Off-shore enhanced oil recovery in the North Sea: The impact of price uncertainty on the investment decisions

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ABSTRACT

Although CO_2 Capture and Storage (CCS) is considered a key solution for CO_2 emission mitigation, it is currently not economically feasible. CO_2 enhanced oil recovery can play a significant role in stimulating CCS deployment because CO_2 is used to extract additional quantities of oil. This study analyzes the investment decision of both a carbon emitting source and an oil company separately by adopting a real options approach. It is shown that when uncertainty is integrated in the economic analysis, CO_2 and oil price threshold levels at which investments in CO_2 capture and enhanced oil recovery will take place, are higher than when a net present value approach is adopted. We also demonstrate that a tax on CO_2 instead of an emission trading system results in a lower investment threshold level for the investment in the CO_2 capture unit. Furthermore, we determine a minimum CO_2 selling price between the two firms and show that CO_2-EOR has the potential to pull CCS into the market by providing an additional revenue on the capture plant. However, when CO_2 permit prices are above an identifiable level, the EU ETS does not necessarily result in the adoption of CCS and stimulates oil production.

1. Introduction

There is a wide range of ways to reduce greenhouse gas emissions. In the case of CO_2, large-scale reductions can be achieved by e.g. increasing energy efficiency, by applying renewable energy sources, or by CO_2 capture and geological storage (CCS). CCS consists of separating the CO_2 from the flue gas of large industrial plants and transporting it to a suitable underground reservoir for long-term storage (IPCC, 2005). The International Energy Agency (IEA, 2014) considers CCS as a key solution for CO_2 mitigation, covering 14% of total reductions needed by 2050 for the 2-Degrees Scenario. However, a rapid adoption of CCS is not expected due to high investment costs in conjunction with low CO_2 permit prices (Abadie and Chamorro, 2008). Nykvist (2013) shows that if this technology is to be pursued, more demonstration plants are required, pilot plants should be scaled up, and both public funding and the CO_2 emission price should increase. Another way to enhance the viability of CCS, is the effective use of CO_2. For instance, all major new CCS projects in the US are conditioned on enhanced oil recovery (EOR) (Krahe et al., 2013; Nykvist, 2013). EOR is the recovery

of additional oil to the oil produced by pressure depleting (pumping) at the production well. CO_2 enhanced oil recovery (CO_2-EOR) entails the injection of CO_2 in mature oil fields in order to mobilize the oil. In particular, the injected CO_2 reduces the oil's viscosity and acts as a propellant, resulting in an increased oil extraction rate (Leach et al., 2011). CO_2-EOR is considered to play a significant role in stimulating subsequent CCS deployment (Scott, 2013). As regards the deployment of CO_2-EOR in North western Europe, the situation is different to that in North America as Europe's oilfields are mostly located offshore and the thicker, compartmentalized reservoirs could result in a less effective sweeping of the reservoir with CO_2 (Scott, 2013). The main challenge however is the lack of sufficient quantities of readily available CO_2 (Awan et al., 2008). Although in both the UK and the Netherlands, demonstration projects were envisaged, they failed to secure funding, leaving North Sea CO_2 -EOR an open question (Scott, 2013).

1.1. Previous studies on the techno-economic feasibility of CO_2-EOR

There are various techno-economic analyses that study the eco-

nomic feasibility of CO_2-EOR projects. Leach et al. (2011) developed a theoretical framework for an onshore CO_2-EOR project that analyzes the co-optimization of oil extraction and CO_2 storage through the oil producer's choice of the fraction of CO_2 in the injection stream at each moment for given CO_2 and oil prices. Also the effect of carbon taxes and oil prices on oil production and CO_2 storage is determined. They show that an EOR project is inelastic to carbon taxes. Market conditions favoring high oil prices however, are likely to induce increases in CO_2 storage, essentially as a by-product of producers' attempts to increase oil production. Applying a net present value (NPV) approach, Ravagnani et al. (2009) show for a fertilizer industry in Brazil, that investment in an EOR project is economically feasible. Revenues from the sale of additional oil recovered and revenues from CO_2 credits owing to CO_2 storage cover both annual costs and investment costs, considering a project lifetime of 20 years. The sensitivity analysis they carry out for various parameter values indicate that there is an approximate risk of 30% that the NPV is negative. Klokk et al. (2010) present a mathematical model for designing a carbon dioxide value chain at the Norwegian Continental Shelf. Considering an oil price of 50 USD/bbl (± 45 €/bbl) and a CO_2 price of 27 USD/tonne (± 24 €/tonne), the calculated NPV is positive. The sensitivity analysis they carried out shows that for an oil price of 50 USD/bbl, the CO_2 price should not be lower than 16 USD and for a CO_2 price of 27 USD/ton, oil prices should be at least 45 USD/bbl to ensure a positive NPV. Kemp and Kasim (2013) study the economics of nine interconnected oil fields for the deployment of CO_2-EOR in the Central North Sea region of the UK Continental Shelf. Applying Monte Carlo simulation modelling, these authors find that if the CO_2 price is as low as $10 per tonne (± 14 €/tonne), positive returns for the EOR investment can be achieved.

1.2. Multiple economic actors, multiple investment decisions

All of the aforementioned studies consider the CO_2-EOR project as one investment decision and implicitly assume that a CO_2 stream will be readily available. Leach et al. (2011) assume that the full savings of avoided purchase of emissions permits will be passed on to the oil producer because aggregate CO_2 emissions outstrip all estimates of aggregate CO_2 storage by EOR. Klokk et al. (2010) however, clearly show that revenues and costs are unequally distributed in the value chain. Avoided CO_2 permit costs do not cover operational and investment costs of a CO_2 capture unit. They indicate that some kind of profit sharing would be required between the different participants. Also Fleten et al. (2010) consider the adoption of CO_2-EOR as one investment problem and add the benefits of the additional oil produced to the cost of CO_2 capture. However, in reality a trade in CO_2 between a carbon emitting source (a coal fired power plant in our case) and an oil company will need to take place. Mendelevitch (2014) subscribes this issue and develops a model in which a CO_2 producer, a storage operator, a CO_2 transmission system operator and a CO_2 trader are integrated. If the CO_2 is used, the CO_2 producer receives the clearing price determined by balancing the cash flows between the three other parties. If the CO_2 is not used for EOR but permanently stored in a saline aquifer, the CO_2 producer has to pay the CO_2 transmission system operator for the management of the transport and storage activities. If the storage operator uses the CO_2 for EOR, it has to pay for the CO_2. Different from Mendelevitch (2014) we do not consider a CO_2 trader or CO_2 transmission system operator. We assume that a trade in CO_2 will directly take place between a CO_2 producer and and oil producer. Furthermore, whereas Mendelevitch (2014) determines a clearing prices at the capture facility gate as a revenue for the CO_2 producer and a different CO_2 clearing price at the CO_2-EOR injection well as a cost to the oil producer, we analyze the specific investment treshold levels for the CO_2 producer and oil producer separately. Based on these results, we then define the price regions for which a trade in CO_2 can take place between these two firms.

1.3. Market price uncertainties

Furthermore, most of the aforementioned studies that evaluate CO_2-EOR economically give evidence of oil and CO_2 price uncertainties, but only address this issue by a sensitivity analysis. Only Fleten et al. (2010) describe the oil price and CO_2 price as Geometric Brownian motion processes and model these uncertainties by a binomial lattice. From the 1980 s on, it is increasingly recognized that the net present value (NPV) and discounted cash flow methods are inadequate to deal with issues like uncertainty, the irreversibility of an investment decision, and the flexibility of the decision process. Dixit and Pindyck (1994) and Trigeorgis (1996) illustrate that, under market uncertainty, the opportunity cost of investing immediately, rather than waiting and keeping open the possibility to invest at a later point in time, is a significant component of the firm's investment decision. It is shown that an increase in market price uncertainty enlarges the opportunity cost of investing now rather than waiting, so there is a greater incentive to wait. It is demonstrated that by integrating uncertainty and irreversibility into the decision analysis, the real options approach gives a better insight into the development and management of natural resources (See e.g. Mezey and Conrad, 2010) and into the adoption of pollution control and renewable energy systems, including the evaluation of policy instruments (See e.g. Szolgayová et al., 2014; Heydari et al., 2012; Reuter et al., 2012; Wirl, 2006). Different from the above mentioned studies, we apply a continuous time real options analysis and follow the concepts of dynamic programming to define the investment threshold levels. Dynamic programming is a general mathematical technique for the optimization of sequential decisions under uncertainty. A whole sequence of decisions is split into two components: the immediate decision and a valuation function that encapsulates the consequences of all subsequent decisions.

We first develop two real options models to evaluate the investment in a CO_2 capture unit and the investment in enhanced oil recovery separately. We consider the investment decisions to be made by the electricity producer and the oil company as two separate decisions. To analyze the investment decision of the electricity producer who has to invest in a CO_2 capture unit, we present a real options model that considers the avoided payment of CO_2 emission allowances as an uncertain revenue stream. Based on this model we determine the critical CO_2 price level at which the firm is willing to invest in the CO_2 capture unit. As regards the enhanced oil recovery, CO_2 is input to the production process and hence a cost to the oil producer. For the investment decision in the enhanced oil recovery we present a second real options model that considers the oil price and the cost of CO_2 as uncertain. Based on this second model we define the critical oil price at which the oil producer will be willing to invest in EOR, given the cost of CO_2. For the CO_2 capture investment decision we show that when uncertainty is integrated in the decision analysis, the threshold level of the CO_2 price is higher compared to a net present value approach. As regards the oil producer, the integration of uncertainty results in a higher oil price threshold level and lower threshold levels for the CO_2 cost compared to the net present value approach. Furthermore we show that compared to the CO_2 emission trading system a tax on CO_2 reduces uncertainty for the investment in the CO_2 capture unit. Consequently, under a CO_2 tax the CO_2 price level at which the electricity producer invests in the CO_2 capture unit is lower. After the two separate investment analyses, we study the investment decision of the electricity producer again, considering the revenue stream as the sum of the avoided payment of CO_2 emission allowances and the revenue from selling the captured CO_2 to the oil company. Based on this analysis we define the CO_2 and oil price regions in which a trade in CO_2 can take place between the electricity producer and the oil producer. For different oil price levels and CO_2 permit price levels, we show how the investment cost in both technologies needs to shared between the two firms to make the investment in CO_2-EOR economic-