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The role of industrial and market symbiosis in stimulating CO_2 emission reductions

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Abstract

An increasing concern for climate change puts pressure on industrial firms to achieve carbon emission reductions. These could be realized through cooperation among firms in industrial chains, which leads to industrial symbiosis. By taking a real options approach, we make the timing component of the investment decisions explicit. This is important in assessing the impact of carbon-reducing investment over a specific time-span. We show that a joint venture between a CO_2 emitting firm and a firm that can use the CO_2 will result in a higher probability that an investment in CO_2 capture will take place within a specific time period, which reduces the amount of CO_2 emitted substantially. We also show that, in addition to industrial symbiosis, cooperation between firms can benefit from "market symbiosis" as well, in the sense that investments are more likely to take place in markets that are positively correlated. This is an important result, given that the EU has set binding targets to its Member States for reducing their emissions.

1 Introduction

Increasing concern about climate change puts pressure on industrial firms to reduce their carbon emissions. The European Union (EU) has set binding greenhouse gas emission reduction goals. By 2030, these emissions should be reduced by 43% and the share of renewable energy should be increased to 32% (European Commission, 2014). The EU emission trading system (EU ETS) set up in 2005 is one of the corner stones of the EU's policy to reduce greenhouse house emissions cost effectively and hence to combat climate change. In addition, different European countries also implemented a carbon tax to further reduce carbon emissions (World Bank, 2021). By putting a price on carbon, costs that are otherwise external are taking into account in a firms' investment decisions, shifting market preferences away from fossil fuel based technologies.

Recently, it has been recognized that besides carbon pricing, carbon emission reductions (CER) can also be realized through cooperation among industrial chains (Agi et al., 2020, Fahimnia et al., 2015). Especially the utilization of waste CO_2 can reduce greenhouse gas emissions. Through the adoption of carbon capture utilization and storage (CCUS) technologies, a '*circular carbon economy*' can be built. By utilizing CO_2 as an input to the production process, firms aim to lower the carbon footprint of the materials, chemicals and fuels that they produce (Naims, 2020). Inter-firm collaboration on CER can take place (i) within the firms' own industrial chain leading to a vertically extended chain, (ii) through collaboration with competitors leading to a horizontally extended chain, or across different industrial chains leading to industrial symbiosis (Zhang and Wang, 2014). Industrial Symbiosis involves the synergistic exchange of materials and energy between traditionally separated industries that are geographically grouped in a collaborative network (Chertow, 2000). Although examples of industrial symbiosis exist all over the world, this type of collaboration appears to be underdeveloped and not fully exploited (Albino et al., 2016).

Current literature in green supply chain management focuses on the optimization of the vertical chain (Agi et al., 2020). Some studies (see e.g. Ghosh and Shah, 2015) optimize an existing, two echelon supply chain and investigate the price level and/or produced quantity required to minimize carbon emissions or maximize profit. Other studies, like Chiou and Hu (2001), investigate different constellations of environmental joint ventures and analyze the impact on joint profits and total emissions. In He et al. (2020) for instance, a Stakelberg game model is developed for waste recycling to analyze waste pricing under three scenarios: non-symbiosis, partial symbiosis, and complete symbiosis. It is studied how internal and external factors of the enterprises affect the formation of the symbiotic relationship and pricing decisions about waste recycling. Another example is the paper by Zhang et al. (2017) in which a mixed integer linear programming (MILP) model is developed to analyze the fair design of integrated carbon capture, transport and storage infrastructure in Qatar under carbon trading scheme. Fair design of CCS infrastructure for power plants is determined by determining the carbon trading price and the annual amount of CO_2 transferred under two fairness scenarios: same saving ratio and game theoretical Nash approach.

The above-mentioned applications use traditional methods from game theory and are, thus, at heart static. The impact of changing market conditions and influencing factors in the dynamic process of inter-enterprise industrial symbiosis are usually determined by comparative analyses and sensitivity analyses. The issue of *timing* a cooperative investment is ignored (Agi et al., 2020). Yet, since climate targets are typically explicitly tied to given time scales (see e.g. European Commission, 2014), the timing of investment is crucial for two reasons. First, the success of time-limited environmental target requires enough firms to invest early enough to meet the target. Secondly, the earlier investment in carbon-reducing technologies takes place, the larger the effect on the cumulative carbon stock in the atmosphere. Delayed investment implies a delayed emission peak and a higher post peak reduction rate, which in turn results in a replacement of capital that is expected to be more costly as it is more abrupt (Bosetti et al., 2012).

In this paper we focus on the timing of carbon-reducing investment by cooperating firms through industrial symbiosis. Only a few papers analyze the optimal time to establish a supply chain in the face of market uncertainty. For example, Chen (2012) considers a supplier and a retailer that jointly determine the optimal time to set up a centralized supply chain, given demand uncertainty. Bicer and Hagspiel (2016) value quantity flexibility by considering a contract that allows the retailer to adjust the initial order quantity, which helps the retailer reduce supply–demand mismatches. Lukas and Welling (2014) consider an environmental context and determine the optimal timing of climate friendly investments in a supply chain. Wang and Qie (2018) integrate real options theory with game theory to investigate the investment threshold of carbon capture and storage (CCS). They compare the CCS investment threshold for a scenario of centralized decision making with a scenario of a dual-echelon supply chain. For the latter, they adopt a Stackelberg game in which a CO_2 storage operator first decides on its investment threshold, followed by the power producer who decides on its willingness to invest in carbon capture and to pay a CO_2 transfer price to the storage operator, given the CO_2 storage operator's decision-making. They find that CCS investment requires a much higher threshold under the dual-echelon supply chain than under the centralized scenario. The most comprehensive analysis integrating cooperative game theory and real options analysis is by Banerjee et al. (2014). They employ a two-stage decision-making framework for the optimal exercise of jointly held real options: the parties determine the sharing rule as an outcome of Nash bargaining and one of them makes the exercise decision. The scenario in which the exercise decision is made first is then contrasted with the one in which the division of proceeds precedes the exercise decision.

In the aforementioned studies, the developed real options models are one-dimensional as the firms of the supply chain are operative in one and the same market, facing one source of uncertainty. However, to achieve large scale CO_2 emission reductions, also new value chains need to be created, connecting the operations of firms that are currently operating in different markets. The economic benefits resulting from cost reduction in raw materials purchase and waste disposal are considered the most important factor that motivates firms to establish a symbiotic collaboration. The balance between realized cost savings and the industrial symbiosis construction costs is a critical determinant of CER collaborations through industrial symbiosis. Albino et al. (2016) state that industrial symbiosis will emerge spontaneously, as an independent choice of both parties involved if the so-called win-win condition is satisfied. This condition implies that all parties should achieve an economic benefit sufficient to cover the risk of the investment and that also the benefit gained in case of industrial symbiotic exchange is higher than in absence of the cooperation. However, such analysis has never been made in a dynamic context. The evolution of the associated cost and revenue flows through time and the flexibility of a firm to postpone investment are often not considered. This paper analyzes the real options, held by two firms operative in two different markets. They can invest on their own or join forces and set-up a joint venture to achieve carbon emission reductions. As an illustration, we consider a coal-fired power plant that emits CO_2 and holds an option to invest in carbon capture and storage (CCS), and an oil producing company that can buy CO_2 to enhance its oil production (CO_2 enhanced oil recovery, or CO_2-eor). We develop a two-dimensional real options model and show that, although a joint venture between the two companies where the CO_2 produced by one can be captured and used by the other faces multiple sources of uncertainty, the CO_2 price level at which it is optimal to invest in a carbon capture unit is always lower than when the power plant would make the investment decision individually. Importantly, in our model, the CO_2 price level that optimally triggers CCS is not a constant, but is a function of the oil price. The higher the oil price, the lower the CO_2 price that triggers investment in CCS. The intuition for this result is that the option to extract additional oil adds an additional benefit to the decision to invest in CO_2 capture and hence, CO_2 will be captured earlier if a joint venture is established. The result is driven by the assumption that the CO_2 and oil prices are imperfectly correlated. This then creates a "market symbiosis", which is similar in nature to the well-known diversification effect in portfolio theory: the two sources of uncertainty cancel each other out, to some extent, when they are positively correlated.

It is important to note that, although the joint venture leads to earlier investment in CO_2 capture, it does not lead to carbon storage. Rather, the joint venture generally prefers to use the captured CO_2 for additional oil extraction over aquifer storage. So, the "price" for earlier investment in carbon capture is increased production of oil, which leads to higher carbon emissions. However, using a realistic example, simulations show that the benefits of earlier carbon capture easily outweigh the cost of higher carbon emissions. Furthermore, we show that in addition to industrial symbiosis, the creation of a joint venture could also result in what we call "market symbiosis": a positive correlation between the oil and CO_2 price processes adds value to the investment and hence increases the likelihood of investment, resulting in increased emission savings compared to the stand-alone case.

The paper is organized as follows. In Section 2 we describe the investment models for the stand-alone firms as well as for a joint venture. Then, in Section 3 we introduce a hypothetical but realistic case study to illustrate the model. The model results and insights are presented in Section 4. We conclude in Section 5.

2 The Model

In this section we consider two firms of which one, the *upstream* firm, produces a waste flow that can form the input of the production process of a second, *downstream*, firm. We first show the individual investment decisions, then we develop an investment model as if both firms would form a joint venture. Section 2.1 and Section 2.2 are an application of a standard real options analysis where there is a single firm, facing an investment decision given one source of uncertainty. Both these investment problems are analyzed using a dynamic programming approach as outlined by Dixit and Pindyck (1994) and applied in other studies like for instance Boomsma and Linnerud (2015) and Compernolle et al. (2017). In Section 2.3, the standard real options approach is extended by considering two sources of market uncertainty and multiple options that are held by the joint venture. For each of these models we determine the price levels at which it is optimal to invest and we calculate the probability that investment will take place within a specific time period. We model uncertainty on a probability space $(\Omega, \mathscr{F}, \mathbb{P})$. Dynamic revelation of information is modeled by the filtration $\mathbf{F} = (\mathscr{F}_t)_{t\geq 0}$.

2.1 The upstream firm

Consider an upstream firm U that produces an annual waste flow Q_U for which it pays a unit price P_U. The price level is stochastic and its time-varying pattern will be formally expressed by a geometric Brownian motion (GBM), which is assumed to be the unique strong solution to the stochastic differential equation (SDE)

$$dP_{U,t} = \alpha_U P_{U,t} dt + \sigma_U P_{U,t} dW_{U,t}, \tag{1}$$

where $W_U = (W_{U,t})_{t\geq 0}$ is a Wiener process adapted to the filtration $\mathbf{F}$.

Suppose that the upstream firm has the option to invest, by incurring a sunk cost $K_U > 0$, in a technology that avoids the waste flow and its associated cost. We assume that the investment is infinitely-lived and that the firm discounts cash flows at the constant rate $r > \alpha_U$. Following the standard real options approach the investment problem is formalized as an optimal stopping problem, i.e. the firm's value equals

$$\begin{aligned} V_U^*(P_U) &= \sup_{\tau \in \mathcal{M}} \mathbb{E}\left[-\int_0^\tau e^{-rt} Q_U P_{U,t} dt - e^{-r\tau} K_U \right] \\ &= -\frac{Q_U P_U}{r-\alpha_U} + \underbrace{\sup_{\tau \in \mathcal{M}} \mathbb{E}\left[e^{-r\tau} \underbrace{\left(\frac{Q_U P_{U,\tau}}{r-\alpha_U} - K_U \right)}_{\equiv F_U(P_{U,\tau})} \right]}_{\equiv V_U(P_U)}, \end{aligned} \tag{2}$$

where $\mathcal{M}$ is the set of stopping times adapted to $\mathbf{F}$.

As long as the price of the waste flow is below some threshold value, P_U^* (to be determined below), the investment project is not deep enough in the money. As a consequence, the value of waiting is larger than the value of investing and, hence, investment in the waste-reducing technology is postponed.

Solving the optimal stopping problem (2) is standard (see, e.g., Dixit and Pindyck, 1994) and gives the value function of the upstream firm:

$$V_U^*(P_U) = \begin{cases} -\frac{Q_U P_U}{r-\alpha_U} + \left(\frac{P_U}{P_U^*}\right)^{\beta_U} \left(\frac{Q_U P_U^*}{r-\alpha_U} - K_U\right) & \text{if } P_U < P_U^*, \\ -K_U & \text{if } P_U \geq P_U^*, \end{cases} \tag{3}$$

where

$$P_U^* = \frac{\beta_U}{\beta_U - 1} \frac{r-\alpha_U}{Q_U} K_U, \tag{4}$$

is the optimal investment trigger and $\beta_U > 1$ is the positive root of the quadratic equation

$$\mathscr{Q}_U(\beta) \equiv \frac{1}{2}\sigma_U^2 \beta(\beta - 1) + \alpha_U \beta - r = 0. \tag{5}$$

For the case study example below, we consider a coal-fired power plant that has the option to invest in a CO_2 capture and storage (CCS) installation. The captured CO_2 is transported to an off-shore aquifer. Upon making the investment, the firm avoids the payment of CO_2 emission allowances.

2.2 The downstream firm

The downstream firm, D, also has an investment option, which, upon investment of a sunk cost $K_D > 0$, creates an additional production capacity Q_D to be sold at a stochastic unit-price P_D. We assume that this price process follows the GBM

$$dP_{D,t} = \alpha_D P_{D,t} dt + \sigma_D P_{D,t} dW_{D,t}, \tag{6}$$

where W_D is a Wiener process adapted to $\mathbf{F}$. Furthermore, it is assumed that $\alpha_P < r$ and that $\mathbb{E}[dW_{U,t}dW_{P,t}] = \rho dt$, for some $\rho \in (-1,1)$. The life-time of this project is $T \in (0,\infty]$. The assumption that the two Wiener processes W_U and W_D are not perfectly correlated, i.e. that $|\rho| < 1$, is crucial to our model of industrial symbiosis. We will see below that it is this assumption that allows industrial symbiosis to be boosted by what we call *market symbiosis*.

The downstream firm's investment problem can be written as the optimal stopping problem

$$\begin{aligned} V_D(P_D) &= \sup_{\tau \in \mathcal{M}} \mathbb{E}\left[\int_\tau^{\tau+T} e^{-rt} Q_D P_{D,t} dt - e^{-r\tau} K_D\right] \\ &= \sup_{\tau \in \mathcal{M}} \mathbb{E}\Bigg[e^{-r\tau} \underbrace{\left(\frac{Q_D P_{D,\tau}}{r-\alpha_D}\left(1-e^{-rT}\right) - K_D\right)}_{\equiv F_D(P_{D,\tau})}\Bigg]. \end{aligned} \tag{7}$$

It is, again, standard to solve the optimal stopping problem (7), which gives the value function:

$$V_D(P_D) = \begin{cases} \left(\frac{P_D}{P_D^*}\right)^{\beta_D} \left(\frac{Q_D P_D^*}{r-\alpha_D}\left(1-e^{-rT}\right) - K_D\right) & \text{if } P_D < P_D^*, \\ \frac{Q_D P_D}{r-\alpha_D}\left(1-e^{-rT}\right) - K_D & \text{if } P_D \geq P_D^*, \end{cases} \tag{8}$$

where

$$P_D^* = \frac{\beta_D}{\beta_D - 1} \frac{r-\alpha_D}{Q_D\left(1-e^{-rT}\right)} K_D, \tag{9}$$

is the optimal investment trigger and $\beta_D > 1$ is the positive root of the quadratic equation

$$\mathscr{Q}_D(\beta) \equiv \frac{1}{2}\sigma_D^2 \beta(\beta-1) + \alpha_D \beta - r = 0. \tag{10}$$

For the case study example below, we consider an oil producer who has the option to invest in CO_2EOR where it uses CO_2 to increase its oil production. If the firm makes its investment decision separately from the upstream firm, it buys CO_2 externally, at a constant price. As long as the oil price is below some threshold value, P_D^*, to be determined, the investment project is not deep enough in the money. As a consequence, the value of waiting is larger than the value of investing and, hence, investment is postponed.

2.3 The cooperative investment problem

Instead of making the investment decisions separately, suppose that both firm could decide to join forces. The downstream firm could use the waste flow of the upstream firm to create its additional revenue. In that case, the oil producer does not buy CO_2 externally and the electricity producer does not have to pay for CO_2 storage in an offshore aquifer as the CO_2 can be stored in the oil reservoir. By combining their efforts, the investment will be cheaper, which we model by assuming that if both investments take place simultaneously, then the total sunk costs are $K \in (0, K_U + K_D)$.

We can then formulate the joint investment problem by computing the *combined* firms' value function. That is, we treat the firms as if they formed a joint venture.

2.4 A simpler case: constant carbon costs

The fully stochastic model does not lend itself to many analytical results due to its two-dimensional state space. However, we can get some analytical insight in the value of cooperation by considering the case where the upstream firm's carbon costs are constant, i.e. $\alpha_U = \sigma_U = 0$.

Now, the joint venture could, of course, decide to pursue only one of the two options, leaving the other open for potential investment in the future. Or it could invest in both projects at the same time and capture the cost advantage. The economically interesting case is when the joint venture would invest jointly in CCS and EOR at an earlier date than the downstream firm would on its own, even if the upstream firm would never invest in CCS on its own. The following proposition characterizes such situations.

Proposition 1 *Suppose that $K \in (0, K_U + K_D)$. If the price of carbon, P_U, is such that $Q_U P_U / r \in (K - K_D, K_U)$, then the upstream firm will never invest in CCS, but a joint venture will always invest in both CCS and EOR simultaneously as soon as the trigger*

$$\hat{P}_D = \frac{\beta_D}{\beta_D - 1} \frac{r - \alpha_D}{Q_D} \frac{rK - Q_U P_U}{r},$$

is hit (from below). In addition, the joint venture invests earlier than the downstream firm would on its own.

Proof. The upstream firm's optimal stopping problem can be written as

$$V_U^*(P_U) = -\frac{Q_U P_U}{r} + \sup_{t \in \mathbb{R}_+} \left[e^{-rt} \left(\frac{Q_U P_U}{r} - K_U \right) \right].$$

Obviously, the supremum is attained at $t = 0$ if $rK_U \leq Q_U P_U$ and at $t = \infty$ if $rK_U > Q_U P_U$. In the former case the upstream firm invests immediately, in the latter case it never invests.

If the joint venture (JV) invests simultaneously in CCS and EOR, then the JV's problem is

$$V_J(P_U, P_D) = -\frac{Q_U P_U}{r} + \sup_{\tau \in \mathcal{M}} \mathbb{E} \left[e^{-r\tau} \left(\frac{Q_D P_D (1 - e^{-rT})}{r - \alpha_D} - \frac{rK - Q_U P_U}{r} \right) \right].$$

As in the case of the stand-alone analysis of the downstream firm above, the solution to this optimal stopping problem is to invest as soon as the trigger

$$\hat{P}_D = \frac{\beta_D}{\beta_D - 1} \frac{r - \alpha_D}{Q_D} \frac{rK - Q_U P_U}{r},$$

is hit (from below). Some simple algebra then reveals that

$$\hat{P}_D < P_D^* \iff P_U > \frac{r(K - K_D)}{Q_U},$$

so that the JV will always invest in CCS and EOR at an earlier date than the downstream firm invests in EOR if the condition holds. ■

From the proof of Proposition 1 it is clear that the reason for joint investment lies in the fact that the investment in CCS acts as a kind of discount on the investment in EOR. This creates the industrial symbiosis that can make investments in de-carbonization economically attractive. For higher carbon costs, the JV investment trigger goes down, as is intuitively clear. This effect stops when $Q_U P_U / r = K_U$. At that point a stand-alone upstream firm would invest immediately in CCS, whereas a joint venture —may wait until $\hat{P}_D$ is hit and invest simultaneously in CCS and EOR. In such cases it may, thus, happen that a joint venture leads to *later* investment in carbon reduction technologies.

2.5 Two sources of uncertainty: market symbiosis

In a model where both the upstream and downstream prices are stochastic, there is another effect that can make investment economically attractive: diversification. A joint venture is subjected to shocks in both P_U and P_D, rather than only one of these. As a result, the joint venture holds a better diversified portfolio (if the shocks are positively correlated) and this can make investment more attractive. In the context of this paper, we refer to this diversification effect as *market symbiosis*.

To explore market symbiosis in detail, we first note that the NPV of first investment of the joint venture is given by the maximum of the following three values:

1. the PV of the cash flows of simultaneous investment in CCS and EOR;
2. the PV of the cash flows of investment in CCS plus the value of the option to invest in EOR at a later date; and
3. the PV of the cash flows of investment in EOR plus the value of the option to invest in CCS at a later date.

That is, the NPV of investment at current prices (P_U, P_D) is equal to

$$J(P_U, P_D) = \max\left\{ \frac{Q_D P_D}{r - \alpha_D}\left(1 - e^{-rT}\right) - K, V_D(P_D) - K_U, \right. \\ \left. \frac{Q_D P_D}{r - \alpha_D}\left(1 - e^{-rT}\right) - K_D + V_U(P_U) \right\}. \tag{11}$$

The value function of the joint venture is then the solution to the optimal stopping problem

$$
\begin{aligned}
V_J^*(P_U, P_D) &= \sup_{\tau \in \mathcal{M}} \mathbb{E}\left[-\int_0^\tau e^{-rt} Q_U P_{U,t} dt + e^{-r\tau} F_J(P_{U,\tau}, P_{D,\tau}) \right] \\
&= -\frac{Q_U P_U}{r - \alpha_U} + \underbrace{\sup_{\tau \in \mathcal{M}} \mathbb{E}\left[e^{-r\tau} \underbrace{\left(J(P_{U,\tau}, P_{D,\tau}) + \frac{Q_U P_{U,\tau}}{r - \alpha_U} \right)}_{\equiv F_J(P_{U,\tau}, P_{D,\tau})} \right]}_{\equiv V_J(P_{U,\tau}, P_{D,\tau})} .
\end{aligned} \tag{12}
$$

Since the state space of this optimal stopping problem is two-dimensional and the NPV function is not homogeneous of degree 1, there is no known analytical solution to (12). However, because of the Markovian structure of the problem, a solution to the Hamilton-Jacobi-Bellman equation in Proposition 2 below is a solution to the optimal stopping problem in 12:

$$
V_J(P_U, P_D) = \sup_{\tau \in \mathcal{M}} \mathbb{E}\left[e^{-r\tau} F_J(P_{U,\tau}, P_{D,\tau}) \right].
$$

Proposition 2 *Suppose that there exists a C^2-a.e. function $\varphi : \mathbb{R}_+^2 \to \mathbb{R}$, $\varphi \geq F_J$, that solves the Hamilton-Jacobi-Bellman equation*

$$
\max\{F_J - \varphi, \mathscr{L}\varphi - r\varphi\} = 0, \quad \text{on } \mathbb{R}_+^2, \tag{13}
$$

where $\mathscr{L}$ is the characteristic operator of the process (P_U, P_D), i.e.

$$
\begin{aligned}
\mathscr{L}\varphi(P_U, P_D) =& \frac{1}{2} P_U^2 \sigma_U^2 \varphi''_{UU}(P_U, P_D) + \frac{1}{2} P_D^2 \sigma_D^2 \varphi''_{DD}(P_U, P_D) + \sigma_U \sigma_D P_U P_D \varphi''_{UD}(P_U, P_D) \\
&+ \alpha_U P_U \varphi'_U(P_U, P_D) + \alpha_D P_D \varphi'_D(P_U, P_D).
\end{aligned}
$$

Then $V_J = \varphi$ and the optimal stopping time is the first exit time of the set

$$
\mathcal{C} = \left\{ (P_U, P_D) \in \mathbb{R}_+^2 \;\middle|\; \varphi(P_U, P_D) > F_J(P_U, P_D) \right\}.
$$

The proof of this proposition can be found in Appendix A. The boundary of the *continuation region* $\mathcal{C}$ is denoted by $\partial\mathcal{C}$. This boundary is the optimal investment trigger in the sense that first investment should take place when $\partial\mathcal{C}$ is hit (from the interior of $\mathcal{C}$). That is, the optimal investment time is

$$
\tau^* = \{ t \geq 0 \mid (P_{U,t}, P_{D,t}) \notin \mathcal{C} \}.
$$

We develop a Markov chain approximation to the HJB equation in Proposition 2 to numerically find the optimal investment boundary $\mathcal{C}$ and value function V_J. Details of this procedure can be found in Appendix B.

To get some insight in the investment boundary $\partial\mathcal{C}$, first note that

$$
(0, P_D^*) \in \partial\mathcal{C}, \quad \text{and} \quad (P_U^*, 0) \in \partial\mathcal{C}, \quad \text{i.e.}
$$

if the price facing the upstream (downstream) firm is zero, then the optimal investment decision is the same as for the stand-alone downstream (upstream) firm. Secondly, joint investment is only optimal if (P_U, P_D) is such that

$$\frac{Q_D P_D}{r-\alpha_D}\left(1-e^{-rT}\right) - K \geq V_D(P_D) - K_U, \quad \text{and}$$
$$\frac{Q_D P_D}{r-\alpha_D}\left(1-e^{-rT}\right) - K \geq \frac{Q_D P_D}{r-\alpha_D}\left(1-e^{-rT}\right) - K_D + V_U(P_U),$$

so that there exist $\bar{P}_U < P_U^*$ and $\bar{P}_D < P_D^*$, such that

1. the joint venture invests simultaneously in CCS and EOR if $(P_{U,\tau^*}, P_{D,\tau^*})$ is such that $P_{U,\tau^*} \geq \bar{P}_U$ and $P_{D,\tau^*} \geq \bar{P}_D$;

2. the joint venture invests in CCS (and perhaps later in EOR) if $(P_{U,\tau^*}, P_{D,\tau^*})$ is such that $P_{U,\tau^*} \geq \bar{P}_U$ and $P_{D,\tau^*} < \bar{P}_D$;

3. the joint venture invests in EOR (and perhaps later in CCS) if $(P_{U,\tau^*}, P_{D,\tau^*})$ is such that $P_{D,\tau^*} \geq \bar{P}_D$ and $P_{U,\tau^*} < \bar{P}_U$.

Note that every sample path of (P_U, P_D) that ends up with the joint venture investing ends up in one of these scenarios at that time.

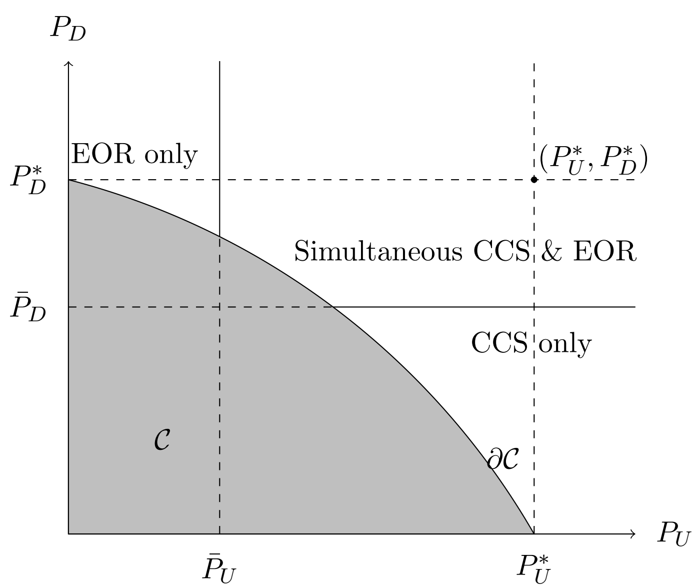

Figure 1: Sketch of the state space with the investment boundary $\partial\mathcal{C}$.

A sketch of the continuation region is given in Figure 1. The diversification effect is illustrated by the fact that the continuation region is not the "box" with corner points $(0,0)$, $(0, P_D^*)$, $(P_U^*, 0)$, and (P_U^*, P_D^*), but, rather, a subset of this "box", i.e.

$$\mathcal{C} \subset \left\{ (P_U, P_D) \in \mathbb{R}_+^2 \;\middle|\; P_U < P_U^*, P_D < P_D^* \right\}.$$

The following proposition shows that this is a *strict* subset in the sense that the point (P_U^*, P_D^*) is not in the closure of $\mathcal{C}$ (denoted by $\bar{\mathcal{C}}$).[1]

Proposition 3 *Suppose that a function φ satisfying the conditions of Proposition 2 exists. Then $(P_U^*, P_D^*) \notin \bar{\mathcal{C}}$.*

Proof. It is obvious that (P_U^*, P_D^*) cannot lie in $\mathcal{C}$ itself, for if is optimal to invest in CCS and EOR separately at combined sunk cost $K_U + K_D$, then it can not be not optimal to invest in CCS and EOR simultaneously at sunk cost $K < K_U + K_D$.

To show that $(P_U^*, P_D^*) \notin \partial\mathcal{C}$, recall from the proof of Proposition 2 in Appendix A that $V_J = \varphi$ and that $\varphi \geq F_J$ satisfies the variational inequalities

$$\begin{cases} \mathscr{L}\varphi(P_U, P_D) - r\varphi(P_U, P_D) \leq 0 & \text{when } \varphi(P_U, P_D) = F_J(P_U, P_D), \text{ and} \\ \mathscr{L}\varphi(P_U, P_D) - r\varphi(P_U, P_D) = 0 & \text{when } \varphi(P_U, P_D) > F_J(P_U, P_D), \end{cases}$$

on $\mathbb{R}_+^2$. Similarly, V_U and V_D satisfy the variational inequalities

$$\begin{cases} \mathscr{L}_i V_i(P_i) - rV_i(P_i) \leq 0 & \text{when } V_i(P_i) = F_i(P_i), \text{ and} \\ \mathscr{L}_i V_i(P_i) - rV_i(P_i) = 0 & \text{when } V_i(P_i) > F_i(P_i), \end{cases}$$

for $i = U, D$ respectively, where

$$\mathscr{L}_i \psi = \frac{1}{2}\sigma_i^2 P_i^2 \psi'' + \alpha_i P_i \psi',$$

is the characteristic operator of the process P_i.

From continuity it follows that

$$\mathscr{L}_i V_i(P_i^*) - rV_i(P_i^*) = \mathscr{L}_i F_i(P_i^*) - rF_i(P_i^*) = 0, \quad i = U, D.$$

Therefore, it holds that

$$\begin{aligned} 0 &= \sum_{i=U,D} \{\mathscr{L} V_i(P_i^*) - rV_i(P_i^*)\} \\ &= \mathscr{L} F_J(P_U^*, P_D^*) - rF_J(P_U^*, P_D^*) + \underbrace{K_U + K_D - K}_{>0} \\ &> \mathscr{L} F_J(P_U^*, P_D^*) - rF_J(P_U^*, P_D^*). \end{aligned}$$

[1] Note that continuity of V_J and F_J imply that $\mathcal{C}$ is an open set.

But then it cannot hold that $(P_U^*, P_D^*) \in \partial\mathcal{C}$, because continuity requires that $\mathscr{L}F_J(P_U^*, P_D^*) - rF_J(P_U^*, P_D^*) = 0$. ■

As a consequence, the optimal investment region of the joint venture is strictly larger than the combined investment regions of the stand-alone firms. There are two factors that determine how much larger the investment region is:

1. *industrial symbiosis*: the fact that $K < K_U + K_D$ gives the joint venture a "discount" on joint investment, which accelerates investment, and
2. *market symbiosis*: correlation between P_U and P_D creates a diversification effect for the joint venture, which accelerates investment.

The quantitative extend of these two effects is investigated (numerically) in the next section.

3 Case study

In Europe, the North Sea is at the centre of CCUS deployment. Two CCS facilities already store 1.7 MtCO2/year and there are a number of oil fields in a late phase of their life cycle (International Energy Agency, 2020). Oil production on the Norwegian Continental Shelf is mature and several fields will be decommissioned over the next years. By implementing Enhanced Oil Recovery (EOR) technology, the remaining oil reserves could be improved. A well-known practice in United States and Canada is injecting CO_2 into oil reservoirs, which has the additional advantage of storing CO_2 thus reduce CO_2 emissions. Research results indicate that the potential to increase oil recovery and store CO_2 in oil fields in the North Sea by CO_2 injection is significant (Halland et al., 2018).

We illustrate the model developed in Section 2 using a hypothetical but realistic case study, using data from (Compernolle et al., 2017) and (Roefs et al., 2019).

For the upstream firm, we consider a coal-fueled super critical steam turbine power plant which produces 7013 GWh electricity annually, thereby emitting 4.59 mln tonnes of CO_2. The power plant holds the option to invest in Carbon Capture and Storage (CCS) which involves an investment in a CO_2 capture unit and CO_2 transport and storage costs. The CO_2 is assumed to be transported to an offshore aquifer where it is permanently stored. The investment involves a capital cost for the capture unit and additional operational costs and a cost for transport and storage. If the firm invests in this capture unit, it does not have to pay CO_2 emission allowances anymore. Table 1 presents the cost parameter values.

Description	Value	Unit
Capital expenditure	1 040	Mln €
Operational expenditure	7.22	€/t CO_2
CO_2 transport and storage	14.97	€/t CO_2
Quantity of CO_2 emitted (Q_U)	4.59	Mln t/y
Discount rate (r)	0.15	/
Total discounted cost CCS (K_U)	1 719	Mln €

Table 1: Total cost calculation of the CCS investment in case the electricity company operates as a single investor. See Compernolle et al. (2017) for further cost details.

For the downstream firm, we consider an offshore oil company which holds an option to invest in CO_2 enhanced oil recovery. This investment involves a capital cost for building a platform to inject and recycle CO_2 and additional operational costs, including the purchase and transport of CO_2. CO_2-EOR will be operational for 15 years and the additional oil produced will result in additional revenues for the oil company. Table 2 presents the cost parameter values.

Description	Value	Unit
Capital expenditure	1 543	Mln €
Operational expenditure	37.70	€/bbl
CO_2 purchase price	25.00	€/t CO_2
Quantity of CO_2 supplied	4.59	Mln t/y
Quantity of oil produced (Q_D)	8.25	Mln bbl/y
EOR operational period (T)	15	years
Discount rate (r)	0.15	/
Total discounted cost EOR (K_D)	1 924	Mln €

Table 2: Total cost calculation of the EOR investment in case the oil company operates as a single investor. See Compernolle et al. (2017) for further cost details.

If both firms decide to form a joint venture, then they have three investment options. If the joint venture decides to invest in both a capture unit and CO_2-EOR, then total costs are reduced. At the level of the electricity producer, the payment of transport and storage disappears. At the level of the oil company, the payment for the CO_2 supply disappears, the CO_2 transport costs is included in the operational expenditure. A decision of the JV to invest in both a capture unit and CO_2-EOR, would result in a sunk cost K of about 3 082 Mln Euro (see Table 3 for further detail). Note that the estimated cost saving is rather rudimentary and not further detailed. In practice, CO_2 sources need to be matched to the appropriate sinks and any mismatch could result in additional costs. There might exist uncertainty about the energy use related to the CO_2 capture and separation from the source and CO_2 transportation between the source and sink. Moreover, other uncertainties that might lead to a mismatch need to considered such as temporal and spatial characteristics (e.g. operating life) of the source and sink, because these components operate independently of one another, and are controlled and operated by separate entities (Ghiat and Al-Ansari, 2021). Nevertheless, major cost reductions could to be realized by shifting the focus away from large-scale, stand-alone CCUS facilities, towards industrial hubs. The principal benefit of such approach to CCUS deployment is the possibility of sharing CO_2 transport and storage infrastructure across multiple firms. This can support economies of scale and reduce unit costs, including through greater efficiencies and reduced duplication in the infrastructure planning and development phases. Such hubs can also make it feasible to capture CO_2 at smaller industrial facilities (International Energy Agency, 2020). Although we only consider two firms, our results hint to the impact that such cost reductions might have on the investment decision.

Description	Value	Unit
Capital expenditure capture unit	1 040	Mln €
Capital expenditure EOR	1 543	Mln €
Operational expenditure CO_2 capture	7.22	€/t CO_2
Operational expenditure EOR	37.70	€/bbl
Quantity of CO_2 captured (Q_U)	4.59	Mln t/y
Quantity of oil produced (Q_D)	8.25	Mln bbl/y
EOR operational period (T)	15	years
Discount rate (r)	0.15	/
Total discounted cost CO_2-EOR (K)	3 082	Mln €

Table 3: Total cost calculation of the CO_2-EOR investment option of the JV.

Table 4 gives a summary of the parameter values used in the model for the different investment scenarios that are considered. Both firms could invest on their own or join forces and decide either (i) to invest in CCS and keep the option to invest in EOR alive, (ii) to invest in CO_2-EOR and buy CO_2 externally at a specified price while still paying a carbon price for its own CO_2 emissions (keeping the option to invest in CCS alive), or (iii) to invest in both CO_2 capture and EOR and use its own CO_2 for enhanced oil recovery. For both the oil price and the EU ETS price we estimated the GBM growth and volatility rate based on historical data. We estimate the GBM parameter values for the oil price process using the weekly Brent spot prices for the period 2008-2021 (US Energy Information Administration, 2021). The GBM parameter values for the carbon price process under an emission trading system are estimated using the monthly ECX EUA (European Union Allowance) futures prices for the period 2008-2021 (Quandl, 2021).

Description	Parameter	Value	Unit
Individual investment decision: electricity company (CO_2 is transported to an offshore aquifer)			
Quantity of CO_2 emitted	Q_U	4.6	Mt
Sunk cost CCS	K_U	1 719	Mln €
CO_2 price volatility	σ_U	0.47	/
CO_2 price growth rate	α_U	0.16	/
Individual investment decision: oil company (CO_2 is purchased)			
Quantity of oil produced during EOR	Q_D	8.25	Mln bbl/y
Sunk cost CO_2-EOR_D	K_D	1 924	Mln €
Oil price volatility	σ_D	0.36	/
Oil price growth rate	α_D	0.03	/
Joint investment decision			
Sunk cost if only CCS	K_U	1 719	Mln €
Sunk cost if only EOR (CO_2 purchased externally from the JV)	K_D	1 924	Mln €
Sunk cost if JV invests in both CO_2 capture and EOR	K	3 082	Mln €
CO_2 price volatility	σ_U	0.2	/
CO_2 price growth rate	α_U	0.04	/
Initial CO_2 price level	$P_{U,0}$	35	€/t
Oil price volatility	σ_D	0.2	/
Oil price growth rate	α_D	0.05	/
Initial oil price level	$P_{D,0}$	40	€/bbl
Discount rate	r	0.18[2]	/

Table 4: Parameter values of the real options models.

4 Results and discussion

4.1 Investment threshold boundaries

Using the model described in Section 2 and the parameter values listed in Table 4, we can explore the optimal investment boundary of the joint venture. Before looking at the joint venture, it is instructive to describe the two firms as "stand-alone" decision makers. If the carbon price is constant in time, the electricity producer will, on its own, only invest in a CO_2 capture unit and geological aquifer storage if the market price of CO_2 exceeds, roughly, 67 EUR/t ($P_U^* = 67.41$). This is represented by the dotted vertical line in the left panel of Figure 2. When the carbon price is considered stochastic, the investment threshold value increases to 112 EUR/t ($P_U^* = 111.75$). This is represented by the dotted vertical line in the right panel of Figure 2.

The oil producer's stand-alone investment trigger is an oil price of at least 80 EUR/bbl ($P_D^* = 79.97$). This is represented by the dotted horizontal lines on the left and right panel of Figure 2.

The investment boundary of the joint venture is represented by the solid black line in Figure 2, which is obtained by implementing the algorithm described in Appendix B. With a constant carbon price (left panel), the joint venture will always invest in carbon capture and EOR at an earlier date than the stand-alone firms would do for $45.42 \geq P_U \geq 67.41$. When $P_U \geq 67.41$ and $P_D \leq 56$, the joint venture will lead to later investment in a carbon reducing technology than the upstream stand-alone firm.

The solid black line in the right panel of Figure 2 represents the investment boundary when both the oil and the carbon price are considered stochastic. Note that if the oil price is 0, then the joint venture invests at a CO_2 price which is equal to the stand-alone threshold value of the electricity producer: $(P_U^*, 0) = (111.75, 0)$. In that case, the joint venture only invests in CCS and will never invest in CO_2-EOR. Similarly, if the CO_2 price is zero, it is optimal for the joint venture to invest in CO_2-EOR only at the individual investment trigger of the oil producer: $(0, P_D^*) = (0, 79.97)$. The optimal investment boundary is always below the investment threshold points of each of the separate firms and hence cooperation between both firms stimulates investment. The triangular area (below the individual threshold values and above the joint venture threshold boundary) in Figure 2 shows for which price levels investment in CO_2 capture will take place when the two firms cooperate. If the two firms would not combine their efforts, there would be no investment in CO_2 capture for these price combinations.

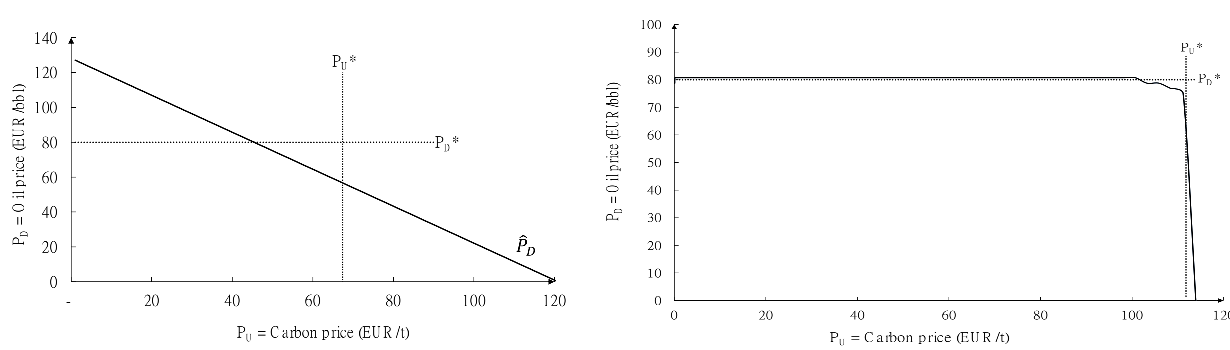

Figure 2: Stand-alone investment thresholds (dotted black lines) and the optimal investment boundary for the joint venture (solid black line). Left panel: constant carbon price, right panel: stochastic carbon price.

Whereas the individual firms only face a single market uncertainty, the joint venture operates in two markets, the oil market and the carbon market and, thus, faces two sources of uncertainty. Nevertheless, the additional uncertainty does not shift the optimal investment boundary above the stand-alone threshold value. The reason that the optimal investment boundary is below the individual threshold levels is twofold. A first reason is the synergy in costs when a full investment in CO_2-EOR takes place: the oil producer does not have to pay for the required CO_2 and the electricity producer does not have to pay a fee for storing the CO_2. A second reason is that when the individual firms remain separate, they do not have the option to invest in the other market. However, if the joint venture decides to invest in one market only (either the installation in a capture unit, or the EOR installation at the oil platform), then the joint venture still holds the option to invest in the other market. This option has a value which is not present if the firms remain separate.

The left panel of Figure 3 shows that when the carbon price volatility is reduced to 0.1, the stand-alone investment threshold value of the electricity producer shifts to the left and the joint venture threshold boundary shifts down. Moreover, the triangular area becomes larger, indicating that the added value of the joint venture in stimulating investment in carbon reducing technologies increases, with decreasing carbon price volatility. If the carbon price growth rate is set to 0, the investment boundaries shift to the right.

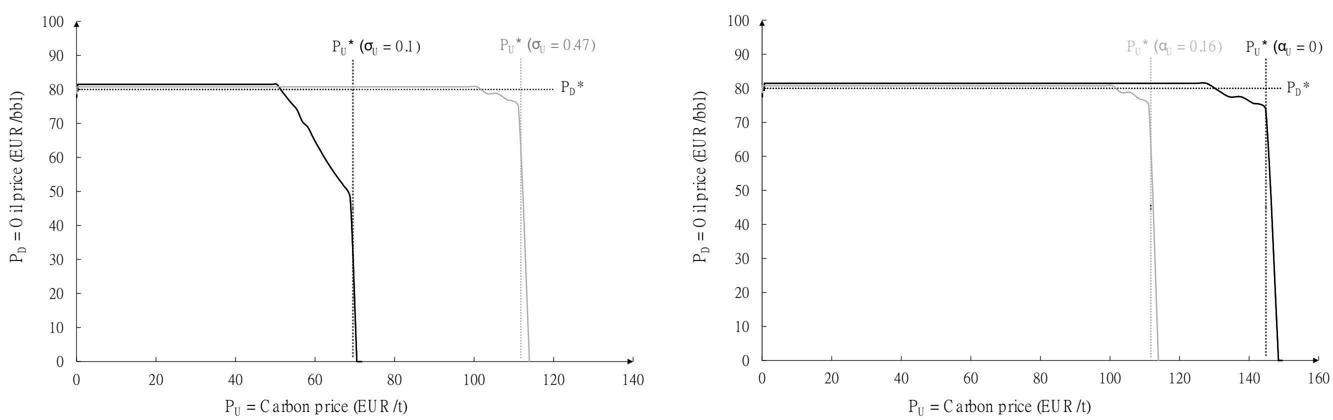

Figure 3: Stand-alone investment thresholds (dotted black lines) and the optimal investment boundary for the joint venture (solid black line). Left panel: reduced carbon price volatility, right panel: carbon price growth rate is set to zero.

Because of the cooperation between the two firms, the probability that CO_2 will start being captured at the power plant within the next 5 years increases. We simulate 50,000 sample paths of (P_U, P_D) with $(P_{U,0}, P_{D,0}) = (35, 40)$, to estimate the probability of CCS investment within a certain time frame. As a stand-alone firm, there is only a 34% probability that within 5 years CO_2 will be captured at the power plant. When both firms join forces, this probability increases to 41%.

In accordance with Figure 3, Figure 4 shows that the probability of investment in CO_2 capture is always higher than the probability of investment in CO_2 capture by the upstream firm on its own. The probability to invest increases with decreasing volatility in the carbon price and increases with increasing carbon price growth rate. The third panel of Figure 4 shows that the larger the industrial symbiosis and hence, the smaller $\zeta = \frac{K}{K_U+K_D}$, the larger the probability that the joint venture invests in CO_2 capture.

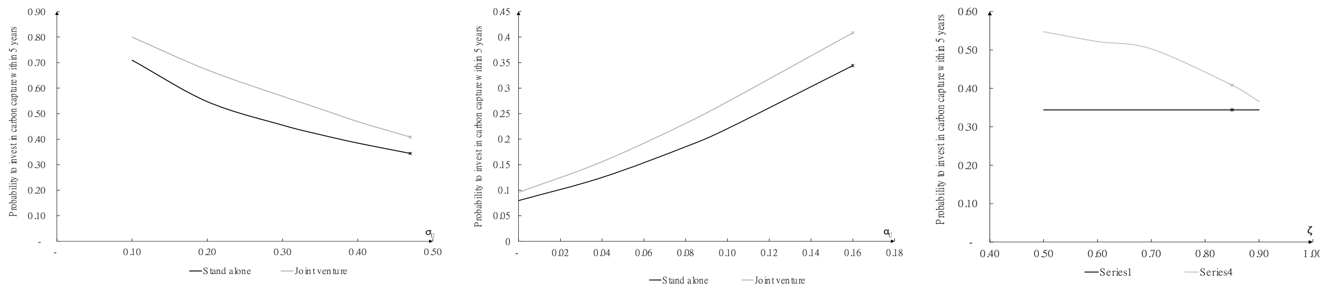

Figure 4: Probability to invest in CO_2 capture within 5 years for the stand alone upstream firm and the joint venture, given different values of σ_U, α_U, and $\zeta = \frac{K}{K_U+K_D}$. * marks the base case values

4.2 Investment choice of the joint venture

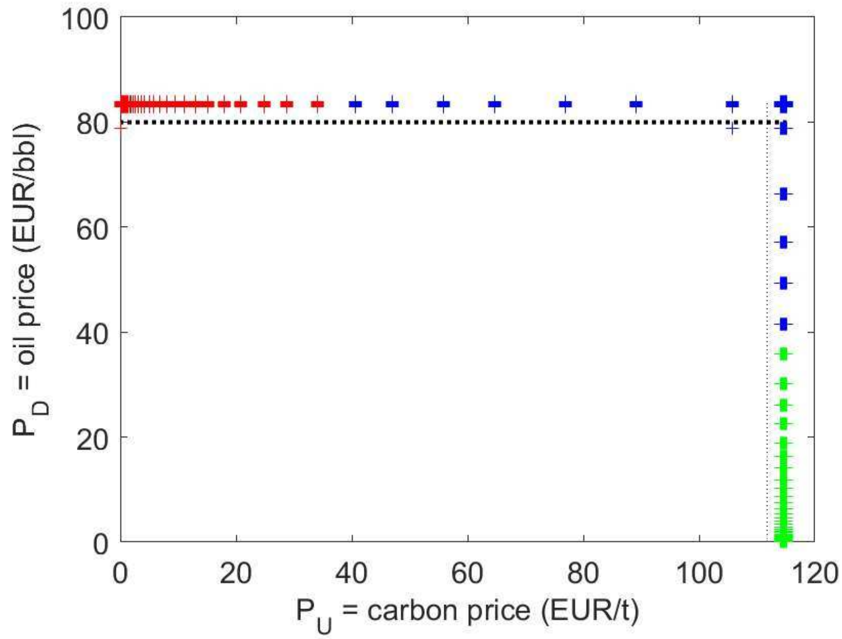

Figure 5: Investment choice of the joint venture. Red area: region where the joint venture only invests in EOR; bleu area: region where the joint venture invests in both CCS and EOR; green area: region where the joint venture only invests in CCS.

Figure 5 shows which investment option is selected by the joint venture for specific CO_2 and oil price levels. For the base case values ($\sigma_U = 0.47$, $\alpha_U = 0.16$, and $\zeta = \frac{K}{K_U+K_D} = 0.85$), there is a 52% probability that the joint venture will invest within 5 years. In 12% of the cases, the joint venture will decide to adopt CO_2-EOR but only invest in a CO_2 injection and recycling installation and buy CO_2 elsewhere while holding the option to invest in a CO_2 capture unit at the level of the power plant open. The power plant then continues to emit CO_2 for which it pays CO_2 emission allowances (the red area). In most cases (25% of the cases), the JV decides to invest in both the capture unit and CO_2-EOR (the bleu area). The power plant does not emit CO_2 and the captured CO_2 is used for additional oil extraction. The investment in CO_2 capture takes place for $P_U \geq \bar{P}_U = 40.54$ EUR/t. Hence, compared to the stand-alone case, the threshold boundary for investing in CO_2 capture is reduced from 111.75 EUR/t to 40.54 EUR/t for given oil prices of 79.97 EUR/bbl or higher. Besides, the joint venture also reduces the investment boundary for CO_2-EOR. Whereas in the stand-alone case, investment in CO_2-EOR would only take place at an oil price of 79.97 EUR/bbl or higher, in the case of a joint venture, CO_2-EOR investment would take place for $P_D \geq \bar{P}_D = 34.85$ EUR/bbl for given CO_2 price levels of 111.75 EUR/t or higher.

In 15% of the cases, the joint venture will invest in carbon capture and storage and keep the option to invest in CO_2-EOR alive. In that case, no additional oil is extracted and the captured CO_2 is stored in an off-shore aquifer. Hence, the joint venture stimulates investment in CO_2-EOR and in most cases, the CO_2 is sourced from the electricity plant. Although the joint venture stimulates investment in CO_2 capture, it does not stimulate investment in CCS. The value of the option to invest in CO_2-EOR seems to be too low.

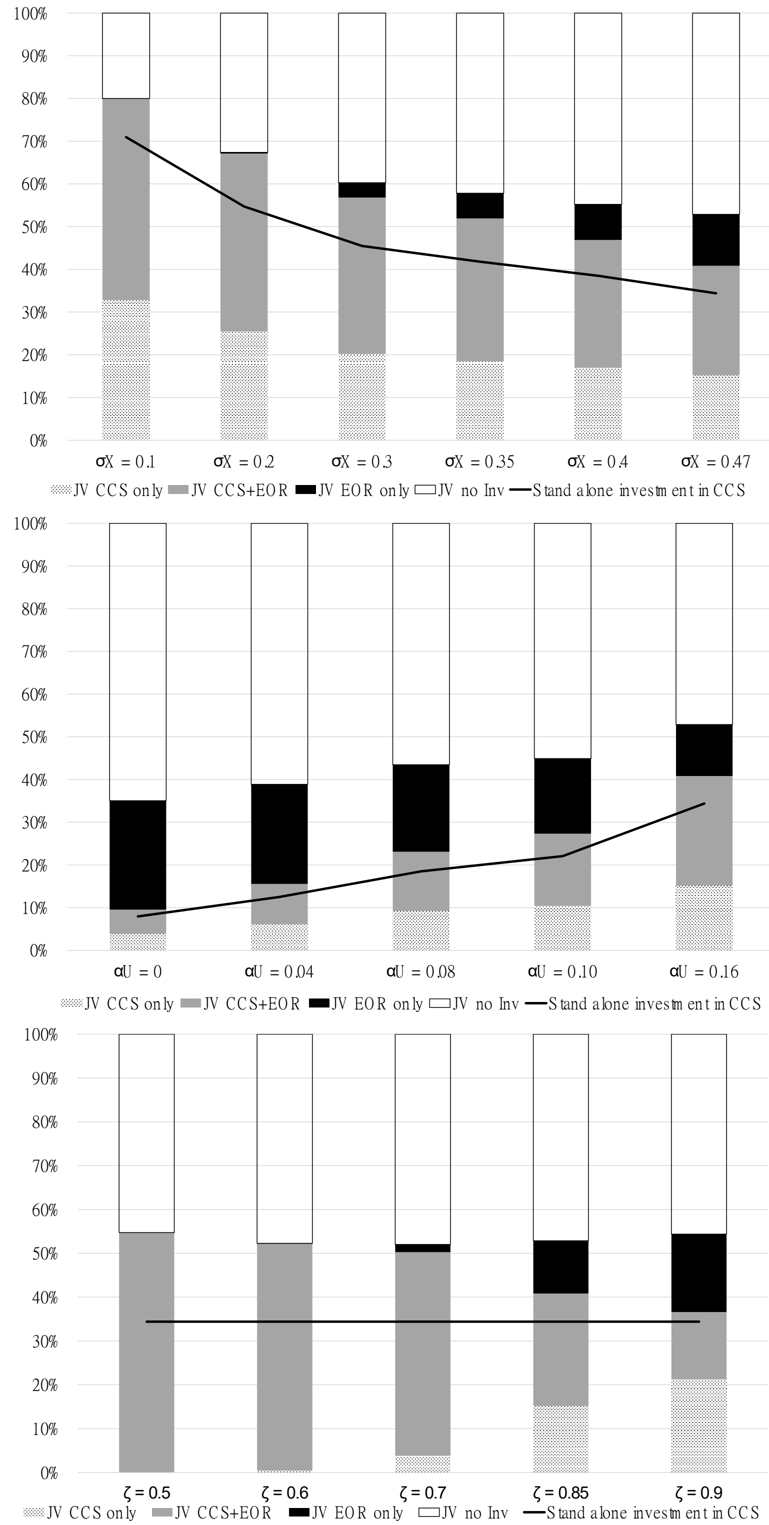

Figure 6: Investment choice of the joint venture for different values of σ_U, α_U, and $\zeta = \frac{K}{K_U + K_D}$.

Figure 6 shows how the choice of the joint venture changes when the carbon price volatility and the carbon price growth rate would be smaller. A decrease in the carbon price volatility will increase in the likelihood that the joint venture invests. The smaller σ_U, the smaller the number of cases for which the joint venture would decide to invest in EOR only. For changes in the carbon price growth rate, we observe the opposite effect. When the carbon price growth rate is smaller, the likelihood that the joint venture invests not only decreases, the number of cases where the joint venture invests only in EOR also becomes larger.

The likelihood that the joint venture will invest only changes a bit for different values of ζ. In accordance with the previous section, Figure 6 shows that the probability of CO_2 capture (CCS only and CCS+EOR) increases for smaller values of ζ. However, when ζ is relatively low, the joint venture will decide in all cases to immediately invest in both CCS and EOR when the threshold boundary is reached. When ζ increases, it is more likely that the joint venture invests only in CCS or only in EOR, keeping the other option alive.

In the next section, we assess the environmental impact associated with these choices.

4.3 Environmental impact of cooperation

From an environmental perspective, it is most important to limit CO_2 emissions. Without investments taking place, and hence without capturing CO_2, the coal-fired power plant has an annual environmental impact of 4.59 million t CO_2 emitted. At the level of the oil field, the environmental impact before investment in EOR is zero. As long as the oil producer decides not to invest in CO_2-EOR, the oil reservoir is abandoned and no operations are taking place. To illustrate the benefit of cooperation in terms of environmental impact, we use the results presented in Roefs et al. (2019) as input data. In Roefs et al. (2019) an environmental life cycle analysis is applied to assess the Global Warming Potential of CCS and CO_2-EOR investments in the North Sea region. The scenario with the lowest level of CO_2 emissions is the investment in CCS. Per tonne of CO_2 captured, the environmental impact is about 0.1026 t CO_2 eq., resulting in an impact of 0.47 mln t CO_2 eq. per year. If the oil company stands alone, an additional barrel of oil produced after CO_2-EOR investment, has an impact of 0.125 t CO_2 eq. resulting in an annual impact of 1.03 mln t CO_2 eq. Because the oil producer stands alone, it purchases CO_2 externally and the power plant continues to emit CO_2 also after the investment in CO_2-EOR is made. The environmental impact associated with the joint venture options are as follows:

1. In case the joint venture invests in CO_2-EOR, the environmental impact is 1.03 mln t CO_2eq./y.;
2. In case the joint venture invests in CCS without oil extraction (K_U investment), potentially

followed by CO_2-EOR (K_D investment) at a later date, the environmental impact of CCS (the K_U investment) is about 0.47 mln t CO_2eq./y;

3. In case the joint venture invests in CO_2-EOR with CO_2 sourced externally, potentially followed by CCS at a later date, the environmental impact of the investment (K_D investment) is 5.62 million t CO_2eq./y. In this scenario there is no investment in CO_2 capture and the electricity plant continues emitting CO_2

We then simulate 50,000 sample paths for a period of 50 years, with $(P_{U,0}, P_{D,0}) = (35, 40)$ to estimate the amount of CO_2 emissions saved through CO_2 capture technology (either stand-alone or in combination with CO_2-EOR) as well as the societal value of the CO_2 capture investment. Figure 7 shows the probability density function of the simulation results.

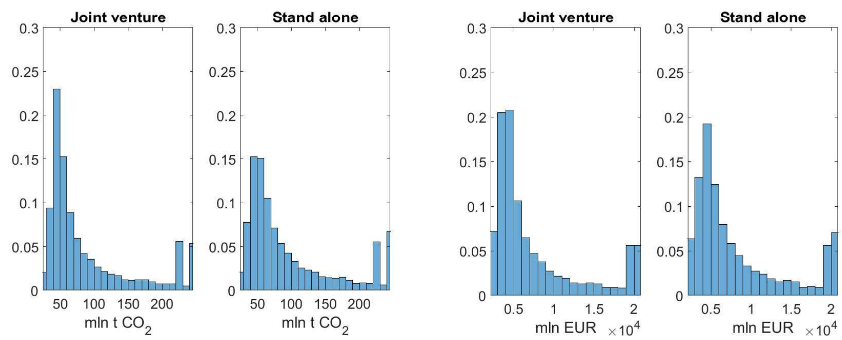

Figure 7: Probability density function of the amount of CO_2 emitted (left panel) and the associated societal value (right panel) in case both firms stand alone or cooperate. The probability mass reflects scenarios where no investment takes place within the specified time horizon.

On average CO_2 would be captured during a period of 33.75 years if the electricity producer operates on its own (within a time span of 50 years). If the electricity producer would decide to join forces with an oil producer, on average, CO_2 would be captured during a period of 35.38 years. Although the joint venture does not stimulate investment in CCS and the captured CO_2 is being used for additional oil extraction, joining forces with the oil company would result in a CO_2 emission reduction of 7.65 mln t over a period of 50 years compared to the stand-alone case. Considering a social cost of carbon of 80 EUR/t and a social discount rate of 2%, this emission reduction results in a saved social cost of €650 mln.

The environmental impact associated with the investment choice of the joint venture is shown in Figure 8. When the volatility of the carbon price (σ_U) decreases, the joint venture is less likely to invest in EOR only and the amount of CO_2 emitted by the joint venture over a period of 50 years decreases from 92.20 mln t (for $\sigma_U = 0.47$) to 46.82 mln t CO_2 emissions (for $\sigma_U = 0.10$) on average.

However, also the stand alone electricity producer will invest more early in CO_2 capture and hence, the CO_2 emissions associated with the stand-alone case are limited as well.

When the growth rate of the carbon price decreases, the average amount of CO_2 emitted by the joint venture over a period of 50 years increases from 92.20 mln t (for $\alpha_U = 0.16$) to 198.71 mln t (for $\alpha_U = 0$). Reason is that when the carbon price is not expected to grow, investment by the joint venture is postponed and the joint venture is more likely to only invest in EOR. Although a joint venture emits less CO_2 than in case both firms stand alone, the added value of the joint venture in terms of CO_2 emissions saved decreases with decreasing carbon price volatility and a decreasing carbon growth rate.

Figure 8 shows that the amount of emissions saved by the joint venture increases with decreasing K. Hence, the stronger the industrial symbiosis, the larger the added value of the joint venture. For $\zeta = 0.5$, the amount of CO_2 emitted by the joint venture over a period of 50 years is reduced to 77.02 mln t (on average).

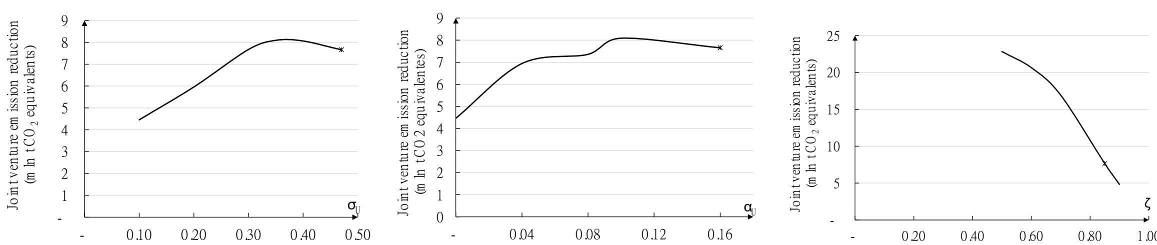

Figure 8: Average CO_2 emission reduction realized by the joint venture, for different values of σ_U, α_U, and $\zeta = \frac{K}{K_U + K_D}$.

4.4 The impact of market symbiosis

In the previous section, the correlation between the two stochastic price processes is relatively low ($\rho = 0.072$). To generalize the results, the left panel of Figure 9 shows the impact of stronger, positively correlated CO_2 and oil prices on the investment threshold boundary. The threshold level in case of a zero oil price or a zero CO_2 price does not change. The threshold boundary of the JV however, increases and the triangular area under the individual boundaries decreases. If within a symbiotic alliance of two firms, the correlation between two stochastic price processes would be negative, then the threshold boundary would be lower compared to the base case. This results is important as it shows that in addition to potential cost savings, industrial symbiosis could be accompanied with a market symbiosis, causing a shift in the investment threshold boundary.

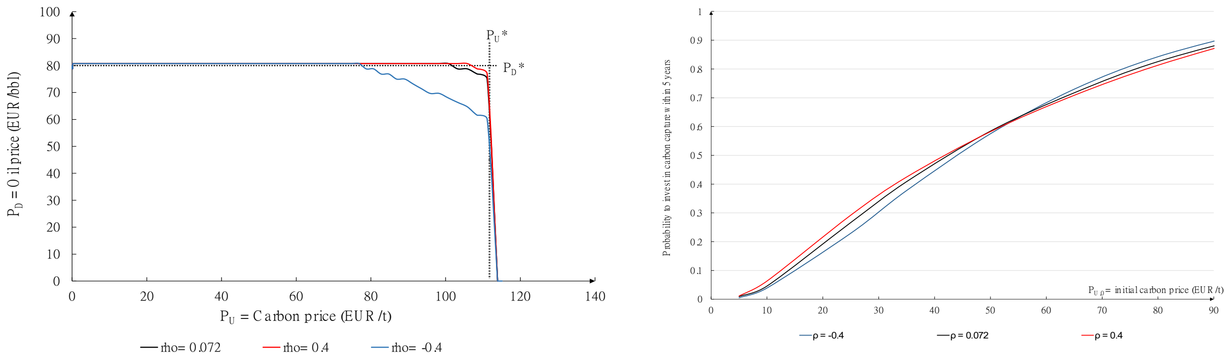

Figure 9: Left panel: individual investment thresholds and the threshold boundary for the joint venture in case of positively and negatively correlated price processes. Right panel: probability that the joint venture invests in carbon capture (CCS only and CCS+EOR) for different levels of ρ.

Note that a higher threshold boundary does not necessarily imply a lower probability that investment takes place within a certain time period. On the contrary, the right panel of Figure 9 shows that with increasing correlation, the probability of investment increases as well. If the positive correlation between the oil and CO_2 price would be stronger, the probability that the joint venture invests in carbon capture would be larger for initial CO_2 price levels ($P_{U,0}$) lower than 53 €/t. Because of the positive correlation, an increase in the price of oil, is likely to be followed by a price increase in CO_2. Hence, besides an industrial symbiosis, also a market symbiosis can take place when two firms join forces. However, for larger CO_2 price levels, this effect disappears. For negatively correlated price processes we find an opposite result. A market symbiosis will take place for initial CO_2 price levels larger than 53 €/t. For lower CO_2 price levels, the probability to invest would be lower if the price processes would be negatively correlated.

The left panel of Figure 10 shows the choice of the joint venture for different levels of ρ. When the correlation is negative or positively weak, the more likely it is that the joint venture invests. However, under these market conditions, the joint venture is also more likely to only invest EOR and less likely to invest in carbon capture. These investment choices will impact the environmental effect of the joint venture, shown in the right panel of Figure 10. For lower levels of initial CO_2 price levels, the average amount of CO_2 emissions that are saved if the two firms join forces, increases with increasing CO_2 price levels. Reason is that when the initial CO_2 price level is low, the investment in CCS by the stand alone electricity producer is less likely. For larger initial CO_2 price levels, it is more likely that the threshold point is reached more early. Because a stand alone electricity producer is also more likely to invest, the added value of the joint venture in terms of CO_2 emissions saved disappears. Moreover, the creation of a joint venture could result in more CO_2 emissions than when both firms would remain separate, resulting in a negative societal value.

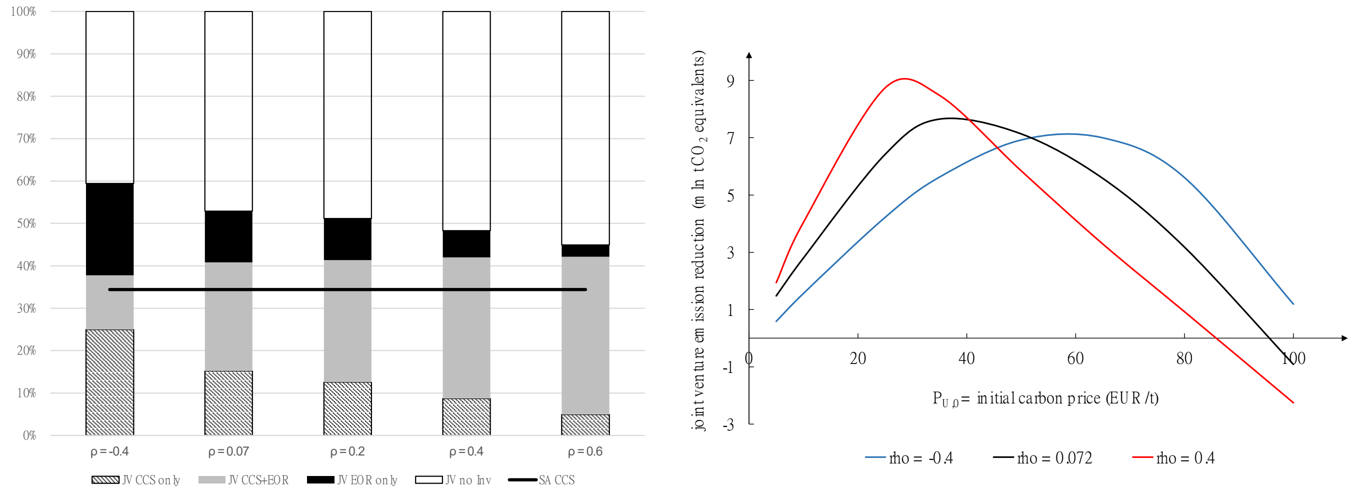

Figure 10: Left panel: choice of the joint venture for $P_{U,0} = 35 EUR/t$. Right panel: average carbon emission reduction realized by the joint venture in case of positively and negatively correlated price processes and for increasing carbon price levels.

5 Conclusion

To combat climate change, CO_2 emissions need to be reduced. Large scale emission reductions will not be realized by a single firm but requires inter-firm cooperation. Given that the EU has set binding targets to its Member States for reducing their emissions, it is important to understand how investment decisions in CO_2 emission reduction technologies are influenced by multiple sources of uncertainty. In particular, CO_2 emission reduction could be realized across different industrial chains, involving firms that operate in different markets and hence face different sources of uncertainty. In contrast to static net present value calculations, a real options approach draws a more realistic picture of the impact of uncertainty on the timing of investment. Within that framework, a particular challenge is to account for multiple correlated stochastic (price) processes associated with the different markets in which these firms operate.

We developed an analytical real options model and ran numerical simulations to compare the CCUS investment decisions of stand-alone firms with the investment decision of a joint venture.

We showed that the creation of a joint venture increases the likelihood of investment in CO_2 capture technology. However, it is more likely that the captured CO_2 will be used for the creation of an additional revenue flow (oil) than for CO_2 storage. This result is governed by two underlying factors: industrial symbiosis and market symbiosis.

First, if total carbon capture and utilization costs are reduced when firms combine their forces, the joint venture creates a “discount” on carbon capture investment, which will accelerate the adoption of CCUS. The larger the cost reduction, the more likely it is that the joint venture invests in both carbon capture and enhanced oil recovery, resulting in larger amounts of CO_2 emissions that are avoided, compared to the case where both firms would stand alone. Second, there is a market symbiosis, in the sense that the correlation between the two stochastic price processes creates a diversification effect. This effect accelerates investment as well. Furthermore, the higher the correlation, the more likely it is that the joint venture invests in both carbon capture and EOR instead of EOR only, resulting in a larger amount of CO_2 emissions saved.

Besides these inter-firm cooperation effects, carbon pricing is integrated in the model. We showed that for lower carbon price volatility and a larger carbon price growth rate, the probability of investment increases, and the joint venture is more likely to exercise both the option to invest in EOR and the option to invest in carbon capture, resulting in lower CO_2 emissions. However, under these market conditions a stand-alone firm is more likely to invest in CCS, so that the added value of the joint venture (in terms of CO_2 emissions saved), when compared with two firms operating on their own, decreases. However, we show that when the carbon and oil prices are such that it is highly likely that a joint venture would invest in EOR but not in CCS,then the creation of the joint venture could result in higher CO_2 emissions than when both firms would remain separate. In addition, if the carbon and oil prices are such that both a joint venture and a stand-alone firm would invest in CCS but the stand-alone oil company would not invest in EOR with a high probability, then the added value of the joint venture in terms of lower CO_2 emissions is also reduced by the fact that the joint venture simultaneously invests in EOR with high probability. These effects could even result in a societal loss.

In conclusion, for rather low carbon prices, more CO_2 emissions will be avoided if firms create a joint venture than if they would operate in isolation. The stronger the industrial and market symbiosis, the larger the added value of creating a joint venture. Policy makers should be aware that this effect will disappear once carbon prices become relatively large and stand-alone CCS investments (without EOR) become profitable as well.

Appendix

A Proof of Proposition 2

To keep notation simple we identify $X = P_U$ and $Y = P_D$. We restrict attention to the set E of points in $\mathbb{R}^2_+$ where all the first and second-order partial derivatives of φ are well-defined. Note that for every $t \geq 0$ it holds that $(X_t, Y_t) \in E$, $\mathbb{P}$-a.s.

For any $\varphi \geq F_J$ that is C^2-a.e., the HJB equation (13) can be re-written as a pair of variational inequalities on $\mathbb{R}_+^2$:

$$\begin{cases} \mathscr{L}\varphi(x,y) - r\varphi(x,y) \leq 0 & \text{when } \varphi(x,y) = F_J(x,y), \text{ and} \\ \mathscr{L}\varphi(x,y) - r\varphi(x,y) = 0 & \text{when } \varphi(x,y) > F_J(x,y). \end{cases}$$

Let

$$\mathcal{C} = \left\{ \, (x,y) \in \mathbb{R}_+^2 \; \middle| \; \varphi(x,y) > F_J(x,y) \, \right\},$$

and define the stopping time

$$\tau_{\mathcal{C}} = \inf \{ \, t \geq 0 \mid (X_t, Y_t) \notin \mathcal{C} \, \}.$$

Noting that

$$\mathbb{E}\left[e^{-r\tau_{\mathcal{C}}}\varphi(X_{\tau_{\mathcal{C}}}, Y_{\tau_{\mathcal{C}}})\right] = 0,$$

on $\{\tau_{\mathcal{C}} = \infty\}$, it follows from Dynkin's formula (see, e.g., Øksendal, 2000) and the fact that $\varphi = F_J$ on $\partial\mathcal{C}$ (by a.s.-continuity of sample paths) that

$$\begin{aligned} \mathbb{E}\left[e^{-r\tau_{\mathcal{C}}}J_V(X_{\tau_{\mathcal{C}}}, Y_{\tau_{\mathcal{C}}})\right] &= \mathbb{E}\left[e^{-r\tau_{\mathcal{C}}}\varphi(X_{\tau_{\mathcal{C}}}, Y_{\tau_{\mathcal{C}}})\right] \\ &= \varphi(x,y) + \mathbb{E}\left[\int_0^{\tau_{\mathcal{C}}} e^{-rt}\left(\mathscr{L}\varphi(X_t,Y_t) - r\varphi(X_t,Y_t)\right)\mathrm{d}t\right] \\ &= \varphi(x,y). \end{aligned}$$

Now consider any other stopping time $\tau \in \mathcal{M}$. Then another application of Dynkin's formula shows that

$$\begin{aligned} \mathbb{E}\left[e^{-r\tau}J_V(X_\tau, Y_\tau)\right] &\leq \mathbb{E}\left[e^{-r\tau}\varphi(X_\tau, Y_\tau)\right] \\ &= \varphi(x,y) + \mathbb{E}\left[\int_0^{\tau} e^{-rt}\left(\mathscr{L}\varphi(X_t,Y_t) - r\varphi(X_t,Y_t)\right)\mathrm{d}t\right] \\ &\leq \varphi(x,y). \end{aligned}$$

Therefore, it follows that $V_J = \varphi$ and that the optimal stopping time in (B.1) is $\tau_{\mathcal{C}}$, as claimed.

■

B Numerical implementation

Our numerical implementation of the optimal stopping problem (12) uses the Markov chain approximation method as described in, e.g., Kushner (1997) and Kushner and Dupuis (2001). Our optimal stopping problem is of the form

$$V(x,y) = \sup_{\tau \in \mathcal{M}} \mathbb{E}\left[-\int_0^{\tau} e^{-rt}c(X_t)\mathrm{d}t + e^{-r\tau}F(X_\tau, Y_\tau)\right], \tag{B.1}$$

where

$$\begin{bmatrix} \mathrm{d}X/X \\ \mathrm{d}Y/Y \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} \mathrm{d}t + \begin{bmatrix} \sigma_1 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_y \end{bmatrix} \begin{bmatrix} \mathrm{d}W_1 \\ \mathrm{d}W_2 \end{bmatrix},$$

and $x \mapsto c(x)$ represents the running costs, which are here given by the costs of CO_2 emissions.

For numerical stability is desirable to use the following transformation of variables:

$$U := \log(X), \quad \text{and} \quad V := \log(Y).$$

Letting the functions $\hat{F} : \mathbb{R}_2 \to \mathbb{R}$ and $\hat{c} : \mathbb{R} \to \mathbb{R}$ be such that

$$\hat{F}(u, v) := F\left(e^u, e^v\right), \quad \text{and} \quad \hat{c}(u) := c\left(e^u\right), \quad \text{all } u, v \in \mathbb{R},$$

we can then rewrite (B.1) as

$$\hat{V}(u, v) = \sup_{\tau \in \mathcal{M}} \mathbb{E}\left[-\int_0^\tau e^{-rt}\hat{c}(U_t)\mathrm{d}t + e^{-r\tau}\hat{F}(U_\tau, U_\tau)\right],$$

where

$$\begin{bmatrix} \mathrm{d}U \\ \mathrm{d}V \end{bmatrix} = \begin{bmatrix} \alpha_1 - \sigma_1^2/2 \\ \alpha_2 - \sigma_2^2/2 \end{bmatrix} \mathrm{d}t + \begin{bmatrix} \sigma_1 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2 \end{bmatrix} \begin{bmatrix} \mathrm{d}W_1 \\ \mathrm{d}W_2 \end{bmatrix},$$

which has the property that

$$V\left(x, y\right) = \hat{V}(\log(x), \log(y)), \quad \text{all } x, y \in \mathbb{R}_{++}.$$

Note that a straightforward application of Ito's lemma gives that

$$\mathrm{d}U = (\mu_1 - \sigma_1^2/2)\mathrm{d}t + \sigma_1\mathrm{d}W_1, \quad \text{and} \quad \mathrm{d}V = (\mu_2 - \sigma_2^2/2)\mathrm{d}t + \sigma_2\mathrm{d}W_2.$$

The basic idea is to replace the the continuous-time stochastic process (U, V) by a discrete-time Markov chain (U^h, V^h), where $h > 0$ is the step-size on a grid over

$$G := [\underline{u}, \overline{u}] \times [\underline{v}, \overline{v}]$$

for some $\underline{u} < \overline{u}$ and $\underline{v} < \overline{v}$ that ensure that G is large enough to produce an accurate approximation to $\hat{V}$. In our case we choose

$$\underline{u} = \underline{v} = -10, \quad \overline{u} = \log(P_U^*), \quad \text{and} \quad \overline{v} = \log(P_D^*).$$

Any point (u, v) on the grid is such that

$$u \in \mathcal{N}_u^h := \{\underline{u}, \underline{u} + h, \ldots, \overline{u} - h, \overline{u}\}, \quad \text{and} \quad v \in \mathcal{N}_v^h := \{\underline{v}, \underline{v} + h, \ldots, \overline{v} - h, \overline{v}\}.$$

Introducing, for each $a \in \mathbb{R}$, the notation $a^+ := \max\{0, a\}$ and $a^- := \max\{-a, 0\}$, the approximating Markov chain on the grid has the following transition probabilities on $\mathcal{N}_u^h \times \mathcal{N}_v^h$:

$$
\begin{aligned}
p^h(u \pm h, v|u,v) &= \frac{(\sigma_1^2 - |\rho|\sigma_1\sigma_2)/2 + h\left(\alpha_1 - \sigma_1^2/2\right)^{+}}{Q^h(u,v)},\\
p^h(u, v \pm h|u,v) &= \frac{(\sigma_2^2 - |\rho|\sigma_1\sigma_2)/2 + h\left(\alpha_2 - \sigma_2^2/2\right)^{+}}{Q^h(u,v)},\\
p^h(u+h, v+h|u,v) = p^h(u-h, v-h|u,v) &= \frac{\rho^+\sigma_1\sigma_2}{2Q^h(u,v)},\\
p^h(u+h, v-h|u,v) = p^h(u-h, v+h|u,v) &= \frac{\rho^-\sigma_1\sigma_2}{2Q^h(u,v)},
\end{aligned}
$$

where

$$
Q^h(u,v) = \sigma_1^2 + \sigma_2^2 - |\rho|\sigma_1\sigma_2 + \left|\alpha_1 - \tfrac{1}{2}\sigma_1^2\right| h + \left|\alpha_2 - \tfrac{1}{2}\sigma_2^2\right| h.
$$

Note that the transition probabilities are non-negative if $\rho = 0$ or if

$$
|\rho| < \frac{\sigma_1}{\sigma_2} < |\rho|^{-1}, \quad \text{when } \rho \neq 0.
$$

Given a grid $\mathcal{N}_u^h \times \mathcal{N}_v^h$, our time disretization is chosen such that our discrete-time Markov chain approximation of (B.1) (to be defined below) converges (weakly) to (B.1). It turns out (see, e.g., Kushner and Dupuis, 2001) that a sequence of time points with (potentially state-dependent) time intervals of length

$$
\Delta t^h(u,v) := h^2/Q^h(u,v),
$$

achieves this.

From Proposition 2 we know that the solution to (B.1) should satisfy the Hamilton–Jacobi–Bellman (HJB) equation

$$
\hat{V}(u,v) = \max\left\{\hat{F}(u,v), \mathscr{L}\hat{V}(u,v) + (1-r)\hat{V}(u,v) - \hat{c}(u)\right\}, \tag{B.2}
$$

here written as a fixed-point equation, where $\mathscr{L}$ is the characteristic operator of (U, V), i.e.

$$
\mathscr{L}\varphi := \frac{1}{2}\sigma_1^2\varphi_{11}'' + \frac{1}{2}\sigma_2^2\varphi_{22}'' + \rho\sigma_1\sigma_2\varphi_{12}'' + (\alpha_1 - \sigma_1^2/2)\varphi_1' + (\alpha_2 - \sigma_2^2/2)\varphi_2'.
$$

Using the transition probabilities of our Markov chain approximation we can discretize the characteristic operator for functions φ^h defined on the grid $\mathcal{N}_u^h \times \mathcal{N}_v^h$:

$$
\begin{aligned}
\hat{\mathscr{L}}^h\varphi^h(u,v) :=\ & p(u+h,v|u,v)\varphi^h(u+h,v) + p(u,v+h|u,v)\varphi^h(u,v+h)\\
&+ p(u-h,v|u,v)\varphi^h(u-h,v) + p(u,v-h|u,v)\varphi^h(u,v-h)\\
&+ 1_{\rho\geq 0}\left[p(u+h,v+h|u,v)\varphi^h(u+h,v+h) + p(u-h,v-h|u,v)\varphi^h(u-h,v-h)\right]\\
&+ 1_{\rho<0}\left[p(u+h,v-h|u,v)\varphi^h(u+h,v-h) + p(u-h,v+h|u,v)\varphi^h(u-h,v+h)\right].
\end{aligned}
$$

We now replace the HJB equation (B.2) by the discrete-time approximation

$$W^h(u,v) = (TW^h)(u,v), \tag{B.3}$$

where the operator T is given by

$$(TW^h)(u,v) := \max\left\{\hat{F}^h(u,v), (1 - r\Delta t^h(u,v))\mathscr{L}^h W^h(u,v) - c(u)\Delta t^h(u,v)\right\}.$$

Using Blackwell's theorem (Aliprantis and Border, 2006, Theorem 3.53), it is fairly easy to show that the operator T is a contraction mapping. From the Banach fixed point theorem (Aliprantis and Border, 2006, Theorem 3.48) it follows that the fixed-point problem (B.3) has a unique fixed point. In addition, repeated application of T leads to convergence to the fixed point W^h, which then acts as our approximation to the value function V.

To summarize, we start with an initial guess W_0^h on the grid $\mathcal{N}_u^h \times \mathcal{N}_v^h$. From this initial guess we extract an initial guess of the continuation region, G_0, by extracting all points $(u,v) \in \mathcal{N}_u^h \times \mathcal{N}_v^h$ for which $W_0^h(u,v) > \hat{F}(u,v)$. We then compute a new iteration, W_1^h by applying the operator T, i.e.

$$W_1^h := TW_0^h.$$

This procedure is repeated until the change between W_n^h and W_{n-1}^h (in the sup norm) falls below 1. That is, our final approximation is to the nearest \$1,000.

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