine-based chemical absorption of CO_2 is technically mature and currently available for commercial application[7-9]. By 2021, approximately 12 carbon capture power plants (CCPPs) were operating or under construction in China, most of which are small-scale demonstration projects[10]. The largescale utilization of CCS is limited because of its high capture and energy penalties. The carbon capture cost of post-combustion capture systems ranges from 300 to 450 CNY/t (41–62 USD/t, as of 2024) CO_2 at present[7], with 20–60% of the cost originating from energy consumption[11, 12]. The energy penalty of CCS with amine-based chemical absorption is 4–6 GJ/tCO_2[10]. Approximately 20–40% of the electricity output of a coal-fired plant is reduced owing to the operation of the carbon capture system[8]. The cost and energy consumption of carbon capture systems are projected to decrease gradually with the development of CCS technology[7, 10]. However, high capture costs and energy penalties remain substantial barriers to CCS installation over the next decade.

The flexible operation of CCPPs has been suggested to reduce capture costs and

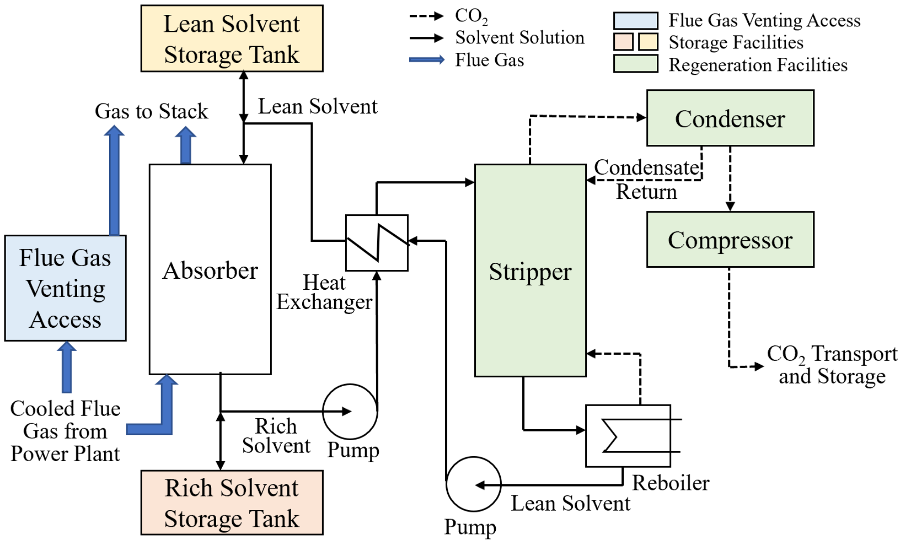


Fig. 1. Schematic diagram of post-combustion carbon capture and storage. Components that can contribute to flexibility are highlighted. Under the flue gas venting strategy, flue gas can be vented directly into the atmosphere through flue gas venting access. Under the solvent storage strategy, rich/lean solvent storage tanks are added for solvent storage. Under the solvent storage coupling with additional regeneration strategy, in addition to the extra rich/lean solvent storage tanks, regeneration facilities (including the stripper, condenser, and compressor) are over-dimensioned to accelerate the regeneration process.

energy penalties by taking advantage of synergies with variable renewable energy (VRE)[13-15]. A typical post-combustion carbon capture system comprises three main elements: an absorber, where CO_2 is removed from the flue gas; a stripper, where CO_2 is released from the sorbent; and a compressor, where CO_2 is compressed for further transportation and storage (Fig. 1). The energy penalties of these three stages account for 8–9%, 54–57%, and 33–38%, respectively[8]. Conventional carbon-capture systems operate continuously. With specific technical retrofits, the energy consumption of the carbon capture system, particularly in the CO_2 release and compression processes, can be adjusted over time. This allows the interplay of the CCPP with VRE to aid in renewable integration and simultaneously reduce the CCS energy penalty and capture costs. Specifically, during periods of peak demand and low VRE generation, the carbon capture system can decrease its energy consumption and allow more steam to generate electricity, whereas during off-peak hours, the carbon capture system can operate at full load to maximize carbon reduction and utilize otherwise curtailed renewable electricity. Therefore, power system flexibility is improved, and the curtailment of wind and PV electricity can be reduced[13, 16]. Specific strategies for the flexible operation of CCPPs investigated in previous studies include: (1) flue gas venting (FGV), which allows flue gas to be vented directly into the atmosphere, bypassing the capture units and largely reducing energy consumption[9, 16-18]; (2) solvent storage (SS), which adds two extra reservoirs of solvent to postpone the energy-intensive regeneration process[8, 9, 13, 19-21]; (3) SS coupling with additional regeneration (SS + AR), which over-dimensions regeneration facilities, including the stripper, condenser, and compressor, to enable faster regeneration and increase the potential for postponing the regeneration process[8, 16, 18].

A large body of literature has investigated the effects of the flexible operation of CCPPs in terms of economic benefits, environmental impact, and system operation. Assuming fluctuating electricity prices, Qiu et al.[19] optimized the operation of an individual CCPP with SS and concluded that flexible operation could significantly increase the operating profit. Singh et al.[22] comprehensively considered the fixed and variable costs of flexible CCPPs and found that flexible CCPPs could become profitable with proper market incentives and cost reductions in the capture technology. Van der Wijk et al.[16] investigated the benefits of flexible CCS in a future northwest European power system and found that equipping CSS with SS and additional regeneration facilities would reduce the CO_2 intensity of Dutch electricity in 2030 from 155 to 151 kg CO_2/MWh. Regarding power system operation, Lin et al.[23] suggested that by storing a rich solvent during the peak load period and regenerating it later in the off-peak period, the energy penalty of the carbon capture system can be postponed, and the net power capacity range of the CCPP can be increased. Li et al.[24] reported that flexible CCS devices could provide more upward and downward spinning reserves. Cui et al.[25] reported that a flexible CCPP reduces the wind curtailment rate from 5.48% to 2.16% in an isolated system. Existing studies on flexible CCPPs are primarily based on individual plants[14, 17, 19, 22, 24, 26, 27] or isolated energy systems[25, 28], whereas few studies have modeled flexible CCPPs from a largescale power system perspective[16]. The synergies of flexible CCPPs with intermittent wind and PV electricity in future largescale power systems with high-penetration renewables have not yet been characterized, and their economic and environmental benefits remain unknown.

Concerning future largescale power systems facing the challenge of VRE integration, many studies have been conducted on low-carbon power system planning and operation, considering various carbon mitigation strategies. Jain et al.[29] developed a power sector decarbonization planning model with high-level spatial, temporal, and technical details for VRE and conventional power plants. The optimization results suggest that there will be continued requirements for coal-fired plants to provide flexibility, and with instruments, such as a carbon tax, the capacity share of low-emission gas-fired plants will increase. Wang et al.[30] applied a bilateral trading mechanism with active demand-side management to a low-carbon operational planning model. With these strategies, the proportion of energy with low carbon intensity in the energy mix is increased, and system carbon emissions are reduced. Various studies have investigated the economic and environmental impacts of a portfolio of carbon capture technologies on future power systems. Wang et al.[31] considered carbon capture technology in an economic operating model and applied a life-cycle assessment method to calculate the system carbon emissions. The results suggest that carbon capture technology can significantly reduce system carbon emissions by 72.66% while increasing the total cost. Bistline et al.[32] found that adding carbon capture to a set of carbon mitigation technologies lowered the costs of deep decarbonization, especially for high mitigation levels. Xiao et al.[33] suggested that applying CCS combined with VRE is beneficial for reaching the carbon peak of the power sector, although it significantly increases power generation costs. However, in these studies, the flexible CCPP was not considered or only marginally considered, and the system energy penalty and CO_2 mitigation costs remained high[34]. Furthermore, existing studies have not fully considered the range of flexible CCS configurations arising in particular from the fixed costs of different capture equipment and variable capture costs.

Compared to existing studies, the contribution of this paper includes:

(1) The synergies of the flexible CCPP with VRE were investigated in a largescale power system, and the potential economic and environmental benefits of the flexible CCPP were analyzed.

(2) Various flexible CCS configurations are considered and compared. The operational constraints of each configuration were modeled in detail, and the fixed and variable costs for different CCS units were calculated.

(3) We adopted a cost-optimal unit commitment model (UCM) to jointly optimize the operation of power generation and carbon capture units in largescale power systems.

We consider the Huabei (northern) regional power system in China, which includes Beijing, Tianjin, Hebei, Shandong, Shanxi, and the western region of Inner Mongolia[35], and accounts for nearly 20% of the power generation in China[4]. We included the technical and economic characteristics of flexibly operated CCS in an emission-optimal UCM. We compared scenarios with 5%, 10%, and 20% penetration of post-combustion CCS with different configurations in 2030. The hourly operation of the flexible CCPP is optimized along with other renewable and conventional power plants in future power systems, and its interplay with the VRE is characterized. Based on this, the system-level benefits of the synergies between the flexible CCPP and VRE were quantified in terms of renewable integration, fuel consumption, total system emissions, and carbon mitigation costs. The results suggest that under a 10% CCS installation rate on coal-fired plants, flexible CCS with 4-h of SS and a 70% carbon capture rate will result in a 9.8% reduction in the total carbon emissions of the power system, with a CO_2 mitigation cost of 269 CNY/t (37 USD/t).

2 Methodology

2.1 Model and scenarios

This study adopted a UCM for power system optimization. The installed capacity of the power plants and the configurations of the CCS units were predetermined in each scenario. The hourly operations of power plants and carbon capture units were optimized over a weekly horizon under the constraints of demand-generation balance and system operation requirements. Compared with that of existing studies, our UCM is improved in the following two aspects: First, the hourly operation of the flexible CCPP is included in the model and optimized along with other power generation units. Second, to maximize the environmental benefits of the flexible CCPP, we set the objective of the model to minimize system CO_2 emissions. Therefore, the carbon capture units are forced to operate at a higher level to increase the amount of CO_2 captured. Meanwhile, the fuel consumption of the power generation units is minimized to reduce the amount of CO_2 produced. The constraints considered in the UCM include (1) demand-generation balance; (2) output range, ramping limits, and minimum on/off times of thermal power plants; (3) operational limits for power storage systems and combined heat and power (CHP) units; (4) operational limits for carbon capture units with different configurations; and (5) hourly requirements for reserves. The details of the UCM settings are provided in Supplementary Note 1.

It is projected that the installation of coal-fired plants in Huabei will reach 370 GW by 2030, accounting for 28.7% of China's total coal-fired plant installations and ranking first among the seven regional power systems in China[6]. Due to their proximity to CO_2 utilization and storage sites, including the Ordos Basin and Bohai Bay Basin, the coal-fired plants in Huabei are well-positioned for retrofitting with CCS and are promising for early demonstrations[7, 36]. Therefore, the Huabei regional power system in China was selected as a case study to evaluate the synergies between a flexible CCPP and VRE in 2030.

Table 1. Flexibility configuration scenarios used in this study

Scenario abbreviations	Flexibility strategies	Flexibility options	CCS installation proportion
no-CCS	NA	NA	0%
Inflex	NA	NA	5%, 10%, 20%
FGV	Flue gas venting	50% and 75% average capture rates	5%, 10%, 20%
SS	Solvent storage	2 h, 4 h, and 6 h solvent storage times	5%, 10%, 20%
SS + AR	Solvent storage and additional regeneration	2 h, 4 h, and 6 h solvent storage times and corresponding ARs	5%, 10%, 20%

CCS, carbon capture and storage; FGV, flue gas venting; SS, solvent storage; SS +AR, solvent storage coupling with additional regeneration.

Three flexibility strategies (FGV, SS, and SS + AR), an inflexible option, and a no-CCS scenario were investigated. In each flexible CCS scenario, we assume that the SS system operates in daily cycles, storing the sorbent during peak load hours in a day and regenerating it during off-peak hours. In the FGV scenarios, the average capture rates of the carbon capture facilities (CO_2 flowing into the capture unit divided by the total CO_2 produced in each unit and day) were set to 50% and 75%, respectively [14]. In the SS scenario, we assumed 2, 4, and 6 h of SS under full load generation[8, 9]. In the SS + AR scenarios, the SS time was set to 2, 4, and 6 h, and the regeneration system was over-dimensioned at a rate defined by:

$$OR = \frac{H_s}{H - H_s} \tag{1}$$

where OR is the over-dimensional rate of the regeneration system, H_s is SS time, and H is the cycling period of the CCS system, assumed as 24 h. For instance, in the SS + AR scenario with 4 h of SS, the regeneration system is required to regenerate the solvent stored throughout the day during the regeneration period of 20 h, whereas in the remaining 4 h, it is shut down for flexible operation. Therefore, the regeneration system must be over-dimensioned by 120%[8]. It is predicted that the CCS installation rate of coal-fired plants (capacity with CCS installed divided by the total coal-fired plant capacity) will range from 5 to 20% in China by 2030[33, 37, 38]. We tested CCS installation rates of 5%, 10%, and 20%. The aforementioned scenarios are summarized in Table 1.

In the simulation of a flexible CCS, the amount of CO_2 absorbed by the CCS unit in each CCPP and each time period ($CCS_{i,t}^{a}$) must not exceed the amount of CO_2 produced ($C(p_{i,t})$) multiplied by the absorption rate of the CCS units (CCS_{AR}, CO_2 absorbed and mitigated divided by CO_2 flowing into the units, assumed to be 90%[16]).

$$0 \leq CCS_{i,t}^{a} \leq C(p_{i,t}) \cdot CCS_{AR} \tag{2}$$

where i is the CCS unit and t is the time period. The calculation of the CO_2 produced by the coal-fired units is described in Supplementary Note 3. The average capture rate of the carbon capture facilities is calculated by dividing the CO_2 flowing into the capture unit by the total CO_2 produced in each unit and each day, which is less than 100% in the FGV scenarios and equal to 100% in the other scenarios. For the CCS units without SS, the amount of CO_2 stripped should be equal to the amount of CO_2 absorbed during each time period. For CCS units with SS, SS and regeneration for CCS units should satisfy the following constraints:

$$CCS\_sto_{i,t} = CCS\_sto_{i,t-1} + CCS_{i,t}^{a} - CCS_{i,t}^{s} \tag{3}$$

$$0 \leq CCS\_sto_{i,t} \leq CCS\_sto_{i,max} \tag{4}$$

where $CCS\_sto_{i,t}$ is the amount of CO_2 in the rich solvent stored in the tank. $CCS_{i,t}^{a}$ and $CCS_{i,t}^{s}$ are the amounts of CO_2 absorbed and stripped, respectively. $CCS\_sto_{i,max}$ denotes the maximum storage capacity. The CO_2 stripping rate for each CCS unit should not exceed the full-load CO_2 production rate of the thermal unit (C_i^f) multiplied by the over-dimensional rate of the regeneration system (OR, which equals zero for CCS units without additional regeneration):

$$0 \leq CCS_{i,t}^{s} \leq C_i^f \cdot OR \ (i \in \{\Omega_{CCS}\}) \tag{5}$$

$$OR = \begin{cases} H_s/(H - H_s) \ (AR \ scenarios) \\ 0 \ (otner \ scenarios) \end{cases} \tag{6}$$

Equations (2) – (6) that describe the CCS unit operation are used as the UCM constraints.

In each scenario, the operation of the power and carbon capture systems was characterized, and renewable energy curtailment, CO_2 emissions, fuel consumption, and CO_2 capture and mitigation costs were calculated. A combined FGV-SS option was also tested to search for a cost-optimal option. In addition, sensitivity analysis was performed to assess the robustness of the results, where the model input for renewable plant installation capacity varied.

2.2 Data and assumptions

2.2.1 Hourly wind and PV output potential

To assess the wind energy potential, we considered several grid cells in the Huabei region with a spatial resolution of 1/3° longitude by 1/4° latitude. The wind profile data at 100 m above ground level were obtained from the Global Wind Atlas 3.0[39]. In each grid cell, the hourly capacity factor of the wind turbine was estimated using wind profile data and the power curve of the GE 2.5 MW turbines. We calculated the areas available for wind power exploitation using ArcGIS. Certain areas unsuitable for turbine siting, such as forests, glaciers, water bodies, urban areas, and steeply sloped areas (>20%), were excluded[40]. The density of the wind turbine installations was assumed to be 5 MW/km^2.

The physical potential of the PV system was assessed using the methodology reported by Chen et al.[41]. Solar radiation data were obtained from Version 5 of the Goddard Earth Observing System Forward Processing developed by the Global Modeling and Assimilation Office of the US National Aeronautics and Space Administration[42]. The scale of the PV grid cells was 5/16° longitude × 1/4° latitude, which is consistent with the spatial resolution of the solar radiation data. To estimate the hourly capacity factor, 265 W polysilicon PV modules with a conversion efficiency of 16.2% were adopted. Forests, water bodies, glaciers, steeply sloped areas (>5%), as well as areas with solar radiation less than 1400 kWh/(m2 · a), were considered unsuitable for PV exploitation. The hourly PV output of each grid cell was obtained.

2.2.2 Power demand and unit installation in 2030

Typical daily load profiles and total daily consumption data by province for 2019 were obtained from the National Development and Reform Commission[43]. We used daily total consumption data to scale up typical daily profiles and obtain full-year demand profiles by province. We further scaled the yearly profiles from 2019 to scenarios in 2030, assuming an annual growth rate of 2.7% for power demand[44].

Projections of power plant installation capacity, as well as storage and inter-regional transmission capacity in 2030, were provided by the State Grid Energy Research Institute[6], as detailed in Supplementary Note 2.1. The unit information for thermal power plants in Huabei was derived from the China Electricity Council[45] and the World Resources Institute[46]. One hundred and fifty GW out of the total 370 GW coal-fired power plants were assumed to be CHP units[47].

2.2.3 Environmental and Economic assessment

To calculate fuel consumption and CO_2 emissions, coal-fired power plants were classified into different capacity intervals with varied standard coal consumption for a full-load power supply, ranging from 270 to 291 kgce/kWh (see Supplementary Note 3.1)[45]. The fuel consumption of coal-fired power plants is higher during low-load periods. A heat rate curve was adopted in the fuel consumption calculation to characterize the variation in the coal consumption rate at different load rates (see Supplementary Note 3.2)[48]. The fuel demand of gas-fired units was assumed constant at 199.26 m^3/MWh[49]. The CO_2 emission rates of standard coal and natural gas were 2.457 $kgCO_2$/kgce and 1.885 $kgCO_2/m^3$. The absorption rate of the CCS units (CO_2 mitigated divided by the CO_2 flowing into the units) was assumed to be 90%[16].

The carbon capture costs of the CCS system consist of three parts: investment costs, operation and maintenance (O&M) costs, and fuel costs. In the calculation of investment costs, we assume that the capital costs for CCS units are amortized over their lifetimes:

$$LoanPayment_i = CapitalCost \cdot \frac{r \cdot (1+r)^{\tau}}{(1+r)^{\tau} - 1}, i = 1,2,\dots,\tau \tag{7}$$

where $LoanPayment_i$ is the installation loan payment of the CCS unit in year i. τ is the lifetime of the CCS unit, assumed to be 20 years. r is the interest rate on the annual loan payment, set at 4.3%, which is consistent with the prevailing commercial rates in China[50]. The CCS installation cost of the nonflexible post-combustion CCPP was assumed to be 2700 CNY/kW (372 USD/kW)[51]. Investment costs (CNY/tCO_2) were derived by dividing the annual investment loan payment by the amount of CO_2 captured each year. For the flexible options, we assumed that flexible CCS venting had no significant additional investment costs compared with those of a non-flexible unit, because it is very likely that a normal capture unit can vent flue gas during start-up or shutdown procedures. The flexible CCPP with SS required additional lean and rich sorbent storage tanks, and the flexible CCPP with SS and AR required additional storage tanks and an over-dimensional regeneration system. We considered a 1 Mt/year carbon capture unit as an example and calculated the extra costs for each component in flexible retrofitting. Table 2 presents the results of the study. For instance, flexible retrofitting with 4 h SS or 4 h SS + AR resulted in a 7.8% or 19.8% increase in installation cost, respectively.

Table 2. Installation costs of a 1 Mt/year post-combustion carbon capture system with different flexible and non-flexible options (unit: 10^4 CNY)

	Cost of non-flexible option	Cost of flexible options with 2, 4, and 6 h SS			Scale factor in SS + AR options	Cost of flexible options with 2, 4, and 6 h SS + AR		
		H_s=2h	H_s=4h	H_s=6h		H_s=2h	H_s=4h	H_s=6h
Equipment Costs								
ventilating device	836	836	836	836	0.59	880.84	934.65	1000.40
pump	877	877	877	877	0.59	924.03	980.49	1049.46
packed tower	3883	3883	3883	3883	0.226	3962.77	4058.51	4175.49
storage tank	778	2334	3890	5446		2334	3890	5446
heat exchanger	3886	3886	3886	3886	0.59	4094.41	4344.55	4650.17
CO_2 liquefaction device	10683	10683	10683	10683	1	11654.08	12819.60	14243.64
valve	347	347	347	347	0.59	365.61	387.95	415.24
heating and ventilation device	450	450	450	450	0.59	474.13	503.10	538.49
insulation equipment, water treatment device, and flue	6260	6260	6260	6260	0.59	6595.73	6998.68	7491.01
electrical equipment	2800	2800	2800	2800	0.59	2950.17	3130.40	3350.61
instrumentation and control equipment	930	930	930	930	0.59	979.88	1039.74	1112.88
water equipment	250	250	250	250	0.59	263.41	279.50	299.16
cooling tower	1520	1520	1520	1520	0	1520	1520	1520
Engineering Costs								
process part	1755	1755	1755	1755	0.59	1849.12	1962.09	2100.12
electrical part	220	220	220	220	0.59	231.80	245.96	263.26
instrumentation and control part	30	30	30	30	0.59	31.61	33.54	35.90
heat and water part	60	60	60	60	0.59	63.22	67.08	71.80
cooling tower	135	135	135	135	0	135	135	135
Civil Construction Costs								
main system	2550	2550	2550	2550	0.59	2686.76	2850.90	3051.45
cooling tower system	250	250	250	250	0	250	250	250
Others								
technical service	1200	1200	1200	1200	0	1200	1200	1200
debugging	100	100	100	100	0	100	100	100
project management	200	200	200	200	0	200	200	200
Total cost	40000	41556	43112	44668		43746.57	47931.73	52700.08

Note: The cost of the non-flexible option is from an existing study based on a demonstration carbon capture power plant project[52]. In the SS scenarios, only an extra solvent storage tank is added. In the SS + AR scenarios, besides adding extra storage tanks, regeneration facilities are over-dimensioned. The extra cost of each component (except the solvent storage tank) in the SS + AR options is calculated by multiplying the component cost by the scale factor and the over-dimension rate. The scale factor is the percentage of the value of components that are scaled up for flexibility in SS + AR options, as given by [8]. The calculation of the over-dimension rate is presented in Formula (1) (section 2.1). SS, solvent storage; SS +AR, solvent storage coupling with additional regeneration.

The O&M costs were derived from an existing study based on a demonstration CCPP project, including absorbent charges, water costs, labor costs, and equipment maintenance costs[52]. The equipment maintenance cost scales with flexibility as detailed in Supplementary note 4[8]. The total O&M costs in different scenarios ranged from 58 to 66 CNY/tCO_2 (8 to 9 USD/tCO_2). The fuel costs of the carbon capture system were calculated as follows:

$$FuelCost_x = \sum_{k=coal,gas} \left(m_{k,x} - m_{k,0}\right) \cdot p_k \tag{8}$$

where $FuelCost_x$ is the total annual fuel cost for the CCS units in scenarios x, $m_{k,x}$ and $m_{k,0}$ are the amount of fuel k (k=coal and gas) consumed annually in scenarios x and 0. p_k is the price of fuel k. We considered an industrial coal price of 800 CNY/tce *[700, 900]* (110 USD/tce *[97, 124]*) and an industrial natural gas price of 3.2 CNY/m^3 *[2.2, 4.2]* (0.44 USD/m^3 *[0.30, 0.58]*) [53].

Note that owing to the energy penalty of the CCS units and the additional production of CO_2, the amount of CO_2 reduction is less than the amount of CO_2 captured:

$$Reduced_{CO_2,x} = Captured_{CO_2,x} - Penalty_{CO_2,x} \tag{9}$$

where $Captured_{CO2,x}$ is the amount of CO_2 captured in scenario x, $Reduced_{CO2,x}$ is the net CO_2 reduction in scenario x, and $Penalty_{CO2,x}$ is the CO_2 penalty caused by the additional output of thermal units (compared to the no-CCS scenario) in the CCS-penetrated scenarios. All these values were calculated annually. We define:

$$CCSCost_x = InvestmentCost_x + O\&MCost_x + FuelCost_x \tag{10}$$

$$CaptureCost_{CO_2,x} = \frac{CCSCost_x}{Captured_{CO_2,x}} \tag{11}$$

$$MitigationCost_{CO_2,x} = \frac{CCSCost_x}{Reduced_{CO_2,x}} \tag{12}$$

where $CCSCost_x$ is the annual additional system cost incurred by the CCS units, including the investment, O&M, and fuel costs. In addition to CO_2 capture costs ($CaptureCost_{CO2,x}$) widely investigated in existing studies, we assessed CO_2 mitigation costs ($MitigationCost_{CO2,x}$) in the CCS-penetrated scenarios to evaluate the economics of CO_2 mitigation by CCS and compare it with other options and the carbon price.

3 Results

3.1 Power system operation and curtailment rate

The dispatch and operation of the CCS absorber and stripper for the different scenarios were simulated hourly. Results for January 8 to 14, with a CCS installation rate of 10%, are shown in Fig. 2. An interplay between the flexible CCPP and VRE was observed in flexible CCS scenarios. The net load of electricity (total power demand minus renewable output) in Huabei peaks twice a day, at approximately 9:00 and 21:00, when the electricity demand is high and renewable output is relatively low. Renewable electricity curtailment mainly occurs during the off-peak periods, from 3:00 to 6:00 and 12:00 to 17:00. In the Inflex scenarios, the amount of CO_2 absorbed and stripped each hour depends mainly on the output of the coal-fired power plants; the CO_2 stripped is lower than the CO_2 absorbed because of the 90% absorption rate of the CCS units. In the SS and SS + AR scenarios, CO_2 stripping mainly occurred during off-peak periods, using otherwise curtailed electricity for absorbent regeneration. In the FGV scenarios, CO_2 was stripped as soon as it was absorbed because of the absence of an SS system, whereas CO_2 absorption and stripping reached a low point in the peak-load periods when the flue gas was vented to lower peak demand. The non-heating seasons reflect a similar pattern, although conventional coal-fired power plants have relatively higher operational flexibility than that of the CHP plants, and renewable power curtailment in off-peak periods is lower in the non-heating seasons.

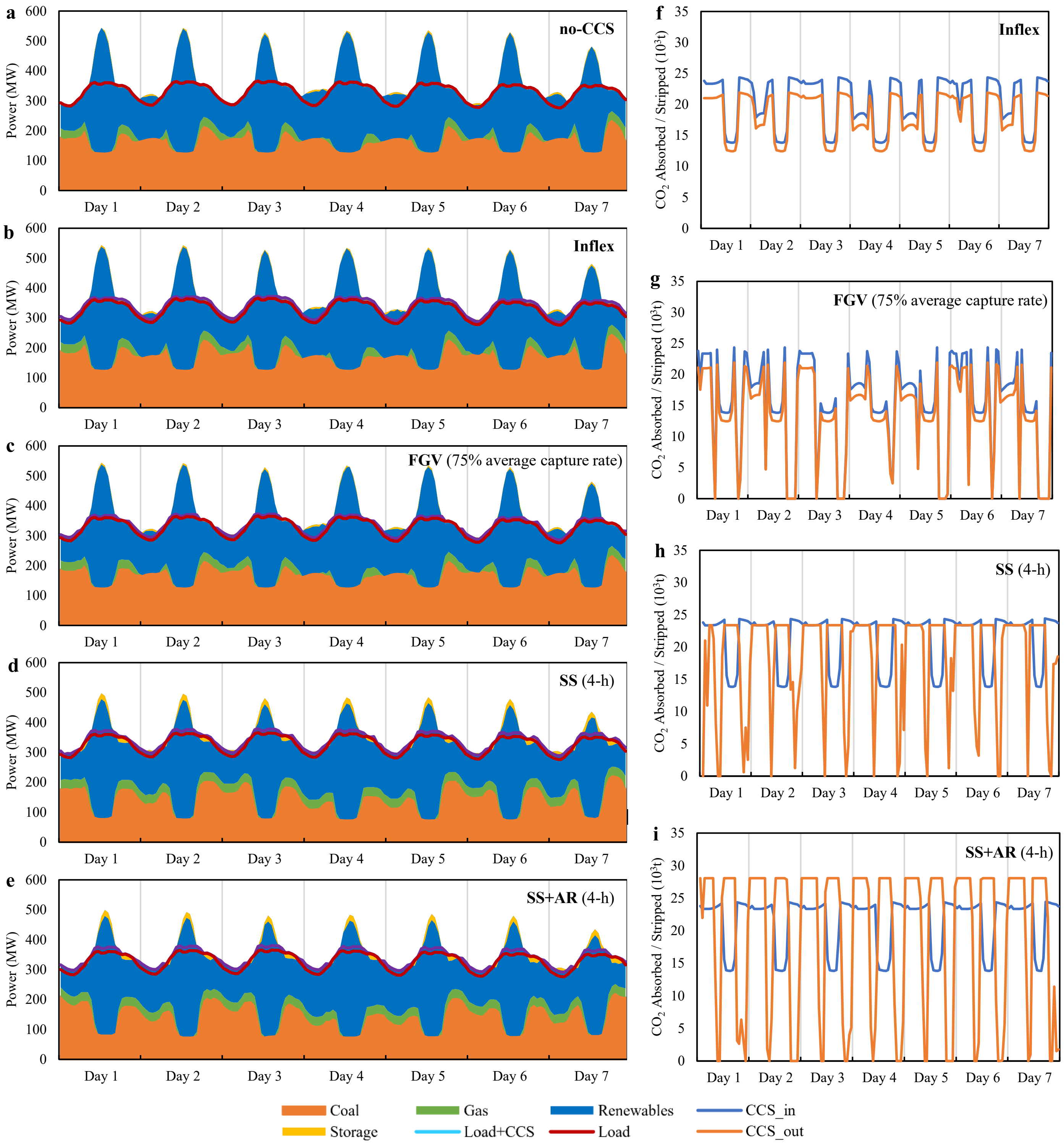


Fig. 2. Hourly dispatches of power generation of the Huabei power system (a–e) and hourly operations of CCS absorber and stripper (f–j) for different scenarios from January 8 to 14, 2030. Inflex (inflexible CCS), FGV (flue gas venting), SS (solvent storage), and SS + AR (solvent storage plus additional regeneration) represent different flexible options of the CCS units. In each scenario with CCS illustrated previously, the CCS installation rate is set at 10%. CCS, carbon capture and storage.

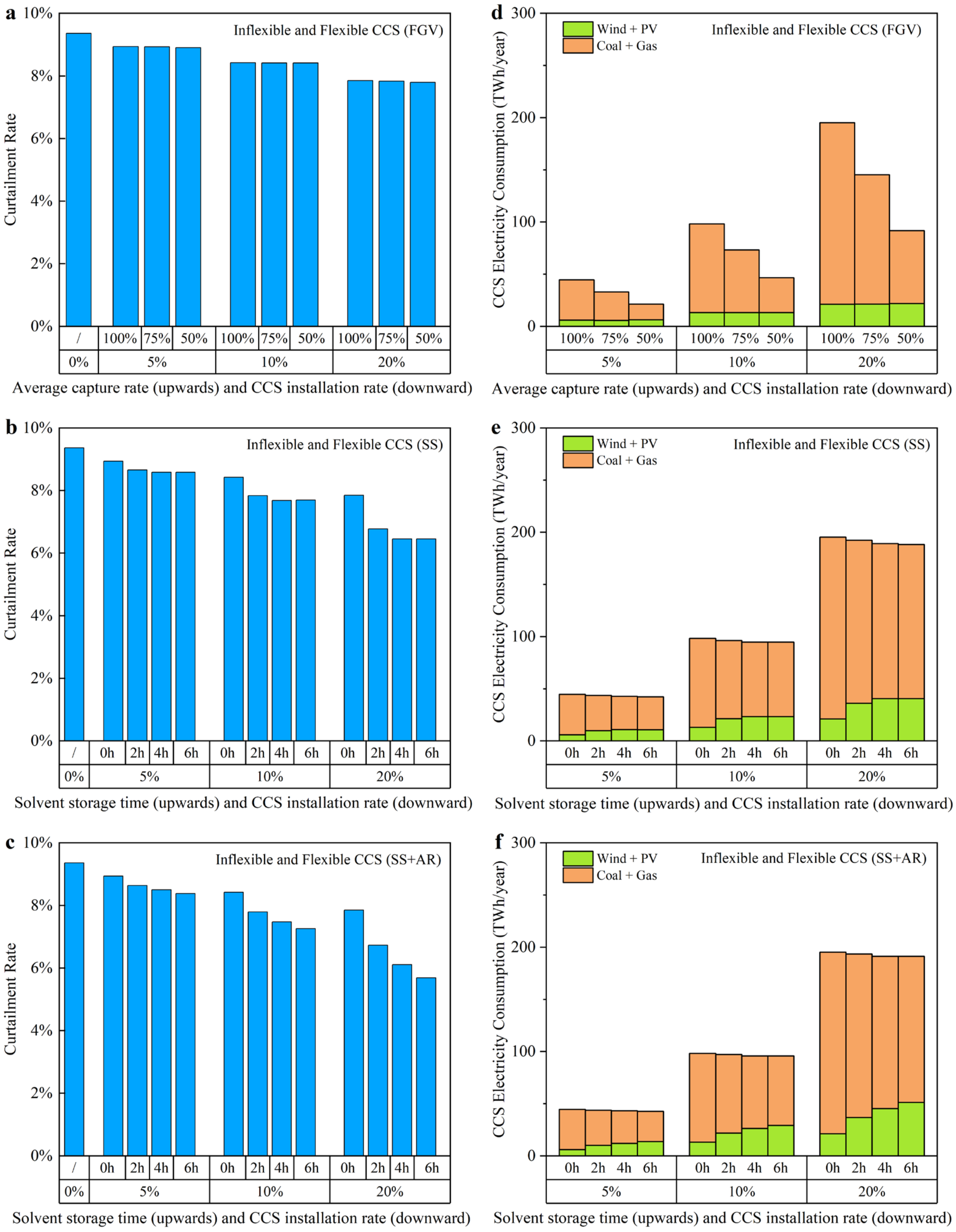


Fig. 3. Wind and PV electricity curtailment rate (a–c) and decomposed CCS electricity consumption (d–f) for different scenarios. The electricity consumption of the CCS units is provided either by the additional output of thermal power plants or by the otherwise curtailed renewable electricity. The additional output of thermal power plants in each scenario with CCS is obtained by subtracting the coal-fired and gas-fired power generation in the no-CCS scenario from that in this scenario. The otherwise curtailed electricity utilized by CCS in each scenario is calculated by subtracting the amount of wind and PV electricity curtailed in the no-CCS scenario from that in this scenario. CCS, carbon capture and storage; FGV, flue gas venting; SS, solvent storage; SS +AR, solvent storage coupling with additional regeneration.

We also found a significant decline in wind and PV curtailment rates in scenarios with a flexible CCPP, as shown in Fig. 3(a–c). Under a 10% CCS installation rate, the fraction of curtailed energy declined from 8.42% in the Inflex scenario to 8.41% in the FGV (75% average capture rate) scenario, 7.68% in the SS (4-h) scenario, and 7.47% in the SS + AR (4-h) scenario. In the scenarios with CCS, the electricity consumption of the CCS units was provided either by the additional output of the thermal power plants or by otherwise curtailed renewable electricity, as illustrated in Fig. 3 (d–f). In the FGV scenarios, the electricity consumption of the CCS units in the peak-load periods was lowered owing to FGV; thus, the additional thermal output in those periods was reduced, whereas electricity consumption remained almost unchanged in the off-peak periods, resulting in a slight reduction in the curtailment rate. In the SS and SS + AR scenarios, the electricity consumption of the CCS units in the off-peak periods was increased to take advantage of the otherwise curtailed wind and PV electricity for CCS regeneration; thus, the curtailment rate was reduced. Compared with that of the SS scenarios, the curtailment rate of renewable electricity decreased more rapidly with an increase in SS time in the SS + AR scenarios, especially from 4-h to 6-h SS. This is because the CCS regeneration facilities in the SS + AR scenarios are over-dimensioned and capable of regenerating more absorbents during off-peak hours. The reduction in the curtailment rate in the SS scenarios with 6-h of SS was limited by the regeneration rate of the CCS units.

3.2 Fuel consumption and CO_2 emission

Based on the aforementioned hourly simulation results, fuel consumption and CO_2 emissions for different scenarios were analyzed. The annual coal and natural gas consumptions of the Huabei power system under different scenarios are illustrated in Fig. 4(a–c). Coal consumption increased as the CCS installation rate increased owing to the energy penalty of the carbon capture system, whereas gas consumption remained almost unchanged. As shown in Fig. 2, as flexible resources, gas-fired units generated electricity in peak-load periods and were shut down in off-peak periods, exhibiting the same trend in different scenarios. Among the three flexibility options, the system-wide coal consumption decreased with an increase in flexibility, taking advantage of its synergies with renewables to reduce the additional output of thermal units, as shown in Fig. 3(d–f).

The annual amount of CO_2 captured, emitted, and CO_2 reduction rate compared with those of the no-CCS scenario are detailed in Fig. 4(d–f). The CO_2 reduction rate increased in the SS and SS + AR scenarios because of the decrease in fuel consumption, whereas more CO_2 was emitted in the FGV scenarios because of the significant

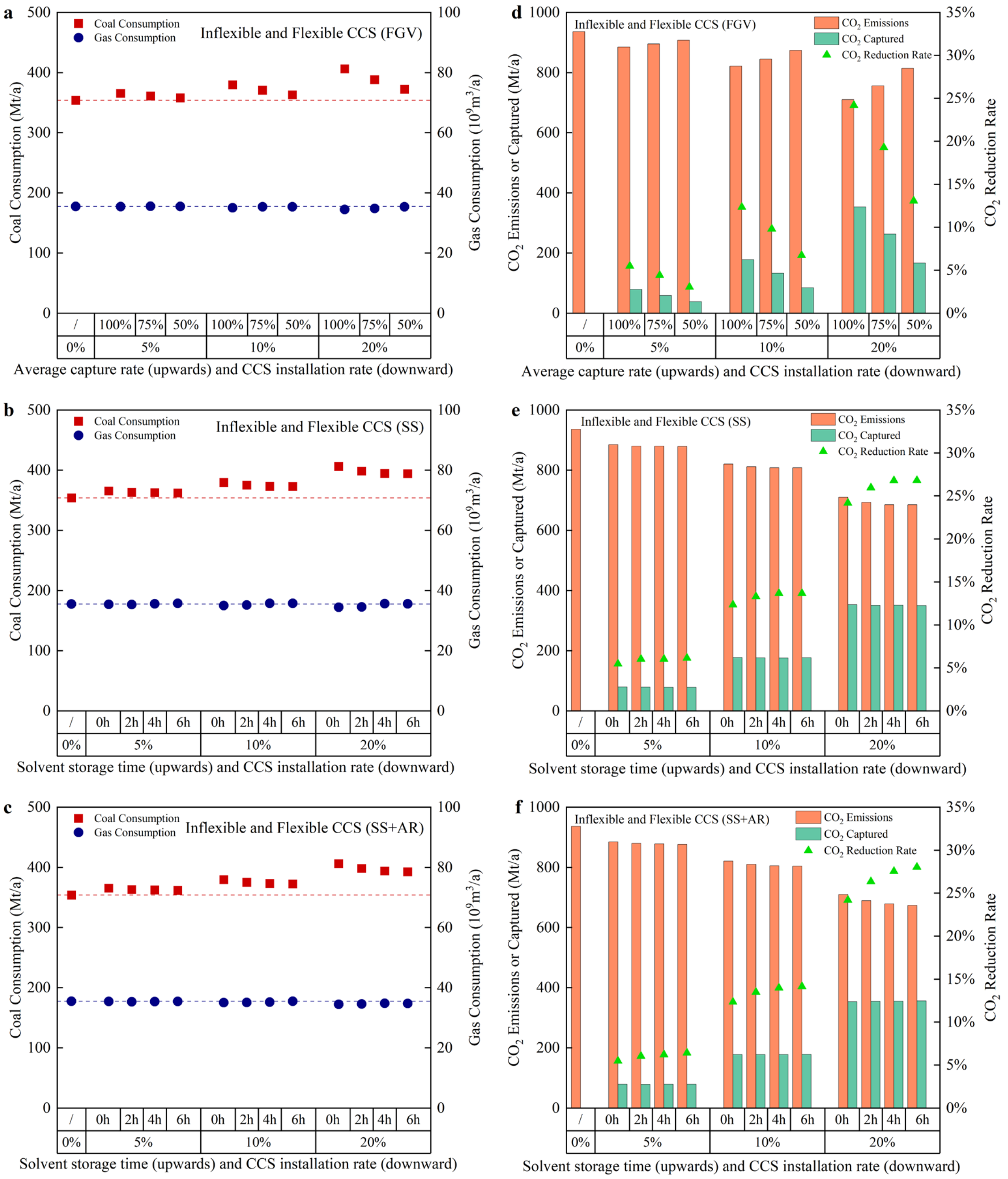


Fig. 4. Fuel consumption (a–c) and CO_2 emission, capture, and reduction rate (d–f) of the entire Huabei power system in different scenarios. CCS, carbon capture and storage; FGV, flue gas venting; SS, solvent storage; SS +AR, solvent storage coupling with additional regeneration.

reduction in CO_2 capture.

The coal energy penalty (additional coal consumption compared with that in the no-CCS scenario) was reduced more rapidly in the FGV scenario than in the SS and SS + AR scenarios. For instance, under a 10% CCS installation rate, the coal energy penalty was reduced by 65.2% in the FGV (50% average capture rate) scenario, 25.6% in the SS (6-h) scenario, and 27.7% in the SS + AR (6-h) scenario compared with those in the Inflex scenario. However, a loss in the CO_2 captured and reduction rate also occurred in the FGV scenario. Under a 10% CCS installation rate, the CO_2 reduction rate decreased from 12.3% in the Inflex scenario to 6.7% in the FGV (50% average capture rate) scenario, whereas it increased to 13.7% in the SS (6-h) scenario and 14.1% in the SS + AR (6-h) scenario. Flexibility retrofitting with SS or SS + AR is more suitable than that with FGV for simultaneously reducing the energy penalty and CO_2 emission.

3.3 CO_2 capture and mitigation costs

The CO_2 capture costs in different scenarios are illustrated in Fig. 5(a–c) and are decomposed into investment, O&M, and fuel costs. Note that CO_2 capture costs are the costs of capturing a unit of CO_2 by the carbon capture system, which do not reflect the system cost of CO_2 mitigation, owing to the energy penalty and additional CO_2 production caused by the CCS system (see Section 2.2.3). Therefore, CO_2 mitigation costs were also calculated and plotted in Fig. 5(d–f), with error bars marking the range of changes caused by fluctuations in coal price ([700,900] CNY/tce, [97, 124] USD/tce) and natural gas price ([2.2, 4.2] CNY/m^3, [0.30, 0.58] USD/m^3).

It is indicated in Fig. 5(a–c) that among the three flexible options, there is a trade-off between the reduction in fuel costs and the increase in investment and O&M costs in the flexible CCS scenarios. On the one hand, fuel costs are reduced due to the reduction of system coal consumption. On the other hand, in the FGV scenarios, CCS investment costs spread to each ton of CO_2 captured increased rapidly owing to the loss of the amount of CO_2 captured, whereas in the SS and SS + AR scenarios, investment costs and O&M costs increased because of the additional construction and maintenance costs of SS and regeneration facilities. Therefore, FGV with a 50% average capture rate and SS or SS + AR with 6-h of SS could become uneconomical compared with that of other scenarios. A similar trend was found for CO_2 mitigation costs among the different scenarios (Fig. 5[d–f]), although they were higher than the CO_2 capture costs owing to the CO_2 penalty of the carbon capture system. The relation between the CO_2 reduction rate and CO_2 mitigation costs for the different scenarios is illustrated in Fig. 6. The flexible options SS and SS + AR reduce CO_2 emissions and mitigation costs simultaneously (except for the 6-h scenarios), whereas FGV reduces CO_2 mitigation costs (except for the 50% scenarios) but increases emissions compared with that of the Inflex scenarios. Scenarios with higher CCS installation rates have significantly higher CO_2 reduction potential. However, CO_2 mitigation costs also increased, mainly because of the higher proportion of thermal electricity in CCS energy consumption (Fig. 3[d–f]) and, consequently, a higher energy penalty.

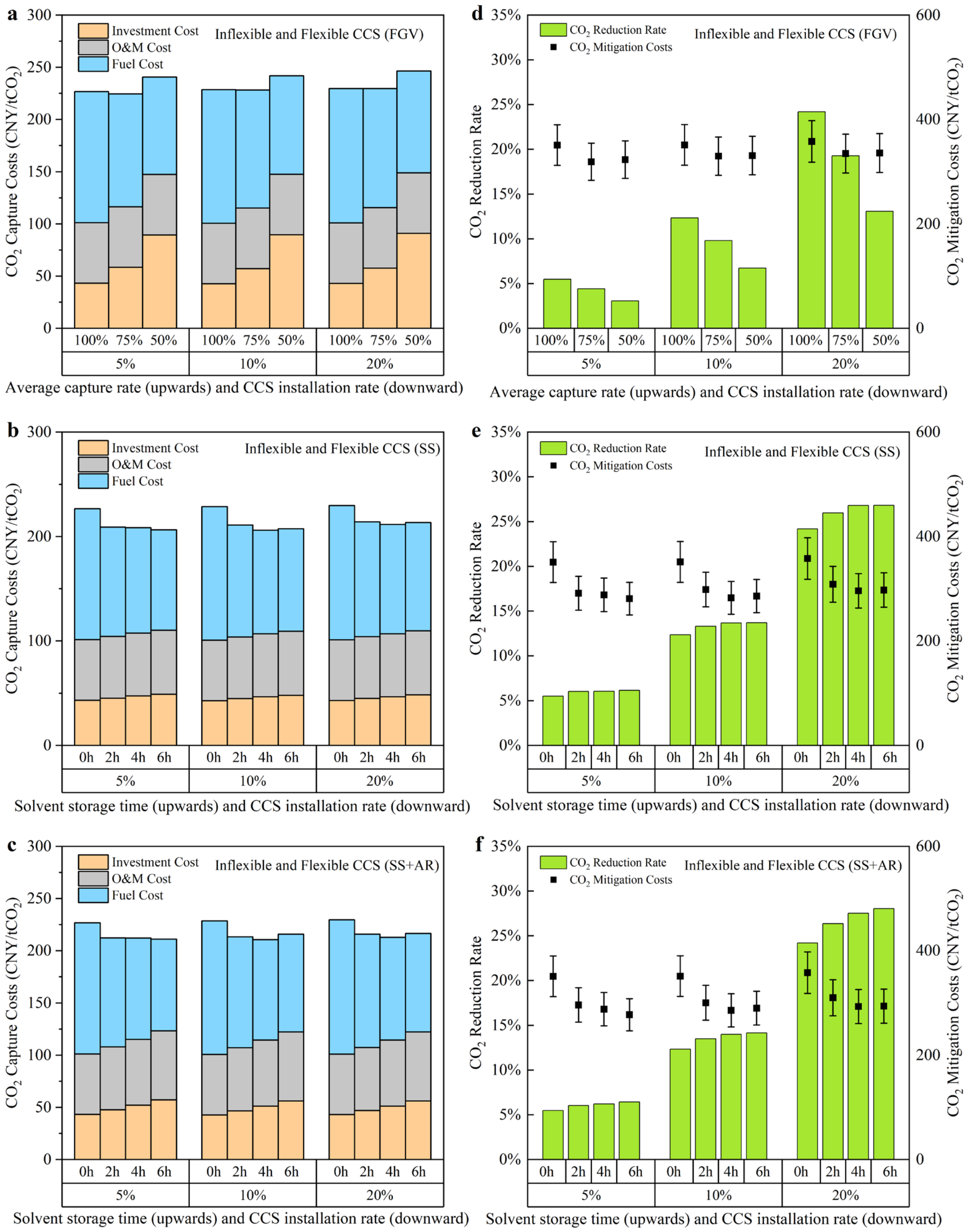


Fig. 5. CO$_2$ capture costs and CO$_2$ mitigation costs in different scenarios. CO$_2$ capture costs and CO$_2$ mitigation costs are derived from dividing additional system costs by the amount of CO$_2$ captured or reduced, respectively, as detailed in section 2.2.3. The error bars mark the range of changes in CO$_2$ mitigation costs caused by fluctuations in coal price ([700,900] CNY/tce, [97, 124] USD/tce) and natural gas price ([2.2, 4.2] CNY/m^3, [0.30, 0.58] USD/m^3). CCS, carbon capture and storage; FGV, flue gas venting; SS, solvent storage; SS +AR, solvent storage coupling with additional regeneration.

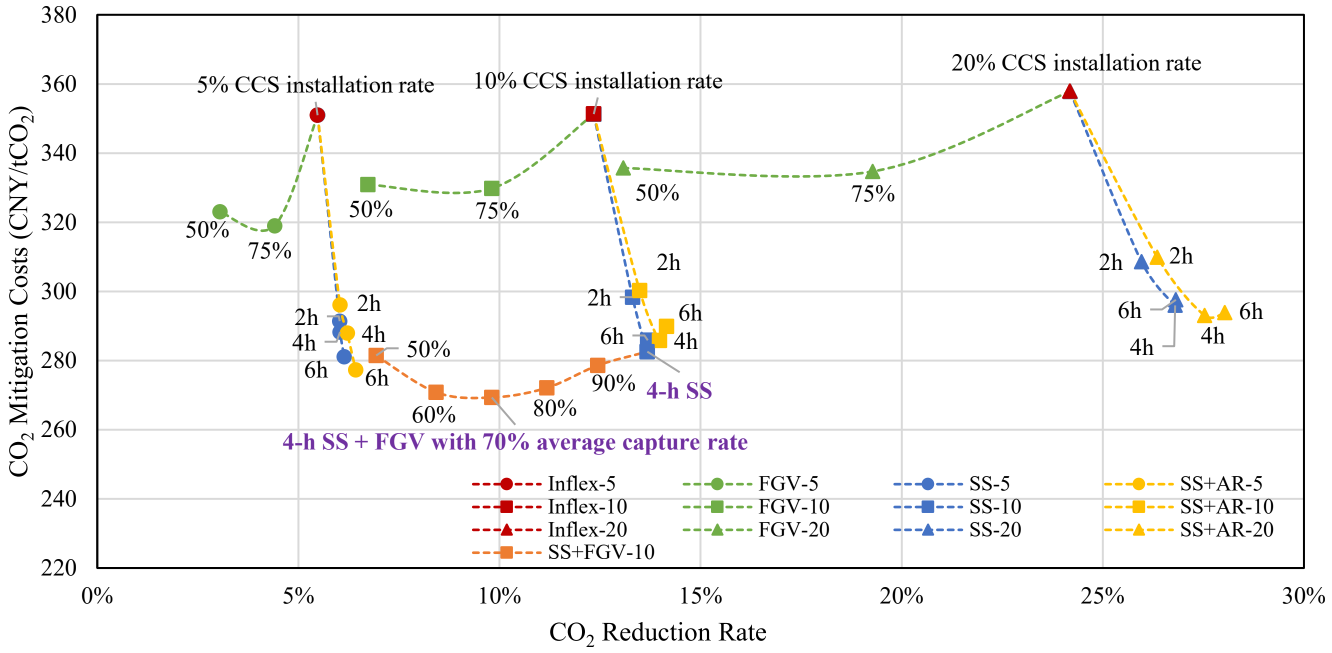


Fig. 6. CO$_2$ reduction rates and CO$_2$ mitigation costs in different scenarios. Colors refer to different flexible options (Inflex, FGV, SS, and SS + AR), and symbols (○, △, and △) refer to different CCS installation rates (5%, 10%, and 20%). The combined SS-FGV-10 scenario has a 10% CCS installation rate and 4-h solvent storage and varies CO$_2$ capture rates. CCS, carbon capture and storage; FGV, flue gas venting; SS, solvent storage; SS +AR, solvent storage coupling with additional regeneration.

Under a 10% CCS installation rate, employing a 4-h SS system would realize the lowest costs for CO$_2$ capture of 206 CNY/tCO$_2$ (28 USD/tCO$_2$), which is 9.9% lower than that in the Inflex scenario. The lowest CO$_2$ mitigation cost of 283 CNY/tCO$_2$ (39 USD/tCO$_2$) was also realized with this flexible option, a reduction of 19.6% compared with that in the Inflex scenario. The SS + AR scenarios could further reduce fuel consumption, but the reduction in fuel costs was insufficient to recover the additional costs for regeneration facility expansion; therefore, they become less economical than the SS scenarios. In the FGV scenarios, the investment costs increased rapidly with a decrease in the CO$_2$ capture rate. As a result, the CO$_2$ capture costs in the FGV scenarios with a 75% average capture rate were only slightly lower than those in the Inflex scenarios.

3.4 Combined FGV-SS scenarios

In the previous sections, carbon capture units with different flexible strategies, including FGV, SS, and SS + AR, were analyzed and compared. This raises the question: what is the optimal flexible strategy with the lowest CO$_2$ mitigation costs? As indicated in Section 3.3, the SS strategy was more cost-effective than the SS + AR strategy, and under a 10% CCS installation rate, the lowest CO$_2$ mitigation cost was realized in the scenario with 4-h of SS. A cost-declining trend was also observed in the FGV scenarios. If the SS strategy is combined with FGV, a lower CO_2 mitigation cost may be realized. Therefore, we tested a series of combined SS-FGV scenarios under a 10% installation rate, with a 4-h SS time and an average CO_2 capture rate ranging from 50% to 100%, the results of which are illustrated in Fig. 6 (orange line and dots).

As shown in Fig. 6, CO_2 mitigation costs could decline with the introduction of FGV, indicating a synergy between the SS and FGV strategies. In the combined SS-FGV scenarios, the carbon capture system can take advantage of the otherwise curtailed renewable electricity in off-peak periods to reduce electricity costs. Meanwhile, the peak electricity load of the system is reduced because of FGV during peak-load periods, which further reduces the system fuel consumption and energy penalty of the CCS units. However, an increasing trend in CCS investment costs also occurs with a decrease in the average capture rate in scenarios with FGV, owing to the loss of the amount of CO_2 captured in the lifespan of the CCS units. With a 10% CCS installation rate, an optimal CO_2 mitigation cost of 269 CNY/tCO_2 (37 USD/tCO_2) was realized in the scenario with 4-h of SS and a 70% average capture rate. The CO_2 reduction rate in this scenario was 9.8%, which was significantly lower than that in the SS scenario without FGV.

4 Discussion

The flexible operation of CCPP has been suggested as a cost-effective measure to decarbonize power systems with increasing VRE penetration. Under a CCS installation rate of 10%, the CO_2 capture and mitigation costs estimated in this study were 229 and 351 CNY/tCO_2 (32 and 48 USD/tCO_2) in the non-flexible scenario and 210 and 269 CNY/tCO_2 (29 and 37 USD/tCO_2) in the cost-optimal scenario (flexible CCS with 4-h SS and 70% average capture rate). We compared the results with those of existing studies (see Table 3), which indicate that various factors may influence the cost estimation of CCS. First, only the carbon capture process was considered. After capture, CO_2 is transported through pipelines and stored or utilized via different methods, including CO_2-enhanced crude oil recovery and CO_2-enhanced water recovery with saline aquifer storage. Levelized costs of CO_2 pipeline transportation range from 0.15 to 0.5 CNY/t · km (0.02 to 0.07 USD/t · km), which are 22.5 to 75 CNY/t (3 to 10 USD/t) if transporting 150 km on average[36], while levelized costs of CO_2 utilization and storage process are highly uncertain, depending on the actual condition of the project. Regardless of the transportation, utilization, and storage processes, the cost estimation of CCS in this study was lower than that in other studies. Second, incentive policies would significantly affect CCS costs. For instance, Lockwood[54] assumed a higher load factor (75%) for a CCPP with a degree of priority dispatch, and the estimated CO_2 mitigation cost was 215 CNY/t (30 USD/tCO_2). The selection of the capture technique, location, and year of retrofitting also influences the estimation of CO_2 capture and mitigation costs.

Table 3. Estimation of CO_2 capture and mitigation costs in China in existing studies (unit: CNY/t CO_2)

Institute or authors	Ref.	CO_2 capture costs	CO_2 mitigation costs	Notes
This study		228	351	Non-flexible scenario, 10% CCS installation rate in 2030
This study		210	269	4 h SS + FGV (70%), 10% CCS installation rate in 2030
Huang et al.	[55]	220		2030 projection
Wei et al.	[36]	210–350		
Rubin et al.	[56]	283	387	Estimation of 2015
IEA	[57]	380–420		Global projection of 2030

IPCC	[58]	441	616	Global estimation of 2017
Toby Lockwood	[54]	165	215	Beyond 2025, with subsidies and other incentives, utilization and storage not considered
Wang et al.	[37]		483	Utilization and storage considered
Global CCS Institute	[59]		420	2017 estimation

CCS, carbon capture and storage; FGV, flue gas venting; SS, solvent storage.

Sensitivity tests on the installation capacity, fuel price, CCS unit lifetime, and interest rate were conducted to assess their influences on emissions and cost estimations, as detailed in Supplementary Note 5. The wind and solar PV installation capacities in this study were 230 and 350 GW, respectively, and they were scaled up (down) to 75%, 125%, and 150%, respectively, in the sensitivity test. The results suggest that CO_2 capture and mitigation costs are significantly reduced in the 125% RE and 150% RE scenarios, and the CO_2 reduction rate is increased, mainly because of the higher proportion of otherwise curtailed renewable electricity in the total CCS electricity consumption and the lower energy penalty. These results suggest a further reduction in flexible CCS costs for future power systems with a higher proportion of renewables. With varied fuel price (coal: [700, 900] CNY/tce ([97, 124] USD/tce), natural gas price: [2.2, 4.2] CNY/m^3 ([0.30, 0.58] USD/m^3)), CCS unit lifetime ([15, 25] years) and interest rate ([3.3%, 5.3%]), CO_2 mitigation costs range from 239 to 299 CNY/t (33 to 41 USD/t). However, under a 10% CCS installation rate, the cost-optimal situation still occurred in the combined 4-h SS and FGV (70% average capture rate) scenario.

To the best of the authors' knowledge, this is the first attempt to investigate the synergies between flexibly operated CCPP and variable renewable energy in largescale regional power systems. We conclude that a flexibly operated CCS can take advantage of otherwise-curtailed renewable electricity during off-peak periods, thereby reducing its energy penalty and saving costs. Regional power systems also benefit from lower renewable energy curtailment rates and higher operational flexibility. Based on the aforementioned results, we recommend flexible CCS as a cost-effective and environmentally friendly carbon removal strategy for power system decarbonization. However, we admit that, although significantly lower than the non-flexible scenarios, the CO_2 mitigation cost in the cost-optimal scenario is still much higher than that of other carbon mitigation strategies, including installing wind and solar PV generators (estimated 43–194 CNY/t (6 to 27 USD/t)[60, 61]). The CO_2 mitigation cost is also higher than the carbon price in Chinas current carbon market (approximately 60–70 CNY/t (8–10 USD/t)), which hinders the largescale utilization of flexible CCS. However, the marginal carbon abatement cost for renewable energy will increase with higher wind and PV penetration rates in future power systems because of the challenge of power system flexibility and a significantly higher curtailment rate[32, 60]. Therefore, carbon dioxide removal technology is an important strategy for the deep decarbonization of future power systems[32], and flexible CCS with a relatively low cost has positive prospects for future applications. To realize the potential benefits of flexible CCS, various efforts should be undertaken in the coming decades. For instance, certain incentives, including subsidies and tax reductions, will be beneficial for the early-stage deployment of flexible CCPPs. The optimal operation of a flexible CCPP should also be introduced to realize lower operating costs through the interplay between flexible CCPPs and variable renewables. Continued efforts should be made to carry out technological innovations in flexible CCS to further reduce costs.

Concerning the practical deployment and operation of CCS, we recommend installing flexible CCS with FGV and SS and operating in partial capture mode in the short term to realize the lowest carbon mitigation cost. This is beneficial for short-term deployment, which is mainly limited by its relatively high carbon mitigation cost. In the long-term, with stricter carbon emission constraints, flexible CCS units could adopt SS as the main flexible strategy and operate in full capture mode. Flexible CCS can play an important role both in carbon mitigation and in providing power system flexibility. Above all, there are opportunities for near-term CCS deployment with the flexibility to increase carbon stringency over time.

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