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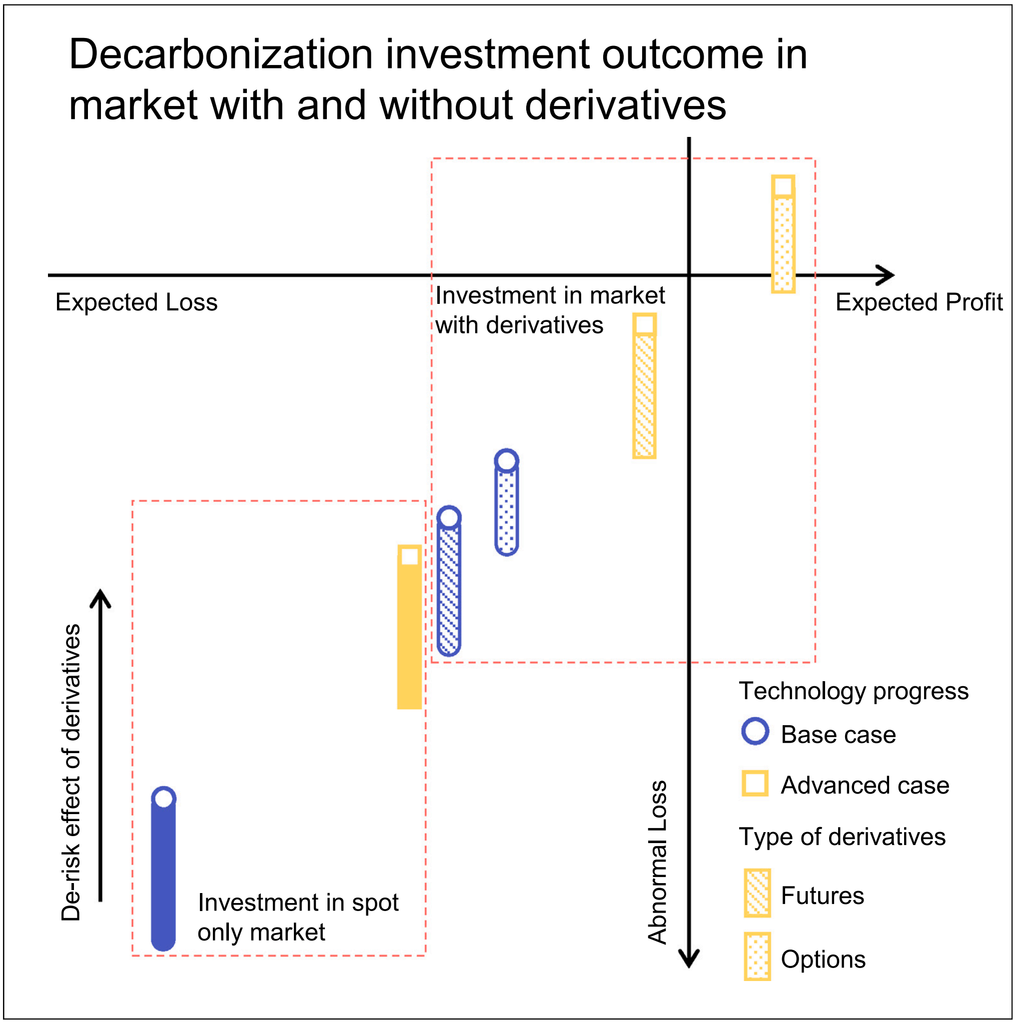

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Highlights

Decarbonization investment faces massive loss under the current emission trading system

Derivatives help projects resist loss or hold profit under market fluctuation

Investment can be feasible with 42–66% debt share when options are available

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Influence of carbon derivatives on carbon capture investments in coal-based power sector, a China perspective

Chengyao Wang[1,3,*] and Xianzhe Wang[2,*]

SUMMARY

Coal-based power sector needs deep carbon emission reduction in the upcoming 20 years to fulfill China's carbon peaking and carbon neutrality pledge. Due to the low and fluctuating carbon price in the emission trading system, decarbonization projects are risky and face massive potential losses. To promote decarbonization investment, a lot of policies of subsidy have been set forth. However, market instruments, which could be efficient and motivating for market entities, should have received more attention. In this article, the influence of carbon derivatives on decarbonization investment and financing is analyzed for different technology progresses and price trajectories. Results show that carbon futures and options have de-risking ability, lowering expected variation and financial cost, and consequently, making decarbonization project feasible. For advanced technology and optimistic outlook, investment can be feasible with 42–66% debt share when options are available. For the base case and neutral price outlook, derivatives can pull subsidy down by around 1%.

INTRODUCTION

Coal-based power sector, the largest carbon emission sector in China, accounts 50%[1] carbon emission each year. It is impossible to totally eliminate the use of coal in power sector in foreseeable future as coal power plants guarantee the stability of power grid with continuous and flexible energy output[2,3] and most plants have come into service for less than 20 years.[4] Consequently, capturing carbon dioxide from coal burning is a necessary method to achieve carbon peaking and carbon neutrality pledge[5] and fulfill obligations of the Pairs Agreement to control climate change. Currently, the total capacity of capture projects (operating and planned) in China is about 3 $MtCO_2$/year, and capacity for power sector is less than 1 $MtCO_2$/year.[6,7] In order to ensure goals of carbon neutrality and mitigation of temperature rising, total emission reduction requirement of coal power sector is 200 $MtCO_2$ per year and is supposed to be in full operation before 2040. As for short-term target, 6 $MtCO_2$ emission reduction, about 20% of emission from the coal power sector, needs to be reached by 2025.[8] Since the construction period is around 2–3 years, there is an evident gap between the capture capacity needed and potential capacity in 2025. In other words, carbon capture projects with at least 5 $MtCO_2$ have to start construction within one year.

To stimulate firms spending money in the realm of decarbonization, Chinese government has made attempts in policy with almost 1000 documents since 2006 from supply-side, demand-side, and environmental regulation perspective.[9] To facilitate firms to invest in carbon capture projects, scholars set forth creative ideas to make investing in carbon capture projects profitable. Tax exemption[10] and free allocation are the initial and mostly used methods, but may face problems on subsidies agreements and hinder reduction incentives transmitting along the value chain.[11,12] Other instruments include price floor, namely long-term options,[13] carbon contracts-for-difference,[11,14,15] and so on, which can be regarded as guarantees from government. These guarantees not only work as de-risking measures for carbon capture investments, but also alleviate governments' credibility on emission reduction policies.[16–18] Most market assumptions were static in these researches, not practical for the longevity of carbon capture equipment. Amid market evolving, financial performance for a certain project will also change. That is, investment decision depends highly on the outlook of the carbon price trajectory. Moreover, in nature, price guarantees, long-term put option, and carbon contracts are all subsidies in disguise. That is, last resort for the gap between required return and earning from carbon capture is still government expenditure. Without enough market mechanism and motivation, government subsidy easily suffers from rent-seeking or other inefficient circumstances.[19]

Emission trading system (ETS) is a market-oriented direct carbon pricing instrument via cap-and-trade or rate-based approach.[20] ETS has been placed high expectations in supporting decarbonization investment as carbon pricing will internalize emission externality, and market mechanism could ensure decisions of economic entities in line with long-term climate goal.[21,22] However, the influence of ETS is controversial from empirical studies. With different-to-different model, it's found that there are both employment double dividend and Porter effect in

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regions with ETS comparing to non-pilot provinces and cities,[23] though effectiveness is spatially uneven.[24] ETS triggers internal incentives of firms to invest in green innovation[25,26] and boost low-carbon economy efficiency not only in pilot area but also in national scale via spillover effect.[27] Other analyses pointed out ETS may not perform as well as expected. Dong et al.[28] conclude ETS works well in emission reduction but will lead to economic loss in the short term, especially in western China. Carbon trading showed little effect on emission reduction in Hubei.[29] Green technology innovation has not occurred in all industry sectors but only in resource-intensive industries.[30] Conversely, some scholars put forward viewpoints that environment regulations will not incentivize firm to invest in environmental protection[31] or only have positive influence on sectors with little pollution but negative effect on pollution-intensive industries.[32] Furthermore, for profit-seeking entities, ETS works as a route to avoid investing for environment so that restricted capital can be used in productive projects, a "crowding out" effect,[33] especially in private sectors. More trading products have been advised including derivatives[29,34]; few works make in-depth study on their effects on maximizing the function of carbon market. Most researches evaluate ETS and emission reduction effects from regional level by statistical models and influencing factors used in these models are macroscopic. In reality, investment is made by micro-entities. A project level analysis will help to understand the relationship of investment decision, outlook of carbon price trajectory, and impeding factors such as capital expenditure (CAPEX), high operating cost (OPEX), and so forth.[35]

For long-term carbon price trajectories, researches put forward several theoretical models and prediction models. In IPCC's Assessment Report, most scenarios assume carbon price to increase exponentially, explicitly or implicitly.[36] That is, emission allowance is similar to an exhaustible resource, and the price follows the "Hotelling rule"[37] that carbon price will rise exponentially with the discount rate. With carbon dioxide removal technologies, CO_2 emission budget is not strictly capped so that Hotelling rule may not reveal the economically optimal pathway.[38] Nordhaus[39] regard a linear increasing price as the optimal carbon price. From cost-benefit analysis and immediate warming response perspective, a carbon price rising at the rate of GDP growth is identified as the optimal.[40]

Besides market conditions, understanding and evaluating capture cost from plant scale are also important. Coal power plant types mainly consist of pulverized coal (PC) plants and integrated gasification combined cycle. PC plant, the traditional type, has the worst efficiency and environmental performance[41] so that bears the most emission reduction task. From a technical perspective, there are several technologies ready for commercial use, including chemical absorption, physical adsorption, and membrane separation.[42] Sub-mature roadmaps and innovations need additional R&D fundings supporting initial deployment and commercialization processes.[43,44] From cost constitution point, plant types, first-of-kind cost, operating cost, capture efficiency, and electricity penalty are prominent technical factors.[45] Capture efficiency varies with capture methods.[46] For the most widely used technology, amine-based absorption, capture efficiency is around 90% and has potential to rise higher.[47] Electricity penalty has a linear relation to capture amount when capture efficiency is not too high.[48] Other than technical factors, financing methods, and grid purchase price also influence capture cost as opportunity cost. In 2022, the financing cost for PC plant in China is around 8.19%, with equity cost at 9.04% and after-tax debt cost at 4.77%.[49] The average grid purchase price is ¥0.469/kWh according to statements of listed power companies.

In this article, we focus on analyzing influence of carbon derivatives on decarbonization investment decisions of PC plants from micro-perspective. An idealized PC plant is used in this study since this kind of power plant plays an important role in smart grids and will exist for a long time in the carbon neutrality stage.[50] Three price trajectories, price submitted to Hotelling rule (HOT), increasing linearly (LIN), and growing at GDP growth (GDP), are analyzed. To evaluate factors on carbon capture cost and study levelized cost of captured CO_2 (LCOC), a techno-economic analysis (TEA) model is established. Then we evaluate effect of derivatives with a project-level risk-return trade-off framework.[51] Boundary conditions for bankability and dependence on subsidy are explored by Value-at-Risk (VaR) method with Mont Carlo simulation.

CO_2 utilization and carbon markets in China

Carbon dioxide itself is not a widely traded commodity under status quo technology. Although several roadmaps are promising to be mature in the near future to utilize CO_2, such as chemical or biological processes and mineral carbonation, only enhanced oil recovery (EOR) have reached commercial phase in large scale now. Up to the end of 2022, twenty-six CO_2-EOR projects have started operating in China.[52] CO_2-EOR projects not only vest carbon dioxide with economic value, but also reduce emissions from oil extraction by about 400 $kgCO_2eq/bbl$.[53] Nevertheless, retrofitting extraction facility to CO_2 flooding EOR needs high capital investment, around ¥ 40/bbl.[54] The highest CO_2 price to make EOR project profitable is lower than ¥ 200/tCO_2[54,55] without subsidy. Sectors with high CO_2 concentration gas are fitted as source of CO_2 for EOR project, such as coal chemical industry and ammonia processing, rather than sectors with fuel combustions.[53] Beyond cost, most EOR sites locate in the northwest and northeast China, and coal-based power plants mainly operate in the middle and southeast. Only 12% coal-based power plants are suitable as CO_2 source for EOR[6] so that it's difficult for coal-fired power plant to get revenue directly from carbon captured.

In this article, the analysis focuses on revenue from selling emission allowance in ETS. Up to the end of 2022, there are one national ETS and eight regional ETSs in China. Generally speaking, a rate-based approach is performed; that is, emission intensity is emphasized. The first regional pilot ETS was launched in 2013[56] and national ETS started to run in 2021.[57] Product in national ETS is spot Carbon Emissions Allowance (CEA) and regional ETSs support local emission allowance as well as certified emission reduction and forward contracts of emission allowance. CO_2 emitters acquire emission allowance from regulator and are supervised on the amount of emission. Allowance no less than emission is required to turn over after each period of settlement. National ETS includes power sector that covers around 2000 firms, and this article will focus analysis on nation ETS due to the simple market relationship. In national ETS, CEA is allocated by Ministry of Ecology and Environment and settled every year.[58,59] In practice, amount of allowance of a certain entity is granted by the regulator of province. The

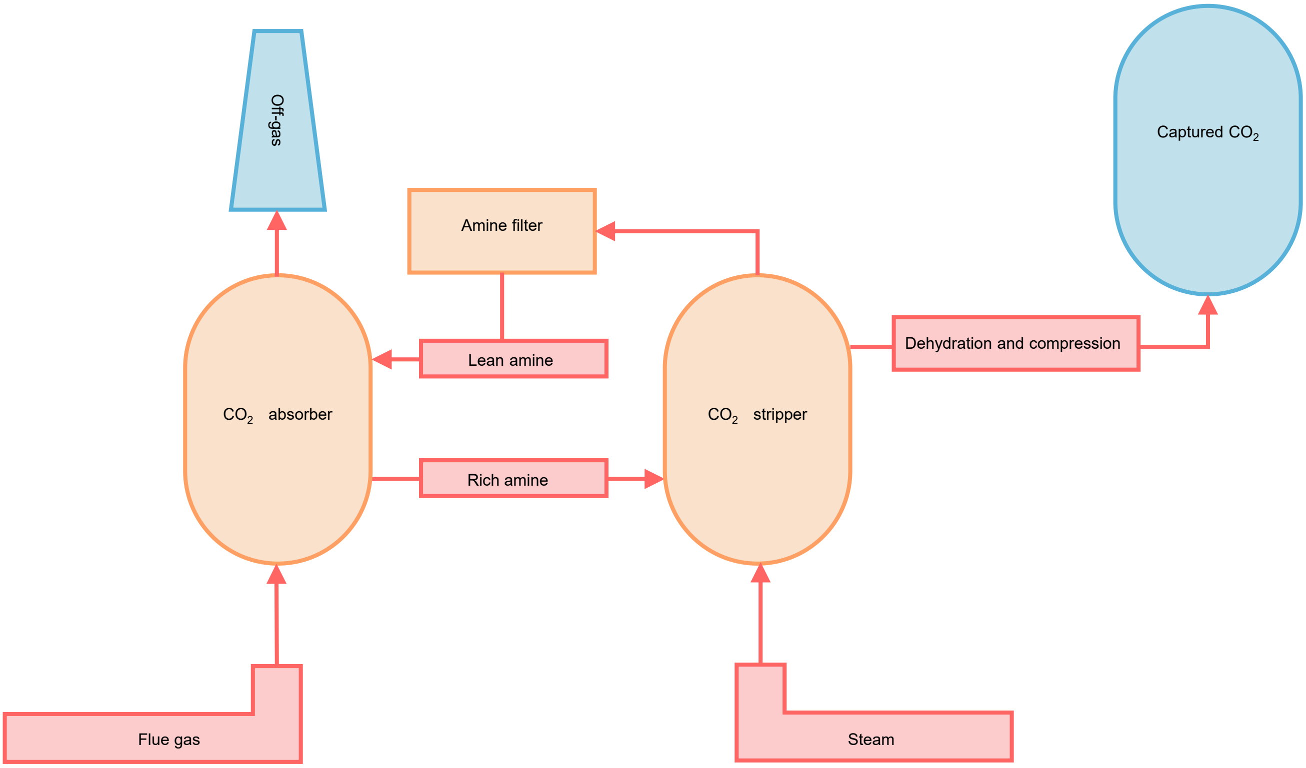

Figure 1. Schematic of a typical amine-based post combustion capture system

national total allowance is the sum of allowance granted by each province. At present stage, allowance is granted free. Firms will receive around 70% of allowance in the middle of the settlement year based on the estimation of power supplied, and get all allowance in the next year according to electricity generated in the corresponding year. A surplus allowance is allowed to cover deficit in the following settlement period. Actual emission is inspected through the fuels consumed in the settlement period. Carbon content of fuel is detected for 93% of firms and the rest is set as the upper value of province.

Initial carbon price was set by MEE in 2021 at ￥45.28/tCO_2 (exclusive of 6% value added tax), and then is determined by the bid-ask mechanism in Shanghai Environment and Energy Exchange. Up to the end of 2022, total trading volume is 230Mt and average carbon price is ￥50.94/tCO_2. Prices and trading volume of CEA are volatile, affected by the settlement period to a large extent. For the first month of the start of national ETS, average price is ￥47.71/tCO_2, 5% higher over opening price. The highest price is ￥59.43/tCO_2 and emerged in the last month of the first settlement period. The lowest price, ￥29.02/tCO_2, also emerged in the last month. Trading volume appears the similar situation. 76% transaction of the first settlement year (5.5 months) happened in the last month. The highest daily trading volume is 2 million times of the lowest in the first year. This phenomenon occurred mainly due to the powerlessness of firms to manage their allowance asset. At early stage of settlement period, companies tend to hold all CEA to address risks of over-expected emission and those lacking allowance tries to fill the gap, leading to high prices. When the settlement date approaching, those without enough allowance have to solve the problem as soon as possible and those with redundant allowance are inclined to sell all untapped CEA to get revenue. As a result, extreme high and low prices arise. In this article, we assume that there exist counterparties to achieve a transaction and the start price of allowance is ￥51.89/tCO_2 (equivalent to ￥55/tCO_2 with value added tax).

RESULTS

Techno-economic analysis of carbon capture

As introduced in introduction, there are several pathways to capture carbon dioxide. In this article, amine-based post-combustion capture system is used for the TEA model as it is the most suitable way to equip established power plants and is the most mature technology.[60] The carbon capture system consists of CO_2 absorber, CO_2 stripper, amine filter, and CO_2 compressor. A schematic of the post-combustion system is shown in Figure 1.

Under the base case assumption in the STAR Methods section, LCOC of a typical post-combustion capture system is ￥364.36/tCO_2. A sensitivity analysis was carried out to find dependence of LCOC on external and new-facility-related parameters, change by 20%. A local analysis is conducted so that the independent influence of each factor is revealed. CAPEX, OPEX, capture efficiency, electricity penalty, loading factor, and financing cost are the top influential factors. We can see in Figure 2 that LCOC is most sensitive to financing cost. When financial

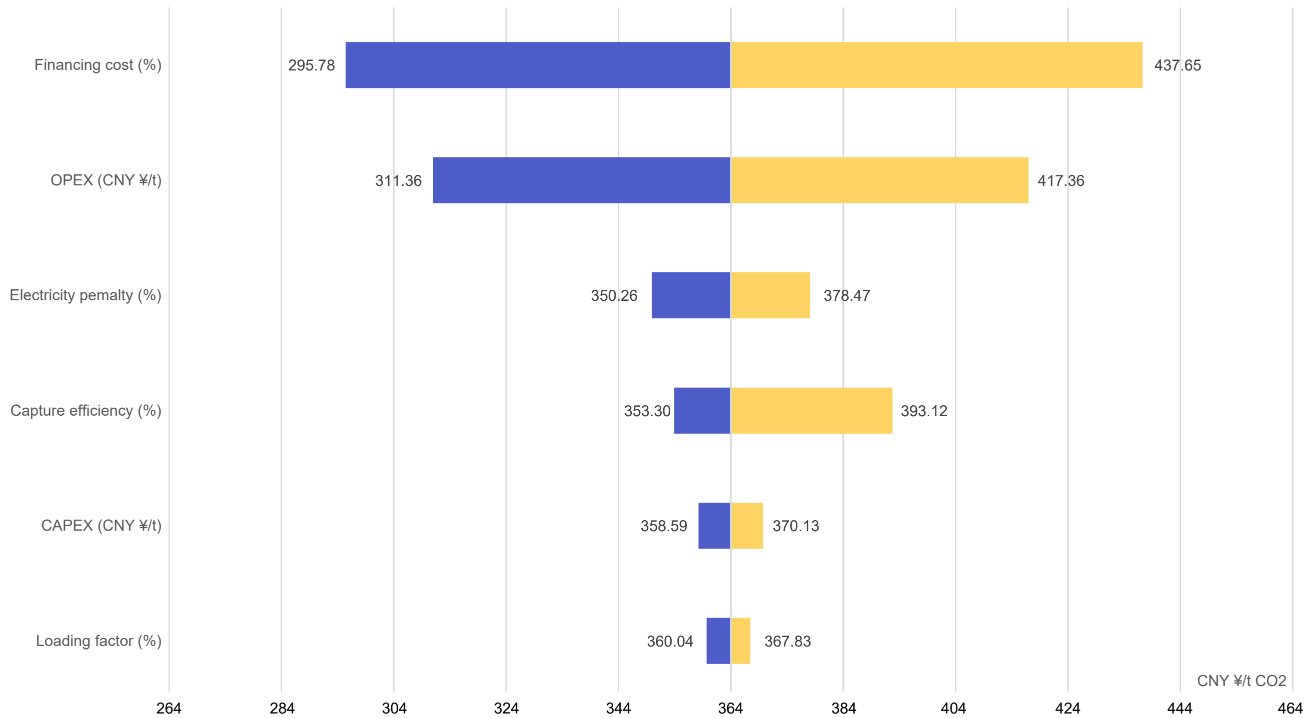

Figure 2. Sensitivity of LCOC to different parameters

cost ranges from 7.23 to 10.85%, LCOC fluctuates between ¥ 295.78–437.65/tCO_2; ranging extent is around 20% of base LCOC. Financing cost, namely discount rate, interacts with the status quo and outlook of carbon price via financing means of investments. We will discuss financing methods and investment decision in detail in the following section. Followed by financing cost is OPEX. LCOC changes about 15% as 20% OPEX change, from ¥ 311.36/tCO_2 to 471.36/tCO_2. Capture efficiency has asymmetrical and counterintuitive influence. When capture efficiency drops to 72%, LCOC increase to ¥ 393.12/tCO_2. Upper limit for capture efficiency is 100% so that the levelized cost can decrease up to around ¥ 10/tCO_2. The variance amount of LCOC to capture efficiency is much less than intuition. A 20% decrease in capture efficiency which will leads to less CO_2 captured and a huger absorber to meet capture goal, only results in 8% higher LCOC, and 10% efficiency improvement brings about less than 3% cost benefit. This is because the marginal effect is not taken into account. For a general model for investment decision, capture efficiency is a temperate factor. Electricity penalty has a mild effect on LCOC, making a change in the LCOC about ¥ 15/tCO_2. Initial investment has a small influence considering the long serving period. The loading factor plays a non-linear role on the levelized cost as emission characteristics varies while loading ranges widely. Under constant capture efficiency assumption, loading factors' influence is not significant.

Besides the base case, two more scenarios, advanced and marginal cases, are considered in the following analysis. In the advanced scenario, factors influence LCOC decrease considerably via technology progress according to researchers' predictions. Detailed assumptions are described in STAR Methods. Advanced LCOC decreases by 17% to ¥ 302.68/tCO_2. Marginal cost is the unit variable cost under advanced case, which represent the bottom CEA price that can maintain the daily operation of a project. Marginal LCOC is ¥ 285.59/tCO_2.

These two scenarios are based on brand-new investment assumption. That is, a total set of carbon capture equipment is affiliated to existing PC plant. As just mentioned, some technology improvement will bring marginal effect, exerting noticeable effect on operating projects. For a base case operating facility with 20-year life left, an increase in capture efficiency to advanced scenario, 92%, will drag capture cost by ¥ 8/tCO_2, equivalent to a 7% decrease in CAPEX. OPEX and electricity penalty have marginal effect on LCOC at ¥ 65/tCO_2 and ¥ 14/tCO_2, equivalent to CAPEX decrease by 55% and 12%, respectively. As there are few operating carbon capture facilities in PC plants, this article concentrates on new investment. While more and more projects go into operation, a detailed analysis from economic perspective on technology updating will be necessary.

Investment decision solely with equity financing

We firstly investigate project decision totally financed by equity with cost at 9.04%,[49] which tends to be the most likely financing cost for a risky investment. We compared investment timepoint of three LCOC scenarios under different price trajectories. In order to directly show outcomes under different assumptions and price changes, we calculated the market equivalent price of CEA (EPOC) under each price trajectory (STAR Methods), representing expected revenues if investment occurs in a certain year, besides projects' net present value (NPV) factor.

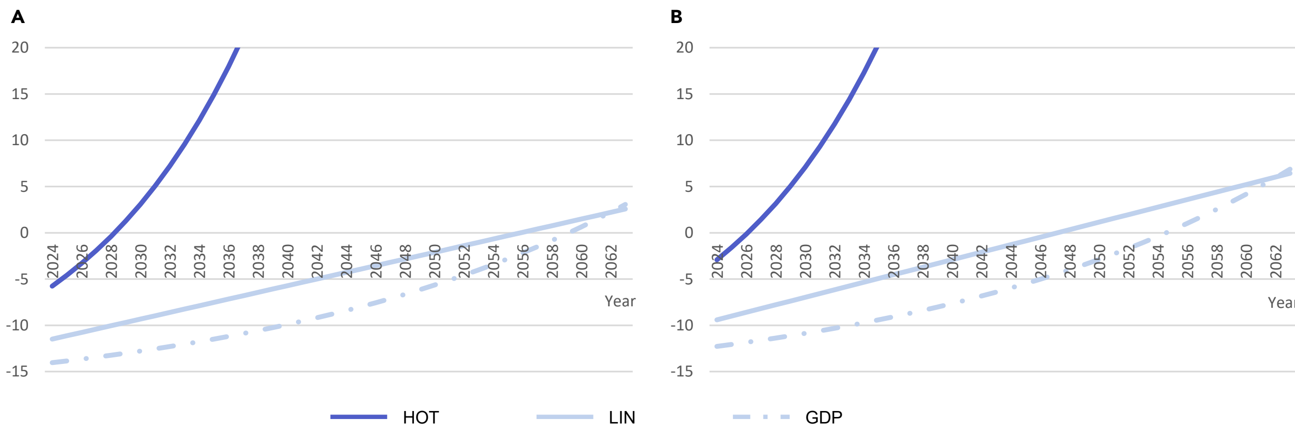

Figure 3. NPV factor of investment under base and advanced case for three price trajectories
(A) Base case and (B) Advanced case.

NPV factor in spot only market of each trajectory is shown in Figure 3. NPV factor of current investment is less than −1 no matter for base or advanced case, which means no initial commitment can be realized in the working period but operating cost requires additional investing. Base case investment will gain an NPV factor over zero in 2029 under optimistic price assumption (HOT) but will remain negative NPV factor before 2060 under GDP, near the end of project life. For advanced case, a positive NPV factor will occur as soon as 2027 and become lucrative in 2055 for all trajectories. EPOC gives the same conclusion more intuitively, shown in Figure 4. EPOC for HOT penetrates up advanced cost in 2027 and base cost in 2029. GDP achieves the same effect in 2055 and 2060, respectively. EPOC of LIN is higher than that of GDP before 2061. That is, under LIN assumption, investment will suffer less loss in the near future. As for yearly operating outcome in the near future, no operating profit can be achieved before 2041, and operating loss may maintain over 2063. It is obvious that investing in carbon capture projects now is not financially viable. Without essential improvements in financing method and operating efficiency, projects are not able to survive independently in near future. Existing carbon capture projects are not decided out of economic considerations but out of ESG concerns or political issues, as most power companies in China are state-owned business. This conclusion corresponds to empirical studies and the "crowding out" effect mentioned previously.

We take in to account two derivatives, futures and options, to evaluate the influence of derivatives on investment decision. The maturity time of these products are set to be 2 years. The exercise price of option is set at the marginal cost, the lowest price to maintain carbon capture system. Figure 5 shows EPOCs, as well as the coefficient of variation (CV) of EPOCs if hedging with each derivative. Cashflows of futures are based on the expected price of CEA from each trajectory. Prices of options and CVs of EPOCs are derived from a Mont Carlo simulation. Due to hedging cost and opportunity cost, EPOCs under all price assumption decrease at different degrees. For HOT, futures drag EPOC down by around 5.4% as pricing mechanisms of futures will make short seller suffer when price surges rapidly and options make EPOC decrease by 1.6% due to option fees. For GDP and LIN, option have more influence on EPOC than futures, since prices in most of the capture system's life period are lower than the marginal cost and options burden power plants with fees. In other words, NPV factor of project decreases and break-even time for carbon capture investment defers correspondingly. However, as for CV factors, derivatives have positive effects. Futures contribute to the stability of EPOC by 3%–11%. Options, providing insurance for OPEX, significantly reduce the fluctuation of EOPC, by 23%, 85%, and 99% for each trajectory.

Previous outcomes show investing in carbon capture facility currently total with equity funds for PC plants may not be an economic feasible decision, even OPEX itself cannot be covered. Under the most optimistic assumption (HOT price trajectory and advanced case), rational investment will happen in about 4 years (Year 2027). Derivatives are not directly economically useful for equity funds but still have some effective influence for certain companies. As mentioned previously, some firms are willing to precipitate money in carbon capture projects for purposes other than economic return. For these investors, economic factors impacting decision most are not profit but the largest loss. With derivatives, the expected loss can be better controlled, as shown in Figure 6. For the base case, futures can narrow the abnormal loss rate (gap of NPV factor between expected and risk situation) by 0.3%–2.6%; and option can do by 2.3%–4.2%. In absolute value, under HOT, the excessive loss is ¥ 59 million less in a market with futures and ¥ 165 million less with options. For GDP assumption, the loss is alleviated by ¥26 and ¥208 million; for LIN, the number is ¥24 and ¥177 million (Table 1). Even if NPV is still negative, making the largest loss under control is a positive incentive for companies to invest for non-economic objectives.

Investment decision with debt capital and governmental subsidy

As equity can absorb some risks, debt capital has more certain cash flow and always requires lower premium than equity. In power sector, cost of debt is 4.77%,[49] around half of the cost of equity. If a project is financed by equity and debt, LCOC could decrease further and a project is easier to be feasible. However, excessive debt may lead to high bankruptcy risk and push up the financing cost. To analyze projects' feasibility

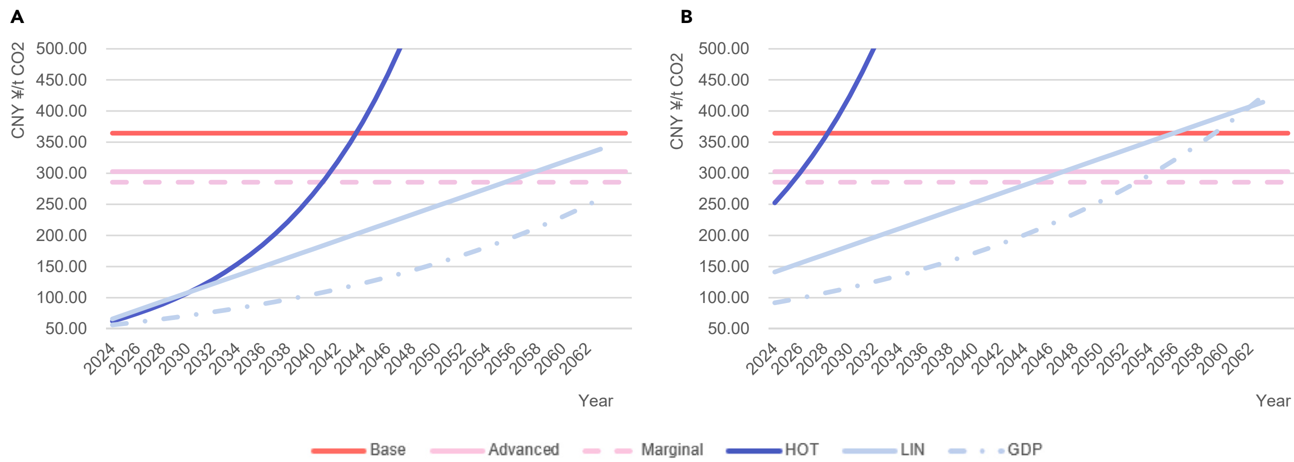

Figure 4. Expected price, EPOC of each trajectory compared with LCOC under different scenarios

(A) Expected price of CEA and (B) EPOC for three trajectories.

in detail, we adopt a risk-return trade-offs framework based on project finance and financial management.[51] We try to reveal whether debt capital is acceptable in the presence of derivatives, and the viable equity-debt mix under uncertain carbon price.

Figure 7 shows LCOC in two cases with different debt ratios and EPOC under three trajectories. Under the best equity-debt mix, LCOC decreases to ¥357.97/tCO_2 and ¥297.02/tCO_2 for the two cases, 1.8% and 1.9% lower than that with equity financing only. Correspondingly, equivalent price rises as high as ¥320.25/tCO_2, ¥100.11/tCO_2, and ¥153.44/tCO_2 for three trajectories. Although investments under most assumptions are still not economic feasible, decision for a certain project may reverse to viable after debt introduced under the most optimistic price assumption, HOT.

To further evaluate investment decisions under uncertain carbon price, we separate advanced LCOC into OPEX, interest, and equity premium; we also run a Mont Carlo simulation to mimic carbon price pathways for VaR analysis. LCOC components for advanced case is plotted in Figure 8, compared with expected EPOC in HOT and its 99% and 95% likely range with and without derivatives. OPEX consists 94%–96% of LCOC and needs to be totally financed out of the revenue from selling allowance since no operating can maintain without enough cashflow. Interest, the incremental cost derived from debt, also requires certainty to some extent. Equity premium is served posterior after all expenditures. Revenue under 99% confidence limit is considered to be certain income that can serve OPEX and interest. Revenue over 99% but under 95% likely range can be regarded as sub-certain to serve interest. Revenue over 95% likely range is uncertain income that has to be financed by equity and revenue over the expected value is almost to be financed by subsidy. Without derivatives, the highest debt share is zero as certain revenue cannot fulfill OPEX no matter for base or advanced case, the same conclusion in the previous section. Futures makes

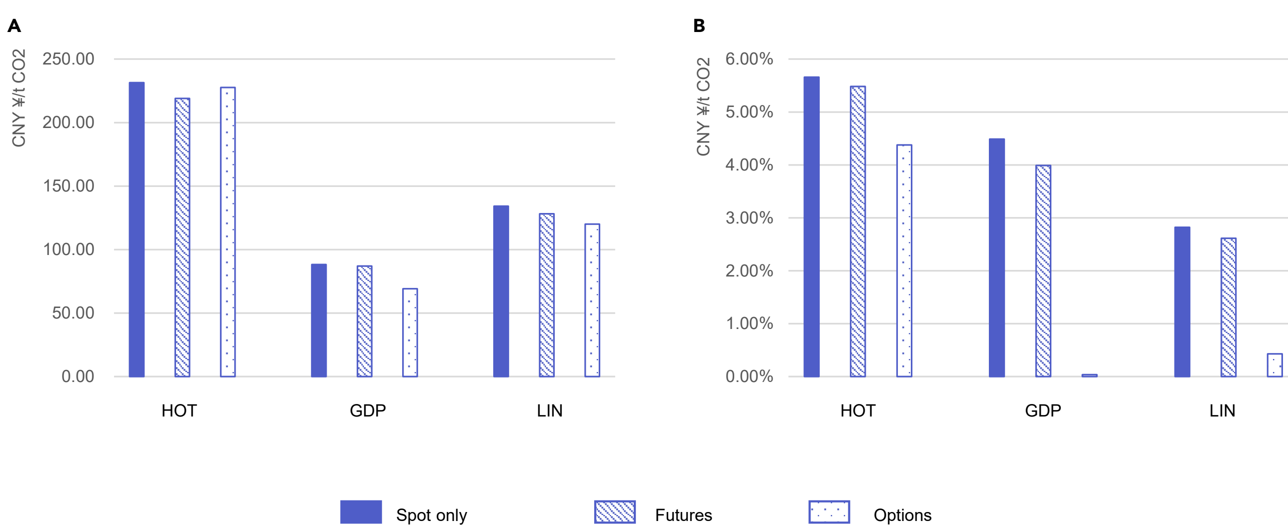

Figure 5. EPOC and coefficient of variation of EPOC with and without derivatives

(A) EPOC and (B) CV of EPOC.

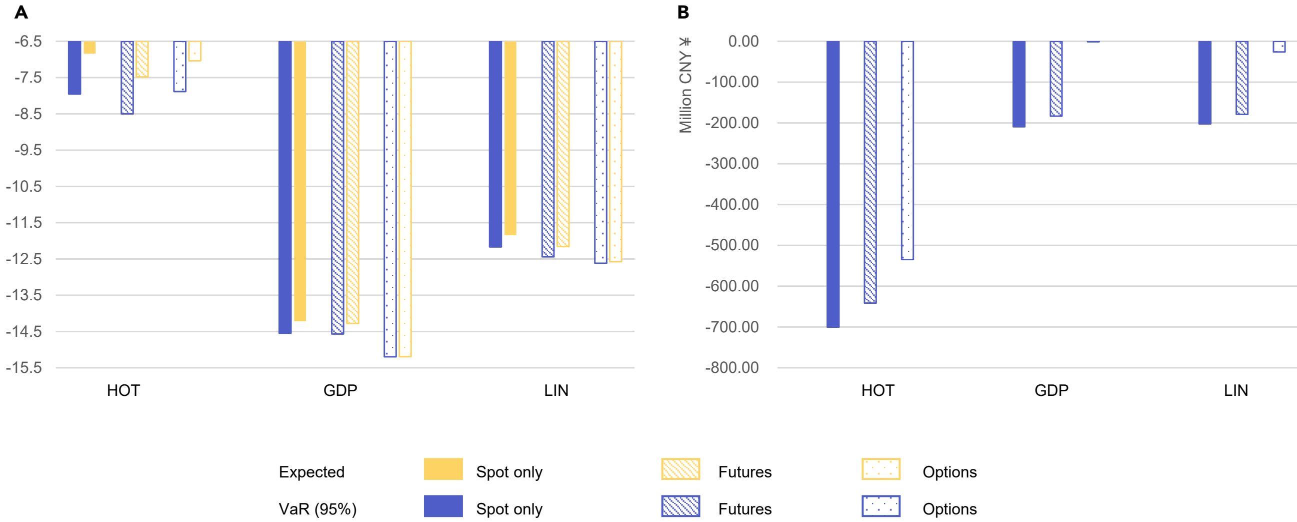

Figure 6. NPV factor and excessive loss for the base case

(A) NPV factor of VaR (95%) and (B) excessive loss.

little improvement to promote investment and even bring EPOC down because of frictions in transaction. Options deliver positive outcome for advanced case. In this scenario, carbon capture investment produces operation surplus with debt share from 42% to 66%. As for debt, revenues are able to cover interest with debt share between 37% and 69%. Equity premium can be served within reasonable risk interval. Overall, feasible debt share interval is 42%–66%. In short, advanced case under HOT trajectory is economic feasible when options added to the market.

Effect of derivatives may seem limited in the previous analysis as there are strict conditions such as technology progress and specific carbon price trajectory. However, if subsidy is considered, derivatives are still able to exert useful influence on carbon market. When carbon price outlook is not as optimistic as HOT or technology progress is not mature enough to reach advanced case, carbon capture investment has to be subsidized by government to maintain. Subsidy mainly contain two parts: rigid part to serve OPEX, sub-rigid part to serve debt. Options can change the structure of subsidy. Under the most conservative price assumption (GDP), options make a decline of rigid subsidy by 1.1% for the base case with almost no change in the total amount of subsidy. Under LIN, the total subsidy descends a little and rigid part decreases by 1.7%. For HOT assumption, rigid subsidy decreases by 16.9% for the base case (Table 2). In view of a 600 MW project with forty-year life period, the present value of rigid subsidy will decrease by ¥ 131–518 million for different trajectories. Even if all sub-rigid part were realized, options could still pull the present value of all subsidy down by 11–35 million, a sizable amount in carbon capture investment.

Policy implication of carbon derivatives

As one of the direct carbon pricing instruments, ETS is considered to be able to limit and reduce CO_2 emission in a cost-effective manner. In practice, effect of ETS depends on many political and economic issues.[56,61] Volatile carbon price weakens the effect of ETS because of high risk. Carbon derivatives help project resist abnormal loss or hold necessary profit under market fluctuation, acting as an additional policy tool

Table 1. NPV factor, VaR (95%), and abnormal loss for the base case

Price trajectory	Type pf derivative	Expected NPV factor	NPV factor VaR (95%)	Abnormal loss (Million CNY ¥)
HOT	Spot only	−6.84	−7.95	−700.27
	Futures	−7.48	−8.50	−641.62
	Options	−7.04	−7.89	−534.88
GDP	Spot only	−14.22	−14.55	−209.38
	Futures	−14.28	−14.57	−183.15
	Options	−15.20	−15.20	−1.14
LIN	Spot only	−11.85	−12.17	−202.42
	Futures	−12.16	−12.44	−178.76
	Options	−12.58	−12.62	−25.88

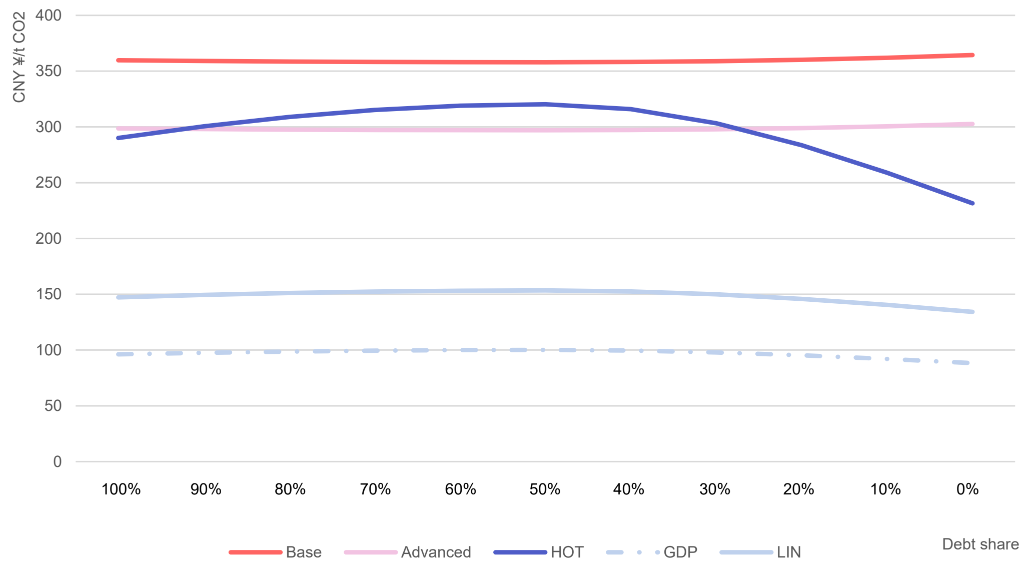

Figure 7. LCOC and EPOC under different debt ratio

of ETS to stimulate carbon capture investment. Derivatives optimize ETS by empowering projects with ability to bear reasonable debt and lowering financing cost of projects. From whole society perspective, total cost of decarbonization also decreases due to less subsidy required, especially rigid subsidy.

The carbon market itself faces several other challenges, such as carbon leakage, perverse incentives, and so on.[22,62] Carbon derivatives could act as complementary tools to alleviate some challenges other than direct positive impact on low-carbon investment, but still has some downsides.

Carbon leakage derives from carbon policy discrepancy of different countries or jurisdictions. Economic entities are inclined to move product line from areas with stringent emission regulations to those with mild or no regulations.[63] ETS in China has not widely encountered this situation just because power plant is difficult to move and carbon cost can't flow along the value chain due to electricity price control from government. As more sectors are included in ETS, carbon leakage will become an essential problem.[64] Climate excise contribution is proposed as an effective way to restrain carbon leakage, which applies a uniform excise duty on carbon-intensive products. To avoid double charging, free emission allowance is allocated to producers.[65] Allocating futures or call options could create a long-term stable outlook of decarbonization project and production, encouraging investment. Furthermore, derivatives are tools for price discovery, releasing useful signal on future emission situation to the market. Besides producers, consumers also have motivation to carry on transactions to hold price outlook of raw materials with high emission. Margin trading mechanism will attract speculators, providing liquidity and smoothing abnormal fluctuations.

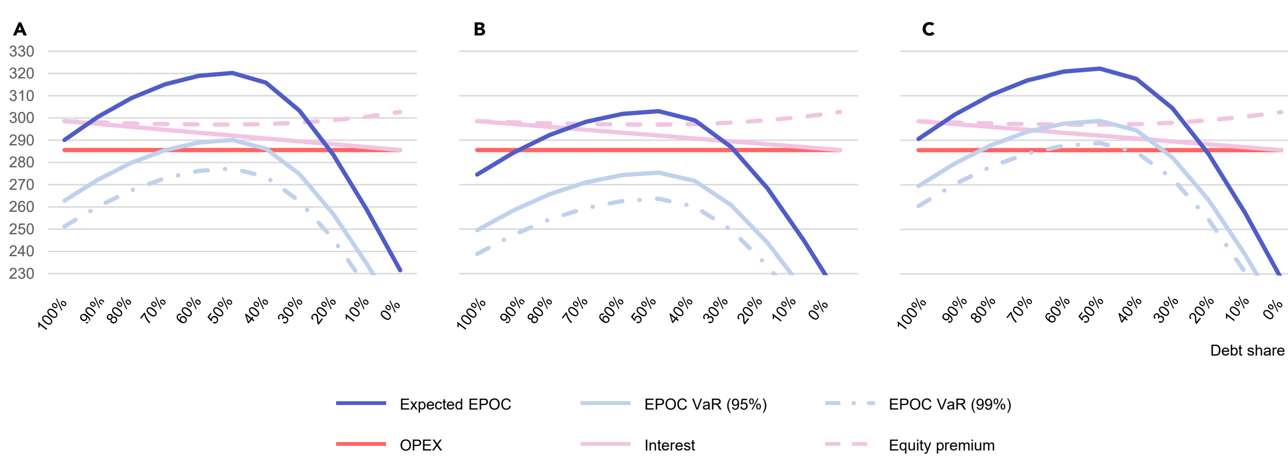

Figure 8. Component of advanced LCOC, EPOC and EPOC VaR at different debt ratio

(A) Spot only market, (B) Market with futures, and (C) Market with options.

Table 2. Subsidy structure for different assumptions for the base case

Price trajectory	Derivative condition	Rigid subsidy	Sub-rigid subsidy	Change in PV of rigid subsidy	Change in PV of total subsidy
HOT	Spot only	68	0	−518	−518
	Options	56	0		
GDP	Spot only	256	4	−131	−11
	Options	253	7		
LIN	Spot only	202	4	−153	−35
	Options	198	7		

Perverse incentives always arise under rate-based ETS with high carbon price. Revenue from carbon markets may make some high-emission sectors more profitable, promoting capacity growth and leading to even higher emission amount than that without ETS, especially if emission sectors are not totally included in ETS.[66] Derivatives as a de-risk instrument against potential risk from market fluctuation may amplify the perverse incentive, hindering emission reduction goals. Effective incentive depends on specific allocation mechanism for each sector, requiring detailed operating and emission data of each industry, just as the work for power sector.[67] As some derivatives are settled in cash instead of emission allowance, market transaction may be biased. Elaborated trading rules are necessary and need evolving according to market condition.

In summary, ETS could be more effective in booming investment, preventing carbon leakage, and enhancing market efficiency with derivatives. Nevertheless, drawbacks require more attention as derivatives may intensify some shortcomings.

DISCUSSION

This article analyzes role of market derivatives, instead of subsidy in disguise, in promoting PC plants investing in carbon capture projects, besides spot allowance trading. Return of carbon capture projects is quantitively measured. To evaluate revenue and cost through the long life-period of projects, LCOC and EPOC are used to reflect projects' profitability. The promoting impact of futures and options are assessed from de-risking and decreasing cost perspective, comparing to a spot only market. Options are found to be effective, stabilizing the outlook of a project. Instead of totally equity financing in spot market, debt financing is acceptable under certain situation with derivatives, leading to less financing cost for a project. These results indicate that derivatives do have ability to support investors in carbon capture projects to resist risk from uncertainty in the carbon market. Other than direct subsidy, price floor, or contracts-for-difference, there also exist market instruments that will facilitate carbon capture investment. Contrary to static subsidy, carbon derivatives, as financial products, are priced and circulated according to market mechanism, which not only stabilize revenue, but also provide financing convenience.

For advanced case under optimistic price trajectories, derivatives help carbon capture investment in the near future become economic acceptable for PC plants. Even though most cases still face deficit after options introduced, subsidy needed for projects to maintain break-even decreases. In addition, character of subsidy changes, rigid subsidy constitutes less part in the total subsidy. For advanced case under HOT trajectory, it is almost certain that with options, carbon capture project will serve debt with share between 42% and 66% and make surplus for equity holder, no need for subsidy from government. For the base case under HOT, the biggest operating loss decreases by 16.9% percent. That is, 16.9% less of rigid subsidy. For base case under GDP and LIN assumption, rigid subsidy decreases by 1.1% and 1.7%. Consequently, NPV of government expenditure on rigid subsidy decreases.

In addition to alleviating risks that carbon capture projects face from carbon price, derivatives have more potential contributions to decarbonization process as a complementary policy tool. CEA prices nowadays are deemed to be lower than reasonable by some scholar; derivatives provide more channel for market mechanism helping CEA price discovery, leading to a price better reflecting average cost of emission reduction. Besides the power sector, derivatives could also be a hedging method for other environmental investment. That is, more decarbonization resources could be excavated, lowering comprehensive emissions reduction cost of society. If global emission considered, derivatives can supplement climate excise contribution to impede carbon leakage. Via cross-market arbitrage, abnormal cave, and fluctuation will be smoothed, maintaining global carbon market effectively.

Limitations of the study

Four key limitations exist in the realm of this article. Firstly, we treat CEA as securities and the term structure of CEA derivatives are designed as financial commodity. It's appropriate for market participants with continuous hedging purpose but not for speculator. In the real carbon market, CEA is a special transaction object. Total tradeable volume is decided by allocation policy and operation situation of specific sector. CEA has certain maturity date and may encounter liquidity deflation near settlement date. Inner value for different plants varies due to different efficiency and allowance held, so that trading behavior is not decided solely by price. Trading features of CEA are lacking to form well-designed structure and pricing theory of derivatives.[68,69] A more profound study of the nature and characteristics carbon market is needed for elegant derivatives.

Secondly, as for financing methods, we adopt project finance frame, as depicted in STAR Methods. Although there are reasonable arguments that most decision makers will choose project finance method to evaluate new decarbonization projects, some firms may prefer corporate finance channel considering financial cost, regulation of state-owned-enterprise, or requirement of audit.[70] If a project investment is evaluated from whole corporate perspective, the financing cost will change among projects. So will project feasibility.

Thirdly, some input parameters and assumptions may bring about errors on analysis outcomes. The technology improvement rate could be higher or lower than expected, influencing the effect of derivatives. Due to the low maturity of China's ETS, historical carbon trading statistics used in analysis may not reflect future trading condition. There is no consensus on carbon price distribution, and that used for simulation may be biased. Price trajectories may also go out of presupposed direction. With technology and market gradually become mature, studies could be conducted to more preciously inspect the role of carbon derivatives.

Finally, as discussed in TEA result, technology progresses have marginal effect on operating equipment. Economic performance of existing facilities upgradation may be different from newly built project discussed in this article. Consequently, key factors influencing decision on retrofitting may be different. With the process of more and more decarbonization facilities starting to build in China, consolidated analysis of technology advances and updating equipment in operation will help achieve lower the decarbonization cost of whole society.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Data of CEA trading	China Caron Emissions Registration and Clearing Co., Ltd	https://www.chinacrc.net.cn/list/18.html
Software and algorithms		
TEA model	Hao et al., 2020[88]	https://doi.org/10.1016/j.est.2020.101273
Financial management model	Gatti, S., 2019[51]	https://doi.org/10.1016/C2016-0-01618-2
Microsoft Excel	Microsoft Corporation	https://www.microsoft.com/zh-cn/microsoft-365/excel

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to the lead contact, Chengyao Wang (wangchengyao@shiep.edu.cn).

Materials availability

The study did not generate new materials.

Data and code availability

- The data reported in this paper will be shared by the lead contact upon request.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

TEA model for carbon capture and sensitive analysis

Key assumptions of the TEA model were summarized in Table. Installed capacity of coal-fired power plant varies a lot in China, from less than 100 MW to over 1 GW.[71] In the base case, a coal-fired power plant installed capacity is set to be 600MW considering the eliminating backward production capacity policy. The emission coefficient is estimated by the average emission data in 2021.[72] CAPEX of carbon capture system is decided by design parameters and other process variables and is set as the average according to the installed capacity in the base case.[73–76] The capture rate and electricity penalty are estimated according to the feature of a MEA-based system which is the typical technology pathway adopted in this article.[7,73,77] Operating cost is influenced by several internal and external factors, including working phase and character of heat transfer medium, operating pressure, price of fuels, and so on.[45,78,79] The average is adopted for the base case. So is the transport and storage cost. Construction of carbon capture facilities begins at the start of 2023 and system comes into use at the end of 2024. Salvage value at the end of project is 20% of the initial CAPEX and the future value is set to be zero. All cashflow is discounted to the start of 2023 (the starting year of project). Tax reduction from annual depreciation is not taken into account.

Parameter	Value
Assumption for the TEA analysis of carbon capture system	
Installed capacity (MW)	600
Emission coefficient (tCO_2/MW)	0.8210
Capture efficiency	90%
Unit CAPEX (CNY/kW)	1050
Operating cost (CNY/MW)	265
Electricity penalty	11.1%

(*Continued on next page*)

Continued

Parameter	Value
Allowance coefficient (tCO_2/MW)	0.8159
System life (year)	40
Maintenance cost per annum	5% of CAPEX
Loading factor	85%

A sensitive analysis is conducted to evaluate influences of parameters on LCOC and figure out the important ones. As a standardized way to interpret TEA results, sensitive analysis can be explored based on the uncertainty of primary data, financial assumptions, and state of technology.[80] In this article, factors that play a role in investment decision and essential to advanced case for following analysis are mainly focused. A local sensitivity analysis is applied to recognize quantitative relationship of each factor and LCOC.[81] Two external factors, financing cost and loading factor, are tested, which reflect influence from financial market and power market on investment decision. Technology factors related to newly built facility are concentrated, including capture efficiency, unit CAPEX, OPEX, electricity penalty, system life, and maintenance cost. All parameters are changed by 20% to compare the influence on LCOC. Parameters about the existing power plant are taken as precondition for carbon capture investment.

According to the outcome of sensitive analysis, four factors have obvious influence on new project are adopted to construct advanced case. For initial investment, lower CAPEX at ¥ 950/kW is taken for advanced scenario, which could be achieved via optimizing the industrial chain of construction, upgrading absorption cycle, and so on.[82–84] Capture efficiency and electricity penalty is supposed to rise by substituting absorbing solvents, such as mixed-amine and organic acid, and modifying capture process.[85,86] As high as 93% capture efficiency can be realized under ideal condition. 3-15% energy will be saved under optimized process, equivalent to an electricity penalty at 10.77-9.44%. In advanced case, capture efficiency is considered to be 92% and electricity penalty to be 10%. Transport and storage cost depends on scale effect to large extent. As large-scale construction of transport infrastructure and storage site for CO_2, in advanced case, these two parts of cost are set as expected forward marginal cost.[87–89] So that OPEX is 215 in total. In advanced case, LCOC is considered from a completely new-built perspective.

Financial management model

We adopt a general project finance model to evaluate the feasibility of a certain project, where the cashflow from the project is the only source to serve debt (interest and principal) and project's assets act as the collateral.[51] Although entities are able to choose to finance by traditional method or project-based method in practice, project finance is preferred on decarbonization project to isolate risks from major business due to the large initial investment and uncertain carbon market.[70] Project finance will lead to a uniform outcome for all firms in the market as it relies less on the profitability or reputation of the sponsor. Furthermore, risk and return of carbon capture project are quite different from the power sector, project finance perspective could better reveal the feasibility of the investment. According to theory of capital structure, project finance method will lead to the same or slightly pessimistic result,[90] which will enhance the conclusion of this article.

For a project with 40-year life time, cash outflow is set or assumed in the previous section. Cash inflow is considered to be allowance selling revenue. Revenue is denoted by R_i:

$$R_i = P_i \cdot \min(C_i, A_i)$$

Where subscript i denotes the year after start of the project; P_i is CEA price; C_i is amount of carbon captured, which is obtained from the following equation:

$$C_i = Ca \cdot B \cdot L_i \cdot F_i \cdot CE$$

Where Ca is installed capacity; B is emission coefficient; L_i is loading factor; F_i is correction factor according to loading factor; CE is capture efficiency. A_i is allowance allocated:

$$A_i = E_i \cdot AC$$

Where E_i is the total electricity on grid; AC is the allowance coefficient. To simplify analysis, all cashflow is assumed to occur at the end of year.

Another key parameter for project measure is required return rate, acting as the discount rate for net present value (NPV). Discount rate is made up from Damodaran's estimation and conversion of cost of equity (r_e) and cost of debt (r_d). As debt share varies from 0 to 100%, r_e and r_d will not be constant. When debt share is close to 0%, r_d will be close to risk free rate since there exists enough equity capital to serve interest and principal. Yield of 10-year state bond at the end of 2022 is taken as the risk-free rate and assumed constant over evaluating period. On the contrary, if a project is financed totally by debt, r_d will be the same as r_e without debt because of the same risk level. Analogically, r_e will rise as high as venture capital if debt consists most capital, so that we set r_e at 45%[91] when debt share close to 100%. r_e and r_d can be obtained by the following equations:

$$r_e = r_{e0} \cdot \left(e^{5e} - 1\right) / t_e$$

$$r_d = r_{d0} \cdot \left(e^{5d} - 1\right) / t_d$$

Where r_{e0} is the initial cost of equity without debt and is set at 9.04%; r_{d0} is the initial cost of debt when debt share close to zero and is set as 3.27%, the risk-free rate; t_e and t_d are conversion factors to adjust margin and are set at 25 and 4 respectively.

Discount rate r_a is weighted average cost of r_e and r_d and can be obtained:

$$r_a = r_e \cdot e + r_d \cdot d$$

Where e is equity share; d is debt share; and $e + d = 1$.

NPV is acquired by the following equation:

$$NPV = \sum_{i=1}^{n} \frac{R_i - OPEX_i}{(1 + r_a)^i} - CAPEX + \frac{V_{sal}}{(1 + r_a)^n}$$

Where $CAPEX$ is the capital expenditure occurred at the start of the project; n is the year that a project obsoletes after construction starts; $OPEX_i$ is the generalized cost relating project operation, including operating cost, electricity penalty cost, transport and storage cost and maintenance cost; and V_{sal} is the salvage value of equipment at the end of a project.

Levelized cost of CO_2-captured and equivalent price of CEA

As NPV is incomparable among projects with different initial expenditure and NPV factor is a dimensionless number, it is difficult to interpret feasibility of a project in certain market condition intuitionally. To better reflect all liabilities a project has to serve with one proxy in price perspective, we introduce LCOC and EPOC. LCOC can be obtained from the following equation:

$$LCOC = \left(CAPEX + \sum_{i=1}^{n} \frac{OPEX_i}{(1 + r_a)^i} - \frac{V_{sal}}{(1 + r_a)^n}\right) \cdot \frac{r_a \cdot (1 + r_a)^{n-1}}{(1 + r_a)^n - 1}$$

Similar to LCOC, EPOC is the proxy we construct to reflect CEA price over the whole life period of a project. EPOC can be obtained from the following equation:

$$EPOC = \sum_{i=1}^{n} \frac{P_i}{(1 + r_a)^i} \cdot \frac{r_a \cdot (1 + r_a)^{n-1}}{(1 + r_a)^n - 1}$$

Price variation within one year is neglected and all transactions are assumed to happen at the end of each year.

VaR model for debt tolerance and subsidy analysis

Discount rate in NPV reflects risk-induced required return. However, the outcome of NPV only disclose whether investors can expect the return will be achieved but doesn't reveal the extreme situation they might have to bear. If revenues from allowance selling are less than OPEX, creditor and equity holder (sponsor) will receive nothing, and more equity share will be necessary for project to maintain.[92] Under this situation, some scenario with positive NPV may not be valid as debt shares seek services with certainty to some extent. To explore viable situation of decarbonization investment, we use Value-at-Risk method to evaluate financial performance under abnormal carbon price. Considering unexpected profit might have little influence on investment decision, we focus on the extreme situation on the left side. The VaR of NPV is defined as:

$$VaR_\alpha^-(NPV) = inf\{t \in \mathbb{R} : \mathbb{P}(NPV \leq t) \geq \alpha\}$$

Where α is the risk level and $\alpha \in (0, 1)$. Distribution of NPV is or assumed to be known to execute analysis so that we run a Mont Carlo simulation of CEA[93] price to mimic the distribution.

Simulated prices (P_{si}) are obtained via follow equation:

$$P_{si} = P_{ei} \cdot \left(1 + \frac{CV_{CEA}}{\sqrt{n}} * \varepsilon\right)$$

Where P_{ei} is the expected price under certain price trajectory; CV_{CEA} is the coefficient of variation of CEA price sample; n is the number of samples; ε is a random digit obeying normal distribution, whose mean is zero and standard deviation is one. Ninety price sets are constructed for each price trajectory.

Terms of derivatives and pricing through Mont Carlo simulation

Nature of CO_2 emission allowance is controversial due to the special process of allocation, transaction, and settlement. From the legal relation of each party, emission allowance is a special right granted to certain entities, possessing general properties of a commodity.[94] Meanwhile, the right is separated in to standard certificates and tradeable in exchanges. For this matter, emission allowance is supposed to be securities. Different to general securities, such as stocks, emission allowance usually has certain maturity time, which can't satisfy continuous trading. Therefore, some researchers take emission allowance as financial commodity and others as physical commodity.[95]

As the topic is evaluate derivatives for power plants, whose main purpose is hedging CEA price risks, there exist few chances for liquidity risks and maturity risks.[96] In this article, we treat allowance as securities and price derivatives as financial futures and options. Maturity time (t) for futures and options is 2 years. For futures, forward price (P_t) is derived from spot CEA price (P_0):

$$P_t = P_0 \cdot (1 + r_a)^t$$

For options, exercise price (P_e) is set as ￥285.59/tCO_2. Type of option is European that can only be exercised when maturity. As there lack enough data of CEA transaction, fee of option (P^i_{opt}) is estimated via Mont Carlo simulation of CEA price and can be obtained:

$$P^i_{opt} = \frac{\sum_{k=1}^{m} \max\left(P_e - P^k_{si}, 0\right)}{m \cdot (1 + r_f)^2}$$

Where P^k_{si} is the simulated price; m is the number of price sets; r_f if the risk-free rate, 3.27%.

Assumptions of subsidy

To stimulate power plant investing in carbon capture project, government subsidy seems to be necessary and effective when market revenues are not fascinating.[74] There are several ways to transport economic benefit to the firm implementing decarbonization project, including additional allowance quota, direct investment subsidy, electricity price subsidy, and subsidy for CO_2 captured. Additional allowance quota may lead to inflation in the carbon market and covey a negative signal about emission reduction. Direct investment subsidy will burden government with financial pressure, and even full investment subsidy may fall to trigger firms to start decarbonization project.[97] Electricity price subsidy is also negative signaling, causing distortion price of electricity from coal and other low-carbon sources. In this paper, a capture-based subsidy method is adopted. Subsidy is determined by the gap between allowance allocated and CO_2 emission. A standard amount of money for every ton of emission reduction is pre-determined and we analyze the standard amount under different assumption.