1 Introduction

As the world is facing resource shortages and unprecedented environmental challenges the transition towards resource efficient, low carbon circular economies is a necessity. To reach this objective the involvement of all economic actors is required. However, in the extant literature on organizations and the environment the unit of analysis primarily lies at the level of the individual actors instead of a network of actors (Patala et al., 2014). Patala et al. (2014) define eco-industrial networks as industrial networks that aim to decrease environmental impact through cooperative actions. These networks include industrial symbiosis networks, green supply chains, and environmental solution networks and are distinguished in terms of network architecture and the operational logic through which environmental objectives are pursued.

Focus of this paper is on combined investment decisions in eco-industrial networks that result in multiple uncertain revenue streams. De Schepper et al. (2012) analyse the combined investment in a photovoltaic (PV) noise barrier. Such investments result in an economic profit for private investors, in reduced noise nuisance for the surrounding residents and a certain amount of avoided CO_2 emissions. Taking into account the social benefits, the photovoltaic noise barrier is economically feasible. However the authors indicate that the economic feasibility is subject to uncertainty. In another study, these authors provide a method to compare the economic payoff of individual complementary technologies with the payoff of their integrated combination (De Schepper et al, 2015). For a case study of PV solar power and battery electric vehicles (BEV) these authors indicate for varying electricity prices when it is optimal to invest in the combination of both technologies. Van Dael et al. (2013) apply a net present value approach and a Monte Carlo sensitivity analysis to assess the economic feasibility of a biomass energy conversion park and show that from a socio-economic point of view it is energetically and economically more feasible to invest in the integrated model than in the separate modules.Other examples that address the economic feasibility of eco-industrial networks can be found in the literature on enhanced landfill mining (see for instance Van Passel et al., 2013) and industrial symbiosis (See for instance Martin et al., 2015).

This paper contributes to the literature on eco-industrial networks by developing a real options model to address uncertainty in the revenue streams resulting from the combined investment in (eco) industrial networks. Adkins and Paxson (2011) provide a theoretical framework to study the impact of two stochastic processes on the investment decision. Current real options models that consider multiple types of uncertainty often address cost and revenue uncertainty simultaneously (see for instance Huisman et al., 2013). p to our knowledge, this is the first paper that addresses uncertainty for two stochastic revenue streams. The developed model is based on the theoretical framework provided by Adkins and Paxson (2011) and is applied for a case study on CO_2 enhanced oil recovery.

Although carbon capture and storage is considered as a key solution for CO_2 mitigation, a rapid adoption of CCS is not expected due to high investment costs in conjunction with low 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 up-scaled, and both 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 naturally produced. 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).

2 Model

For the adoption of CO_2-EOR two firms need to cooperate. One firm has to invest in CO_2 capture and another firm has to invest in enhanced oil recovery (EOR). Due to uncertain CO_2 prices and oil prices, the investment in both installations will result in two uncertain revenue streams. In what follows we use the quasi-analytical method proposed by Adkins and Paxson (2011). If the firm captures the CO_2, it avoids the payment of CO_2 emission allowances. An investment in EOR will result in additional oil recovery.We assume that the time-varying pattern of the CO_2 permit price can be formally expressed by a geometric Brownian motion process.

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

$$P_{pp}(0) = 0. \tag{2}$$

With α_{pp} and $\sigma_{pp} \in \mathbb{R}^+$, and dz_{pp} as the increment of a standard Brownian motion. Also the oil price is assumed to follow a geometric Brownian motion process.

$$dP_{oil}(t) = \alpha_{oil} P_{oil}(t)\, dt + \sigma_{oil} P_{oil}(t)\, dz_{oil}, \tag{3}$$

$$P_{oil}\left(0\right)=0. \tag{4}$$

With α_{oil} and $\sigma_{oil}\in\mathbb{R}^{+}$, and dz_{oil} as the increment of a standard Brownian motion.

At any instant, the project flow of this project is given by

$$\pi\left(P_{oil},P_{pp}\right)=Q_{oil}P_{oil}+Q_{pp}P_{pp}$$

We allow the prices of CO_2 and oil to be dependent, and therefore we introduce the parameter ρ where $Cov\left[dz_{oil},dz_{pp}\right]=\rho\sigma_{oil}\sigma_{pp}dt$ represents the correlation between the two Brownian motions (z_{oil} and z_{pp}), with $|\rho|\leq 1$. The decision of the firm to invest in CO_2EOR depends on both the oil price and the CO_2 price. We have a two factor model corresponding to the two uncertain processes. We let $V(P_{pp},P_{oil})$ denote the value of the firm if it decides to invest in CO_2EOR, which is given by the following Bellman equation:

$$V\left(P_{oil},P_{pp}\right)=\pi\left(P_{oil},P_{pp}\right)dt+E\left[V\left(\pi\left(P_{oil},P_{pp}\right)+d\pi\left(P_{oil},P_{pp}\right)\right)e^{-rdt}\right]. \tag{5}$$

Expanding $E[dV\left(P_{pp},P_{oil}\right)]$ with Ito's lemma we obtain the partial differential equation

$$-rV\left(P_{oil},P_{pp}\right)+\alpha_{pp}P_{pp}\frac{\delta V\left(P_{oil},P_{pp}\right)}{\delta P_{pp}}+\alpha_{oil}P_{oil}\frac{\delta V\left(P_{oil},P_{pp}\right)}{\delta P_{oil}}+\frac{1}{2}\sigma_{pp}P_{pp}^{2}\frac{\delta^{2}V\left(P_{oil},P_{pp}\right)}{\delta P_{pp}^{2}} \tag{6}$$

$$+\rho\sigma_{pp}\sigma_{oil}P_{pp}P_{oil}\frac{\delta^{2}V\left(P_{oil},P_{pp}\right)}{\delta P_{oil}\delta P_{pp}}+\frac{1}{2}\sigma_{oil}P_{oil}^{2}\frac{\delta^{2}V\left(P_{oil},P_{pp}\right)}{\delta P_{oil}^{2}}=0. \tag{7}$$

Next we propose a solution to equation 6. The function that we propose is the following

$$V\left(P_{oil},P_{pp}\right)=AP_{oil}^{\beta}P_{pp}^{\eta}+\frac{P_{oil}}{r-\alpha_{oil}}+\frac{P_{pp}}{r-\alpha_{pp}}. \tag{8}$$

where $AP_{oil}^{\beta}P_{pp}^{\eta}$ is the value of the option to wait and $\frac{P_{oil}}{r-\alpha_{oil}}+\frac{P_{pp}}{r-\alpha_{pp}}$represents the value of the investment in both the CO_2 capture unit and the enhanced oil recovery. We then compute the derivatives of this function.

$$\frac{\delta V\left(P_{oil},P_{pp}\right)}{\delta P_{pp}}=\eta AP_{oil}^{\beta}P_{pp}^{\eta-1}, \tag{9}$$

$$\frac{\delta V\left(P_{oil},P_{pp}\right)}{\delta P_{oil}}=\beta AP_{oil}^{\beta-1}P_{pp}^{\eta}, \tag{10}$$

$$\frac{\delta^{2}V\left(P_{oil},P_{pp}\right)}{\delta P_{pp}^{2}}=\eta\left(\eta-1\right)AP_{oil}^{\beta}P_{pp}^{\eta-2}, \tag{11}$$

$$\frac{\delta^{2}V\left(P_{oil},P_{pp}\right)}{\delta P_{oil}^{2}}=\beta\left(\beta-1\right)AP_{oilo}^{\beta-2}P_{pp}^{\eta}, \tag{12}$$

$$\frac{\delta^{2}V\left(P_{oil},P_{pp}\right)}{\delta P_{oil}\delta P_{pp}}=\eta A\beta P_{oil}^{\beta-1}P_{pp}^{\eta-1}. \tag{13}$$

Substituting (9),(10),(11),(12), and (13) in (6) and only considering the homogenous part, we conclude that β and η are the roots of the following characteristic root equation

$$Q\left(\beta,\eta\right)=\frac{1}{2}\sigma_{pp}^{2}\eta\left(\eta-1\right)+\frac{1}{2}\sigma_{oil}^{2}\beta\left(\beta-1\right)+\rho\sigma_{oil}\sigma_{pp}\beta\eta+\alpha_{oil}\beta+\alpha_{pp}\eta-r=0. \tag{14}$$

This is an elliptical function of two parameters. Since the solution is not directly obtainable from this function, we have the utilize information from the economic boundary conditions in order to identify their solutions. Following Adkins and Paxson (2011) the search for the η and β is narrowed by identifying which of the 4 quadrants is relevant. A function $H(\beta,\eta)=0$ is envisaged. This function is distilled from the value-matching and smooth pasting conditions. For the two parameters in our model to have a viable solution, the functions $Q(\beta,\eta)=0$ and $H(\beta,\eta)=0$ must intersect in the real space. The function $Q(\beta,\eta)$ has a presence in all four quadrants, so the parametric solutions can take the possible values:

Quadrant 1: $\{\beta_1, \eta_1\}, \beta_1 \geq 0, \eta_1 \geq 0$,
Quadrant 2: $\{\beta_2, \eta_2\}, \beta_2 \leq 0, \eta_2 \geq 0$,
Quadrant 3: $\{\beta_3, \eta_3\}, \beta 3 \geq 0, \eta_3 \leq 0$,
Quadrant 4: $\{\beta_4, \eta_4\}, \beta_4 \leq 0, \eta_4 \leq 0$.

This suggests that the generic solution adopts the explicit form:

$$V\left(P_{oil}, P_{pp}\right) = A_1 P_{oil}^{\beta_1} P_{pp}^{\eta_1} + A_2 P_{oil}^{\beta_2} P_{pp}^{\eta_2} + A_3 P_{oil}^{\beta_3} P_{pp}^{\eta_3} + A_4 P_{oil}^{\beta_4} P_{pp}^{\eta_4} + \frac{P_{oil}}{r-\alpha_{oil}} + \frac{P_{pp}}{r-\alpha_{pp}}. \tag{15}$$

As $\lim_{P_{pp}\to 0} V\left(P_{oil}, P_{pp}\right) = 0$, and $\lim_{P_{oil}\to 0} V\left(P_{oil}, P_{pp}\right) = 0$ then it means that the parameter $\eta > 0$ and the parameter $\beta > 0$.Hence, A_2, A_3, and A_4 should be zero. Because $\lim_{P_{pp}\to\infty}$ and $\lim_{P_{oil}\to\infty} V\left(P_{oil}, P_{pp}\right) = \frac{P_{oil}}{r-\alpha_{oil}} + \frac{P_{pp}}{r-\alpha_{pp}}$, A_1 should be zero as well. This implies that the valuation function takes the form

$$V\left(P_{oil}, P_{pp}\right) = \frac{P_{oil}}{r-\alpha_{oil}} + \frac{P_{pp}}{r-\alpha_{pp}}. \tag{16}$$

To find the value of the option to invest as a function of the price, F(P), we use the above solution for V(P) as the boundary condition that holds at the optimal exercise threshold. The value of the option to wait equals

$$F\left(P_{oil}, P_{pp}\right) = E\left[V\left(\pi\left(P_{oil}, P_{pp}\right) + d\pi\left(P_{oil}, P_{pp}\right)\right) e^{-rdt}\right]. \tag{17}$$

Following the same steps as before, we get the solution

$$F\left(P_{oil}, P_{pp}\right) = A_1 P_{oil}^{\beta_1} P_{pp}^{\eta_1}. \tag{18}$$

The value-matching boundary condition identifies the investment event when P_{oil} and P_{pp} simultaneously attain their respective threshold levels P^*_{oil} and P^*_{pp}. Then the value matching condition results in:

$$\frac{Q_{oil} * P^*_{oil}}{r-\alpha_{oil}} + \frac{Q_{CO_2} P^*_{pp}}{r-\alpha_{pp}} - I_{oil} - I_{pp} = A_1 P_{oil}^{\beta_1} P_{pp}^{\eta_1}. \tag{19}$$

with I_{oil} and I_{pp} the investment cost for the enhanced oil recovery and the CO_2 capture unit respectively. Q_{CO_2} represents the quantity of CO_2 captured and Q_{oil} represents the quantity of additional oil produced. Because Q_{oil} depends on the quantity of CO_2 injected, the value matching relationship can be rewritten as:

$$\frac{Q_{CO_2} * c * P^*_{oil}}{r-\alpha_{oil}} + \frac{Q_{CO_2} P^*_{pp}}{r-\alpha_{pp}} - I_{oil} - I_{pp} = A_1 P_{oil}^{*\beta_1} P_{pp}^{*\eta_1}. \tag{20}$$

with c the ratio of units oil produced per unit of CO_2 injected. The smooth pasting conditions are:

$$\frac{Q_{CO_2} * c}{r-\alpha_{oil}} = \beta_1 A_1 P_{oil}^{*\beta_1 - 1} P_{pp}^{*\eta_1}, \tag{21}$$

$$\frac{Q_{CO_2}}{r-\alpha_{pp}} = \eta_1 A_1 P_{oil}^{*\beta_1} P_{pp}^{*\eta_1 - 1}. \tag{22}$$

This implies that

$$\frac{1}{\beta_1} \frac{P^*_{oil} * c}{r-\alpha_{oil}} = \frac{1}{\eta_1} \frac{P^*_{pp}}{r-\alpha_{pp}}. \tag{23}$$

And therefore

$$P^*_{pp} = \frac{\eta_1}{\beta_1} \frac{(r-\alpha pp) * c * P^*_{oil}}{(r-\alpha oil)}, \tag{24}$$

$$A_1 = \frac{c * P^*_{oil}}{\beta_1 \left(r-\alpha_{oil}\right)} = \frac{P^*_{pp}}{\eta_1 \left(r-\alpha_{pp}\right)}. \tag{25}$$

Using Equation (25) to eliminate A1, the value matching relationship can be expressed as

$$H\left(\beta_1, \eta_1 \mid P^*_{oil}\right) = \frac{c * Q_{CO_2} * P^*_{oil}}{r-\alpha_{oil}} \left(1 - \frac{1}{\beta_1}\left(1-\eta_1\right)\right) - I_{oil} - I_{pp} = 0. \tag{26}$$

The charaterstic root equation (Equation 14), the value matching relationship (Equation 26), and the reduced form smooth pasting condition (equation 23) constitute the 2-factor model from which the investment boundary is generated. Unfortunately, no closed-form solution exists. For different values of P_{oil} we find a different solution for η and β from equation (14) and equation (26). By filling in the solutions into equation (24), we find P^*_{pp}.

3 Numerical example

We apply the model to a hypothetical but realistic case study. Cost data for both the capture unit and the CO_2EOR, the quantity of CO_2 captured and additional oil production are estimated using the PSS simulator developed by Piessens et al. (2012). PSS IV simulates CO_2EOR value chains considering a continuous stream of compressed CO_2 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, CO_2 requirement and various cost data are taken from literature (BERR 2007; Klokk et al. 2010). 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 CO_2EOR. The Claymore field, currently operated by Talisman Energy, has been in production since 1977. Is has an estimated OOIP (Original Oil In Place) of 1455 Mbbl (Million barrels of oil, 1bbl ≃159liters). The Fulmar field, also operated by Talisman Energy, has been in production since 1985 and has an estimated OOIP of 825 Mbbl. 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 Mbbl it is the largest oil fields in the North Sea (European Commission, 2005). Table 1 shows the parameter values.

Parameter	Value	Units	Description
α_{oil}	0.04		oil price drift rate
σ_{oil}	0.2		oil price volatility rate
a_{pp}	0.05		CO_2 price drift rate
σ_{pp}	0.2		CO_2 price volatility rate
ρ	0.05		Correlation coefficient
I_{oil}	3022	Meuro	Investment cost and total discounted operational cost CO_2 EOR
I_{pp}	1371	Meuro	Investment cost and total discounted operational cost CO_2 capture unit
Q_{co2}	4.59	Mtonne	Annual quantity of CO_2 captured and injected
c	1.1	Mbll oil/Mtonne CO_2	Oil to CO_2 ratio
r	0.10		Discount rate

Table 1. CO_2 -EOR parameter values

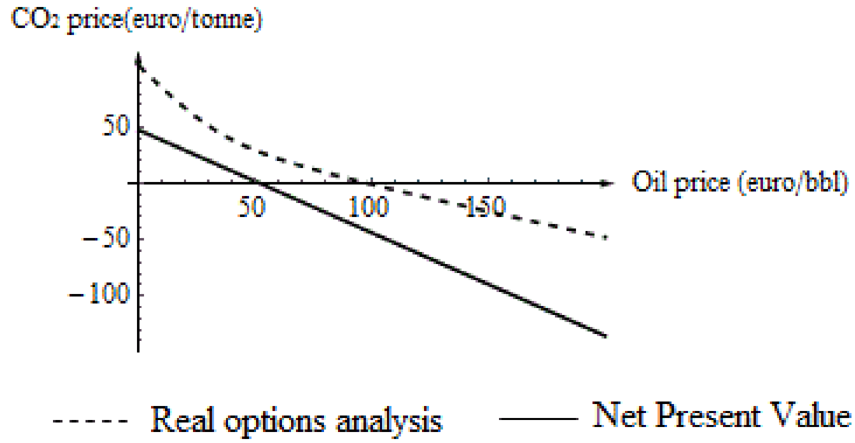
4 Results

In this section we show the model results for the CO_2 -EOR case study.

4.1 Result 1. Uncertainty in the CO_2 price and the oil price increases the threshold levels for the investment in CO_2 -EOR.

In their most recent study Compernolle et al. (2015) study the investments for CO_2 -EOR as two separte investment decisions. They show the investment threshold levels for an electricity producer that has the option to invest in a CO_2 capture unit and an oil producer who has the option to invest in enhanced oil recovery. This analysis shows the investment threshold levels assuming that the activities of both firms are fully integrated, that no transaction of CO_2 will take place between the two firms, and that the investment in CO_2 -EOR results in two uncertain revenue streams i.e. the avoided payment of CO_2 emission allowances and oil revenues. Both revenue streams can cover the entire investment and operational costs. Figure 1 compares the threshold boundary of the two stochastic processes for the NPV analysis and the real options analysis. The higher the oil price, the lower the threshold level for the CO_2 price to make the investment in CO_2 -EOR economically feasible. When taking into account uncertainty, the CO_2 price and oil price threshold levels for the investment in CO_2 -EOR are higher. If an NPV approach would be adopted, for zero CO_2 prices, the investment would be economically feasible for an oil price of 50 euro/bbl. However if uncertainty is integrated in the analysis, the investment threshold level is 100 euro/bbl for a zero CO_2 price.These results correspond to the results of Compernolle et al. (2015) in the case where they assume a CO_2 permit price of 40 euro/tonne CO_2 and a zero CO_2 selling price between the two firms.

Figure 1. CO_2 price and oil price threshold levels for CO_2 -EOR



4.2 Result 2. A higher level of uncertainty does not necessarily increase the investment threshold level

Figure 2 shows that when the volatility in CO_2 permit prices is higher ($\sigma_{pp} = 0.4$), the investment threshold boundary does not shift upwards as would be expected from the standard real options theory. For higher oil price levels, the CO_2 price threshold level is lower than when the CO_2 price volatility is determined at 0.2. Considering one point ($\sigma_{pp} = 0.2$; oil price = 50), Figure 3a shows the CO_2 price threshold level at the point where the value of the option to invest equals the value of the project after investment. Figure 3b shows that in contrast to the standard real options theory, the opportunity cost of killing the option to invest is convex instead of concave. For increasing CO_2 prices, the opportunity cost decreases at an increasing rate. This result suggests that the firm is not only protected from a downside risk by having the option to invest. Also the higher oil revenues protect the firm from a downside risk, even though there is uncertainty in these oil revenues as well.

Figure 2. Investment threshold boundary for different values of CO_2 price volatility

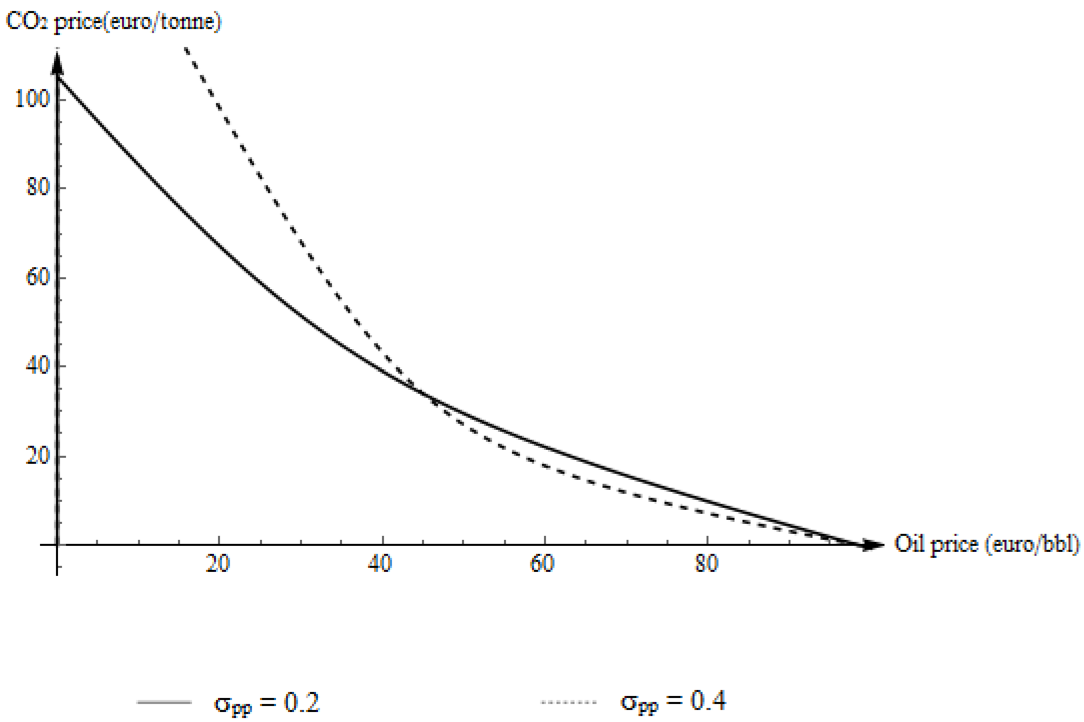
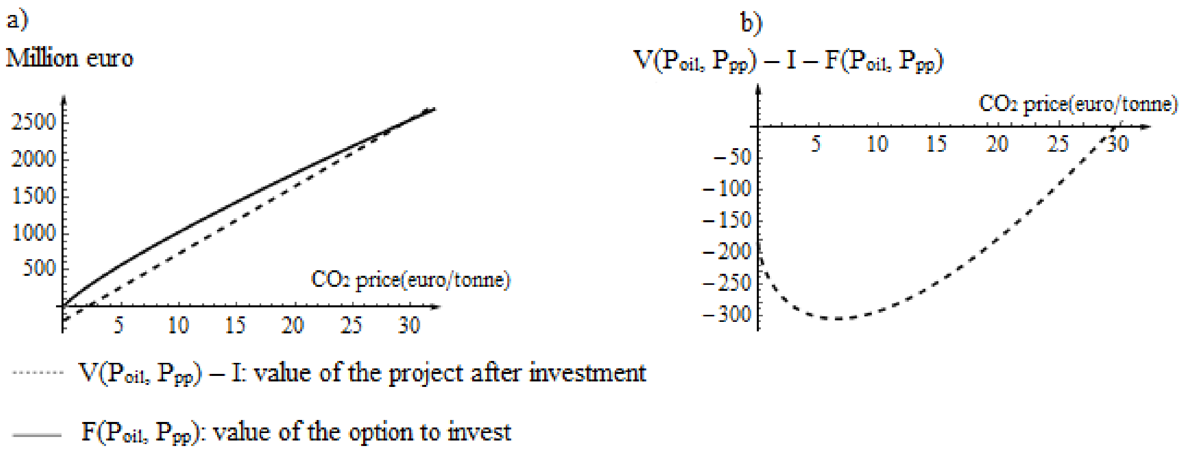


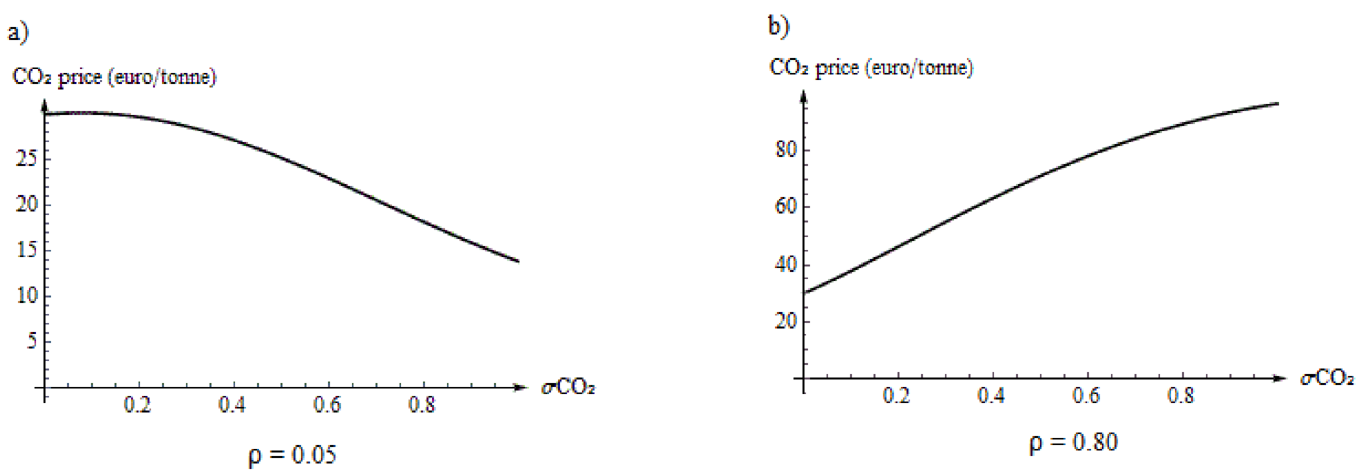
Figure 3. Investment threshold level (a) and opportunity cost killing the option to invest (b) for $\sigma_{pp} = 0.2$ and oil price = 50 euro/bbl



4.3 Result 3. If the prices of the underlying assets are highly correlated, the investment threshold level increases with increasing uncertainty

Figure 4 shows that if the CO $_2$ price is highly correlated with the oil price ($\rho = 0.8$), at an oil price of 50 euro/bbl the CO $_2$ price threshold level increases with increasing CO $_2$ price volatility.

Figure 4. CO $_2$ price threshold level in function of CO $_2$ price volatility for $\rho = 0.05$ and for $\rho = 0.80$ (b)



5 Conclusion and discussion

With this model we extend both the literature in the field of eco-industrial networks and the real options theory.We show that when complementary activities that require separate investments can be fully integrated, the revenue streams resulting from the different underlying assets are mutually reinforcing. If the revenues from these investments are not highly correlated, and if the revenue stream of one underlying asset is relatively high, uncertainty in the revenue resulting from the other underlying asset stimulates total investment.

It should be studied whether experience in CO_2-EOR will reduce the cost of CCS deployment and how it aligns with policy objectives regarding the reduction in CO_2 emissions and investments in renewable energy. Using an oil reservoir after EOR as a CO $_2$ storage project, making use of the existing EOR infrastructure, may be economic and it is therefore desirable to include it in an ROA 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 renewables. Other low carbon technologies such as CCS, woul 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 CO $_2$ emissions in the long term. Such type of analysis should also balance issues as energy security, job security and social welfare in general.

Although the model is applied to one particular case study it can be easily adapted to for instance cases in the field of enhanced waste management (EWM). EWM regards landfills not as a final solution but as temporary storage facilities from which landfilled waste will eventually be valorized by means of recycling and incineration (Jones et al., 2014). EWM includes the valorization of historic waste streams as both Waste-to-Materials (WtM) and Waste-to-Energy (WtE) which can be considered as two stochastic revenue streams. Also in this case, different economic actors are involved: the households that deliver municipal waste and firms that can use this waste for the production of other assets.

Based on this results, further analyses on eco-industrial networks can combine the results of this real options analysis with game theoretical concepts. By applying theory on sequential investment decisions and real option games it can be studied under which conditions a transaction between the economic actors involved can take place and how uncertainty affects this cooperation and the associated investment decisions.

6 References

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