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When to invest in carbon capture and storage: A perspective of supply chain

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ABSTRACT

The purpose of this study is to investigate the investment threshold of carbon capture and storage (CCS) project from the perspective of supply chain, overcoming the limitations of previous works regarding this topic mainly from a single investor's perspective. An analytical real options model was firstly presented for the scenario of centralized decision making, then the model was extended by integrating the real options theory with the game theory to examine the CCS investment threshold for the scenario of dual-echelon supply chain. An interesting finding is that CCS investment requires a much higher threshold under the dual-echelon supply chain than that under the centralized scenario, and this finding is consolidated by a numerical example simulation. Furthermore, the results of the numerical simulation indicated that the CCS investment threshold is positively affected by carbon price volatility, CO_2 capture rate and the transfer payments coefficients, while negatively affected by capital subsidy. These conclusions can provide theoretical foundation for decision-making of CCS investment and related policy-making.

1. Introduction

Carbon capture and storage (CCS) is considered to be a prospective technology to reduce anthropogenic CO_2 emissions and to achieve the target of holding the increase in the global average temperature at or below the critical 2 °C threshold (Thomas, Henriette, & Barbara, 2016). According to IPCC (2014), CCS from fossil-fired and bioenergy-fired plants could jointly contribute to a CO_2 emissions reduction of up to 25% by the year 2100 (Pachauri and Meyer, 2014). The cost of a 50% reduction in emissions by 2050 would be 71% or USD 1.28 trillion higher without the CCS intensively exploited (IEA, 2007). Given China's relative abundance of coal compared to other fossil fuels, it is unlikely that the heavy reliance on coal for electricity generation will change dramatically in the near future. Meanwhile, China signed the Paris Agreement with 125 other countries and set an ambitious target of reducing carbon intensity by 60–65% by 2030 compared to 2005 levels and peaking its carbon emission by around 2030. Under this circumstance, CCS presents an ideal option for China's power sector, since it is particularly useful for reducing greenhouse gas emissions while fossil fuel are continuously used (Shin, Lee, & Kim, 2016). However, various obstacles, such as the irreversibility of the CCS investment, the significant and uncertain expenditure, the energy penalty due to the introduction of CCS, the insufficient investment and progress as regards its plausible large-scale deployment along with infrastructure (e.g. transport, shared platform) (Selosse and Ricci, 2017), and the uncertainties associated with regulatory policies, market, and technology, make the prospect of CCS investment unclear and full of risks. In this context, two highly pertinent issues that need to be urgently settled are what the optimal timing is for the plants to invest in CCS projects given uncertainty in carbon prices, and how the investment timing is affected by the uncertainty factors.

Since CCS can address both economic growth and climate change, various studies of CCS have been conducted. And these studies can be classified into three topics: analysis of the advancement of CCS technology, cost estimation of power generation after CCS introduction, and the effect of greenhouse gas mitigations (Shin et al., 2016). Focusing on the development of CCS technology, Liu and Gallagher (2010) analyzed the opportunities in China and critical technologies for developing a CCS technology roadmap. By SWOT, Zeng, Ouyang, Zhang, and Shi (2014) analyzed the development environment in order to find the main stimulates and obstacles and confirm the feasibility of CCS development in China. Recently, the potential of solar-assisted post-combustion CCS processes have been analyzed (Wang et al., 2017). Apart from these studies, the feasibility of CCS investment has been receiving much attention. At first, researchers conducted their analysis mainly using the traditional discounted cash flow (DCF) method, which fails to regard flexibility and is inappropriate for the evaluation of CCS investment. Since the CCS investment has its own specific characteristics: (1) the investment timing is flexible, i.e., the investor can invest today or postpone his decision in order to obtain better information; (2) the investment cost is mostly or partly irreversible; (3) the high uncertainty of payoff given the current technology and the great influence

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of government policy on CCS investment.

In light of the above characteristics inherent in CCS investment, the real options approach, extended by financial options theory, considers much more flexibility in the management of the project so that it can quantify the value of postponing decisions to implement an irreversible investment under uncertainty. This approach has gained popularity in the evaluation of CCS investments. Abadie and Chamorro (2008) employed a two-dimensional binomial lattice to analyze CCS investment strategy under carbon price uncertainty and electricity price uncertainty. Fuss and Szolgayová (2010) presented a real options model with stochastic fuel prices and stochastic technical change to investigate their impact on replacement investment decisions in the electricity sector. Zhou et al. (2010) adopted a real option analysis to estimate the value of the CCS technology application to three kinds of power plants based on two scenarios of climate policy. Zhang and Li (2011) presented a carbon capture investment model of power producer under carbon price and CCS technology uncertainties with real option theory and explored the investment timing of CCS investment. Zhu and Fan (2011) established a CCS investment evaluation model based on real options theory to evaluate the cost saving effect from power generation enterprises investing in CCS technology to replace existing thermal power. Heydari, Ovenden, and Siddiqui (2012) using a real option model analyzed how a plant decide to invest in either full CCS or partial CCS retrofits considering uncertainties of electricity, CO_2, and coal price. Zhang et al. (2014) developed a real option based model to analyze the investment of CCS technology, considering multiple uncertainties such as carbon price and government incentives. Walsh, O'Sullivan, Lee, and Devine (2014) presents two models of the optimal investment decision for CCS investment under carbon price being determined and stochastic. Wang and Du (2016) employed a quadrinomial model based on real options theory to analyze the effects of government subsidy on critical carbon price for CCS investment.

Although above mentioned studies took the irreversibility, uncertainty and management flexibility of CCS investment into account, most of these studies mainly focused on the decisions from the perspective of single enterprise and highlighted economic returns from CO_2 capture activity, without studying CCS investment from the perspective of the supply chain. By definition, a supply chain is a network of different agents—suppliers, distributors, retailers and the like—that participate in the sale, delivery, and production of a specific good or service. As for CCS, the carbon dioxide is the specific good, and the power producers and the operators for CCS transportation and storage are the involved agents. Actually, CCS process involves the capture and separation of CO_2 in bulk and the subsequent isolation from the atmosphere through geological sequestration, meaning that CCS investment is complex and large-scale activities (Hasan, First, Boukouvala, & Floudas, 2015), including a series of interrelated decision-making process. Accordingly, a collaborative supply chain may be recognized as a possible way to CCS investment. Thus, the purpose of this paper is to analyze the issue of CCS investment timing from the perspective of supply chain. In comparison with the previous studies, this paper contributes to the literature by analyzing how a dual-echelon supply chain will affect the CCS investment threshold. We construct a simple analytical model for a dual-echelon supply chain by integrating real options theory and game theory to analyze the CCS investment threshold, and analyze the effects of a dual-echelon supply chain on CCS investment threshold by comparing the analytical model with that under base case (centralized decision making). Moreover, we investigate how the CCS investment threshold is affected by the volatility of carbon price, uncertainties in CO_2 capture rate, government subsidies and the transfer payments coefficient.

The rest of this paper is organized as follows. Section 2 describes the analytical model for the base case (centralized supply chain). Section 3 extends the analytical model for a dual-echelon supply chain. Section 4 presents a simple numerical example by using representative values of parameters and discusses implications of this model. Section 5 summarizes and concludes the findings.

2. Investment timing based on centralized decision making

2.1. Model description

Under the scenario of centralized decision-making, the actions of capturing, transmitting, and storing carbon dioxide in CCS are all performed by one enterprise, such as the power producer. In this paper, we assume that the actors involved in CCS investment make decisions as an entity. Assuming that supply chain is to be risk-neutral and discounts with the riskless interest rate. This means that the supply chain considering the start of a CCS project weighs the (time-discounted net) benefit of CCS operation and the benefit of waiting and starting it later. Regardless of when starting of CCS investment, the supply chain will receive revenue immediately once the investment starting. And the supply chain can invest at $t = 0$ as early as possible.

Compared with non-retrofitting CCS, we think retrofitted with CCS will bring the supply chain with the cash inflows from the certified emissions reduction (CERs), which is determined by the volume of CERs and the carbon price, and a clean electricity tariff markup, which is similar to the desulfurization electricity price in China. Considering the value of the CCS investment is affected by several uncertain factors, it is reasonable to describe the project value $V(p(t))$ by Eq. (1)[1]:

$$V(p(t)) = E\left[\int_t^{\infty} (Sp(h) + kNw\xi)\mathrm{e}^{-r(h-t)}dh\right] = \frac{Sp(t)}{r-\mu} + \frac{kNw\xi}{r} \tag{1}$$

where S denotes the volume of annual captured carbon dioxide from the carbon capture system. According to the related literature, S can be expressed as:

$$S = Nw\xi\varepsilon\lambda \tag{2}$$

where $Nw\xi$ represents the amount of electricity exported to the grid.[2] N denotes the installed capacity of the generator. ξ denotes the number of annual generating hours of the generator. w is the capacity factor. ε denotes the CO_2 emission intensity, and λ denotes the CO_2 capture rate.

In Eq. (1), k is the additional markup for the clean electricity tariff, and it is set according to the desulfurization electricity price in China. While $p(t)$ describes the variable of carbon price. Following the previous studies, such as Abadie and Chamorro (2008) and Heydari et al. (2012), we model the carbon price $p(t)$ as geometric Brownian motion (GBM):

$$\mathrm{d}p(t) = \mu p(t)dt + \sigma p(t)dz, \quad p(0) = p_0 \tag{3}$$

where μ is the constant drift rate, $0 \le \mu < r$ (r is riskless interest rate). σ is the volatility and $\sigma \in R^+$, and dz is independent increments of Wiener process.

Assuming that supply chain conducts one-time investment in CCS technology and the total investment cost is $I(\lambda) = m\lambda^2/2$, where m is the cost coefficient for CCS investment, which is determined by many factors, including internal factors (e.g. the plant type and size, capacity factor) and external factors (e.g., discount rate, fuel price). λ is the carbon capture rate. Similar to the previous studies, it is assumed that a nonlinear square relationship is existed between the total investment cost and carbon capture rate.

Considering that CCS investment is inseparable from the supports of government incentive. And capital subsidies can lower an investor's cost of financing, which is the main barrier to CCS investment. It is reasonable assumed that the incentive takes the form of capital subsidy. If the government provides power producers with investment subsidy for CCS retrofitting, setting the government subsidy factor is $\gamma(0 \le \gamma < 1)$, then the CCS investment cost can be described as $(1-\gamma)I(\lambda)$.

[1] Following Heydari et al. (2012), we assume that the enterprise has an infinite lifetime.

[2] For simplicity, here without considering the efficiency penalty associated with operating the CO_2 capture facilities and the benefits of captured CO_2 product, such as sell CO_2 to oil company for EOR.