Cooperation under Uncertainty over Investment in CO_2 Emission Reduction Technology along an Industrial Chain

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Abstract

An increasing concern for climate change puts pressure on industrial firms to implement practices for carbon emission reductions. Recently, it has been recognized that such carbon emission reductions can be realized through cooperation among firms in industrial chains.

Central to the adoption of industrial symbiosis is the so-called "win-win condition". It has been assumed in the literature that industrial symbiosis will emerge spontaneously, as an independent choice of both parties involved, under the condition that all parties achieve an economic benefit sufficient to cover the risk of the investment, i.e. the NPV of cooperation should exceed the sum of individual firm NPVs.

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. By taking a real options approach, we make the timing component of the investment decisions explicit. 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. 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 on climate change puts pressure on industrial firms to implement practices for carbon emission reductions. Recently, it is being recognized that carbon emission reductions (CER) can be realized through cooperation among industrial chains. Inter-firm collaboration on CER can take place within the firms' own industrial chain (i.e. vertical extended chain), a firm can collaborate with its competitors (i.e. horizontal extended chain), or collaboration can take place across different industrial chains (i.e. industrial symbiosis).

Current literature in green supply chain management focus on the optimization of the vertical chain. Most studies optimize an existing, two echelon supply chain and investigate the price level and/or produced quantity required to minimize carbon emissions or maximize profit. Then, a centralized and decentralized supply chain are compared and different bargaining-coordination mechanisms (e.g. cost-sharing contract, revenues sharing contracts) are studied.

In these applications of traditional cooperative game theory, the timing at which it is optimal for both firms to enter the cooperation is not determined. Market uncertainty and the managerial flexibility to postpone the investment decision are often not taken into account. Only a few papers analyze the optimal time to establish a supply chain in the face of market uncertainty. Chen (**?**) considers a supplier and a retailer that jointly determine the optimal time to set up a centralized supply chain, given demand uncertainty. Lukas and Welling (**?**) determine the optimal timing of climate friendly investments in a supply chain. The most comprehensive analysis is the one made by Banarjee 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 firms of the supply chain are operative in one and the same market. 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. Industrial Symbiosis (IS) entails 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). 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 IS construction costs is a critical determinant of CER collaborations through IS. 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.

This study analyzes the real options held by two firms which have to option to either invest on their own or join forces and set-up a collaboration to achieve carbon emission reductions. On the one hand, we consider a gas-fired power plant that emits CO_2 and that holds an option to invest in carbon capture and storage. On the other hand, we consider an oil producing company that can buy CO_2 to enhance its oil production. We show that when the gas-fired power plant is not part of a joint venture with the oil producer, the CO_2 price level at which it is optimal to invest in carbon capture and storage is always larger than when the firm would join forces the oil producer. Reason is that the option to extract additional oil adds an additional benefit to the decision to invest in CO_2 capture and storage and hence, CO_2 capture will occur sooner.

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. 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 $(\Omega, F, \mathbb{P})$. Dynamic revelation of information is modeled by the filtration $\mathbf{F} = (F_t)_{t \geq 0}$.

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 can be formally expressed by the geometric Brownian motion (GBM)

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

where $W_U = (W_{U,t})_{t \geq 0}$ is a Wiener process.

Suppose that the upstream firm has the option to invest a sunk cost K_U 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.,

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

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, 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 and gives the value function of the upstream firm:

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

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

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

2.2 The downstream firm

The downstream firm, D, also has an investment option, which, upon investment of a sunk cost K_D, 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. 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 downstream firm's investment problem can be written as the optimal stopping problem

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

For the case study example 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 separate 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.

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

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

where

$$P_D^* = \frac{\beta_D}{\beta_D - 1} \frac{r - \alpha_D}{Q_D} K_D, \tag{9}$$

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

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

2.3 The cooperative investment problem

Instead of making the investment decisions separately, 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 $K < K_U + K_D$.

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. 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 NPV of first investment of this joint venture at current prices (P_U, P_D) is, therefore, equal to

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

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

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

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). We, therefore, develop a finite-difference scheme to numerically approximate the optimal investment boundary and value function. Details of this procedure can be found in Appendix **??**.

There are, however, a few analytical properties of (12) that we summarize in the theorem below. Note that, because of the Markovian structure of the problem, we can split the state space $\mathbb{R}^2_+$ into a *continuation* and *investment* region, given by

$$\mathcal{C} = \{\, (P_U, P_D) \in \mathbb{R}^2_+ \mid V_J(P_U, P_D) > F_J(P_U, P_D) \,\}, \quad \text{and}$$
$$\mathcal{D} = \{\, (P_U, P_D) \in \mathbb{R}^2_+ \mid V_J(P_U, P_D) = F_J(P_U, P_D) \,\},$$

respectively. The boundary of the continuation region is denoted by $\partial\mathcal{C}$. This boundary is the optimal investment trigger in the sense that first investment should take place when the boundary is hit (from the interior of $\mathcal{C}$). That is, the optimal investment time is

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

Proposition 1 *There exists a non-increasing and continuous mapping $P_U \mapsto b(P_U)$ on $(0, P_U^*)$ that describes the boundary ∂C, i.e., for all $P_U \in (0, P_U^*)$ it holds that $(P_U, b(P_U)) \in \partial\mathcal{C}$ and for all $(P_U, P_D) \in \partial\mathcal{D}$ it holds that $P_D = b(P_U)$. In addition, the continuation region is convex. Finally, for all $P_U \in (0, x^*)$ it holds that $b(P_U) < P_D^*$.*

The last part of the proposition states that $(\mathcal{C} \cap \mathbb{R}^2_{++}) \subset (0, x^*) \times (0, y^*)$, or that investment by the joint venture always takes place before either (or both) of the "stand alone" firms would invest. The intuition for this result is that, even when the joint venture only invests in one of the two projects, it still takes the option value of the other project into account. Since the latter is always positive, this increases firm value and leads to earlier investment. The proof of Proposition 1 can be found in Appendix **??**.

3 Results

We illustrate the model developed in Section 2 using a realistic case study where on the one hand, a gas-fired power plant has the option to invest in an installation that captures CO_2. The captured CO_2 is transported to an off-shore aquifer where it is sequestered permanently (carbon capture and storage, CCS). On the other hand, there is an oil producer who has the option to invest in CO_2 - enhanced oil recovery, for which the firm buys CO_2 at a specified price. Both firms could also 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 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. Table 1 presents the parameter values that are applied for a stylized but realistic case for CO_2 enhanced oil recovery in the North Sea region.

Description	Parameter	Value	Unit
Quantity of CO_2 captured	Q_U	4.6	Mt
Quantity of oil produced during EOR	Q_D	41.31	Mt
Total cost CCS	K_U	1 880	MEuro
Total cost CO_2-EOR_{ex}	K_D	11 919	MEuro
Total cost CO_2-EOR_{JV}	K	12 576	MEuro
Initial CO_2 price level	$P_{U,0}$	25	EUR/t
Initial oil price level	$P_{D,0}$	40	EUR/bbl
CO_2 price volatility	σ_U	0.2	/
CO_2 price growth rate	α_U	0.04	/
Oil price volatility	σ_D	0.2	/
Oil price growth rate	α_D	0.05	/
Discount rate	r	0.15	/

Table 1: Parameter values of the individual investment decision for the electricity producer. CO_2-EOR_{ex} refers to the case where the oil producer operates as a single firm, buying the CO_2 externally at a specified price. CO_2-EOR_{JV} refers to the costs associated with the joint investment problem.

3.1 Investment threshold boundaries

Using the model described in Section 2 and the parameter values listed in Table 1, we find that if both firms do not collaborate and make the investment decision on their own, the electricity producer will only invest in a CO_2 capture unit and geological aquifer storage when the market price of CO_2 equals about 80 EUR/t ($x^* = 80.16$). If the oil producer would decide to invest on his own, the oil producer will only invest if the oil price is higher than 55 EUR/bbl ($y^* = 55.34$).

If we would not take into account the managerial flexibility to wait and adopt the NPV approach, then the joint venture invests from an oil price starting at 45 EUR/bbl and a CO_2 price starting at 23 EUR/t. The NPV threshold boundary is calculated as follows:

$$Max \begin{cases} \frac{x_\tau}{r-\alpha_U} - K_U, \\ \frac{y_\tau}{r-\alpha_D} - K_D, \\ \frac{x_\tau}{r-\alpha_D} + \frac{y_\tau}{r-\alpha_D} - K, \\ 0 \end{cases} \tag{13}$$

If we do take into account uncertainty and the value of waiting, then the threshold boundary increases which is in line with standard real options theory. In case of a zero oil price, the joint venture invests at a CO_2 price which is equal to the individual threshold value of the electricity producer: $(x^*, 0) = (80.16, 0)$. If the CO_2 price is zero, it is optimal for the joint venture to invest at the individual investment trigger of the oil producer: $(0, y^*) = (0, 55.34)$. The real options investment threshold boundary is below the investment threshold points of each of the separate firms and hence cooperation between both firms stimulates investment.Figure 1 shows the investment threshold for the individual investment decisions and the investment boundary of the joint venture.

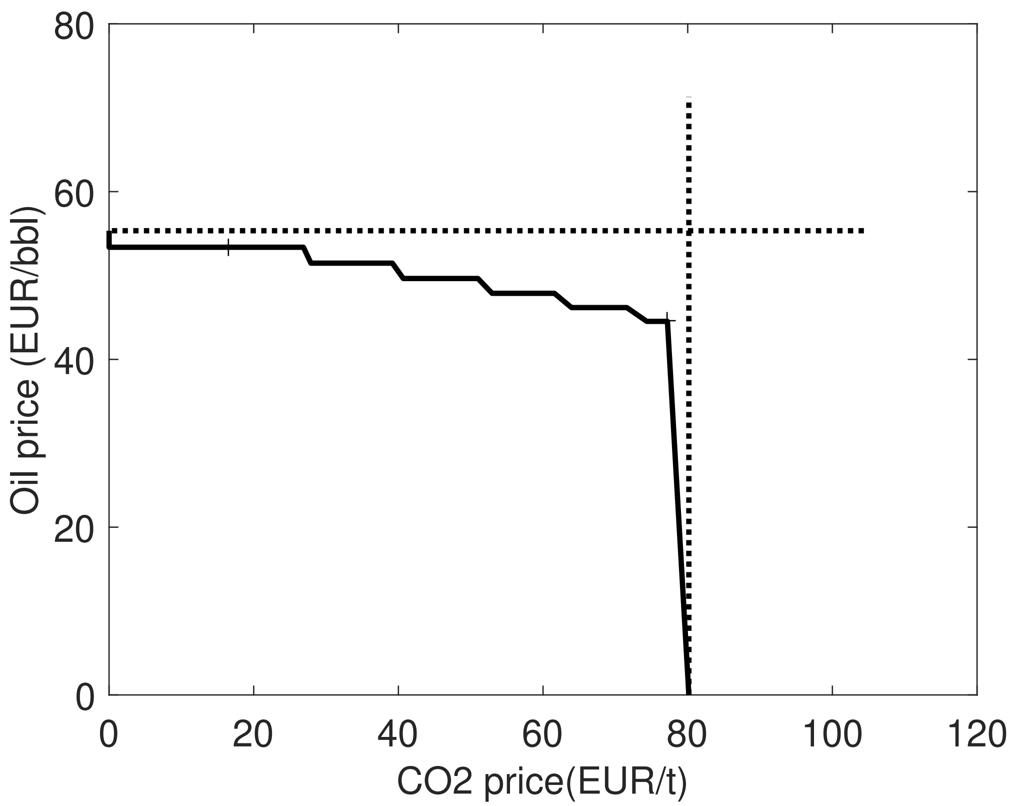

Figure 1: Individual investment thresholds and investment threshold for the joint venture

Whereas the individual firms only face a single market uncertainty, the joint venture operates in two markets and hence faces uncertainty in both markets. Nevertheless, the additional uncertainty does not increase the investment threshold boundary. Reasons that threshold boundary is below the individual threshold levels: - synergy in investment cost when a full investment in CO_2-EOR takes place. - If 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 JV holds the option to invest in the other market. This option has a value which is not present if the firms remain separate.

3.2 Investment choice of the Joint Venture

Figure 2 shows which investment option is selected by the joint venture for specific CO_2 and oil price levels. For CO_2 price levels below 17 EUR/t and oil price levels above 58 EUR/bbl the JV would decide to only make the investment in CO_2-EOR and buy CO_2 elsewhere (the red area) while holding the option to invest in CCS open. The power plant then continues to emit CO_2 for which it pays CO_2 emission allowances. In most cases, the JV would decide to invest in both the capture unit and CO_2-EOR (the blue area). In that case, the power plant does not emit CO_2 and the CO_2 is used for additional oil extraction. If the oil price is lower than 37 EUR/bbl, the joint venture will invest in carbon capture and storage if the CO_2 price is higher than 80 EUR/t and keep the option to invest in CO_2-EOR alive. In that case, no additional oil is extracted and the capture CO_2 is stored in an off-shore aquifer. Note that 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.

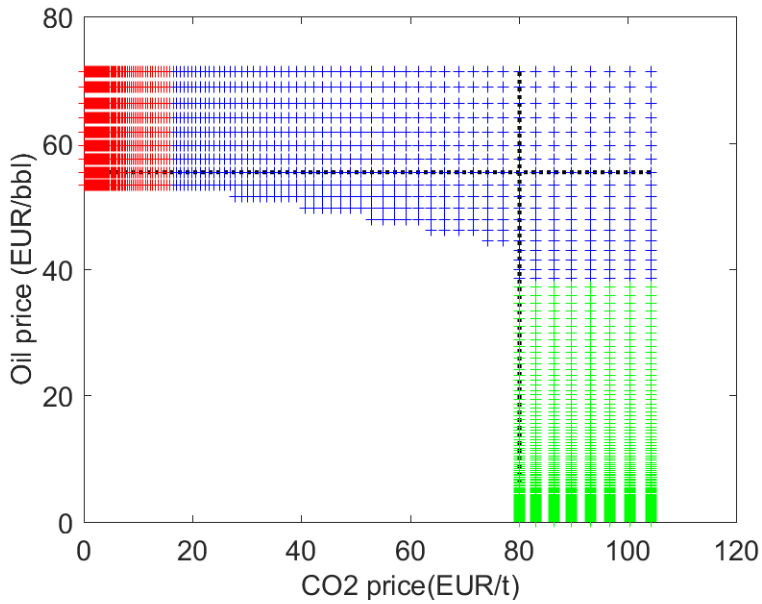

Figure 2: Optimal investment choice of the JV

Because of the cooperation, the probability that CO_2 will be captured at the power plant increases. As a stand-alone firm, there is only a 1.5% probability that within 5 years CO_2 will be captured at the power plant. When both firms join forces, this probability increases to 62%. Figure 3 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.

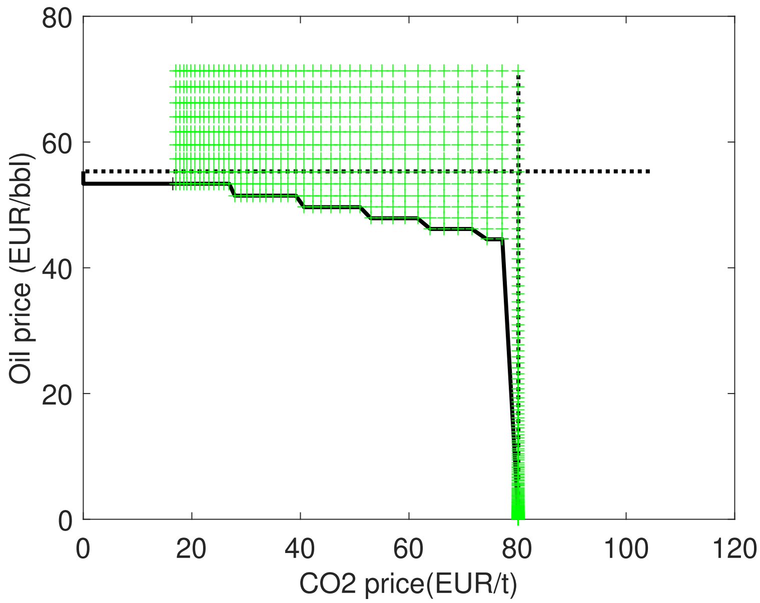

Figure 3: The green crosses show at which price levels investment in the CO_2 capture unit takes place because both forms cooperate. If both firms would remain separate, investment in CO_2 capture would not take place at these price level combinations.

4 Conclusion