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Financing coal-fired power plant to demonstrate CCS (Carbon Capture and Storage) through an innovative policy incentive in China

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Abstract:	Traditional policy incentives for carbon capture and storage (CCS) mainly rely on fiscal subsidies, which tend to put an inordinate strain on public finances. This study attempts to explore a non-fiscal incentive policy, granting a time extension (extra electricity quota), to finance early CCS demonstration projects in China. We find that coal-fired power plant (CFPP) operate at a loss even without CCS retrofitting under the current electricity quota (4000 hours per year), while it can make profits with CCS retrofitting if extra electricity quotas are provided. Specifically, the electricity quota needs to be roughly 4709 to 7260 hours per year with the CO_2 capture level ranging from 0.1 to 1 Mt per year in the demonstration stage. In particular, the levelized cost of electricity (LCOE) of CFPP with a capture level of 1 Mt per year is estimated at 298.8 CNY/MWh if the electricity quota reaches 7000 hours per year, which is approximately equal to that of CFPP without CCS retrofitting and extra electricity quota (292.2 CNY/MWh). Thus, the extra electricity quota can be considered as an economically feasible policy incentive, and related results are able to provide useful information for electric power enterprises and government decision-makers.
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Highlights

- Extra electricity quota is proposed as a incentives mechanism for CCS project.
- The NPV and LCOE are estimated under different electricity quotas.
- Carbon trading can reduce the power generation cost to some extent.
- The critical conditions are discussed in various scenarios.
- The effects of changes in parameters are estimated through sensitivity analysis.

Dear Editors:

We would like to submit the revised manuscript entitled "**Financing coal-fired power plant to demonstrate CCS (Carbon Capture and Storage) through an innovative policy incentive in China**", which we wish to be considered for publication in "***Energy Policy***".

Follow the reviews comments, we have tried out best to address those issues last time, while we made a mistake to upload the unmodified version. We have further revised the manuscript this time and upload the latest revision.

We deeply appreciate your consideration of our revised manuscript, and we look forward to receiving comments from the reviewers. If you have any queries, please don't hesitate to contact me at the address below.

Thank you and best regards.

Yours sincerely,

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Response document

Title: Financing coal-fired power plant to demonstrate CCS (Carbon Capture and Storage) through an innovative policy incentive in China

Subject: Minor Revisions requested JEPO-D-20-02558R2

Response to editor	
Editor's advice	**Authors' response**
Reviewers have now commented on your paper. They see merit in your work, but they advise that you make some minor revisions to your manuscript. Accordingly, you are invited to undertake a minor revision following the recommendations shown in the report appended below.	Thank you very much. We appreciate the opportunity to further revise and improve our paper. As you will see, we have taken every effort to address the concerns raised by the review team. Please read our point-by-point response to the comments of the reviewers for the details.
Responses to the comments from Reviewer #1	
Reviewer1's advice	**Authors' response**
I think the concerns and suggestions have been satisfactorily addressed in the revision.	Thank you for your time spent in reading our paper. We are very happy to hear your positive feedback.
Responses to the comments from Reviewer #2	
Reviewer2's advice	**Authors' response**
The authors have tried hard to deal with the comments provided by reviewers, in part directly and in part through broadening the scope of their references. I applaud their efforts to do so.	We would like to thank you for your time spent in reading our paper and providing further constructive comments to help us improve the paper. We have tried to address those issues and below are the point-

	by-point responses.
Comments <1>: For the most part I am satisfied that their article is publishable in Energy Policy. But I still have some nagging doubts about some of what they say. In my earlier comments I raised question about the incremental pollution that would occur if constraints on coal plant output were relaxed, yet I did not see anything new to address that.	Thank you for your helpful comment. Follow your suggestion, we have further explained this issue. Actually in China, most of the power plants in service are mainly supercritical and ultra-supercritical units which adopt new intelligent equipment and have great improvement in energy consumption, environment and efficiency. Meanwhile, the old power plants with high energy consumption, heavy pollution and low capacity are nearing their operational life. Therefore, the pollution sources are reduced to a large extent. In terms of the operational process, mature technologies, including desulfurization, denitrification and low nitrogen combustion procedures. have been widely applied to power plants in China. In addition, carbon capture device can effectively prevent greenhouse gases from entering the atmosphere in the first place, moreover, some scholars have proposed that this technology has synergistic mitigation effect. Given the above, incremental pollution would not occur if constraints on advanced coal plant were relaxed.
Comments <2>: Further, the authors' proposed expansion of coal fired plants' outputs if they adopt carbon capture must come at the expense of someone else, yet I don't see reference to whose output would be curtailed and what	Thank you for your helpful comment. Follow your suggestion, we have further explained this issue. As you mentioned, the application of CCS does come at an expense of reducing the efficiency of power generation. Given the efficiency of

costs that might have on investment in such other plants.	generation will decrease to some extent, we advocate gaining more generation quota to make up for the loss. Furthermore, we have explained that the electricity quotas are allocated by the local government. Hence, reallocating electricity quotas is even conductive to reducing pollution emissions due to power plant with advanced technologies gaining more quotas while power plant with backward technologies gaining less quotas. Additionally, we suggest the CFPP with CCS retrofitting should be given priority in peak load regulation of the electricity grid to get the extra electricity quota, especially summer peak consumption season.
Comments <3>: Admittedly I am not fully versed on the institutional settings in which investments in Chinese power plants are made, but if I were a planner there I'd insist on full answers to these questions.	Thank you for your helpful comment. Follow your suggestion, we have further explained this issue. At present, China has proposed to realize carbon peak by 2030 and carbon neutral by 2060. Although some policies have decided to eliminate, suspend construction and alleviate more than 50 million kilowatts of coal generation capacity, thermal power has always been playing a decisive role in China's power system in light of the energy structure, installed capacity, power supply capacity, scheduling characteristics and economy. Moreover, CCS is an important technological means of emission reduction to ensure the continuous service of coal-fired power plants. Therefore, the investment incentive for deploying CCS retrofitting projects for coal-fired power plants has important practical

	significance.
Comments <4>: As it is, the article leaves the impression that any expansion of criteria pollutants such as sulfur dioxide or particulates would be minimal, and that any output impact from relaxing quotas on carbon capture coal plants implicitly occurs at other coal plants, further incentivizing the owners of these laggard coal plants to get into the carbon capture game.	Thank you for your helpful comment. Follow your suggestion, we have further explained this point. Pollution levels will decrease with technological innovation and equipment upgrades. In the near future, the line matching power supply will also develop rapidly with the key promotion of UHV (ultra-high voltage) engineering. Meanwhile, the foundation of new coal power industry will usher in a peak, so that the establishment of coal power capacity and electricity quota compensation mechanism will also receive more and more attention. At the same time, the development of carbon capture technology has further accelerated the commercialization process of CCS retrofitting of coal-fired power plants, and the policy incentive and subsidy mechanism has promoted the modern coal power industry to achieve carbon neutrality. Based on the above, granting a time extension (extra electricity quota) is able to finance early CCS demonstration projects in China and incentive the coal-fired power plant to implement CCUS retrofitting to some extent.
Overall I'd like the authors to address these questions more than they do, but in any case the article is publishable in my view.	Thank you very much for your efficient work in processing our manuscript. Following your suggestions, we have carefully made corresponding explanations and improvements. In the future, we will

	continue to conduct more in-depth research to make up for the deficiency of this paper.

Financing coal-fired power plant to demonstrate CCS (Carbon Capture and Storage) through an innovative policy incentive in China

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Abstract: Traditional policy incentives for carbon capture and storage (CCS) mainly rely on fiscal subsidies, which tend to put an inordinate strain on public finances. This study attempts to explore a non-fiscal incentive policy, granting a time extension (extra electricity quota), to finance early CCS demonstration projects in China. We find that coal-fired power plant (CFPP) operate at a loss even without CCS retrofitting under the current electricity quota (4000 hours

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per year), while it can make profits with CCS retrofitting if extra electricity quotas are provided. Specifically, the electricity quota needs to be roughly 4709 to 7260 hours per year with the CO_2 capture level ranging from 0.1 to 1 Mt per year in the demonstration stage. In particular, the levelized cost of electricity (LCOE) of CFPP with a capture level of 1 Mt per year is estimated at 298.8 CNY/MWh if the electricity quota reaches 7000 hours per year, which is approximately equal to that of CFPP without CCS retrofitting and extra electricity quota (292.2 CNY/MWh). Thus, the extra electricity quota can be considered as an economically feasible policy incentive, and related results are able to provide useful information for electric power enterprises and government decision-makers.

Keywords: CCS; Financing; Policy incentive; Electricity quota; LCOE

1. Introduction

The 2015 Conference of the Parties (COP 21) approved the Paris Agreement and agreed to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels"(UNFCCC, 2017). Currently, achieving "carbon neutrality" as soon as possible is a consensus reached by the international community in addressing climate change. In 2020, President Xi Jinping proposed the vision of China striving to reach a peak in carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 at the 75th session of the United Nations General Assembly, and also emphasized the importance of the implementation of this goal in important conferences at home and abroad. The establishment of carbon neutral target points out a new direction for China's low-carbon development and raises new requirements on technological innovation. With the large amount and high intensity of total carbon emissions, China has a shorter cycle to achieve the carbon neutrality objective. Considering the shortcomings of existing technologies, more efforts should be devoted to zero carbon and negative emission technologies that can achieve deep emission reduction. According to IEA (2017, 2020a), carbon capture and storage (CCS), which comprises various options to capture CO_2, and then pressurize and transport it to a geological location for permanent storage, is an essential component of the portfolio of low-carbon technologies available to combat climate change, with a contribution of 14% cut in global carbon emissions by 2060 to the Paris Agreement climate change target. Almost all countries will fail to meet their net-zero emissions targets, and the global cost of reducing emissions will rise by 138% without CCS technology (IEA, 2020b). In the wake of the announcement, *Nature* also explores several proposals for how China could reach neutrality before 2060, indicating that China must first begin to generate most of its electricity from zero-emission sources through CCS technologies in addition to renewable energy (Mallapaty, 2020). At present, about 80% of the global primary energy supply still comes from fossil energy, and trillions of dollars have been sunk into the fossil infrastructure. In this context, CCS appears to help provide a bridge to shift from a fossil fuel-based economy to a sustainable development mode (Praetorius and Schumacher, 2009; Lund and Mathiesen, 2012; Yang et al., 2019; Mikulčić et al., 2019).

Nowadays, China has become the world's largest energy consumer and carbon emitter as a consequence of its coal-dominated energy structure and high-speed economic growth. Electric generation accounts for approximately 50% of the total coal consumption in China, resulting in more than 40% of China's total carbon emissions (Yuan et al., 2018; Yan et al., 2019). Moreover, the demand for electricity consumption will definitely maintain a stable rate of growth owing to accelerated industrialization and urbanization as well as a rising standard of living (Li et al., 2014; Song et al., 2018; Zhang et al., 2019; Tao et al., 2019). Looking forward, projections indicate that thermal power generation is still likely to account for 50% of China's total power generation in 2030 (NDRC, 2017), and coal power capacity is expected to exceed 1100 GW by 2020 and 1350 GW by 2030 (Wang and Wu, 2015). Undoubtedly, CCS is an inevitable technology option for China's electricity generation sector to reduce carbon emissions before renewable energy dominates the energy structure (Zhou et al., 2010; Renner, 2014; Hu and Zhai, 2017; Yang et al., 2019; Lin and Tan, 2021). Many Chinese scholar have pointed out CCS is an indispensable part of technology portfolio for China's goal to achieve carbon neutral (Zhang, 2020; Wang and Zhang, 2021; Liu et al., 2021; Zhang et al., 2021; Xu et al., 2021). Meanwhile, the Chinese government also attaches great importance to the role of CCS in reducing carbon emissions. The recently promulgated 14th

Five-Year Plan of the People's Republic of China explicitly proposes to carry out demonstration of major CCS projects as soon as possible, which is the first time that CCS technology is incorporated into the five-year plan.

According to the IPCC Fifth Assessment Report released by the IPCC in 2018, it is necessary to reduce emissions by 70%-95% from 2010 levels by 2050 to limit the warming to 1.5 ° C (Jiang et al., 2019). Moreover, the IEA (2017) points out that CCS will contribute 32% of the total emission reductions through 2050 in the 1.5 °C scenario (1.5DS) and 14% in the 2 °C scenario (2DS). In China, at least 185 GW of installed coal-fired power capacity should be retrofitted by 2035 and the contribution of CCS-related emissions reductions should reach 50% by 2050 (IEA, 2013, 2017), and the annual emissions reduction should reach at least 1 billion tons accordingly (ACCA21, 2019). Thus, CCS technology is of great significance for China to achieve its mitigation target, and it is currently vital to accelerate CCS demonstration projects in the power generation sector(Viebahn et al., 2015; Zhu et al., 2015; Hu and Zhai, 2017; Yu et al., 2019).

However, the progress in CCS technology is far from large scale commercialization and falls short of the expected demand for achieving targeted emissions abatement (Vinca et al., 2018; Durmaz, 2018). There are many potential barriers preventing the wider implementation of CCS, while the high cost has been previously identified as a major barrier to its adoption (Budinis et al., 2018). The CCS installation could only be considered if it was profitable for the whole value chain from the energy companies' point-of-view (Zhou et al., 2010). Moreover, most of the previous studies have emphasized that CCS is too costly to be commercially viable, and governments have largely failed to offer robust policies to support its development (Duan et al., 2013; Eide et al., 2014; Garðarsdóttir et al., 2018; Yang et al., 2019). As Durmaz (2018) noted, CCS technology has been facing ‘first-of-its-kind’ cost risks, and the solution lies in effective financing through joint efforts and coordinating the functions of the various parties.

A great many of studies have focused on feasible technology options for cost reductions, such as chemical-looping (Jin et al., 2010), and optimizing the steam system (Botros and Brisson, 2011). Even so, auxiliary measures related to market forces and policy support are still indispensable at its initial development stage, among which carbon trading (Zhang et al., 2014; Mo et al., 2015; Ağralı et al., 2018; Morris et al., 2019) and fiscal subsidies (Chen et al., 2016; Yang et al., 2019; Yao et al., 2020) seem to be gaining widespread attention. Nonetheless, it has been proved that there is a large gap between the high abatement costs and low carbon credit prices, and the fluctuating prices make a clear and direct signal more difficult to achieve more income from the CCS investment, thus easily leading to skepticism about a CCS investment (Walsh et al., 2014). Moreover, the entities with CCS retrofitting have not been incorporated into the carbon trading scheme in China in view of unpredictable shocks they might inflict on the immature carbon market (Yang et al., 2019). In contrast, subsidies are a clear policy signal that can offset the generating costs of the power plants directly and reduce investment risks (Chen et al.m 2016). Nevertheless, considering the much larger amount of electricity generated by coal power plants compared to renewable power plants, providing similar subsidies could bring a great financial burden (Chen et al., 2016). Besides, according to China’s energy development strategy (2014-2020), the subsidy for renewable energy will be gradually reduced in 2020. In consequence, fiscal subsidy, presumably, cannot be regarded as a viable long-term strategy.

From the above, it can be seen that there is an urgent need for economically feasible financing support within a consistent policy and regulatory framework. This work attempts to explore a new subsidy incentive mechanism, i.e. granting time extension (extra electricity quota), to motivate CFPP to conduct CCS demonstration. This is mainly based on China's actual situation where the power grid dispatch obeys the principle of "dispatch centrally, manage by classification". In other words, the power grid dispatch is the core of safe electricity production and management in China, and thus the running time for each power plant is assigned by the power regulatory institutions. Since 2005, the Chinese government has engaged in an ambitious effort to move China's energy system away from coal and towards more environmentally friendly sources of energy. However, China's investment in coal power has accelerated sharply in recent years, raising concerns of massive overcapacity. The main reasons include the uncontrolled construction of new coal generation and the drastic fluctuation of power demand, as well as the low price of coal. The overcapacity situation of thermal power can be directly reflected by the index of utilization hour. As shown in Fig.1, the average running time for all types of power-generation equipment declined significantly since 2005, reaching 3825 hours per year in 2019. Among them, thermal power plant operated with 4293 hours per year in 2019, which is well below that in developed countries. Currently, a large number of coal-fired units staying in idle state and the number of utilization hour decreasing significantly (Yuan et al., 2017; Zeng et al., 2017; Yu et al., 2018; Lin et al., 2018). Although the Chinese government decides to eliminate, stop and ease more than 50 million kilowatts of the coal generation capacity in the 13th five-year planning period, thermal power has been undoubtedly playing a fundamental role in China's electric power system for decades from the perspectives of installed capacity, power generation, scheduling characteristic and economical efficiency. Therefore, CCS will be a vital mitigation tool for the continued serving coal-fired power plants. In this paper, we estimate the levelized cost of electricity (LCOE) and investment revenue to investigate how much extra electricity quota is needed to trigger immediate CCS investment. In order to better simulate the current CCS investment environment in China, this paper uses the latest technological and market data from real CCS demonstration projects in China's power sector.

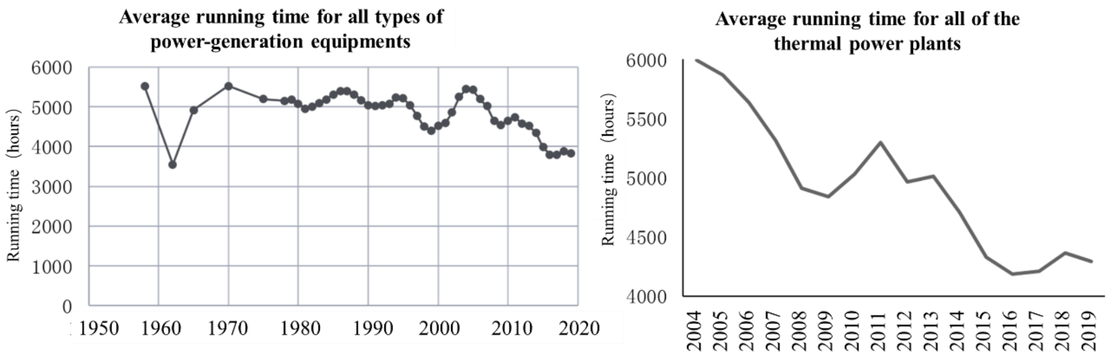

Fig.1. Running time for the power-generation equipment in China.

The remainder of this paper proceeds as follows. Section 2 summarizes the existing financing strategies of CCS projects around the world. Section 3 introduces the basic assumptions and model used in this study. Section 4 presents related data and scenario setting. Section 5 shows the main results and discussion. Finally, Section 6 concludes this study and puts forward some policy proposals.

2. The current financing supports for CCS project

The existing literature tackles the issue of CCS-related financing strategies, as shown in Table 1. We categorize them four ways: government support, market pull, technical advancement and industrial chain.

Undoubtedly, CCS technology is not regarded as a viable abatement option without government support, which is the case for many low-carbon technologies in general (Li et al, 2011; Stechow et al., 2011; Krahé et al., 2013). Strategic planning must explicitly recognize the indispensability of CCS technology in the future energy system, and fortunately it has been approved by the world's major economies. Traditional emission performance standards have been gradually phased out due to unreasonable marginal abatement cost. Subsidies for electricity generation are widely recognized to be effective in raising enthusiasm for CCS investment considering sufficient experience in renewable energy. Nevertheless Duan et al.(2013) held that policies based on subsidies alone will pose a huge burden on government budgets and never offer the cheapest option to meet the reduction targets.

Market-based instruments, especially the carbon market, open a possible window for promoting CCS development. For now, China's emissions trading system will cover the extensive power industry, while Chinese government has not given a clear opinion on whether to incorporate the CCUS project into the carbon trading mechanism as a result of unanticipated impacts on vulnerable carbon market (Lin and Tan, 2021). Moreover, carbon prices are unstable and uncertain, the investors, facing uncertain income from the carbon market, are more desperate for a clear and direct signal for more income from CCS investment. Accordingly, some scholars highlight that the volatile carbon trading price is unlikely to deliver sufficient incentives, and therefore they need to be combined with other auxiliary means (Wang and Du, 2016; Billsona and Pourkashanian, 2017).

Additionally, a considerable number of studies have concentrated on technical-economic assessments of different systems with carbon capture (Kunze and Spliethoff, 2012; Skorek-Osikowska et al., 2013). Some scholars took into full consideration the learning effect of various components by employing historical learning curves to evaluate the future cost of several carbon capture systems (Hadjipaschalis et al., 2009; Wu et al., 2016). In essence, their results show that the unit capital cost and the cost of electricity drop dramatically through technological advancement, though the cost reduction may still not be enough at present to create an incentive for CCS investment. In terms of industrial clustering, sharing CO_2 transport and storage infrastructure offers cost savings and enables smaller sources to undertake CCS, though these advantages cannot be realized in the short term.

Table 1

Summary of current financing around the world.

			Examples of practical application	Related studies
Government support	Policy support	Strategic deployment	EU: "7th Framework Programme". US: "Future Gen". UK: "The Clean Growth Strategy " China: "Medium and Long-term Science and Technology Development"; Special Plan for Scientific and Technological Innovation in Response to Climate Change"	
		Mandates (Emission constraint; CCS readiness; Power Purchase Agreement)	EU: Newly built coal-fired power plants (CFPP) above 300MW should be evaluated for CCS suitability. UK: CCS must be installed in all new CFPP with carbon emissions reaching 450g/kWh. Canada: Emissions of CFPP should be equivalent to gas-fired power plants. US: The grid must ensure a portion of electricity coming from power plants that equip with CCS in Illinois.	Eide et al. (2014) held that imposing a less strict emission standard is more likely to incentivize investment in CCS technology. Wilko and Reinhard (2013) believed that capture-readiness competes with alternative options of power plant replacements, but is not necessarily preferable from an economic perspective. Mo et al. (2018) indicated that carbon capture ready investment does not appear to be economically viable under current conditions in China due to low carbon price. Ding et al. (2019) found the value of flexibility brought by capture readiness design is significant and is equal to approximately 15% of initial capital investment
	Financial support	Tax credits	US: 45Q Act-"Tax Credit for Carbon Sequestration"	Fan et al. (2019) argued that tax credit for CO_2 storage provides the motivation needed for CCS investment during the 12-year period; however the economic benefits cannot be sustained over the 40-year lifetime.
		Loan guarantees	US: The Omnibus Appropriations Act for FY2009 provides $6 billion in loan guarantees for CFPP generation activities at retrofitted and new facilities that incorporate CCS.	
		Subsidy (R&D, Investment, Feed-in tariff, Storage/Utilization)	UK: Contract for difference	Duan et al. (2013) proposed that subsidy policy alone never offers the cheapest option to meet the reduction targets. Zhu and Fan (2014) proved that putting the subsidy into CCS R&D process can be more effective in comparison with CCS generation process. Wen and Lin (2014) insisted that the ability of asset management of government is the critical factor affecting the subsidy policy making and operating subsidy is more favorable. Chen et al.(2016) indicated that subsidy from $0.01

				to $0.05/kWh can raise CCS investment potential by 9.66%-39.18%, shorten investment period by 0.39-1.95 years. Yang et al.(2019) compared the impacts of different subsidy schemes and pointed out that subsidy for CO_2 utilization is more favorable in consideration of the development of full-chain CCS project.
Market pull	Carbon price	Carbon allowance	EU: Incorporating CCS into ETS in 2009	Gerbelová et al. (2013) estimated the breakeven CO_2 price interval for plants to be 85–140 $ per tones of CO_2. Višković et al. (2014) stated that CCS can become the preferred option compared to a typical ultra-supercritical plant when the carbon price is higher than approximately 65 €/t CO_2. Üçtuğ et al. (2014) indicated that for CCS to be feasible, carbon credit prices must be above 15 Euros per ton. Zhang et al. (2014) noted that when the current carbon price increased to 350.0 RMB/ton CO_2, a power plant would execute CCS retrofitting immediately. Walsh et al. (2014) proved that that adoption of CCS technology is not optimal at current carbon prices. Wang and Du (2016) estimated the critical carbon prices at 103.56 RMB/ton with 100% subsidy and 217.95 RMB/ton without subsidy. Morris et al. (2019) believed that carbon prices of 35–40$/t$CO_2$ make CCS technologies on coal-based generation cost-competitive against other modes of generation and that carbon prices higher than 100$/tCO2 favor a major expansion of CCS.
		Carbon tax	Norway: Promoting the development of CCS through carbon tax.	Hu and Zhai (2017) confirmed that an emission tax policy to encourage CCS implementation for 90% CO_2 capture at the baseload coal-fired plants requires a CO_2 price of $41/tonne.
		CDM	Incorporating CCS into CDM in 2010	Eto et al.(2013) put forward that large quantity of IGCC with CCS becomes realizable when the certified emission reduction (CER) prices are above US$56/tCO2.
		CO_2 sale price	US: Petra Nova; Norway: Snøhvit; Canada: Boundary Dam; China: CNPC Jilin Oilfield	Hu and Zhai (2017) noted that the CO_2 sale price of $24/tonne is needed for EOR operations to offset the added cost for CCS.
Technical advancement	Capture technologies	Second-generation technology	The cost and energy penalty of the 2nd generation CCUS will be reduced by 30% compared with the 1st generation CCUS.	Fan et al.(2018) stressed that policymakers should provide greater support for the second-generation CCS technologies and promote them actively in 2030–2035.
		Combustion technology	Oxyfuel, integrated gasification combined cycle (IGCC), and post-combustion systems with carbon capture.	Hadjipaschalis et al.(2009) argued that oxyfuel combustion technology is very competent among the carbon capture alternatives, while IGCC with carbon capture seems to be slightly more preferable for economic consideration.
	Utilization technologies	EOR, ECBM, EGR, etc.		Ağralı et al. (2018) highlighted that CCU should be prioritized as a means of reducing carbon emissions in an economically rewarding manner.
Industrial chain	Business model	Vertical integration model	Saudi Arabian National Oil Company	Yao et al. (2018) pointed that vertical integration model has the advantage of reducing transaction costs and thus is appropriate for the early stage of CCS development.
		Joint venture model	An AOSP joint venture: Shell Canada Energy（60%）, Chevron Canada Limited (20%), Marathon Oil Canada Corporation（20%.）	Yao et al. (2018) believed that extensive development of CCS will never be realized without collaboration among sectors and specialization advantage can further cut cost.

	CCS operator model	Liang (2009) noted that a more market-driven model is designed with further diversification of the participating entities.
	CO_2 transporter model	Stigler (1951) noted that vertical disintegration is the typical form of development in growing industries, and therefore a business model with higher vertical specialization level is introduced by Yao et al (2018).
Industry clustering	Industrial zone	Onarheim et al. (2015) discussed that implementing a joint CCS chain could possibly lower the CCS unit costs, while the possibility for carbon leakage could decrease the competitiveness. Brownsort et al.(2016) stressed that CCS clusters, where multiple CO_2 emitting sources share CO_2 transport and storage infrastructures, offer cost savings and enable smaller sources to undertake CCS. Berghout et al. (2017) highlighted that CCS-related industrial zones requires a sufficiently high CO_2 price and a rapid replacement of the capital stock.

Overall, these four aspects (government support, market pull, technical advancement and industrial chain) are inextricably and reciprocally linked for financing CCS projects (Herzog, 2011; Krahé, 2013). In particular, the adequacy of government support via policy incentives is probably key among them, meaning that it is currently unclear whether CCS will indeed develop into a cost competitive component of a future emission abatement portfolio once relevant obstacles can be overcome, while it is definitely the case that CCS will not become a viable mitigation option without policy support (Li et al., 2011; Krahé et al., 2013). Subsidies are such a clear policy signal that can offset the generating costs of the power plants directly and reduce investment risks under the condition of both high uncertainty & low initial carbon price (Chen et al., 2016; Wang et al., 2016; Yang et al., 2019). Moreover, unlike other kinds of low-carbon technology such as renewable energy, the subsidy level of CCS may not decrease in the future because of rising trend of fuel costs and worse technology applicability in large-scale deployment (Yao et al., 2020). Specifically, direct governmental financial incentives are crucial for early demonstration projects which have unclear business advantages (Liang and We, 2009, Li et al., 2011; Chen et al., 2016). The traditional financial incentives are generally fiscal-based policies, including guaranteed loans for CCS projects, discounted tax rates for income related to CCS, subsidies for feed-in tariffs or initial capital investment etc. The above financial tools have a certain rationality, but at the same time also have some flaws which have been discussed in depth by Krahé et al. (2013). In particular, governments have faced fiscal burdens in recent years due to global low economic growth, and such financial tools may consume scarce fiscal resources (Jeon et al., 2015; Yao et al., 2020). Hence, it is necessary to seek new policy-related financing strategies.

Based on the above, this study puts forward an innovative subsidy incentive, i.e. granting time extensions (extra electricity quota), to finance an early CCS demonstration project in China. Although a CFPP is capable of running around 85-90% of the year, it is utilized significantly less than this due to the control of electric power systems in many countries (Spek et al., 2017). For example, in the Netherlands, Austria, Germany, and Italy, the utilization rate of CFPP is roughly 60%, 29%, 47%, and 46%, respectively. Likewise, the utilization rate is less than 50% in China (Fig.2). It should be noted that the incremental pollution would not occur if constraints on advanced coal plant were relaxed. Actually in China, most of the power plants in service are mainly supercritical and ultra-supercritical units which adopt new intelligent equipment and have great improvement in energy consumption, environment and efficiency. Meanwhile, the old power plants with high energy consumption, heavy pollution and low capacity are nearing their operational life. Therefore, the pollution sources are reduced to a large extent. In terms of the operational process, mature technologies, including desulfurization, denitrification and low nitrogen combustion procedures. have been widely applied to power plants in China. In addition, carbon capture device can effectively prevent greenhouse gases from entering the atmosphere in the first place, moreover, some scholars have proposed that this technology has synergistic mitigation effect.

This study will estimate the investment revenue and LCOE of CFPP with CCS retrofitting under the scenarios of various electricity quotas based on the latest technological and market data from real CCS demonstration projects. Our aim is to provide a clear picture of CCS costs and an economic feasible financing incentive for accelerating CCS engineering practices as soon as possible. Additionally, in view of the uncertain circumstances, we also conduct a sensitivity analysis on coal price and feed-in tariff, and other critical conditions, including carbon price, electricity quota, capture level and LCOE, under various scenarios. Overall, this study has a straightforward implication in terms of innovative policy incentive. In particular we show how this new policy incentive affects the current investment revenue and cost of power generation. Our results are based on various scenarios that have not been discussed in previous studies and are able to provide useful information for electric power enterprises and government decision-makers.

3. Methodology

3.1. Basic assumptions

1) In general, a CFPP has a lifespan of 45 years, though its average remaining lifespan in China is currently roughly 28 years. Thus, it is assumed that the investment cost of CCS retrofitting will be shared equally over 45 years, and the CFPP is still able to run 28 years if it is retrofitted with CCS. Correspondingly, the investment payback period is also assumed to be 28 years.
2) The supercritical pulverized coal units are retrofitted with CCS technology. This is in accordance with the fact that CCS technology is mainly demonstrated by supercritical coal fired power plant in China. The Haifeng project, which is a demonstration project compatible with multiple carbon capture technologies, is the first of its kind built on an ultra-supercritical coal

fired power plant.

3) Post-combustion capture technology is adopted, and captured CO_2 is transported by tankers and finally stored in saline aquifers on land.

4) CPFF is permitted to extend the running time to some extent according to CO_2 capture capacity.

5) CFPP with CCS retrofitting is able to participate in carbon trading.

6) The vertical integration business model that considers capture, transport and storage as a whole is used in this study. In the early stage of CCUS, cooperation among different sectors has been difficult to achieve, and thus the vertical integration model is applied in China's state-owned electricity enterprises. Due to its high degree of integration, the transaction cost is generally taken to be zero (Yao et al., 2018; Yang et al., 2019). This is also in line with the actual situation of current demonstration projects in China.

3.2. Cost accounting of a CCS project

The cost differential relative to the CFPP without CCS retrofitting mainly includes: (i) the installation of CO_2 capture equipment, (ii) operation and maintenance (O&M) costs when operating the capture equipment, and, (iii) the transportation and storage of CO_2. It should be noted that existing research saw a wide range of the estimated costs, depending on the underlying assumptions, e.g., technology options, conversion efficiencies, load hours, and fuel prices (Stechow et al., 2011).

3.2.1 Incremental investment cost of CO_2 capture procedure

$$C_{cap}^{capture} = UC_{cap}^{capture} \times Q_{CO_2}^{capture} \tag{1}$$

where $C_{cap}^{capture}$ is the total incremental investment cost of CO_2 capture equipment of CFPP; $UC_{cap}^{capture}$ is the unit investment cost of CO_2 capture equipment, which is related to the CO_2 capture capacity; $Q_{CO_2}^{capture}$ is the captured amount per year.

3.2.2 Incremental O&M costs of CO_2 capture procedure

$$C_{\mathrm{O\&M}}^{capture} = C_{equ} + C_{fuel\&abs} + C_{power} \tag{2}$$

where $C_{\mathrm{O\&M}}^{capture}$ is the incremental O&M costs of CO_2 capture procedure; C_{equ} is the O&M costs of CO_2 capture equipment; $C_{fuel\&abs}$ is the addition costs of fuel and absorbent; C_{power} is the electricity output penalty cost caused by CO_2 capture per year.

$$C_{equ} = k_{equfac} \times Q_{CO_2}^{capture} \tag{3}$$

$$C_{fuel\&abs} = (v \times P_{vap} + a \times P_{abs}) \times Q_{CO_2}^{capture} \tag{4}$$

$$C_{power} = L_{power} \times P_{power} \times Q_{CO_2}^{capture} \tag{5}$$

where k_{equfac} is O&M costs factor of CO_2 capture equipment; v and a represent the consumption amount of steam and absorbent for capturing one ton CO_2, respectively; P_{vap} and P_{abs} represent the price of steam and absorbent, respectively; L_{power} is the electricity output penalty for capturing per ton of CO_2; P_{power} is the electricity price, which is equal to the average electricity price of coal-fired units nationwide.

3.2.3 Costs of CO_2 transport and storage

$$TC_{CO_2} = UTC_{CO_2} \times Q_{CO_2}^{capture} \tag{6}$$

$$SC_{CO_2} = USC_{CO_2} \times Q_{CO_2}^{capture} \tag{7}$$

where TC_{CO_2} and SC_{CO_2} denote the total CO_2 transport cost and storage cost per year, respectively; UTC_{CO_2} and USC_{CO_2} denote the unit CO_2 transport cost and storage cost, respectively. It should be noted that the storage cost includes monitoring cost for 20 years after the injection wells close.

3.3. Power generation cost of CFPP

3.3.1 CO_2 emissions of CFPP

According to the method proposed by Wang (2013), we calculate CO_2 emissions from CFPP as follows:

$$Q_{CO_2}^{emit} = 44/12 \times PSCC \times IC \times RT \times Q_{net}^{S} / Q_{net}^{L} \times Car \times t_{CO_2} \tag{8}$$

where $Q_{CO_2}^{emit}$ is the CO_2 emissions amount of CFPP per year; $PSCC$ is the unit power supply coal consumption, which decreases with the increase in running hours; IC is the installed capacity of coal-fired power plants; RT is annual running time of coal-fired power plants; Q_{net}^{S} is the low calorific value of standard coal; Q_{net}^{L} is low calorific value of coal used in coal-fired power plants; Car is carbon content of the coal; t_{CO_2} is the proportion of carbon in coal oxidized to CO_2.

3.3.2. Depreciation expenses of fixed assets of CFPP

$$C_{cap}^{plant} = UC_{cap}^{plant} \times IC \times \omega \times (1-\theta) / \tau_2 \times \tau_1 \tag{9}$$

where C_{cap}^{plant} is the depreciation expenses of fixed assets of CFPP; UC_{cap}^{plant} is the unit cost of coal power projects (600MW ultra supercritical unit); ω is the fixed asset formation rate; θ is the residual value rate of fixed assets; τ_2 is the design life of CFPP; τ_1 is the residual life of CFPP.

3.3.3. Total O&M costs of CFPP

1) O&M costs of power generation equipment

$$C_{\mathrm{O\&M}}^{plant} = C_{cap}^{plant} \times R_{\mathrm{O\&M}}^{base} \tag{10}$$

where $C_{\mathrm{O\&M}}^{plant}$ is the O&M costs of power generation equipment; $R_{\mathrm{O\&M}}^{base}$ is the O&M costs factor of power generation equipment.

2) Costs of desulfurization and denitrification

$$DSC = IC \times RT \times UDSC \tag{11}$$

$$DNC = IC \times RT \times UDNC \tag{12}$$

where DSC and DNC are total desulfurization cost and total denitrification cost of CFPP per year, respectively; $UDSC$ and $UDNC$ are unit desulfurization cost and unit denitrification cost of CFPP, respectively.

3) Laboure cost

$$C_{lab} = N_{lab} \times W_{lab} \times (1 + R_w) \tag{13}$$

where C_{lab} is the Laboure cost; N_{lab} is the number of employees; W_{lab} is the annual salary of employees; R_w is the factor of welfare social insurance.

4) Material cost

$$C_{mat} = IC \times RT \times R_{mat} \tag{14}$$

where C_{mat} is the total material cost per year; R_{mat} is the material cost of per kWh power.

5) Sewage charges

$$C_{pdf} = Q_{SO_2}^{emit} \times P_{SO_2} + Q_{NOx}^{emit} \times P_{NO_x} \tag{15}$$

$$Q_{SO_2}^{emit} = 32/16 \times PSCC \times IC \times RT \times Q_{net}^{S} / Q_{net}^{L} \times Sar \times t_{SO_2} \times (1 - \eta_{SO_2}) \tag{16}$$

$$Q_{NO_x}^{emit} = 30.8/14 \times PSCC \times IC \times RT \times Q_{net}^{S} / Q_{net}^{L} \times Nar \times n_N / m_N \times (1 - \eta_{NO_x}) \tag{17}$$

where C_{pdf} is the sewage charges of CFPP per year; $Q_{SO_2}^{emit}$ is the SO_2 emissions amount per year; P_{SO_2} is the charge standard of SO_2 emission equivalent; Q_{NOx}^{emit} is the NO_x emissions amount per year; P_{NO_x} is the charge standard of NO_x emission equivalent; Sar is the sulfur content of the coal; t_{SO_2} is the proportion of sulfur in coal oxidized to SO_2; η_{SO_2} is the SO_2 removal rate, which is based on wet flue gas desulfurization technology; Nar is the Nitrogen content in the coal; n_N is the conversion rate of fuel nitrogen; m_N is the proportion of NO_x produced by fuel nitrogen to total NO_x; η_{NO_x} is the NO_x removal rate, which is based on selective catalytic reduction (SCR) technology.

6) Fuel cost

$$C_{coal} = IC \times RT \times PSCC \times Q_{net}^{S} / Q_{net}^{L} \times P_{coal} \tag{18}$$

where C_{coal} is the fuel cost; P_{coal} is the coal price which is equal to the average electricity coal price of China during January 2014 to March 2019.

7) Other costs

$$C_{other} = IC \times RT \times R_{other} \tag{19}$$

where R_{other} is the cost factor of other expenses.

3.3.4 Taxes and loan interest charges

The electricity price includes desulfurization and denitrification subsidies, as well as the value-added tax. The value-added tax rate (T_{vat}) is set as 17% in this study, while loans and the corresponding interest charges are not considered.

3.4. NPV of CFPP without CCS retrofitting

$$NPV_{plant} = \sum_{t=\tau_1}^{\tau_2} \{[IC \times RT \times (1-\gamma) \times P_{power} / (1+T_{vat}) - (C_{O\&M}^{plant} + DSC + DNC + C_{lab} + C_{mat} + C_{pdf} + C_{coal} + C_{other})] \times (1+r_0)^{\tau_1 - t}\} - C_{cap}^{plant} \tag{20}$$

where NPV_{plant} is net present value (NPV) of *CFPP without CCS retrofitting*; γ is the power consumption rate for station service, which decreases with the increase of running hours; r_0 is the discount rate.

3.5. NPV of CCS retrofitting investment

It is assumed that CCS retrofitting occurs at $t = \tau_1$ and the project construction phase is one year. The we have,

$$NPV_{CCS} = \sum_{t=\tau_1+1}^{\tau_2} [Q_{CO_2}^{capture} \times P_{carbon} + \Delta I_{RT} - (C_{O\&M}^{capture} + TC_{CO_2} + SC_{CO_2}) \times e^{-\beta(t-\tau_1)}] \times (1+r_0)^{\tau_1 - t}\} - C_{cap}^{capture} \quad (21)$$

$$\Delta I = NPV_{plant}^{\Delta RT} - NPV_{plant} \quad (22)$$

where P_{carbon} is carbon price; ΔI is the additional profits from increased electricity quota of CFPP; $NPV_{plant}^{\Delta RT}$ is the NPV of CFPP getting extra electricity quota; β is the parameter reflecting the effect of technology improvement on CCS operation and maintenance costs (including CO_2 transport and storage costs).

3.6. NPV of CFPP with CCS retrofitting

$$NPV_{plant+CCS} = NPV_{plant} + NPV_{CCS} \quad (23)$$

Overall, the NPV of CCS project is affected by the cost and revenue discussed above.

3.7. LCOE of CFPP with/without CCS retrofitting

Levelized cost of electricity (LCOE) is a widely used indicator to reflect the cost of power generation, which takes many factors, such as time and depreciation of fixed assets, into consideration. The LCOE of CFPP without CCS retrofitting can be calculated as follows

$$LCOE_{without\ CCS} = \frac{\sum_{t=1}^{\tau_1} [(C_{O\&M}^{plant} + DSC + DNC + C_{lab} + C_{mat} + C_{pdf} + C_{coal} + C_{other}) / (1+r_0)^t] + C_{cap}^{plant} \times \tau_1}{\sum_{t=1}^{\tau_1} [(IC \times RT) / (1+r_0)^t]} \quad (24)$$

Based on above mentioned, the LCOE of CFPP with CCS retrofitting can be calculated as Eq. (25)

$$LCOE_{with\ CCS} = LCOE_{without\ CCS} + \frac{\sum_{t=\tau_1+1}^{\tau_2} [((C_{O\&M}^{capture} + TC_{CO_2} + SC_{CO_2}) \times e^{-\beta(t-\tau_1)} - Q_{CO_2}^{capture} \times P_{carbon}) / (1+r_0)^{t-\tau_1}] + C_{cap}^{capture}}{\sum_{t=1}^{\tau_1} [(IC \times RT) / (1+r_0)^t]} \quad (25)$$

4. Data processing and scenarios setting

4.1. Related parameters used in the model

Table 2 lists the values of related parameters used in this study. According to the actual situation in China, the installed capacity of CFPP is set to be 1200MW (2×600MW). It should be noted that some parameters are selected in consultation with experts and industrial partners from the energy and utility sector, and some parameters are taken from the *Technology Roadmap on Carbon Capture, Utilization and Storage in China* (2019). In particular, some technical parameters are collected from *Haifeng Carbon Capture Test Platform* in *Guangdong*, China. Moreover, most of these parameters are validated against representative CCS costing studies, such as Zhang et al.(2014), Zhu et al. (2015), and Fan et al. (2019). Based on the latest technological data of real CCS demonstration projects, the capture equipment is generally assumed to capture 90% regardless of the actual capture level. Additionally, the efficiency loss is lower than 5% even the capture level reaches 1 Mt/a, which has little influence on the power generation cost and thus can be ignored in the demonstration stage.

Table 2

Parameters of CCS retrofitting investment.

Parameters	Description	Value
$UC_{cap}^{capture}$	unit investment cost of CO_2 capture equipment	800 CNY/t
k_{equfac}	O&M costs factor of CO_2 capture equipment	30 CNY/t
v	Steam consumption for capturing 1t CO_2	1.2 t
a	Absorbent consumption for capturing 1t CO_2	1.44×10^{-5} t

P_{vap}	Steam price	200 CNY/t
P_{abs}	Absorbent price	25000 CNY/t
L_{power}	Electricity output penalty for capturing 1t CO_2	196 kWh
P_{power}	Feed-in tariff	0.36 CNY/kWh (NDRC, 2015)
UTC_{CO_2}	Unit transport cost of CO_2	0.8 CNY/t·km (MOST, 2019)
UTC_{CO_2}	Unit storage cost of CO_2	60 CNY/t (MOST, 2019)
$PSCC$	Unit power supply coal consumption	274.7 -285.7gce/kWh
IC	Installed capacity of coal-fired power plants	1200 MW (2×600MW)
RT	Annual running time of coal-fired power plants	4000-7000 h
Q_{net}^{S}	Low calorific value of standard coal	29.3076 MJ/kg
Q_{net}^{L}	Low calorific value of coal used in coal-fired power plants	20.9080 MJ/kg
Car	Carbon content of the coal as received basis	49.72%
t_{CO_2}	The proportion of carbon in coal oxidized to CO_2	98%
UC_{cap}^{plant}	Unit cost of coal power projects	3600 CNY/kW (CEC, 2014)
ω	The fixed asset formation rate	95%
θ	The residual value rate of fixed assets	5%
τ_2	The design life of CFPP	45 years
τ_1	The residual life of CFPP	28 years
$R_{\mathrm{O\&M}}^{base}$	O&M costs factor of power generation equipment	2.5%
$UDSC$	Unit desulfurization cost of CFPP	0.0130 CNY/kWh (Shi, 2015)
$UDNC$	Unit denitrification cost of CFPP	0.0111 CNY/kWh (Shi, 2015)

N_{lab}	The number of employees	220
W_{lab}	The annual salary of employees	50000 CNY/a
R_w	The factor of welfare social insurance	60%
R_{mat}	The material cost of per kWh power	0.006 CNY/kWh
P_{SO_2}	The charge standard of SO_2 emission equivalent	1.2 CNY/0.95 kg
P_{NO_x}	The charge standard of NO_x emission equivalent	1.2 CNY/0.95 kg
Sar	The sulfur content of the coal as received basis	0.86%
t_{SO_2}	The proportion of sulfur in coal oxidized to SO_2	80%
η_{SO_2}	SO_2 removal rate	95%
Nar	The Nitrogen content in the coal as received basis	1.48%
n_N	The conversion rate of fuel nitrogen	25%
m_N	The proportion of NO_x produced by fuel nitrogen to total NO_x	80%
η_{NO_x}	NO_x removal rate	80% (Yang, 2015)
P_{coal}	Coal price	450 CNY/t (IMCEC, 2019)
R_{other}	Cost factor of other expenses	0.012 CNY/kWh
T_{vat}	The value-added tax rate	17%
γ	The power consumption rate for station service	4-8%
r_0	The discount rate	8%
P_{carbon}	Carbon price	50 CNY/t (CBEEX,2019)
β	The parameter reflecting the effect of technology improvement on O&M costs of CCS project	5.7% (Wang and Du, 2016)

4.2. Scenarios setting

Based on the statistics released by China Electricity Council (CEC), the annual electricity quota of power generation facilities (≥6000 kW) was 3790 hours in 2017, and that of thermal power plants was 4219 hours (CEC, 2018). Electricity quota (1000h steps in the ladder) is taken as an incentive instrument to motivate CFCC to retrofit CCS for reducing CO_2 emissions. In this study, the benchmark electricity quota of CFPP can be considered to be 4000 h/a, and the largest electricity quota is up to 7000 h/a in view of the actual operation capability of CFPP (Zhu et al., 2016). Accordingly, the "business-as-usual (BAU)" scenario can be considered as the conventional CFPP with the electricity quota of 4000 h/a.

Additionally, CFPP can be designed with the CO_2 capture capacity of 0.1, 0.5 and 1 Mt/a, respectively, as a consequence of the maturity of the current technology. Meanwhile, considering the prominent position of gas-fired generation, the LCOE and critical capture level (capture rate relative to all CO_2 emissions) of CFPP with CCS retrofitting are also estimated when its emission level is equal to that of gas-fired power plants (412g CO_2/kWh).

5. Results and discussion

5.1. Cost-Benefit analysis under different electricity quotas

Fig.2 depicts the NPV of CFPP with different capture levels for different electricity quotas. CFPP operates at a loss under the BAU scenario, with the NPV of -0.52 Billion Yuan, and CCS retrofitting will further increase the losses, with the NPV of -0.95, -2.38 and -4.32 Billion Yuan corresponding to the CO_2 capture capacity of 0.1, 0.5 and 1 Mt/a, respectively. In addition, as a market-oriented policy tool, it is widely recognized that the carbon trading market may bring additional income to CCUS projects through selling excess allocation. Some scholars have clearly pointed out that carbon trading mechanism can effectively offset part of the emission reduction costs of CCS technology and promote the deployment of CCS projects (Zhang et al., 2014; Yao et al., 2018). Therefore, carbon trading can lower the power generation cost to some extent, and its effect increases along with the increase of capture capacity. Nevertheless, CFPP with CCS retrofitting is able to turn into profit if extra electricity quota can be provided. Specifically, the NPV for CFPP with the capture capacity of 0.1Mt/a increases from 0.42 Billion Yuan in scenario with electricity quota of 5000 h/a to 3.54 Billion Yuan in scenario with electricity quota of 7000 h/a. When the captured level reaches 0.5 Mt/a, CFPP can make a profit in the scenario with electricity quota of 6000 h/a or above. It should be noted that CFPP with a capture capacity of 1Mt/a still suffer a loss even with the largest electricity quota (7000 h/a), while it can make a profit if it can participate in carbon trading. However, it should be noted that sufficiently low emissions caps must be set for the mechanism to enable high capital emission reduction technology. It is found that the current economic environment is not enough to trigger immediate investment of the CCS projects, but the introduction of a carbon trading mechanism can significantly improve the investment value of the project and reduce the investment failure probability (Heesh et al., 2021). Overall, to accelerate the development of CCS in the short term, it also needs the joint efforts of other powerful policy incentive tools (Lin and Tan, 2021).

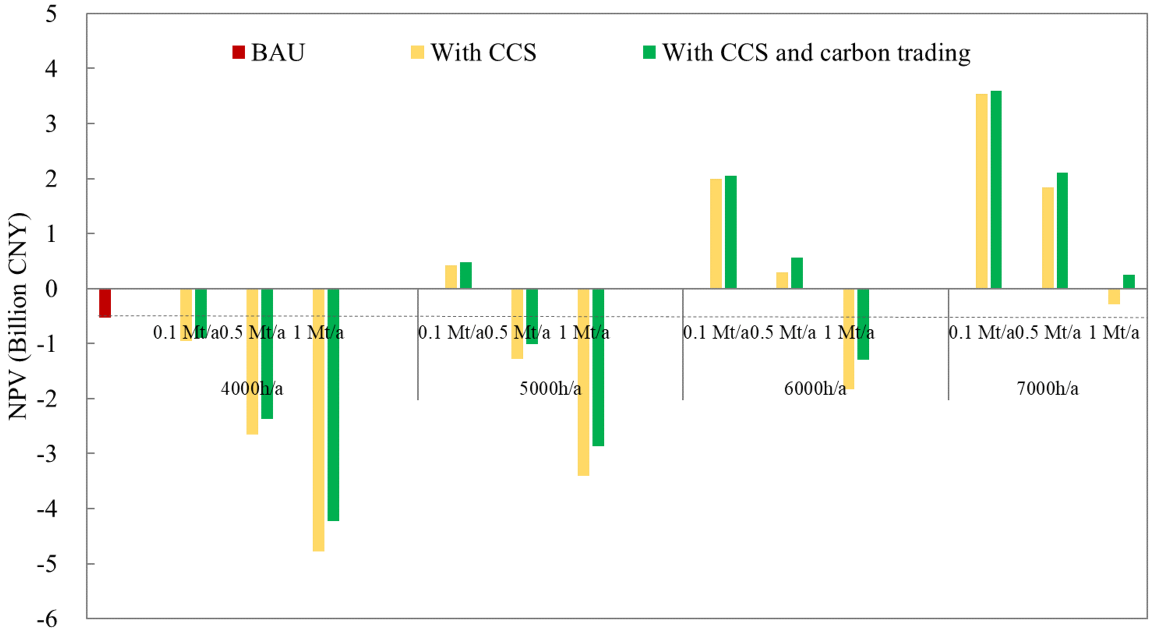

Fig.2. NPV of different capture levels under different electricity quotas

Fig.3 illustrates the LCOE of CFPP with different capture levels in the scenarios of different electricity quotas. It can be observed that CFPP operates with the LCOE of 292.2 CNY/MWh under the BAU scenario. In terms of the current electricity quota (4000 h/a), the LCOE will rise by 2.5% to 25.4% when the CO_2 capture capacity ranges from 0.1 Mt/a to 1 Mt/a. Carbon trading assumes its importance as the captured level increases, with the growth rate of LCOE falling between 2.2% to 22.1%. When the electricity quota increases to 5000 h/a, the LCOE for CFPP with the CO_2 capture capacity of 0.1 Mt/a will drop to 281.8 CNY/MWh (without carbon trading) and 281.1 CNY/MWh (with carbon trading). However, the LCOE for CFPP with the CO_2 capture capacity of 0.5 or 1 Mt/a is still higher than that under the BAU scenario regardless of carbon trading. As the electricity quota increases further, the LCOE for CFPP with the CO_2 capture capacity of 0.5 Mt/a can be lower than that under the BAU scenario even if carbon trading is not considered, with values of 288.9

CNY/MWh (6000 h/a) and 277.1 CNY/MWh (7000 h/a), respectively. Notably, for the CFPP with a capture capacity of 1 Mt/a, its LCOE can be 298.3 CNY/MWh (without carbon trading) and 292.8 CNY/MWh (with carbon trading) when the greatest electricity quota is provided, which almost approaches that under the BAU scenario (292.2 CNY/MWh). Additionally, our findings are roughly in accordance with those obtained by Speka et al. (2017) who noted that the cost variability propagates relatively mildly into the LCOE in case of high power plant utilization scenarios, more so in the case of low power plant utilization scenarios. This can be explained by the fact that the efficiency of boilers will improve with the increase in running time.

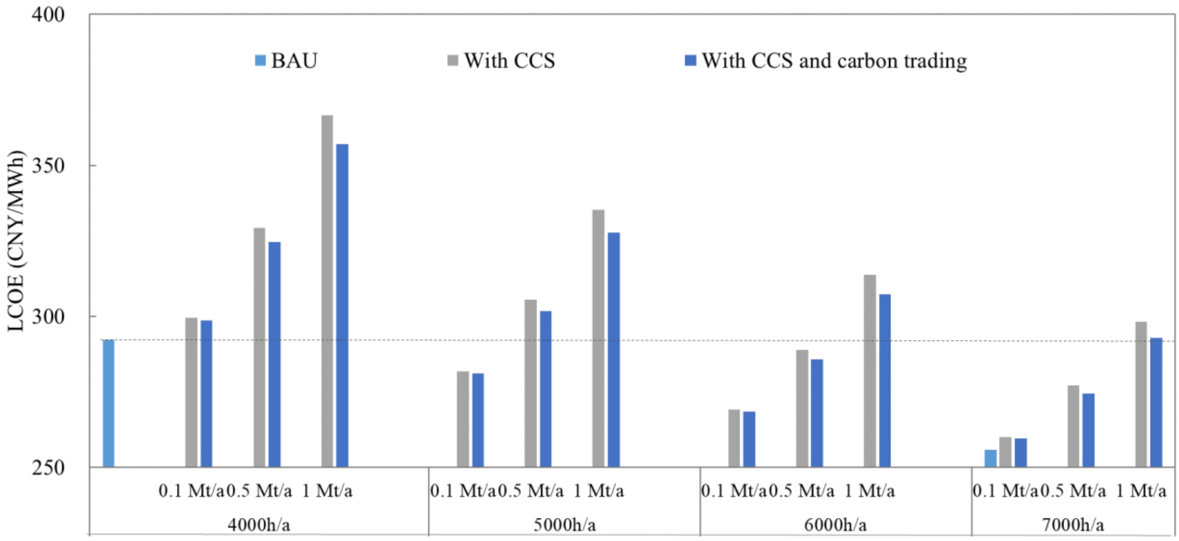

Fig.3. LCOE of different capture levels under different electricity quotas

5.2. Critical condition of CCS investment under different scenarios

A CCS retrofitting project can be executed immediately when the NPV is greater than zero. In order to quantify this gap, the related threshold break-even point is investigated under various scenarios. That is to say, if the actual value is greater than the critical value, CFPP will be retrofitted CCS technology immediately; otherwise, it will be abandoned.

5.2.1. Critical carbon prices with different capture levels and electricity quotas

It has been proved that carbon trading is able to increase the potential of the investment opportunity, and therefore the critical carbon prices under various scenario are estimated. Obviously, the critical carbon price drops as the electricity quota increases under different capture levels (Fig.4). If the CFPP captures 0.1 Mt/a CO_2, the critical carbon price is up to 867 CNY/t with the electricity quota of 4000 h/a, while it can be zero once the electricity quota reaches 5000 h/a. When the CO_2 capture level increases to 0.5 Mt/a, the critical carbon price will fall to 585 CNY/t with the electricity quota of 4000 h/a, and reach 235 CNY/t with the electricity quota of 5000 h/a. Likewise, it can be zero once the electricity quota of 6000 h/a can be provided. As the capture level rises up to 1 Mt/a, the critical carbon price will further decline to 437 CNY/t with the electricity quota of 4000 h/a, while it should increase to 312 CNY/t with the electricity quota of 5000h/a. Additionally, it is noteworthy that the critical carbon prices can be put down to 168 and 27 CNY/t with the electricity quota of 4000 and 5000 h/a, respectively.

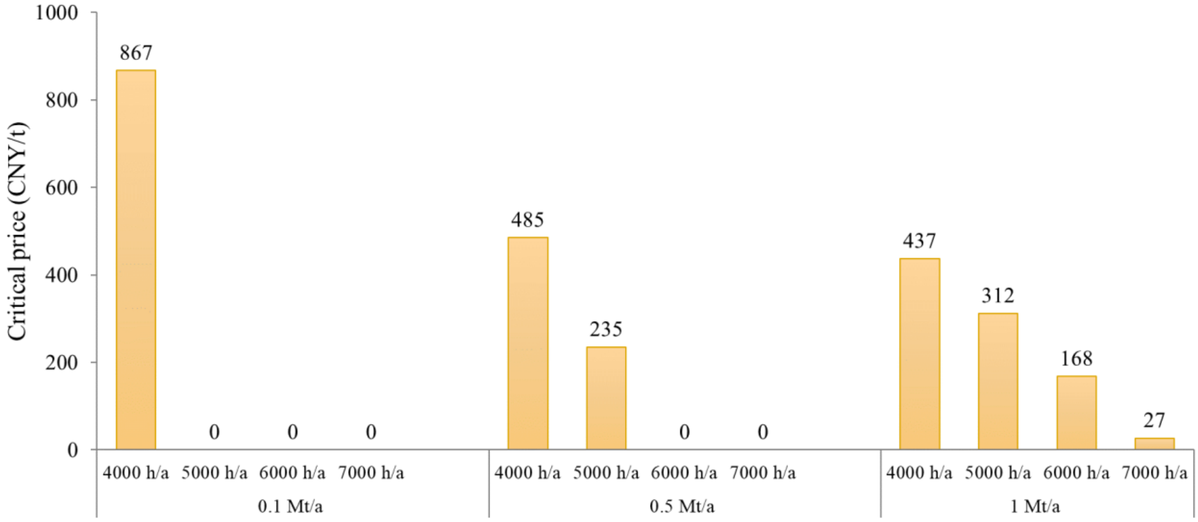

Fig.4. Critical carbon price under various capture level and electricity quota

5.2.2. Critical electricity quota with different capture levels

It should be noted that the CFPP with CCS retrofitting has not been incorporated into the carbon trading scheme in China as a result of unanticipated impacts on the vulnerable carbon market, moreover, the current carbon price is far from the desirable level to trigger CCS investment. In view of this, the critical electricity quotas in the scenarios with different capture levels without the consideration of carbon trading are examined. The results in Fig.2 have proved that CFPP is unprofitable under the current electricity quota (4000 h/a) even without CCS retrofitting, and therefore the present break-even point is also measured. As illustrated in Fig.5, the electricity quota should reach 4400 h/a at present for the CFPP to eliminate losses. Once CCS retrofitting is implemented, the critical electricity quotas should be further increased to 4790, 5823 and 7260 h/a corresponding to the capture capacity of 0.1, 0.5 and 1 Mt/a. Obviously, the demand for extra electricity quota grows as the amount of captured CO_2 increases.

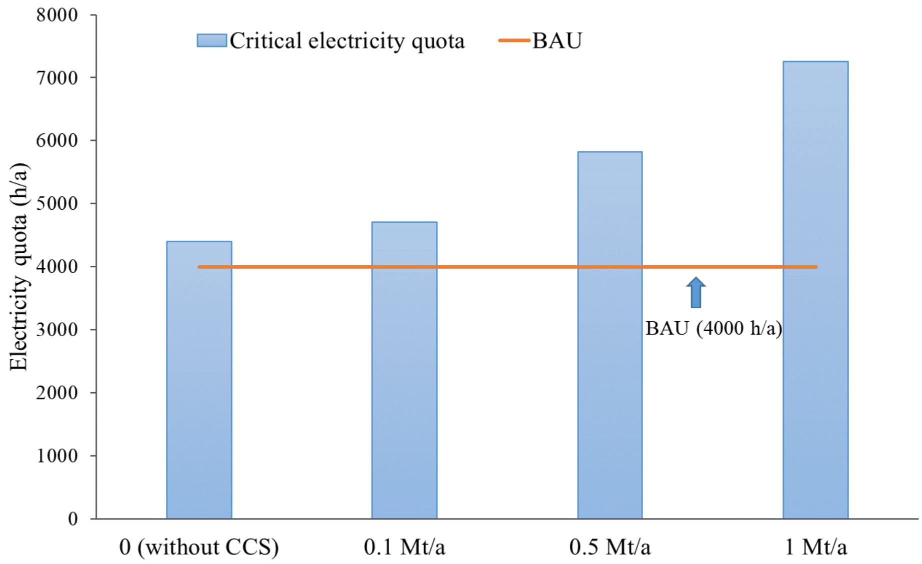

Fig.5. Critical electricity quota under different various capture levels without carbon trading.

5.2.3. Critical capture level when LCOE of CFPP with CCS retrofitting is equal to that under the BAU scenario

It is evident that the extra electricity quota is able to lower the cost of power production, which leaves space for CCS retrofitting. Consequently, we investigated the critical capture level when LCOE of CFPP with CCS is equal to that under BAU scenario. As demonstrated in Fig.6, the critical capture levels are 0.28, 0.57 and 0.86 Mt/a with the electricity quota of 5000, 6000 and 7000 h/a, respectively.

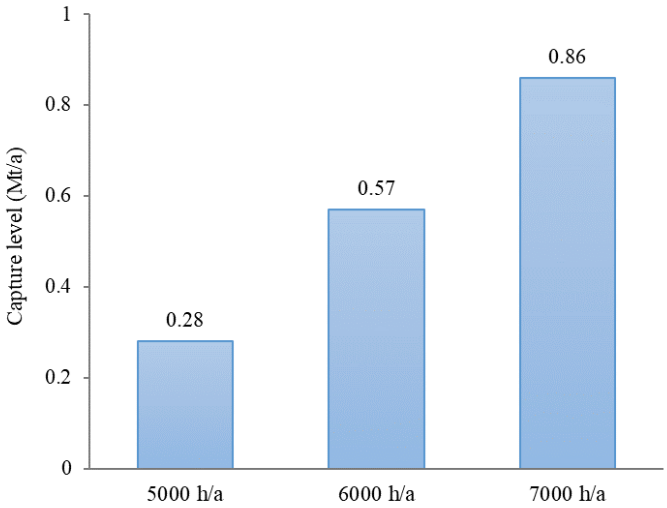

Fig.6. Critical capture level when LCOE of CFPP with CCS is equal to that of BAU scenario.

5.2.4. Critical condition when emission level of CFPP with CCS retrofitting is equal to that of gas-fired generators

Considering that natural gas has been recognized as a lower-carbon bridge to a very low-carbon future, Fig.7 displays the critical condition when emission level of CFPP with CCS retrofitting is equal to that of gas-fired generators under the scenarios with different electricity quotas. As shown in Fig.7 (a), the quantity of captured CO_2 should increase from 1.46 Mt under the scenario with electricity quota of 4000 h/a to 2.32 Mt under the scenario with electricity quota of 7000 h/a, with the capture rate declining from 42.37% to 40.15%. Therefore, it would seem that CFPP should capture above 40% of the total CO_2 emissions if its emission level is equal to that of gas-fired generators. Fig.7(b) displays the corresponding LCOE of CFPP with different capture levels under the scenarios of different electricity quotas. It can be seen that the LCOE presents a downward trend along with the increase of electricity quota, with the value dropping from 400.29 CNY/MWh under the scenario with electricity quota of 4000 h/a to 354.34 CNY/MWh under the scenario with electricity quota of 7000 h/a. Additionally, it can be observed that the space for further decline is gradually shrinking as the electricity quota increases, which can be attributed to the energy penalty and efficiency loss caused by substantial amounts of captured CO_2.

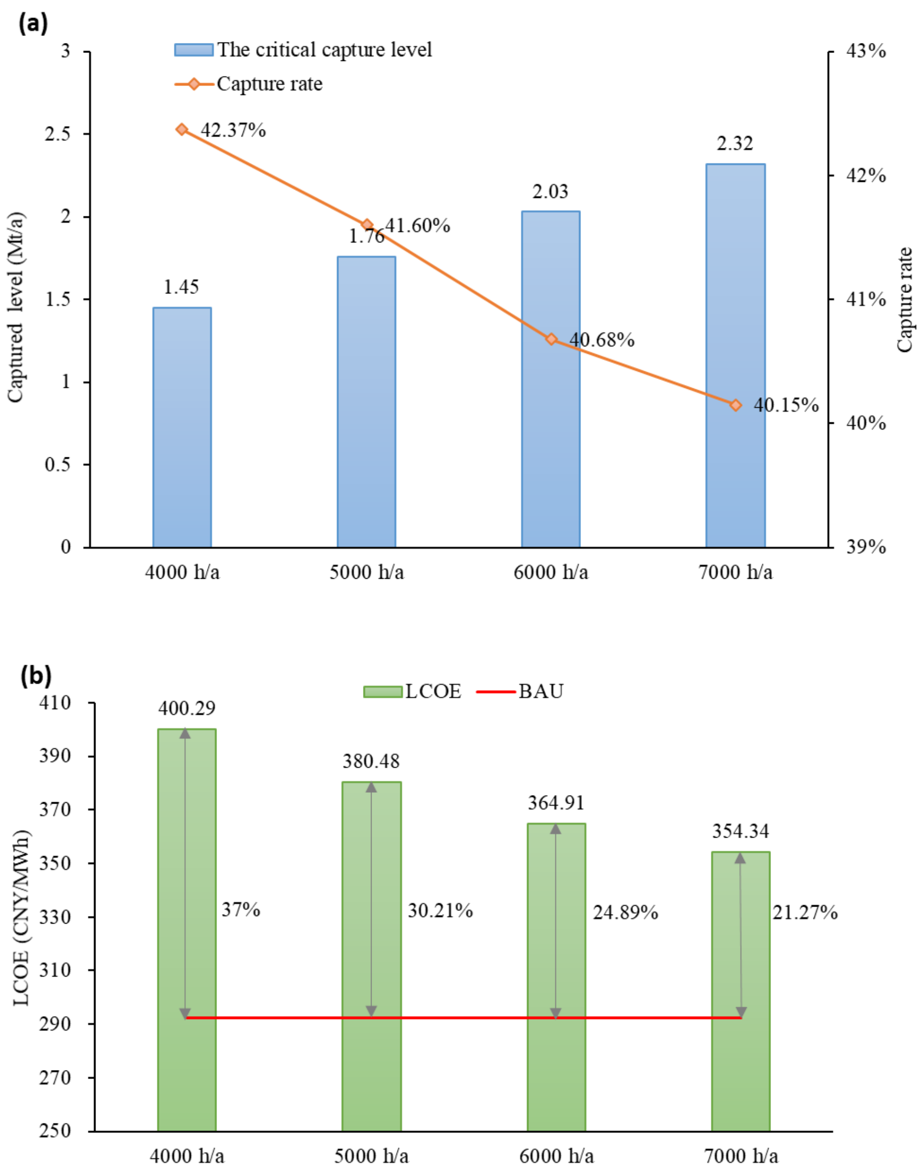

Fig.7. Critical condition when emission level of CFPP with CCS is equal to that of gas-fired generators.

5.3. Sensitivity analysis

According to the study conduct by Yang et al. (2019), the coal price has a great influence on the investment revenue. In this study, the benchmark coal price and capture level are set to be 450 CNY/t and 1 Mt/CO_2, respectively, and a sensitivity analysis of NPV with a fluctuation of ±50 CNY/t around the benchmark coal price is made. As shown in Fig.8, coal price exerts negative effects on investment value. On the one hand, in the scenario without CCS retrofitting, CFPP can maintain its profitability regardless of the coal price fluctuation in case of electricity quota greater than or equal to 6000 hours/a. On the other hand, in the scenario with CCS retrofitting, CFPP will be loss-making even if the coal price comes down to 400 CNY/t with the electricity quota less than 6000 h/a. In other word, there is no investment value for CFPP with a high capture capacity when electricity quota is below 6000 h/a. Nevertheless, if CFPP can get the electricity quota of 7000 hour/a, it is able to make profits when the coal price is less than 440 CNY/t.

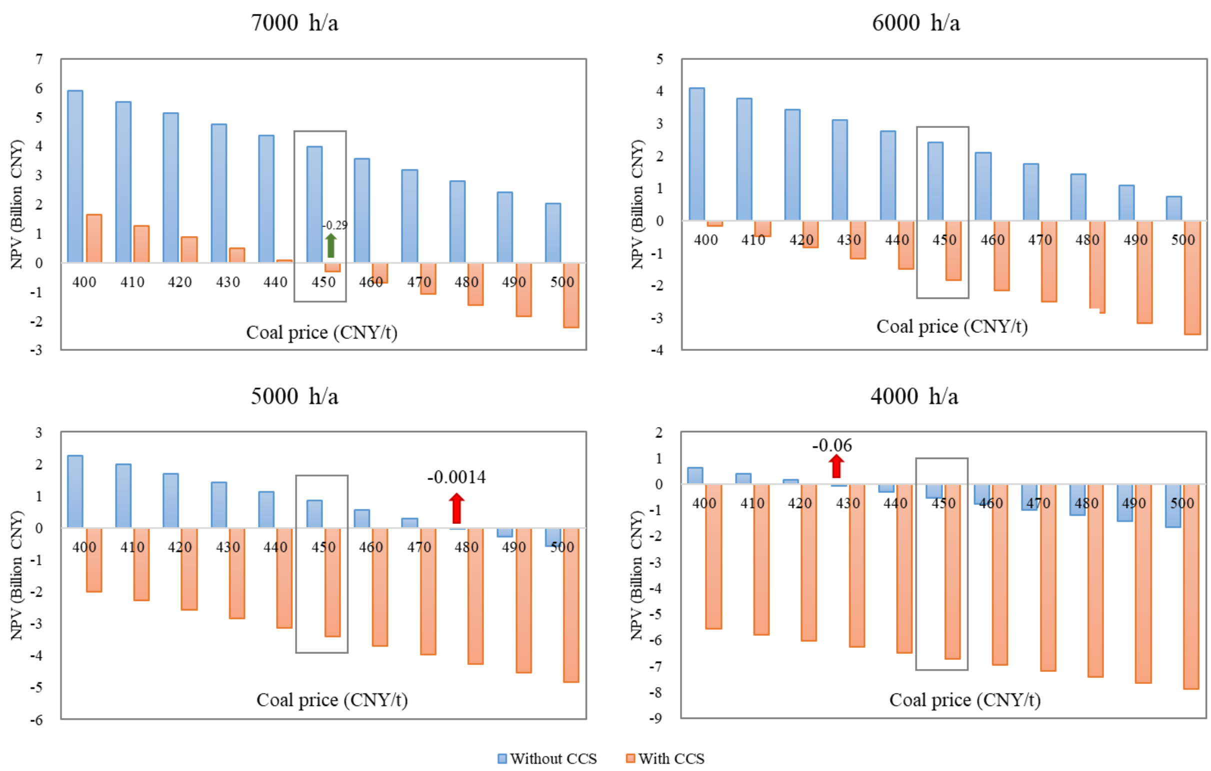

Fig.8. The impacts of coal price fluctuation on optimal investment value.

With coal prices rising sharply and marketization gradually in China, the electricity price still belongs to the typical "market coal and electricity plans", coordinated by the State Planning, meaning that the plant can't simply pass the increased costs to consumers by means of raising the electricity price. The increased installation cost and over consumption cost of the coal of large-scale implementation of CCS is hard to pass to customers through an electricity price adjustment. However, considering the Chinese has committed to electricity market reforms, we also conduct a sensitivity analysis on feed-in tariff.

The benchmark feed-in tariff and capture level are set to be 0.36 CNY/kWh and 1 Mt/CO_2, respectively, and a sensitivity analysis of NPV with a fluctuation of ±0.05 CNY/kWh around the benchmark feed in tariff is made. It can be seen from Fig.9 that the feed in tariff is positively related to the investment value. On the one hand, in the scenario without CCS retrofitting, CFPP is not continuously in profit within the total fluctuation range of feed-in tariff even the highest electricity quota is provided. To be specific, profitability can be achieved when feed-in tariffs reach at least 0.38, 0.35, 0.33 and 0.32 CNY/kWh with corresponding electricity quotas of 4000, 5000, 6000 and 7000 h/a, respectively. On the other hand, in the scenario with CCS retrofitting, CFPP will suffer a loss even if the feed-in tariff rises to 0.41 CNY/kWh with electricity quota less than or equal to 5000 h/a. Nevertheless, if CFPP can receive the electricity quota of 6000 and 7000 h/a, it is able to make profits when the feed-in tariff reach to 0.39 and 0.37 CNY/kWh, respectively. Thus, it can be claimed that CFPP is more sensitive to feed-in tariff than coal price.

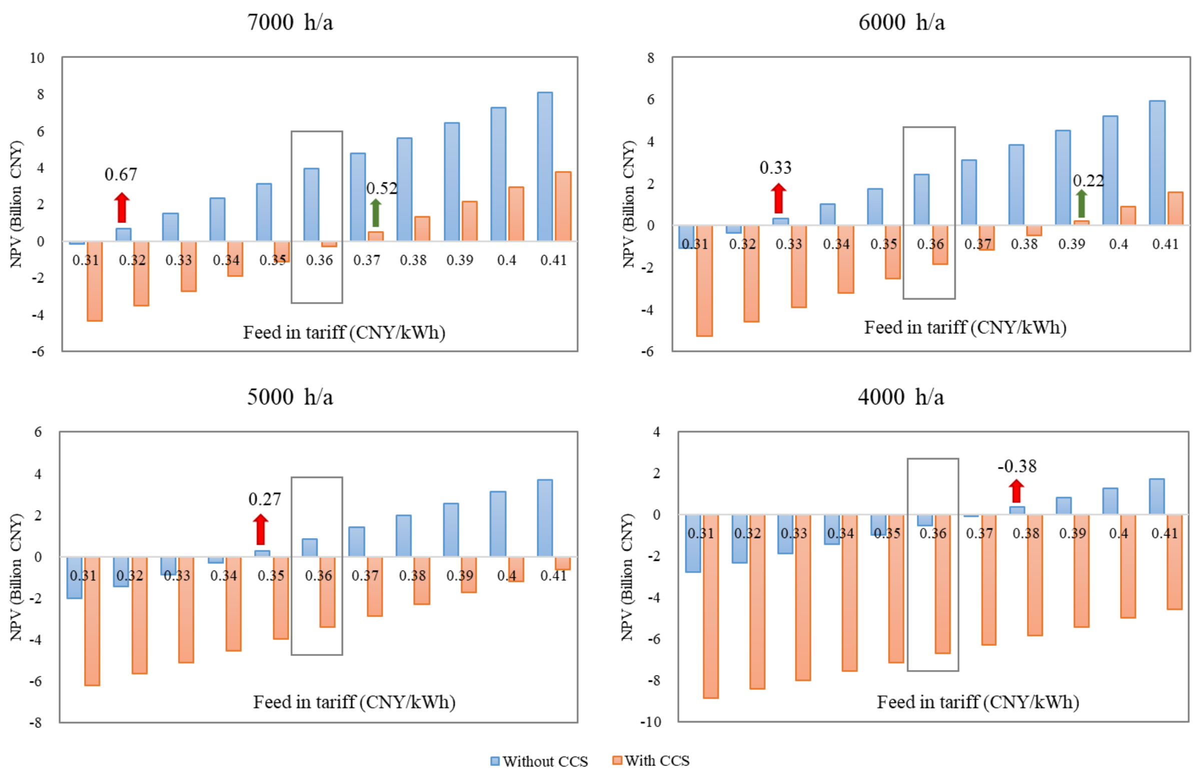

Fig.9. The impacts of feed in tariff on optimal investment value.

6. Conclusion and policy implications

Carbon capture technology is a newly-developed technology that enables the continued use of fossil fuel at large-scale. As the only means to slash emissions for existing coal-fired power plant (CFPP), CCS technology is pivotal for China which is characterized by a coal-dominated energy structure. However, CCS development is plagued with high investment cost, and traditional fiscal subsidy is not feasible in the longer term with regard to the lessons drawn from renewable energy. In this context, using the real-option analysis, a non-fiscal incentive mechanism, i.e. granting time extension (extra electricity quota), is investigated to see whether or not it can be a cost-effective manner to trigger a CCS retrofitting project immediately under low (0.1 Mt/a), medium (0.5 Mt/a) and high (1 Mt/a) capture levels, respectively. Several findings are obtained as follows:

[1] With the present electricity quota (4000 hour/a) in China, the conventional CFPP operates

at a loss, with the net present value (NPV) and levelized cost of electricity (LCOE) of -0.52 Billion Yuan and 292.2 CNY/MWh, respectively, whereas it can eliminate the losses when electricity quota increases to 4400 h/a. CCS retrofitting will further push up the losses, while carbon trading can lower the power generation cost to some extent.

[2] CFPP with CCS retrofitting is able to turn into profit if extra electricity quota can be provided. Specifically, the NPV for CFPP with the CO_2 capture level of 0.1 Mt/a increases from 0.42 Billion Yuan to 3.54 Billion Yuan as the electricity quota increases from 5000 h/a to 7000 h/a. When the capture level reaches 0.5 Mt/a, CFPP can make a profit when the electricity quota is greater than 5823 h/a. It should be noted that CFPP with the CO_2 capture level of 1 Mt/a still suffer a loss even if the highest electricity quota (7000 h/a) is provided, while it can be profitable if participating in carbon trading with the carbon price above 27 CNY/t.

[3] If the current LCOE of CFPP without CCS retrofitting is fixed, the CO_2 capture levels of 0.28, 0.57 and 0.86 Mt/a can be achieved when electricity quotas reach 5000, 6000 and 7000 h/a, respectively. Additionally, if the emission level of CFPP with CCS retrofitting is set to be equal to that of gas-fired generators, more than 40% CO_2 could be captured, resulting in a 21.3% to 37% increase in LCOE.

[4] Coal price exerts negative effects on investment value, while feed-in tariff is positively related to the investment value. The sensitivity analysis for the former indicates that CFPP with high capture level is capable of making profits only if the electricity quota of 7000 h/a is provided, and meanwhile the coal price must be cut to 440 CNY/t or less. The sensitivity analysis for the latter indicates that the profits can be made when the feed-in

tariff increases to at least 0.39 and 0.37 CNY/kWh with the electricity quotas of 6000 and 7000 hour/a, respectively. In comparison, CFPP with CCS retrofitting is more sensitive to feed-in tariff than coal price.

Overall, this study proves that electricity quota can be considered as a cost-effective manner to finance a CCS project in China, particularly in the demonstration stage. According to the estimated results, some policy implications are proposed. Firstly, the government should formulate differentiated quota subsidy policies in support of different scales of CCS demonstration projects, taking into account the installed capacity, capture level, technology application etc.. Secondly, the regions with a low coal price should be targeted as the priority areas for CCS projects. Thirdly, the feed-in tariff for CFPP with CCS retrofitting can be increased to some extent. Fourthly, a CCS demonstration project should be incorporated into the carbon trading system, which would reduce the cost of power production and extra requirement for electricity quota. Finally, we suggest reallocating electricity quotas in view of the fact that the electricity quotas are allocated by the local government. The power plant with advanced technologies should gain more quotas while power plant with backward technologies should gain less quotas. Moreover, the CFPP with CCS retrofitting should be given priority in peak load regulation of the electricity grid to get the extra electricity quota.

As a whole, pollution levels will decrease with technological innovation and equipment upgrades. In the near future, the line matching power supply will also develop rapidly with the key promotion of UHV (ultra-high voltage) engineering. Meanwhile, the foundation of new coal power industry will usher in a peak, so that the establishment of coal power capacity and electricity quota compensation mechanism will also receive more and more attention. At the same time, the development of carbon capture technology has further accelerated the commercialization process of CCS retrofitting of coal-fired power plants, and the policy incentive and subsidy mechanism has promoted the modern coal power industry to achieve carbon neutrality. Based on the above, granting a time extension (extra electricity quota) is able to finance early CCS demonstration projects in China and incentive the coal-fired power plant to implement CCUS retrofitting to some extent. We hold that more quotas can be given to power enterprises with CCS retrofitting conditions and less quotas can be given with relatively backward technology. Moreover, the policy measures proposed in this paper are only applied in the early demonstration phase of CCS development. When large-scale commercial deployment is achieved in the future, more measures will be required and therefore will not result in excess power supply and power grid burden.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: