This item is the archived peer-reviewed author-version of:

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

Reference:

Compernelle Tine, Welkenhuysen K., Huisman K., Piessens K., Kort Peter M.- Off-shore enhanced oil recovery in the North Sea : the impact of price uncertainty on the investment decisions

Energy policy - ISSN 0301-4215 - 101(2017), p. 123-137

Full text (Publisher's DOI): <https://doi.org/10.1016/J.ENPOL.2016.11.034>

To cite this reference: <https://hdl.handle.net/10067/1408580151162165141>

OFF-SHORE ENHANCED OIL RECOVERY IN THE NORTH SEA: THE IMPACT OF PRICE UNCERTAINTY ON THE INVESTMENT DECISIONS

Compernelle, T.^{*1,2}, Welkenhuysen, K.^{2,3,4}, Huisman, K.^{5,6}, Piessens, K.², Kort, P.^{5,1}

¹*University of Antwerp, Department of Economics, Prinsstraat 13, B-2000 Antwerp, Belgium.
tine.compernelle@uantwerpen.be*

²*Geological Survey of Belgium – Royal Belgian Institute of Natural Sciences, Jennerstraat 13, 1000 Brussels, Belgium. kwelkenhuysen@naturalsciences.be; kpiessens@naturalsciences.be*

³*Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Budapestlaan 6, 3584 CD Utrecht, the Netherlands*

⁴*Department Earth and Environmental Sciences, K.U. Leuven, Celestijnenlaan 200E, 3001 Heverlee, Belgium*

⁵*Tilburg University, Department of Econometrics & Operations Research and CentER, Warandelaan 2, 5037 Tilburg, The Netherlands. kuno.huisman@gmail.com; kort@uvt.nl*

⁶*ASML, De Run 6501, 5504 Veldhoven, The Netherlands*

Keywords: CO₂ enhanced oil recovery; uncertainty; real options analysis; investment decision

Abstract

Although CO₂ Capture and Storage (CCS) is considered a key solution for CO₂ emission mitigation, it is currently not economically feasible. CO₂ enhanced oil recovery can play a significant role in stimulating CCS deployment because CO₂ 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, CO₂ and oil price threshold levels at which investments in CO₂ 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 CO₂ instead of an emission trading system results in a lower investment threshold level for the investment in the CO₂ capture unit. Furthermore, we determine a minimum CO₂ selling price between the two firms and show that CO₂-EOR has the potential to pull CCS into the market by providing an additional revenue on the capture plant. However, when CO₂ permit prices are above an identifiable level, the EU ETS does not necessarily result in the adoption of CCS but stimulates oil production.

Abstract

Although CO₂ Capture and Storage (CCS) is considered a key solution for CO₂ emission mitigation, it is currently not economically feasible. CO₂ enhanced oil recovery can play a significant role in stimulating CCS deployment because CO₂ 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, CO₂ and oil price threshold levels at which investments in CO₂ 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 CO₂ instead of an emission trading system results in a lower investment threshold level for the investment in the CO₂ capture unit. Furthermore, we determine a minimum CO₂ selling price between the two firms and show that CO₂-EOR has the potential to pull CCS into the market by providing an additional revenue on the capture plant. However, when CO₂ 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 CO₂, large-scale reductions can be achieved by e.g. increasing energy efficiency, by applying renewable energy sources, or by CO₂ capture and geological storage (CCS). CCS consists of separating the CO₂ 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 (2014) considers CCS as a key solution for CO₂ 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 CO₂ 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 CO₂ emission price should increase. Another way to enhance the viability of CCS, is the effective use of CO₂. 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. CO₂ enhanced oil recovery (CO₂-EOR) entails the injection of CO₂ in mature oil fields in order to mobilize the oil. In particular, the injected CO₂ reduces the oil's viscosity and acts as a propellant, resulting in an increased oil extraction rate (Leach et al. 2011). CO₂-EOR is considered to play a significant role in stimulating subsequent CCS deployment (Scott 2013). As regards the deployment of CO₂-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 CO₂ (Scott 2013). The main challenge however is the lack of sufficient quantities of readily available CO₂ (Awan et al. 2008). Although in both the UK and the Netherlands, demonstration projects were envisaged, they failed to secure funding, leaving North Sea CO₂ -EOR an open question (Scott 2013).

1.1 Previous studies on the techno-economic feasibility of CO₂-EOR

There are various techno-economic analyses that study the economic feasibility of CO₂-EOR projects. Leach et al. (2011) developed a theoretical framework for an onshore CO₂-EOR project that analyzes the co-optimization of oil extraction and CO₂ storage through the oil producer's choice of the fraction of CO₂ in the injection stream at each moment for given CO₂ and oil prices. Also the effect of carbon taxes and oil prices on oil production and CO₂ 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 CO₂ 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 CO₂ credits owing to CO₂ 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. Klok 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 CO₂ 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 CO₂ price should not be lower than 16 USD and for a CO₂ 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 CO₂-EOR in the Central North Sea region of the UK Continental Shelf. Applying Monte Carlo simulation modelling, these authors find that if the CO₂ 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 CO₂-EOR project as one investment decision and implicitly assume that a CO₂ 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 CO₂ emissions outstrip all estimates of aggregate CO₂ storage by EOR. Klok et al. (2010) however, clearly show that revenues and costs are unequally distributed in the value chain. Avoided CO₂ permit costs do not cover operational and investment costs of a CO₂ 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 CO₂-EOR as one investment problem and add the benefits of the additional oil produced to the cost of CO₂ capture. However, in reality a trade in CO₂ 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 CO₂ producer, a storage operator, a CO₂ transmission system operator and a CO₂ trader are integrated. If the CO₂ is used, the CO₂ producer receives the clearing price determined by balancing the cash flows between the three other parties. If

the CO₂ is not used for EOR but permanently stored in a saline aquifer, the CO₂ producer has to pay the CO₂ transmission system operator for the management of the transport and storage activities. If the storage operator uses the CO₂ for EOR, it has to pay for

the CO₂. Different from Mendelevitch (2014) we do not consider a CO₂ trader or CO₂ transmission system operator. We assume that a trade in CO₂ will directly take place between a CO₂ producer and an oil producer. Furthermore, whereas Mendelevitch (2014) determines a clearing price at the capture facility gate as a revenue for the CO₂ producer and a different CO₂ clearing price at the CO₂-EOR injection well as a cost to the oil producer, we analyze the specific investment threshold levels for the CO₂ producer and oil producer separately. Based on these results, we then define the price regions for which a trade in CO₂ can take place between these two firms.

1.3 Market price uncertainties

Furthermore, most of the aforementioned studies that evaluate CO₂-EOR economically give evidence of oil and CO₂ price uncertainties, but only address this issue by a sensitivity analysis. Only Fleten et al. (2010) describe the oil price and CO₂ price as Geometric Brownian motion processes and model these uncertainties by a binomial lattice. From the 1980s 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 CO₂ 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 CO₂ capture unit, we present a real options model that considers the avoided payment of CO₂ emission allowances as an uncertain revenue stream. Based on this model we determine the critical CO₂ price level at which the firm is willing to invest in the CO₂ capture unit. As regards the enhanced oil recovery, CO₂ 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 CO₂ 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 CO₂. For the CO₂ capture investment decision we show that when uncertainty is integrated in the decision analysis, the threshold level of the CO₂ 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 CO₂ cost compared to the net present value approach. Furthermore we show that compared to the CO₂ emission trading system a tax on CO₂ reduces uncertainty for the investment in the CO₂ capture unit. Consequently, under a CO₂ tax the CO₂ price level at which the electricity producer invests in the CO₂ 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 CO₂ emission allowances and the revenue from selling the captured CO₂ to the oil company. Based on this analysis we define the CO₂ and oil price regions in which a trade in CO₂ can take place between the electricity producer and the oil producer. For different oil price levels and CO₂ permit price levels, we show how the investment cost in both technologies needs to be shared between the two firms to make the investment in CO₂-EOR economically feasible. Furthermore, if the CO₂ permit price is higher than 40 €/tonne, then the CO₂ needed for the enhanced oil recovery is not necessarily a cost to the oil producer and for CO₂ permit prices higher than 61 €/tonne, the CO₂ price can stimulate additional oil production. Based on these results and on the results of the sensitivity analysis, we present different policy implications given different oil and CO₂ price scenarios.

2 Models

The two investment problems are analyzed separately by applying the real options theory. The following section describes (i) the real options model that is applied to analyze the decision of the electricity producer to invest in the CO₂ capture unit, considering a stochastic CO₂ permit price and (ii) the real options model that is applied to analyze the investment decision of the oil company, namely the investment in CO₂-EOR, considering a stochastic CO₂ cost and a stochastic oil price.

2.1 Model 1: investment in the CO₂ capture unit

Consider a coal fired power plant that under the European emission trading system (EUETS) is obliged to surrender emission allowances in an amount equivalent to its CO₂ emissions. The electricity producer can invest in a CO₂ capture unit or wait to invest. If the power plant decides to invest in a CO₂ capture unit, it will have to pay an investment cost to install the CO₂ capture unit. The operation of the CO₂ capture unit will result in annual operational costs and an avoided annual payment of CO₂ emission allowances.

It is assumed that the captured CO₂ is permanently avoided and thus is eligible for the EUETS. Hence, the avoided annual payment of CO₂ emission allowances is considered as an annual revenue. We present a real options model that considers uncertainty in CO₂ price levels. This model does not only consider the option to wait with the investment in the CO₂ capture unit. If the firm invests, it also has the option to temporarily suspend the operation if the annual cost of CO₂ capture exceeds the annual revenue. Figure 1 gives a graphical representation of the investment decision of the electricity producer and its economic impact.

Figure 1. Graphical representation of the investment decision of the electricity producer and its economic impact.

The electricity producer is assumed to be risk neutral and discounts with the riskless interest rate. The electricity producer has to decide to invest in a unit that captures CO₂. The real options theory states that when a firm makes an irreversible investment expenditure, it exercises, or kills, its option to invest. It gives up the possibility of waiting for new information to arrive that might affect the desirability or timing of the expenditure. This lost option value is an opportunity cost that must be included as part of the cost of the investment. Applying dynamic programming, we define the critical value of the CO₂ permit price P_{pp}^* for which the value of the capture unit after investment equals the sum of the investment cost and the opportunity cost of the lost option value. An infinite lifetime for the capture unit is assumed. Let $P_{pp} \in \mathbb{R}^+$ be the avoided cost to the power plant for not emitting one tonne of CO₂. We assume that this unit revenue is uncertain and that its time-varying pattern can be formally expressed by a geometric Brownian motion process.

$$dP_{pp}(t) = \alpha_{pp}P_{pp}(t)dt + \sigma_{pp}P_{pp}(t)dz_{pp}, \quad (1)$$

$$P_{pp}(0) = P_0 \quad (2)$$

With α_{pp} and $\sigma_{pp} \in \mathbb{R}^+$, and dz_{pp} as the increment of a standard Brownian motion. We need to determine the critical level of P_{pp}^* , the avoided CO₂ unit cost at which the firm is willing to invest in the capture unit. Following Dixit and Pindyck (1994, p. 186) we assume that the operation of the capture unit entails an annual flow cost C_{cap} , but that the operation can be temporarily and costless suspended when P_{pp} falls below C_{cap} , and costless resumed later if P_{pp} rises above C_{cap} . Therefore, at any instant the profit flow from this project is given by:

$$\pi(P_{pp}) = \max[Q_{Co_2}(P_{pp} - C_{cap}), 0]. \quad (3)$$

With P_{pp} the unit price of one tonne of CO₂ emission avoided, Q_{Co_2} the quantity of CO₂ emissions annually avoided and C_{cap} the annual operation cost of the CO₂ capture unit per tonne CO₂ captured. The value of the project after investment at time t can be expressed as the sum of the operating profit over the interval $(t, t + dt)$ and the continuation value beyond $t+dt$. Thus,

$$V(P_{pp}) = \pi(P_{pp})dt + E[V(\pi(P_{pp}) + d\pi(P_{pp}))e^{-r dt}]. \quad (4)$$

Concerning the value of the CO₂ capture unit after investment, the following proposition can be established (the proof is given in Appendix A).

Proposition 1. The value of the firm after the investment equals

$$V(P_{pp}) = \left\{ \begin{array}{ll} K_1(Q_{Co_2}P_{pp})^{\beta_1}, & \text{for } P_{pp} < C_{cap}, \\ B_2(Q_{Co_2}P_{pp})^{\beta_2} + \frac{Q_{Co_2}P_{pp}}{r - \alpha_{pp}} - \frac{Q_{Co_2}C_{cap}}{r}, & \text{for } P_{pp} > C_{cap}, \end{array} \right\} \quad (5)$$

with

$$K_1 = \frac{C_{cap}^{1-\beta_1}}{(\beta_1 - \beta_2)} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \alpha_{pp}} \right), \quad (6)$$

$$B_2 = \frac{C_{cap}^{1-\beta_2}}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \alpha_{pp}} \right). \quad (7)$$

As long as the firm has not invested yet, it holds the option to invest. The value of the option to invest is denoted $F(P_{pp})$ and is determined in the following proposition. To find the value of the option to invest, we consider the option to invest as a function of the price, $F(P_{pp})$, using the solution for $V(P_{pp})$ as the boundary condition that holds at the optimal exercise threshold. We get the differential equation

$$0 = F'(P_{pp}) \alpha_{pp} (P_{pp}) + \frac{1}{2} F''(P_{pp}) \sigma_{pp}^2 (P_{pp})^2 - r F(P_{pp}). \quad (8)$$

This is a homogeneous linear equation of second order, so its solution is a linear combination of any two linearly independent solutions, say

$$F(P_{pp}) = A_1 (Q_{Co_2} * P_{pp})^{\beta_1} + A_2 (Q_{Co_2} * P_{pp})^{\beta_2}. \quad (9)$$

When P_{pp} is very small, the prospect of it rising to the exercise threshold P_{pp}^* is unlikely. Therefore, the option should be almost worthless at this extreme. It can be proven that $\beta_1 > 1$ and $\beta_2 < 0$ (Dixit and Pindyck, 1994). Hence, we should set A_2 to 0 to ensure that $F(P_{pp})$ goes to zero as P_{pp} goes to zero.

Proposition 2. The value of the option to investment equals

$$F(P_{pp}) = A_1 (Q_{Co_2} * P_{pp})^{\beta_2}. \quad (10)$$

At the threshold level P_{pp}^* , it becomes optimal to exercise the option, and thereby acquire an asset of value $V(P_{pp})$ by incurring the exercise price (sunk cost) of investment I_{Cap} . Two conditions govern this. First, the value of the option must equal the net value obtained by exercising it, this is the value matching condition. Second, the value functions $F(P_{pp})$ and $V(P_{pp}) - I_{Cap}$ should meet tangentially at P_{pp}^* , this is the smooth pasting condition. When $P_{pp} < C_{Cap}$, the investment in a CO₂ capture unit will be postponed because operating costs per tonne CO₂ captured are higher than its unit revenue. Because in that case the option to invest will not be exercised, we use the solution for $V(P_{pp})$ in the operating region, that is, for $P_{pp} > C_{Cap}$. The value matching condition then gives

$$F(P_{pp}^*) = V(P_{pp}^*) - I_{Cap}, \quad (11)$$

$$A_1 (P_{pp}^*)^{\beta_1} = B_2 (Q_{Co_2} * P_{pp}^*)^{\beta_2} + \frac{Q_{Co_2} * P_{pp}^*}{(r - \alpha_{pp})} - \frac{Q_{Co_2} * C_{Cap}}{r} - I_{Cap}. \quad (12)$$

And the smooth pasting condition gives

$$F'(P_{pp}^*) = V'(P_{pp}^*), \quad (13)$$

$$\beta_1 A_1 (Q_{Co_2} * P_{pp}^*)^{\beta_1 - 1} = \beta_2 B_2 (Q_{Co_2} * P_{pp}^*)^{\beta_2 - 1} + \frac{1}{r - \alpha_{pp}}. \quad (14)$$

Eliminating A_1 the equation for the investment threshold is given by Proposition 3.

Proposition 3. The investment threshold level is implicitly given by

$$B_2 (Q_{Co_2} * P_{pp}^*)^{\beta_2} (\beta_1 - \beta_2) + \frac{Q_{Co_2} * P_{pp}^*}{(r - \alpha_{pp})} (\beta_1 - 1) - \beta_1 \left(\frac{Q_{Co_2} * C_{Cap}}{r} + I_{Cap} \right) = 0, \quad (15)$$

with

$$B_2 = \frac{Q_{Co_2} * C_{cap}^{1-\beta_2}}{(\beta_1 - \beta_2)} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{(r - \alpha_{pp})} \right).$$

2.2 Model 2: investment in enhanced oil recovery (EOR)

The real options model developed to evaluate the impact of oil price uncertainty and CO₂ cost uncertainty on the decision to invest in enhanced oil recovery is based on the model developed by Huisman et al.(2013). Consider an oil company that can decide to enhance its oil production by injecting CO₂. After the investment, the oil company has to buy CO₂ that it injects in the oil field to annually produce an additional quantity of oil. Figure 2 gives a graphical representation of the investment decision of the oil producer and its economic impact.

Figure 2. Graphical representation of the investment decision of the oil producer and its economic impact

Following Postali and Pichetti (2006) the oil price follows a geometric Brownian motion (GBM) process.

$$dP_{oil}(t) = \alpha_{oil}P_{oil}(t)dt + \sigma_{oil}P_{oil}(t)dz_{oil}, \quad (16)$$

$$P_{oil}(0) = P_0 \quad (17)$$

With α_{oil} and $\sigma_{oil} \in \mathbb{R}^+$, and dz_{oil} as the increment of a standard Brownian motion. To extract additional oil, the oil company needs to buy CO₂. Because this production cost depends on the CO₂ permit price, the cost of CO₂ behaves according to a GBM as well:

$$dC_{CO_2}(t) = \alpha_{CO_2}C_{CO_2}(t)dt + \sigma_{CO_2}C_{CO_2}(t)dz_{CO_2}, \quad (18)$$

$$C_{CO_2}(0) = C_0 \quad (19)$$

with α_{CO_2} and $\sigma_{CO_2} \in \mathbb{R}^+$, and dz_{CO_2} as the increment of a standard Brownian motion. Denoting the correlation coefficient between the two Wiener processes by ρ , we have that $E[dz_{oil}dz_{CO_2}] = \rho dt$. The profit flow of the oil company at any instant after the investment is denoted by

$$\pi(P_{oil}(t), C_{CO_2}(t)) = Q_{oil}(P_{oil}(t) - c * C_{CO_2}(t)). \quad (20)$$

With Q_{oil} (in bbl) the annual quantity of additional oil produced, c the ratio that indicates the quantity of CO₂ that needs to be bought to produce an additional bbl of oil (in t/bbl). C_{CO_2} the unit cost of the CO₂ that needs to be bought by the oil producer to extract the additional oil (in €/tonne), and T the expected lifetime that additional oil will be extracted by injecting CO₂ (in years).

The expected present value that the firm obtains after it invests, can then be expressed as

$$V(P_{oil}(t), C_{CO_2}(t)) = E \left[\int_{t=0}^T \pi(P_{oil}(t), C_{CO_2}(t)) e^{-rt} dt \right]. \quad (21)$$

Concerning the value of the firm after the investment and based on Huisman et al. (2013) the following proposition can be established (Proof in Appendix B):

Proposition 4. Define the markup ratio as

$$\tau = \frac{P_{oil}}{c * C_{CO_2}}, \quad (22)$$

then the value of the firm after the investment in EOR equals

$$V(P_{oil}, C_{CO_2}) = c C_{CO_2} v(\tau) = c * C_{CO_2} \left[\frac{Q_{oil} * \tau * (1 - e^{-(r-\alpha_{oil})T})}{r - \alpha_{oil}} - \frac{Q_{oil} * (1 - e^{-(r-\alpha_{CO_2})T})}{r - \alpha_{CO_2}} \right]. \quad (23)$$

The value of the option to invest is denoted by $F(P_{oil}, C_{CO_2})$ and is determined in the following proposition (Proof in Appendix B).

Proposition 5. The value of the option to invest in EOR equals

$$F(P_{oil}, C_{CO_2}) = c * C_{CO_2} \phi(\tau), \quad (24)$$

in which

$$\phi(\tau) = Z_1 \tau^{\beta_1} \quad (25)$$

and $\beta_1 (> 1)$ is the positive root of

$$\frac{1}{2} (\sigma_{oil}^2 - 2\rho\sigma_{oil}\sigma_{CO_2} + \sigma_{CO_2}^2) \beta(\beta - 1) + (a_{oil} - \alpha_{CO_2})\beta - (r - \alpha_{CO_2}) = 0 \quad (26)$$

So that

$$\beta_1 = \frac{-b + \sqrt{b^2 - 4(-r + \alpha_{CO_2})(\frac{\sigma_{CO_2}^2}{2} - \rho\sigma_{CO_2}\sigma_{oil} + \frac{\sigma_{oil}^2}{2})}}{2 * (\frac{\sigma_{CO_2}^2}{2} - \rho\sigma_{CO_2}\sigma_{oil} + \frac{\sigma_{oil}^2}{2})}, \quad (27)$$

with

$$b = -\alpha_{CO_2} + \alpha_{oil} - \frac{\sigma_{CO_2}^2}{2} + \rho\sigma_{CO_2}\sigma_{oil} - \frac{\sigma_{oil}^2}{2}. \quad (28)$$

Since both the value of the firm after investment and the value of the option to invest are linear in C_{CO_2} and further depend only on the price-cost ratio τ , the optimal investment decision is completely governed by τ . This implies that a threshold value τ^* exists so that, whenever the price-cost ratio exceeds τ^* , it is optimal for the firm to invest immediately. Otherwise, it is optimal for the firm to wait with the investment. As is standard in real options theory, the threshold value τ^* can be found by employing the value matching and smooth pasting conditions, which can be obtained from Equation (23) and Equation (24). The value matching condition is given by

$$c * C_{CO_2} \phi(\tau^*) = c * C_{CO_2} v(\tau^*) - \left(I_{oil} + \frac{C_{oil} * Q_{oil} * (1 - e^{-rT})}{r} \right), \quad (29)$$

with $\frac{C_{oil} * Q_{oil} * (1 - e^{-rT})}{r}$ the sum of the continuously discounted annual operational costs during the time that additional oil is extracted and with C_{oil} the unit operational cost of extracting additional oil which is considered to be constant. Expression (29) is equivalent with

$$c * C_{CO_2} Z_1 \tau^{*\beta_1} = c * C_{CO_2} \left[\frac{Q_{oil} * \tau * (1 - e^{-(r-\alpha_{oil})T})}{r - \alpha_{oil}} - \frac{Q_{oil} * (1 - e^{-(r-\alpha_{CO_2})T})}{r - \alpha_{CO_2}} \right] - \left(I_{oil} + \frac{C_{oil} * Q_{oil} * (1 - e^{-rT})}{r} \right). \quad (30)$$

The smooth pasting condition equals

$$F'(\tau^*) = V'(\tau^*), \quad (31)$$

$$c * C_{CO_2} Z_1 \beta_1 \tau^{*\beta_1-1} = c * C_{CO_2} \frac{Q_{oil} * (1 - e^{-(r-\alpha_{oil})T})}{r - \alpha_{oil}}, \quad (32)$$

Technical data power plant	Without capture	With capture	Difference
a. Annual production capacity (GWh)	7013	7013	/
b. Availability	85%	85%	/
c. Production efficiency (GWh/kJ)	1.28E-10	1.06E-10	0.22E-10
d. Annual fuel consumption (kJ) = a*b/c	4.66E+13	5.62E+13	0.96E+13
e. Emission factor (tCO ₂ /kJ)	9.27E-0.8	9.27E-0.8	/
f. Capture efficiency	/	0.88	0.88
g. Annual CO ₂ capture (Mton) = d*e*f	/	4.59	4.59
Economic data power plant	Without capture	With capture	Difference
h. Investment cost (M€)	1816	2856	1040
i. Variable operational cost (€/GWh)	3165	3692	527
j. Fixed operational cost (M€/year)	33.69	41.71	8.02
k. Fuel cost (€/kJ)	2.27E-06	2.27E-0.6	/
l. Annual variable operational cost (M€)	18.87	22.01	3.14
m. Annual fixed cost (M€)	33.69	41.71	8.02
n. Annual fuel cost (M€) = d*k	105.75	127.70	21.95
o. Total annual costs (M€) = l+m+n	158.31	191.42	33.11
p. Annual cost per tonne CO ₂ captured (€/tonne) = o/g			7.22

From expression (30) and (32) we obtain the investment threshold as presented in the following proposition.

Proposition 6. Investment threshold for the EOR project

$$\tau^* = \frac{\beta_1}{\beta_1 - 1} \left[\frac{r - \alpha_{oil}}{(1 - e^{-(r - \alpha_{oil})T})} * \left[\frac{(1 - e^{-(r - \alpha_{CO_2})T})}{r - \alpha_{CO_2}} + \frac{\left(I_{oil} + \frac{C_{oil} * Q_{oil} * (1 - e^{-rT})}{r} \right)}{Q_{oil} * c * C_{CO_2}} \right] \right] \quad (33)$$

3 A case study for the North Sea region

We apply the model to a hypothetical but realistic case study. We consider an electricity producer located in the Antwerp harbor region (Belgium) that will build a new coal fired power plant and has to decide whether or not to invest in a CO₂ capture unit as well. The oil company, located in the UK, exploits an off-shore oil field in the North Sea Basin and has to decide whether or not to invest in CO₂-EOR and in a 250 km pipeline to transport the CO₂. Cost data for both the capture unit and the CO₂-EOR, the quantity of CO₂ captured and additional oil production are estimated using the PSS simulator developed by Piessens et al. (2012). PSS IV simulates CO₂-EOR value chains considering a continuous stream of compressed CO₂ delivered from an onshore source or hub, transported by means of pipelines or ships to the oil fields (Welkenhuysen et al. 2014). The generic characteristics of enhanced oil recovery from the oil fields in the North Sea, are based on data and reservoir simulations from three active fields are used: Claymore, Fulmar and Forties. EOR performance, CO₂ requirement and various cost data are taken from literature (Rupert 2014; Pershad et al. 2012).

All three oil fields are located in the offshore UK sector of the North Sea, and are at this early stage regarded as potential targets for CO₂-EOR. The Claymore field, currently operated by Talisman Energy, has been in production since 1977. It has an estimated OOIP (Original Oil In Place) of 1455 MMbbl (Million barrels of oil, 1bbl = ±159 liters). The Fulmar field, also operated by Talisman Energy, has been in production since 1985 and has an estimated OOIP of 825 MMbbl. And lastly, the Forties field is operated by the Apache Corporation. It has been in production since 1975, and with an estimated OOIP of 4200 MMbbl it is the largest oil field in the North Sea (European Commission 2005). The following paragraphs give an overview of the data used to evaluate the investment decisions.

3.1 Data used to evaluate the decision to invest in the CO₂ capture unit

To determine the investment cost and the operational costs of the CO₂ capture unit, we calculate the difference in costs between a new, to be build coal fired power plant with and without a CO₂ capture unit. The installation of the CO₂ capture unit involves an additional investment cost, additional fuel consumption, and additional fixed and variable operational costs. The calculation of the additional costs is based on Piessens et al. (2012).

The parameter values for the real options analysis for the investment decision of the electricity producer are given in Table 2. The annual quantity of CO₂ captured, annual unit costs and the investment cost are calculated in Table 1 and are based on Piessens et al. (2012). Concerning the geometric Brownian motion process for the CO₂ price, the assumed parameter values are in range of the values used by Lukas and Welling (2014). Furthermore, following Pershad et al. (2012) we assume a discount rate of 10%, which is typically applied at energy companies.

Description	Parameter	Value	
Annual operational cost	C_{cap}	7.22	€/tonne
Annual CO ₂ captured	Q_{CO_2}	4.59	Mtonne
Investment cost	I_{cap}	1040	M€
CO ₂ price growth rate	α_{pp}	0.05	
CO ₂ price volatility	σ_{pp}	0.20	
Discount rate	r	0.10	

Technical data EOR	Parameter	Value	Unit	Source
Annual quantity of additional oil produced	Q_{oil}	8.25	MMbbl	Kemp and Kasim (2013), Pershad (2012)
Ratio CO ₂ purchased/additional oil produced	c	0.42	tonne/bbl	Based on Pershad (2012)
Economic data EOR				
Investment cost EOR	I_{Oil}	791	M€	Rupert, 2014
Investment cost CO ₂ transportation pipeline	I_{Oil}	752	M€	Piessens et al., 2012, Vandeginste and Piessens, 2012
Annual operational cost	C_{oil}	37.70	€/bbl	Rupert, 2014
CO ₂ price growth rate	α_{CO_2}	0.05		Lukas and Welling (2014)
CO ₂ price volatility	σ_{CO_2}	0.20		Lukas and Welling (2014)
Oil price growth rate	α_{oil}	0.04		Conrad and Kotani (2005;2007)
Oil price volatility	σ_{oil}	0.23		Conrad and Kotani (2005; 2007)
Correlation coefficient	ρ	0.05		Chevalier, 2012
Discount rate	r	0.10		Pershad et al., 2012
Lifetime oil field	T	15	Years	Pershad et al., 2012

3.2 Data used to evaluate the decision to invest in enhanced oil recovery

The oil company has to decide whether it will invest in CO₂-EOR, given an uncertain CO₂ input cost and uncertain oil revenues. Table 3 shows the parameters values used to evaluate the investment decision of the oil company and the different sources from which the values are derived. Applying CO₂-EOR, the oil company can additionally extract an annual quantity of 8.25 MMbbl during 15 years. This quantity is calculated following Pershad et al. (2012) and Kemp and Kasim (2013) who consider for the UK Claymore field 1455 MMbbl Original Oil In Place and who assume that the additional oil production follows a lognormal distribution with a mean of 2.07 and a standard deviation of 0.65. This results in a cumulative oil production of 123.75 MMbbl during 15 years or an annual average production of 8.25 MMbbl. At the injection site, the existing oil production equipment and infrastructure is extended with a compressor, heater, injection wells, and a treatment plant for separation of the produced oil and CO₂. To extract the additional oil, 7 Mton per year needs to be injected, of which 50% is recycled during oil production. Hence, for each barrel of oil extracted, 0.42 tonne of CO₂ needs to be purchased (based on Pershad et al, 2012). Different from Mendelevitch (2014), we do not consider a CO₂ transmission system operator and assume that the oil company also invests in the CO₂ transportation pipeline. Hence, I_{oil} consists of the investment in EOR (791 M€) and the investment in the CO₂ transportation pipeline (752 M€). Annual operational costs consist of variable operation costs, fixed operational costs and CO₂ recycling costs. Parameter values of the geometric Brownian motion process for the oil price are taken from Conrad and Kotani (2005; 2007). Because the CO₂ cost is related to the CO₂ permit price, it is assumed that it follows the same stochastic process as the CO₂ permit price. As regards the parameter values of the geometric Brownian motion process for the CO₂ cost, the parameter values listed in Table 2 are applied.

4 Results

This section shows the results of the investment analyses. Comparing the results using a real options approach with the results obtained by a NPV analysis, and in line with the real options theory (Dixit and Pindyck, 1994) we show that the integration of uncertainty in the economic model results in higher investment threshold levels. Furthermore, when studying the investment problem of the electricity producer, we find that from the perspective of a private investor, uncertainty in prices of CO₂ emission allowances postpones investments in a CO₂ capture unit. If a tax on CO₂ emission would be applied, no market uncertainty would prevail and the investment threshold level for the electricity producer would decrease from 40 €/tonne to 30 €/tonne. The final result shows the CO₂ and oil price regions for which a trade in CO₂ can take place between the oil producer and the electricity producer. We show that if the CO₂ emission permit price is sufficiently high, the electricity producer will be willing to pay the oil producer to store the captured CO₂. Because we do not evaluate the total activity of the different firms, we do not take into account Corporation Tax on profits. The results are pre-tax.

4.1 Result 1: Integrating uncertainty in the investment analyses increases the investment threshold levels

4.1.1 The investment analysis for the CO₂ capture unit

The electricity producer and the oil company each have their own investment decision to take. We show that for both companies it is important to apply the real options theory and to integrate stochastic price processes within the decision analysis. If the Net Present Value is calculated, investment threshold levels are much lower.

As regards the investment in the CO₂ capture unit, Figure 3 shows the value of the CO₂ capture unit after investment and the value of the option to invest for different CO₂ prices. For a price of 40 €/tonne CO₂ captured, the value of the option to invest equals the net gain of exercising the option to invest. For values of P_{pp} smaller than P_{pp}^* , the value of holding the option to invest is larger than the net gain of exercising the option. Hence, the power plant will only invest in the CO₂ capture unit if it receives a revenue of at least 40 €/tonne CO₂ captured. This analysis implicitly assumes that captured CO₂ will be permanently stored and that the avoided cost of CO₂ emission allowances is ensured.

Figure 3. Value of the CO₂ capture unit after investment and the value of the option to invest for different CO₂ prices

Equation (34) shows the calculation of the CO₂ threshold level when an NPV approach is applied. In line with the real options theory, it shows that when uncertainty is not integrated in the analysis, the threshold CO₂ price level is lower. The electricity producer would invest too soon in the CO₂ capture unit. Not including uncertainty within the decision analysis could thus lead to erroneous investment decisions.

$$P_{CO_2}^*(NPV) = \frac{I_{Cap} * r}{Q_{CO_2}} + C_{Cap} = \frac{1040 \text{ M€}}{4.59 \text{ Mtonne}} + 7.22 \text{ €/tonne} = 29.88 \text{ €/tonne} \quad (34)$$

4.1.2 The investment analysis for EOR

For the oil company, we can deduct from Equation (33) that the firm should invest whenever the current price P_{oil} exceeds $P_{oil}^*(C_{CO_2})$, with C_{CO_2} the cost of CO₂. It is implicitly assumed that a flow of CO₂ will be readily available from an onshore hub to the oil company. The oil company will invest in the CO₂ transportation pipeline network.

$$P_{Oil}^* = \left(\frac{\beta_1}{\beta_1 - 1} \right) \left[\frac{r - \alpha_{oil}}{(1 - e^{-(r - \alpha_{oil})T})} * \left[\frac{c * C_{CO_2} (1 - e^{-(r - \alpha_{CO_2})T})}{r - \alpha_{CO_2}} + \frac{\left(I_{oil} + \frac{C_{oil} * Q_{oil} * (1 - e^{-rT})}{r} \right)}{Q_{oil}} \right] \right] \quad (35)$$

Using a NPV approach, the oil price threshold level equals

$$P_{Oil}^*(NPV) = \frac{r - \alpha_{oil}}{(1 - e^{-(r - \alpha_{oil})T})} * \left[\frac{c * C_{CO_2} (1 - e^{-(r - \alpha_{CO_2})T})}{r - \alpha_{CO_2}} + \frac{\left(I_{oil} + \frac{C_{oil} * Q_{oil} * (1 - e^{-rT})}{r} \right)}{Q_{oil}} \right] \quad (36)$$

Figure 4 shows the threshold boundary at which the oil company should decide to invest in a CO₂-EOR project. It shows the minimum oil price required for the CO₂-EOR project to become economically feasible. The oil price threshold level is determined in function of the CO₂ cost. Both the results of the NPV approach (Equation 36) and the real options model (Equation 35) are shown. In analogy to financial theory, the option to invest in CO₂-EOR can be considered as a call option that should be exercised when the option to invest is sufficiently deep in the money which is in the area above the dashed line. In this area, the NPV is sufficiently larger than the investment cost. When the net present value is negative (area below the solid line), the option to invest is out of the money and no investment takes place. When the NPV is larger than zero, and situated between the solid line and the dashed line, the option to invest is in the money. However, investing in the CO₂-EOR project would be suboptimal because the possibility to delay the project is ignored and the firm is not sufficiently secured to potential future losses.

Figure 4. Oil and CO₂ price threshold boundaries for the investment in CO₂-EOR

Hence, when uncertainty is integrated in the decision analysis, oil price threshold levels are higher than the threshold level determined using an NPV approach. Klokk et al. (2010) only applied an NPV approach and find for their base case example that for an oil price of 50 USD/bbl (± 45 €/bbl) and a CO₂ price of 27 USD/tonne CO₂ (± 24 €/tonne CO₂) the NPV of CO₂-EOR is positive. We show that when uncertainty is integrated in the investment analysis, for a CO₂ cost of 24 €/tonne, the oil price needs to be at least 122 €/bbl. For an oil price of 45 €/bbl the CO₂ cost needs to be negative to economically justify the investment in CO₂-EOR. Also Kemp and Kasim (2013) study EOR investments for different oil fields in the UK Continental Shelf and calculate NPVs for different oil fields. They do not determine investment threshold values but conclude that for low carbon prices with an average of 5 GBP/tonne CO₂ and an average oil price of 80 GBP/bbl (± 113 €/bbl) EOR is economically feasible. If we project the result of Kemp and Kasim on our results, not only the NPV result is positive, but also the threshold level determined by the real options analysis is reached. Comparing our results to those of Mendelevitch (2014), we come to a similar conclusion. Like Mendelevitch (2014) we show that for the given CO₂ and oil price levels, the NPV is positive. However, when uncertainty is integrated, for a CO₂ cost of 83 €/tonne, the oil price level needs to be 178 €/bbl. Different from Klokk et al. (2010), Kemp and Kasim (2013), and Mendelevitch (2014) we do not address uncertainty by a sensitivity analysis. Although a Monte Carlo sensitivity analysis highlights the several substantial risks involved, it only provides a range in NPV. Making a decision based on a range of NPVs is still difficult. The integration of uncertainty in the economic model better supports clear-cut decision making as it clearly shows how the investment threshold level is affected by uncertainty.

4.2 Result 2: A tax on CO₂ emissions results in a lower investment threshold level for the investment in the CO₂ capture unit and for the investment in CO₂-EOR.

Figure 5 shows how the level of uncertainty affects the investment threshold level for the electricity producer (Figure A) and for the oil company (Figure B). Figure 5A shows that when uncertainty in the price of CO₂ emission permits decreases, the critical threshold

level of the CO₂ revenue decreases as well. To decrease uncertainty, policy makers can decide to introduce a carbon tax. According to Krahé et al. (2013) a carbon tax may offer a larger degree of certainty compared to a CO₂ permit trading system, especially if the future trajectory of the tax is known to the investor. Our results shows that compared to the CO₂ permit trading system, the certainty offered by a carbon tax will result in earlier investments in the carbon capture technology.

Figure 5. Effect of uncertainty on the CO₂ permit price threshold level for the investment in CO₂ capture (Figure A) and on the threshold boundary for the investment in CO₂-EOR (Figure B)

When a tax on CO₂ would be applied, the electricity producer would be willing to invest when the carbon tax is about 30 €/tonne ($\sigma = 0$). Due to the volatility ($\sigma = 0.2$) in CO₂ permit prices, the threshold value for the electricity producer to invest in CO₂ capture is 40 €/tonne. Figure 5B also shows that when uncertainty in the CO₂ permit price is reduced to 0 ($\sigma_{CO_2} = 0$) and the uncertainty in oil price does not change ($\sigma_{oil} = 0.2$), the investment threshold level for the oil company (dashed-dotted line) decreases as well. The fact that uncertainty and irreversibility reduce investment is a standard conclusion of real option theory which would not be revealed when adopting an NPV approach. If the volatility of both the oil and CO₂ prices approach zero, the limit of β_1 (Equation 2.27) only depends on the discount rate, α_{CO_2} and α_{oil} , which are the oil and CO₂ price growth rates. Because for this case study, α_{CO_2} is larger than α_{oil} , it follows that β_1 converges to infinity and the real options investment threshold boundary then equals the NPV threshold boundary. The intuition is that, since the growth rate of the CO₂ permit price, which is a cost to the oil producer is larger than the oil price growth rate (the revenue), waiting reduces investment profitability. This implies that the real options decision criterion mimics the one according to the NPV rule. If the option to invest is currently not at the money, the company will also not invest in the future, because the costs will grow more than the revenues. If the option to invest is currently in the money, the company will invest immediately, because if the company would postpone the investment to the future, the NPV will be lower. The company then has no incentive to wait. In case α_{oil} is larger than α_{CO_2} , the limit of β_1 is a fixed value and the real options threshold boundary will be larger than the NPV threshold boundary. If the growth rate of the revenues is larger than the growth rate of the costs, the company will wait to invest until the option to invest is sufficiently deep in the money.

4.3 Result 3: The oil company does not necessarily have to pay for the CO₂ captured by the electricity producer

Most of the existing studies that consider CO₂-EOR do not take into account that a transaction of CO₂ will take place between the electricity producer and the oil company and that a CO₂ selling price needs to be established between these two parties. Mendelevitch (2014) integrates a CO₂ transport system operator, but the transaction values are not determined based on the investment threshold levels of the firms considered. If the electricity producer can sell the captured CO₂ to the oil company, then the revenue that the power plant receives is twofold: the price it receives from selling the CO₂ to the oil company and the avoided payment of emission allowance. The upper panel in Figure 6 shows the minimum selling price required for the electricity producer to invest in a CO₂ capture unit for different CO₂ permit price level. If the CO₂ permit price is below 40 €/tonne, the electricity producer will only invest in a CO₂ capture unit if it receives an additional revenue from the sales of CO₂ and if the transport and permanent storage

of CO₂ is guaranteed by the oil company. If the CO₂ permit price is higher than 40 €/tonne and smaller than 61 €/tonne, the electricity producer could be willing to pay the oil producer a fee for the transport and storage of CO₂. This fee will be maximum the difference between the CO₂ permit price and 40 €/tonne, the investment threshold value for the capture unit. If the CO₂ permit price is higher than 61 €/tonne, it is profitable for the electricity producer to invest in CCS and to pay for the transport and storage of CO₂. In that case, the electricity producer will not be willing to pay the oil company more than 21 €/tonne for the transport and storage of CO₂.

Figure 6. Minimum CO₂ selling price that is required for the electricity producer to invest in a CO₂ capture unit (Figure A) and the region for which a trade in CO₂ will take place between the electricity producer and the oil company (Figure B)

To determine the values of the CO₂ permit prices and oil prices for which a trade in CO₂ can take place between the two firms, the results of Figure 4 and the upper panel of Figure 6 are combined. The higher the CO₂ emission permit price, the lower the minimum required CO₂ selling price and the lower the critical oil price threshold level in this model. For CO₂ emission permit prices equal to 0 €/tonne, the minimum CO₂ selling price is 40 €/tonne (Figure 6A) and at that cost, the oil company will only invest in CO₂-EOR if the oil price is at least 136 €/bbl (Figure 4). In that case, the investment in the CO₂ capture unit will be shared between the oil company and the electricity producer and the oil company will invest in CO₂ transport and storage (by EOR). At CO₂ permit prices equal to 40 €/tonne, a trade in CO₂ will only take place if oil prices are higher than 100 €/bbl. In that case, for oil prices below 136 €/bbl and above 100 €/bbl, the investment in CO₂ transport and storage will be shared between the oil company and the electricity producer. Figure 6B presents the regions in which a trade between the oil company and the electricity producer can take place. In these regions, both firms will make the necessary investments and trade CO₂. When the CO₂ price increases to a level higher than 61 €/tonne, the investment in CCS would be profitable to the electricity producer (ZEP 2011). However, at that point the electricity producer can avoid the cost of transport and storage by selling the CO₂ to the oil producer. At a permit price of 61 €/tonne, CCS will only take place if the oil price is below 80 €/bbl. For higher oil prices, the CO₂ will be traded between the electricity producer and the oil company. Hence, as long as CO₂ permit prices are below 61 €/tonne, CO₂ EOR and the additional oil revenues are needed to ensure the permanent storage of CO₂. When CO₂ permit price increase to a level of 61 €/tonne, the EUETS does not necessarily result in the adoption of CCS but further stimulates oil production.

5 Sensitivity analysis

The minimum oil price that is required for a trade in CO₂ to take place depends on the given CO₂ permit price, the lifetime of the oil field, the rate at which oil is extracted per tonne CO₂ that is bought from the electricity producer, and the discount rate. Figure 7 shows how this minimum oil price level changes for a 20% upward and downward change in the base case parameter values. The first tornado chart assumes for the base case a low permit price of 10 €/tonne and represents the scenario in which the oil producer will have to pay the electricity producer for the CO₂. The second chart assumes for the base case a high CO₂ permit price of 50 €/tonne and represents the scenario in which the electricity producer will be willing to pay the oil producer to store the CO₂ in the subsurface. In the third and fourth tornado chart, the investment cost of the CO₂ transportation pipeline is set to 0 and represents the scenario in which the pipeline is funded by a public authority, given respectively low and high CO₂ permit prices. All charts show that the more the lifetime of the EOR operation can be extended, the lower the oil price threshold level is. Therefore, it would be more profitable to locate the CO₂-EOR installation at clustered oil fields and to use the same the CO₂-EOR equipment at different oil fields sequentially, insofar as it can still be reused. If the investment cost of the CO₂ transportation pipeline is funded by a public authority, the lifetime of the EOR operation becomes less important as the investment cost to the oil producer decreases. The sensitivity analysis shows that a change in quantity of CO₂ that needs to be purchased to extract an additional barrel of oil, does not highly affect the profitability of an investment in CO₂-EOR. If the CO₂ permit price is low, the supply of CO₂ is a cost to the oil producer, so the less CO₂ that needs to be bought, the more profitable CO₂-EOR is. However, when CO₂ permit prices will increase in time, the input of CO₂ could become a revenue to the oil producer as the electricity producer will be willing to pay the oil producer a fee for the storage of CO₂. In that case, the more CO₂ that can be stored in the subsurface, the more profitable that CO₂-EOR becomes. The discount rate highly affects the profitability of the CO₂-EOR investment decision in case of low permit prices. In contrast to standard NPV analysis, a higher discount rate encourages investment. As noted by Dixit and Pindyck (1994), this is a pure manifestation of the option idea: a higher interest rate makes future cash flows less important, therefore it decreases the opportunity cost of exercising the option to invest and decreases the value of waiting. Because of the non-linear relationship in discounting, a decrease in discount rate has a higher impact than an increase. In Figure 7C, the investment cost in the CO₂ pipeline infrastructure is omitted. It is shown that in case of low CO₂ permit prices, the oil price still needs to be higher than 100 €/bbl for the CO₂-EOR operation to become profitable. Hence, in case of low oil prices and low CO₂ permit prices, a public investment in CO₂ transport infrastructure will not be sufficient to stimulate an investment in CO₂-EOR. Figure 7D shows that only in conjunction with high CO₂ permit prices, a public investment in CO₂ transport infrastructure can make CO₂-EOR profitable given low oil prices of 60 €/bbl.

Figure 7. Sensitivity analysis

6 Policy implications

Based on the above results, this section discusses which policy measures can be taken to stimulate investments in CO₂-EOR as an intermediate step towards carbon capture and storage, given different oil and CO₂ price levels.

6.1 Low CO₂ permit price and low oil price

In the case of low CO₂ permit prices and low oil prices, both the electricity producer and the oil company will not have the incentive to invest in CO₂-EOR. This scenario relates to current market conditions where the cap on emissions in the EU and the associated CO₂ price is not sufficient to create a market for investing in carbon capture technologies. Our results show that by implementing a national carbon tax, uncertainty will be reduced and the CO₂ price at which the investment in CO₂ capture is economically justified, will decrease from 40 €/tonne to 30 €/tonne. Note that Heindl et al. (2014) demonstrate that the introduction of a national carbon tax can have a negative impact on the CO₂ permit prices because the demand for emission permits will decrease and will not necessarily result in increased emission abatement because the cap remains fixed and the abatement effort of the country that imposes the tax will be larger than the abatement effort of countries that do not impose the tax. It will increase the abatement effort of one country. Nevertheless, combining the EU ETS with a national carbon tax could speed up the decarbonization of the economy and incentivize innovation (Heindl et al., 2014). Furthermore, in case of low oil prices, an increase in the CO₂ prices will not be sufficient for the adoption of CO₂-EOR. Only if an increase in CO₂ prices is combined with external, public funds in CO₂ transport infrastructure, CO₂-EOR becomes economically feasible at oil prices as low as 60 euro/bbl. Also Morbee et al. (2010) have shown that investing in integrated networks, planned and constructed at a transnational level could catalyze the large scale deployment of CCS technologies. An integrated CO₂ transport network will allow for sharing the built infrastructure with other CO₂ sources and sinks, resulting in economies of scale.

6.2 Low CO₂ permit price and high oil price

In case of low CO₂ permit prices and high oil prices (>100 €/bbl), our results show that oil production can stimulate the investment in carbon capture technologies and that less governmental intervention is required. Through contract agreements with oil producers, CO₂ producers can receive an additional revenue resulting from the sales of CO₂ to the oil producer. These contract agreements will decrease uncertainty in the revenue stream and lower the CO₂ price investment threshold level. In that sense, oil production will stimulate investments in CO₂ capture. Furthermore, a public investment in CO₂ transport infrastructure could evolve from publicly funded towards an integrated network that is regulated by a public authority and for which a fee for its use can be asked. In that case, this fee becomes a policy instrument that can be adjusted to the prevalent market conditions.

6.3 High CO₂ permit price and low oil price

At a CO₂ price of 61 €/tonne, the CO₂ permit price reaches a level that is sufficient to economically justify an investment in CCS. The CO₂ producer does not need the oil producer anymore to share the investment in CO₂ transport and storage. Carbon capture and storage can take place without the involvement of the oil producer. No trade in CO₂ will take place between the oil producer and the electricity producer if the oil price is too low to invest in CO₂-EOR. Nevertheless, the off-shore oil reservoir could be used to store the CO₂ and the electricity producer could take advantage of data on the reservoir characteristics gathered by the oil producer during primary oil recovery. Because of its public good characteristics, geological information is underprovided in the free market and not effectively priced (Haggquist and Soderholm, 2015). A national database that is set up within a regulatory framework that outlines the rules for the provision and use of geological data, could ensure that all the benefits of geological information are fully seized and stimulate investments in subsurface activities such as CCS.

6.4 High CO₂ permit price and high oil prices

When both oil and CO₂ permit prices are high, the electricity producer will be willing to pay for the CO₂ transport and storage and the oil producer will be willing to pay for the CO₂ to extract additional oil by investing in CO₂-EOR. At high oil and CO₂ prices, a trade in CO₂ will take place between the two firms and a CO₂ selling price will be agreed without any governmental intervention.

To balance additional oil production with governmental objectives within the EU regarding the transition towards a low carbon economy, further CO₂ storage after the operation of CO₂-EOR has finished, could be mandated in all four price scenarios. Furthermore, for the CO₂-EOR-operation to take place, CO₂-EOR should be recognized as permanent CO₂ storage and the electricity producer should receive the benefits immediately and not after the CO₂-EOR operation has finished.

7 Conclusion and discussion

Building further on existing studies regarding CO₂ enhanced oil recovery, this study analyzes for the first time the deployment of CO₂-EOR as two separate investment decisions and defines the minimum CO₂ and oil price levels at which a trade in CO₂ can take place between a carbon emitting source and an oil company, considering market price uncertainties. Two real options models are developed: the first model integrates CO₂ price uncertainty into the investment analysis of an electricity producer that has the option to invest in a CO₂ capture unit. The second model considers the investment problem of an oil company and integrates oil price uncertainty and CO₂ cost uncertainty into the analysis. Both models are applied to a hypothetical but realistic case study, considering a post-combustion CO₂ capture unit to be installed at a coal-fired power plant in the Antwerp region. The captured CO₂ is transported by pipelines and injected into an off-shore oil reservoir in the North Sea region. It is shown that for both firms, investment threshold levels are higher compared to the threshold levels calculated on a Net Present Value basis. Hence, by considering the option to delay an investment, we show that the application of the net present value approach results in suboptimal investment decisions compared to the real options approach. Moreover, by applying the real option theory, we can show that regulation in the form of a carbon tax rather than a market based approach reduces uncertainty and, consequently, the CO₂ price threshold level for

the investment in the CO₂ capture unit decreases from 40 €/tonne to 30 €/tonne. If uncertainty in the CO₂ price is lower, CO₂ cost uncertainty for the oil producer diminishes and the oil price threshold level for the investment in CO₂-EOR decreases as well.

By combining the results of the two separate models and introducing a CO₂ selling price, it is shown how a trade between the electricity producer and the oil company could take place. The electricity producer then has a revenue that includes both the avoided cost of CO₂ emission allowances and the payment the electricity producer receives from selling CO₂ to the oil company. It is shown that as long as CO₂ permit prices are below 40 €/tonne, the revenues from additional oil production are required for early investments in CO₂ capture to take place and to ensure the permanent underground storage of CO₂. Only at oil prices higher than 100 €/bbl, the oil company will be willing to invest in CO₂ transport and storage by means of CO₂-EOR, to pay for the CO₂ and hence, use oil revenues to share the investment in CO₂ capture. If permit prices increase, the minimum required oil price for CO₂-EOR decreases because the electricity producer is willing to pay the oil company to store the CO₂ in the oil reservoir. For CO₂ permit prices higher than 40 €/tonne, the investment in CO₂ transport and storage is shared between the oil company and the electricity producer. When CO₂ permit prices increase to 61 €/tonne, CCS (without oil extraction) becomes economically feasible for the electricity producer. However, an investment in CCS, without oil extraction will not necessarily take place. The electricity producer can avoid the cost of transport and storage by trading CO₂ with the oil company and by paying a fee to the oil company. In that case, the oil company receives an additional revenue for storing CO₂ and will invest in CO₂-EOR when the oil price is 80 €/bbl or higher. Hence, in case of CO₂ permit prices higher than 61 €/tonne, an investment in CCS (without oil extraction) will only take place if the oil price is below 80 €/bbl. The sensitivity analysis shows the importance of the projects' lifetime. The longer the lifetime of the CO₂-EOR operation is, the more profitable CO₂-EOR becomes. Without a publicly funded integrated CO₂ transportation network, the oil company should locate the CO₂-EOR installation at clustered oil fields.

In case of low CO₂ permit prices and low oil prices, a carbon tax will not be sufficient to stimulate investment in CO₂-EOR. Combined policy measures, including price instruments, public funds in CO₂ transportation infrastructure and regulations will be required to stimulate investments in CO₂ capture and its permanent storage. If CO₂ permit prices increase, public authorities should be aware that oil production will not stimulate CO₂ capture anymore but that CO₂ capture will stimulate oil production.

By extending the real options analysis with a game theoretical approach, further research can determine which selling price will be established between the two profit maximizing firms. Also the decision to provide CO₂ transportation infrastructure publicly can be made part of a real option game that considers a social welfare maximizing objective function.

Furthermore, it should be studied whether experience in CO₂-EOR will reduce the cost of CCS deployment and how it aligns with policy objectives regarding the reduction in CO₂ emissions and investments in renewable energy. Using an oil reservoir after EOR as a CO₂ storage project, making use of the existing EOR infrastructure, may be economic and it is therefore desirable to include it in a real options scheme for further research. Although EOR projects, if linked to ETS driven capture projects, will normally produce less carbon intense oil than standard production from the same field, they would also increase the net oil reserves. This could lead to a prolonged use of fossil fuels and a delayed introduction of renewables. Other low carbon technologies such as CCS, would likely benefit from technology developments that CO₂-EOR would bring. Evaluation of such hidden effects is necessary to ensure that EOR would lead to a substantial reduction in CO₂ emissions in the long term. Such type of analysis should also balance issues as energy security, job security and social welfare in general.

8 Acknowledgment

We would like to thank the reviewers for their constructive comments which helped us to improve the manuscript. Tine Compennolle thanks the Research Foundation Flanders (FWO) for funding her postdoctoral mandate with Grant number 12M7417N, without which it would have been impossible to revise this work.

9 Appendix A

At any instant the profit flow from this project is given by

$$\pi(P_{pp}) = \max[Q_{CO_2}(P_{pp} - C_{cap}), 0]. \quad (37)$$

The value of the project at time t can be expressed as the sum of the operating profit over the interval $(t, t + dt)$ and the continuation value beyond $t+dt$. Thus,

$$V(P_{pp}) = \pi(P_{pp})dt + E[V(\pi(P_{pp}) + d\pi(P_{pp}))e^{-r dt}]. \quad (38)$$

Expanding the right-hand side using Ito's Lemma, we have

$$V(P_{pp}) = \pi dt + \left[V'(P_{pp})\alpha_{pp}P_{pp} + \frac{1}{2}V''(P_{pp})\sigma_{pp}^2P_{pp}^2 \right] dt + (1 - r dt)V(P_{pp}). \quad (39)$$

Simplifying, dividing by dt , and proceeding to the limit as dt goes to zero, we get the differential equation

$$0 = \pi + V'(P_{pp}) \alpha_{pp} P_{pp} + \frac{1}{2} V''(P_{pp}) \sigma_{pp}^2 P_{pp}^2 - rV(P_{pp}). \quad (40)$$

When held for the short time interval $(t, t+dt)$, the power plant can exercise the current operation option. That is profitable if $P_{pp} > C_{cap}$; the resulting profit flow is just $\pi(P_{pp}) = \max[Q_{Co_2}(P_{pp} - C_{cap}), 0]$.

The differential equation for the value of the project is

$$0 = \pi + V'(P_{pp}) \alpha_{pp} P_{pp} + \frac{1}{2} V''(P_{pp}) \sigma_{pp}^2 P_{pp}^2 - rV(P_{pp}). \quad (41)$$

Because $\pi(P_{pp})$ is defined differently when $P_{pp} < C_{cap}$ and when $P_{pp} > C_{cap}$, we solve the equation separately for $P_{pp} < C_{cap}$ and $P_{pp} > C_{cap}$, and then stitch together the two solutions at the point $P_{pp} = C_{cap}$. In the region $P_{pp} < C_{cap}$, we have $\pi(P_{pp}) = 0$ and only the homogenous part of the equation remains.

$$V(P_{pp}) = K(P_{pp})^\beta; V'(P_{pp}) = \beta K(P_{pp})^{\beta-1}; V''(P_{pp}) = \beta(\beta-1)K(P_{pp})^{\beta-2}. \quad (42)$$

We substitute Equations (42) in Equation (41):

$$\frac{1}{2} \sigma^2 \beta(\beta-1) + \alpha_{pp} \beta - r = 0. \quad (43)$$

and we see that it satisfies the equation provided β is a root of the quadratic equation. The two roots are

$$\beta_1 = \frac{1}{2} - \frac{\alpha_{pp}}{\sigma_{pp}^2} + \sqrt{\left(-\frac{1}{2} + \frac{\alpha_{pp}}{\sigma_{pp}^2}\right)^2 + \frac{2r}{\sigma_{pp}^2}} > 1, \quad (44)$$

$$\beta_2 = \frac{1}{2} - \frac{\alpha_{pp}}{\sigma_{pp}^2} - \sqrt{\left(-\frac{1}{2} + \frac{\alpha_{pp}}{\sigma_{pp}^2}\right)^2 + \frac{2r}{\sigma_{pp}^2}} < 0. \quad (45)$$

The general solution can be written as

$$V(P_{pp}) = K_1(P_{pp})^{\beta_1} + K_2(P_{pp})^{\beta_2}. \quad (46)$$

where K_1 and K_2 are constants to be determined and β_1 and β_2 are the roots of the quadratic equation. In the region $P_{pp} > C_{cap}$, we take another linear combination of the power solutions of the homogenous part, and add on any particular solution of the full equation. The particular solution is then

$$\frac{P_{pp}}{(r - \alpha)} - \frac{C_{cap}}{r}. \quad (47)$$

And the general solution for $P_{pp} > C_{cap}$ is

$$B_1(P_{pp})^{\beta_1} + B_2(P_{pp})^{\beta_2} + \frac{P_{pp}}{(r - \alpha_{pp})} - \frac{C_{cap}}{r}. \quad (48)$$

In the region $P_{pp} < C_{cap}$, operation is suspended and the project yields no current profit flow. However, there is a probability that the price process will at some future time move into the region $P_{pp} > C_{cap}$, when operation will resume and profits will accrue.

The constants in the solution are determined using economic considerations that apply at the boundaries of the regions.

Given, $P_{pp} < C_{cap}$, as P_{pp} becomes very small, the event of P_{pp} rising above C_{cap} becomes unlikely. The expected present value of future profits should then go to zero, and so should the value of the project. However, with $\beta_2 < 0$, $P_{pp}^{\beta_2}$ goes to infinity as P_{pp} goes to 0. Therefore, K_2 should be zero.

Given $P_{pp} > C_{cap}$, when P_{pp} becomes very large, the suspension option is unlikely to be invoked, so its value should be zero. For this we should rule out the positive power of P , by setting B_1 equal to 0. The value of the project is then

$$V(P_{pp}) = \left\{ \begin{array}{l} K_1 (Q_{Co_2} P_{pp})^{\beta_1}, \text{ for } P_{pp} < C_{cap}, \\ B_2 (Q_{Co_2} P_{pp})^{\beta_2} + \frac{Q_{Co_2} P_{pp}}{r - \alpha_{pp}} - \frac{Q_{Co_2} C_{cap}}{r}, \text{ for } P_{pp} > C_{cap}, \end{array} \right\} \quad (49)$$

This still leaves two constants for which we consider the point $P_{pp} = C_{cap}$ where the two regions meet. Equating the values and derivatives of the two component solutions at C_{cap} , we have

$$K_1 C_{cap}^{\beta_1} = B_2 C_{cap}^{\beta_2} + \frac{C_{cap}}{r - \alpha_{pp}} - \frac{C_{cap}}{r}, \quad (50)$$

$$\beta_1 K_1 C_{cap}^{\beta_1-1} = \beta_2 B_2 C_{cap}^{\beta_2-1} + \frac{1}{r - \alpha_{pp}}. \quad (51)$$

These are two linear equations in the unknowns K_1 and B_2 , that readily yield the solution

$$K_1 = \frac{C_{cap}^{1-\beta_1}}{(\beta_1 - \beta_2)} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \alpha_{pp}} \right), \quad (52)$$

$$B_2 = \frac{C_{cap}^{1-\beta_2}}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \alpha_{pp}} \right). \quad (53)$$

10 Appendix B

10.1 Proof of proposition 4

In the stopping region the value of the firm equals

$$V(P_{oil}(t), C_{CO_2}(t)) = E \left[\int_{s=t}^T (Q_{oil}(P_{oil}(s)) - c * C_{CO_2}(s)) e^{-r(s-t)} ds \right]$$

$$\begin{aligned} V(P_{oil}(t), C_{CO_2}(t)) &= E \left[\int_{s=0}^T \left(Q_{oil}(P_{oil}(t)) e^{(\alpha_{oil} - \frac{1}{2}\sigma^2)s + \sigma\omega(s)} \right) e^{-rs} ds \right] - \\ &E \left[\int_{s=0}^T \left(Q_{oil}(c * C_{CO_2}(t)) e^{(\alpha_{CO_2} - \frac{1}{2}\sigma^2)s + \sigma\omega(s)} \right) e^{-rs} ds \right] \end{aligned}$$

$$\begin{aligned} V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * E \left[\int_{s=0}^T \left(e^{(\alpha_{oil} - \frac{1}{2}\sigma^2)s + \sigma\omega(s)} \right) e^{-rs} ds \right] - \\ &C_{CO_2}(t) * Q_{oil} * c * E \left[\int_{s=0}^T \left(e^{(\alpha_{CO_2} - \frac{1}{2}\sigma^2)s + \sigma\omega(s)} \right) e^{-rs} ds \right] \end{aligned}$$

$$\begin{aligned} V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * E \left[\int_{s=0}^T \int_{\omega=-\infty}^{\infty} \frac{1}{\sqrt{s}\sqrt{2\pi}} e^{\frac{-(\omega-0)^2}{2s}} e^{(\alpha_{oil} - \frac{1}{2}\sigma^2)s + \sigma\omega} e^{-rs} d\omega ds \right] - \\ &C_{CO_2}(t) * Q_{oil} * c * E \left[\int_{s=0}^T \int_{\omega=-\infty}^{\infty} \frac{1}{\sqrt{s}\sqrt{2\pi}} e^{\frac{-(\omega-0)^2}{2s}} e^{(\alpha_{CO_2} - \frac{1}{2}\sigma^2)s + \sigma\omega} e^{-rs} d\omega ds \right] \end{aligned}$$

$$\frac{-(\omega - \sigma s)^2}{2s} + \frac{1}{2}\sigma^2 s = \frac{-\omega^2}{2s} - \frac{\sigma^2 s^2}{2s} + \frac{1}{2}\sigma^2 s + \frac{2\omega\sigma s}{2s} = \frac{-\omega^2}{2s} + \omega\sigma$$

$$\begin{aligned} V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * E \left[\int_{s=0}^T \int_{\omega=-\infty}^{\infty} \frac{1}{\sqrt{s}\sqrt{2\pi}} e^{-(r - \alpha_{oil} + \frac{1}{2}\sigma^2)s} e^{\frac{-(\omega - \sigma s)^2}{2s} + \frac{1}{2}\sigma^2 s} d\omega ds \right] - \\ &C_{CO_2}(t) * Q_{oil} * c * E \left[\int_{s=0}^T \int_{\omega=-\infty}^{\infty} \frac{1}{\sqrt{s}\sqrt{2\pi}} e^{-(r - \alpha + \frac{1}{2}\sigma^2)s} e^{\frac{-(\omega - \sigma s)^2}{2s} + \frac{1}{2}\sigma^2 s} d\omega ds \right] \end{aligned}$$

$$\begin{aligned}
V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * E \left[\int_{s=0}^T e^{-(r-\alpha_{oil}+\frac{1}{2}\sigma^2)s} \int_{\omega=-\infty}^{\infty} \frac{1}{\sqrt{s}\sqrt{2\pi}} e^{\frac{-(\omega-\sigma s)^2}{2s} + \frac{1}{2}\sigma^2 s} d\omega ds \right] - \\
&C_{CO_2}(t) * Q_{oil} * c * E \left[\int_{s=0}^T e^{-(r-\alpha+\frac{1}{2}\sigma^2)s} \int_{\omega=-\infty}^{\infty} \frac{1}{\sqrt{s}\sqrt{2\pi}} e^{\frac{-(\omega-\sigma s)^2}{2s} + \frac{1}{2}\sigma^2 s} d\omega ds \right] \\
&\int_{\omega=-\infty}^{\infty} \frac{1}{\sqrt{s}\sqrt{2\pi}} e^{\frac{-(\omega-\sigma s)^2}{2s}} d\omega = 1
\end{aligned}$$

$$\begin{aligned}
V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * E \left[\int_{s=0}^T e^{-(r-\alpha_{oil}+\frac{1}{2}\sigma^2)s} e^{\frac{1}{2}\sigma^2 s} ds \right] - \\
&C_{CO_2}(t) * Q_{oil} * c * E \left[\int_{s=0}^T e^{-(r-\alpha_{CO_2}+\frac{1}{2}\sigma^2)s} e^{\frac{1}{2}\sigma^2 s} ds \right]
\end{aligned}$$

$$\begin{aligned}
V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * E \left[\int_{s=0}^T e^{-(r-\alpha_{oil})s} ds \right] - \\
&C_{CO_2}(t) * Q_{oil} * c * E \left[\int_{s=0}^T e^{-(r-\alpha_{CO_2})s} ds \right]
\end{aligned}$$

$$\begin{aligned}
V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * \left[\frac{-1}{r-\alpha_{oil}} e^{-(r-\alpha_{oil})s} \right]_0^T - \\
&C_{CO_2}(t) * Q_{oil} * c * E \left[\frac{-1}{r-\alpha_{CO_2}} e^{-(r-\alpha_{CO_2})s} \right]_0^T
\end{aligned}$$

$$\begin{aligned}
V(P_{oil}(t), C_{CO_2}(t)) &= P_{oil}(t) * Q_{oil} * \frac{-1}{r-\alpha_{oil}} \left[e^{-(r-\alpha_{oil})T} - 1 \right] - \\
&C_{CO_2}(t) * Q_{oil} * c * \frac{-1}{r-\alpha_{CO_2}} \left[e^{-(r-\alpha_{CO_2})T} - 1 \right]
\end{aligned}$$

Define the markup ratio as

$$\tau = \frac{P_{oil}}{c * C_{CO_2}}, \quad (54)$$

then the value of the firm after investment in EOR equals

$$V(P_{oil}, C_{CO_2}) = c C_{CO_2} v(\tau) = c * C_{CO_2} \left[\frac{Q_{oil} * \tau * (1 - e^{-(r-\alpha_{oil})T})}{r - \alpha_{oil}} - \frac{Q_{oil} * (1 - e^{-(r-\alpha_{CO_2})T})}{r - \alpha_{CO_2}} \right].$$

10.2 Proof of proposition 5

The Bellman equation that $F(P_{oil}, C_{CO_2})$ must satisfy is given by

$$rF(P_{oil}, C_{CO_2}) = \lim_{dt \rightarrow 0} \frac{1}{dt} E[dF(P_{oil}, C_{CO_2})]. \quad (55)$$

Expanding $E[dV(P_{oil}, C_{CO_2})]$ with Ito's Lemma gives

$$\begin{aligned}
rF(P_{oil}, C_{CO_2}) = & \alpha_{CO_2} C_{CO_2} \frac{\partial F(P_{oil}, C_{CO_2})}{\partial C_{CO_2}} + \alpha_{oil} P_{oil} \frac{\partial F(P_{oil}, C_{CO_2})}{\partial P_{oil}} + \frac{1}{2} \sigma_{CO_2}^2 C_{CO_2}^2 \frac{\partial^2 F(P_{oil}, C_{CO_2})}{\partial C_{CO_2}^2} \\
& + \rho \sigma_{CO_2} \sigma_{oil} P_{oil} C_{CO_2} \frac{\partial^2 F(P_{oil}, C_{CO_2})}{\partial P_{oil} \partial C_{CO_2}} + \frac{1}{2} \sigma_{oil}^2 P_{oil}^2 \frac{\partial^2 F(P_{oil}, C_{CO_2})}{\partial P_{oil}^2}.
\end{aligned} \tag{56}$$

To solve this differential equation, we notice that the value of the option to invest is only dependent on the ratio $\tau = \frac{P_{oil}}{C_{CO_2}}$ and the value of the option to invest is homogeneous of degree 1 in (P_{oil}, C_{CO_2}) , so that

$$F(P_{oil}, C_{CO_2}) = c * C_{CO_2} \varphi\left(\frac{P_{oil}}{C_{CO_2}}\right) = c * C_{CO_2} \varphi(\tau). \tag{57}$$

Where $\varphi(\tau)$ is the function to be determined. Differentiating Equation (57) gives

$$\frac{\partial F(P_{oil}, C_{CO_2})}{\partial C_{CO_2}} = \varphi(\tau) - \tau \frac{\partial \varphi(\tau)}{\partial \tau}, \tag{58}$$

$$\frac{\partial F(P_{oil}, C_{CO_2})}{\partial P_{oil}} = \frac{\partial \varphi(\tau)}{\partial \tau} \tag{59}$$

$$\frac{\partial^2 F(P_{oil}, C_{CO_2})}{\partial P_{oil} \partial C_{CO_2}} = -\frac{\tau}{C_{CO_2}} \frac{\partial^2 \varphi(\tau)}{\partial \tau^2}, \tag{60}$$

$$\frac{\partial^2 F(P_{oil}, C_{CO_2})}{\partial C_{CO_2}^2} = \frac{\tau^2}{C_{CO_2}} \frac{\partial^2 \varphi(\tau)}{\partial \tau^2}, \tag{61}$$

$$\frac{\partial^2 F(P_{oil}, C_{CO_2})}{\partial P_{oil}^2} = \frac{1}{C_{CO_2}} \frac{\partial^2 \varphi(\tau)}{\partial \tau^2}. \tag{62}$$

Substitution of Equations (58-62) into Equation (56), dividing by C_{CO_2} and rewriting leads to

$$(r - \alpha_{CO_2}) \varphi(\tau) = (\alpha_{oil} - \alpha_{CO_2}) \tau \frac{\partial \varphi(\tau)}{\partial \tau} + \frac{1}{2} [\sigma_{CO_2}^2 - \rho \sigma_{CO_2} \sigma_{oil} + \sigma_{oil}^2] \tau^2 \frac{\partial^2 \varphi(\tau)}{\partial \tau^2}. \tag{63}$$

The general solution of Equation (63) is equal to

$$\varphi(\tau) = Z_1(\tau)^{\beta_1} + Z_2(\tau)^{\beta_2}. \tag{64}$$

Where β_1 and β_2 are the positive and negative roots of Equation (26). The option to invest will be worthless if the price equals zero, i.e. $\varphi(0) = 0$. Therefore, it must hold that $Z_2 = 0$.

11 References

- Abadie, L.M. and Chamorro, J.M., 2008. European CO₂ prices and carbon capture investments. *Energy Economics* 30(6): 2992-3015
- Awan, A.R., Teigland, R., Kleppe, J., 2008. A survey of North Sea enhanced-oil-recovery projects initiated during the years 1975 to 2005. *SPE Reservoir Evaluation and Engineering* 11(3): 497-512
- Chevallier, J., Time-varying correlations in oil, gas and CO₂ prices: an application using BEKK, CCC and DCC-MGARCH models. *Applied Economics*, 2012. 44(32): p. 4257-4274.
- Conrad, J.M. and Kotani, K., 2005. When to drill? Trigger prices for the Arctic National Wildlife Refuge. *Resource Energy Economics* 27(4): 273-286
- Conrad, J.M. and Kotani, K., 2007. Erratum to "When to drill? Trigger prices for the arctic national wildlife refuge". *Resource Energy Economics* 29(3): 244-245
- Dixit, A. and Pindyck, R., 1994. *Investment under Uncertainty*. In, Princeton University Press
- European Commission 2005. *Enhanced Oil Recovery using Carbon Dioxide in the European Energy System*. Luxembourg
- Fleten, S.-E., Lien, K., Ljønes, K., Pagès-Bernaus, A., Aaberg, M., 2010. Value chains for carbon storage and enhanced oil recovery: optimal investment under uncertainty. *Energy Syst* 1(4): 457-470

- Häggquist, E. and Söderholm, P., 2015. The economic value of geological information: Synthesis and directions for future research. *Resources Policy* 43(0): p. 91-100
- Heindl, P., Wood, P. J. and Jotzo, F., 2014. Combining International Cap-and-Trade with National Carbon Taxes, CCEP Working Paper 1418, November 2014. Crawford School of Public Policy, The Australian National University
- Heydari, S., Ovenden, N. and Siddiqui, A., 2012. Real options analysis of investment in carbon capture and sequestration technology. *Computational Management Science* 9(1): 109-138
- Huisman, K.J.M., Kort, P.M., Plasmans, J.E.J., 2013. Investment in High-tech Industries: an Example from the LCD Industry. In: *Real Options, Ambiguity, Risk and Insurance* (pp. 20-32). A. Bensoussan, S. Peng and (Eds.), JS. Amsterdam: IEEE Computer Society
- IEA. 2014. *Energy Technology Perspectives 2014, Harnessing Electricity's Potential*. OECD/IEA Paris
- IPCC. 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA. From Cambridge University Press
- Kemp, A.G., Kasim, S., 2013. The economics of CO₂-EOR cluster developments in the UK Central North Sea. *Energy Policy* 62: 1344-1355
- Klokk, Ø, Schreiner, P.F., Pagès-Bernaus, A., Tomasgard, A., 2010. Optimizing a CO₂ value chain for the Norwegian Continental Shelf. *Energy Policy* 38(11): 6604-6614
- Krahe, M., Heidug, W., Ward, J., Smale, R., 2013. From demonstration to deployment: An economic analysis of support policies for carbon capture and storage. *Energy Policy* 60: 753-763
- Leach, A., Mason, C.F., Veld, K.v.t., 2011. Co-optimization of enhanced oil recovery and carbon sequestration. *Resource Energy Economics* 33(4): 893-912
- Lukas, E., Welling, A., 2014. Timing and eco(nomic) efficiency of climate-friendly investments in supply chains. *European Journal of Operations Research* 233(2): 448-457
- Mendelevitch, R., 2014. The role of CO₂-EOR for the development of a CCTS infrastructure in the North Sea Region: A techno-economic model and applications. *International Journal of Greenhouse Gas Control* 20: 132-159
- Mezey, E. W. and Conrad, J. M., 2010. Real Options in Resource Economics. *Annual Review of Resource Economics*, Vol 2, 2010. G. C. Rausser, V. K. Smith and D. Zilberman. Palo Alto, Annual Reviews. 2: 33-52
- Morbee, J., Serpa, J., Tzimas E., 2010. The evolution of the extent and the investment requirements of atrans-European CO₂ transport network. JRC technical and scientific reports, Luxembourg
- Nykqvist, B., 2013. Ten times more difficult: Quantifying the carbon capture and storage challenge. *Energy Policy* 55: 683-689
- Pershad, H., Durusut, E, Cretat, A., Black, D., Mackay, E. & Olden, P., 2012. Economic Impacts of CO₂-enhanced oil recovery for Scotland. Final report for Scottish Enterprise, led by Element Energy with Dundas Consultants and the Institute of Petroleum Engineering, Heriot Watt University
- Piessens, K., Welkenhuysen, K., Laenen, B., Ferket, H., Nijs, W., Duerinck, J., Cochez, E., Mathieu, P., Valentiny, D., Dupont, N., Hendriks, C., 2012. Policy Support System for Carbon Capture and Storage and Collaboration between Belgium-the Netherlands "PSS-CCS", Final report. In. Avenue Louise 231, B-1050 Brussels, Belgium, Belgian Science Policy.
- Postali, F.A.S., Picchetti, P. 2006. Geometric Brownian Motion and structural breaks in oil prices: A quantitative analysis. *Energy Economics* 28(4): 506-522
- Ravagnani, A.T.F.S., Ligerio, E.L., Suslick, S.B., 2009. CO₂ sequestration through enhanced oil recovery in a mature oil field. *Journal of Petroleum Science and Engineering* 65(3-4): 129-138
- Reuter, W. H., Fuss, S., Szolgayová, J. and Obersteiner, M., 2012. Investment in wind power and pumped storage in a real options model. *Renewable and Sustainable Energy Reviews* 16(4): 2242-2248
- Rupert, J., 2014. Impact of geological uncertainty on project valuations for offshore CO₂-enhanced oil recovery. *Energy Science Master thesis Utrecht University*
- Scott, V., 2013. What can we expect from Europe's carbon capture and storage demonstrations? *Energy Policy* 54: 66-71
- Szolgayová, J., Golub, A. and Fuss, S., 2014. Innovation and risk-averse firms: Options on carbon allowances as a hedging tool. *Energy Policy* 70(0): 227-235
- Trigeorgis, L., *Real options. Managerial flexibility and strategy in resource allocation*. 1996: MIT Press
- Vandeginste, V. & Piessens, K., 2008. Pipeline design for a least-cost router application for CO₂ transport in the CO₂ sequestration cycle. *International Journal of Greenhouse Gas Control*, 2, p.571-581
- Welkenhuysen, K., Compennolle, T., Piessens, K., Ramírez, A., Rupert, J., Swennen, R., 2014. Geological Uncertainty and Investment Risk in CO₂-enhanced Oil Recovery. *Energy Procedia* 63(0): 7878-7883