The Role of Industrial and Market Symbiosis in Stimulating CO_2 Emission Reductions

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Opening new horizons

Environmental challenges

- Many efforts to reduce CO_2 emission could benefit from cooperation.

→Taking supply chains and network structures into account (industrial symbiosis)

→Optimal timing to invest in a supply chain/network (real options)

→How to share profits (market symbiosis)

Literature review

- Real options theory and cooperative decision making

→E. Lukas and A. Welling (2014). Timing and eco(nomic) efficiency of climate-friendly investments in supply chains. . European Journal of Operational Research 233, 448-457

○ A sequential bargaining game in a supply chain

○ Bargaining over investment in a CO_2 reducing investment project

○ If a CO_2 emission reducing investment depends on the cooperation of a neighbor link in a supply chain, investment will occur later

○ If all parties act cooperatively instead of negotiating sequentially, they should be able to agree and invest more early

Literature review

- Real options theory and cooperative decision making

→Banerjee, S., Güçbilmez, U., Pawlina, G., **2014.** Optimal exercise of jointly held real options: A Nash bargaining approach with value diversion. European Journal of Operational Research 239, 565-578

- Two-stage decision game

- 2 or more parties jointly hold a real option

- If the timing decision precedes bargaining on sharing terms: single party's timing decision is socially efficient. Regardless of the financing policy and which firm makes the exercise decision.

- If the sharing rule is agreed before the exercise timing decision is made: the first-best solution can be attained only if a combination of a stake in the project and cash transfers is used.

Literature review

- Real options theory and cooperative decision making

→Guthrie, Graeme, Intertemporal Decision-Making and the Nash Bargaining Solution (May 26, **2018**). Available at SSRN: https://ssrn.com/abstract=3185252

○ Evaluates the NBS at each point in time in such a way that the partners' beliefs about the future are consistent with their future actions.

○ The intertemporal bargaining problem is treated as a sequence of static bargaining problems.

Our contribution

- Real options theory and cooperative decision making

○ Two echelon supply chain

○ Each player holds an individual investment option

○ Option to create a joint venture

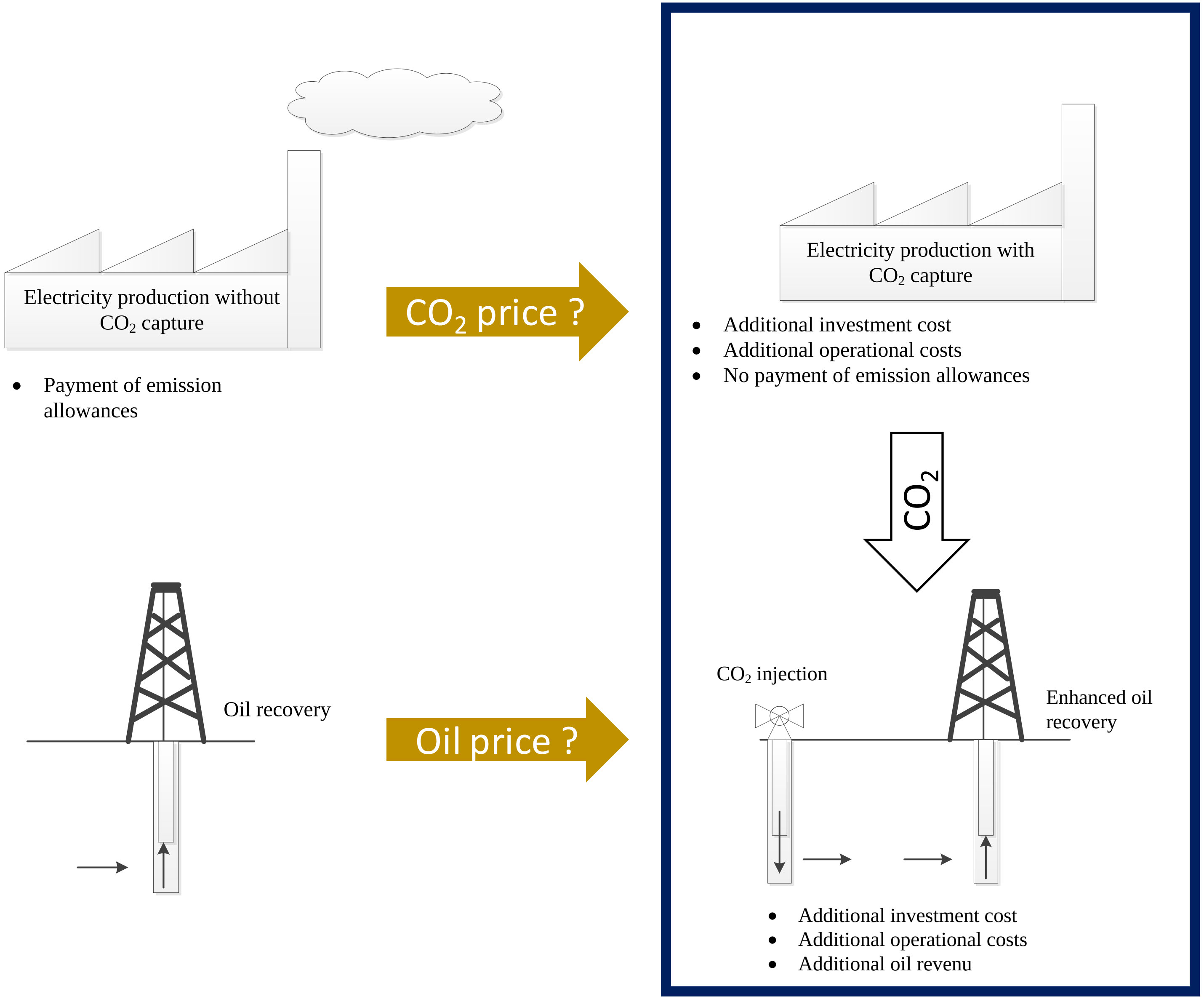
○ We take into account a firm's flexibility to invest on its own

Case study

CO_2 enhanced oil recovery

Investment problem 1

Investment problem 2



Upstream firm: CO_2 emitter

Waste flow: Q_u for which it pays a price P_u

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

The upstream firm has the option to invest (sunk costs K_U) in a technology that abates the CO_2 emission. Its investment problem is formalized as follows:

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

Upstream firm: CO_2 emitter

The value of the upstream firm is

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

where

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

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

$$Q_U(\beta) \equiv \frac{1}{2}\sigma_U^2 \beta(\beta - 1) + \alpha_U \beta - r = 0.$$

Downstream firm: oil producer

The downstream firm has the option to invest in a technology (sunk costs K_D) that produces additional output for which it receives a price P_D, where

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

with $E[dW_{U,t} dW_{D,t}] = \rho dt$. The downstream firm has the option to invest in a technology that produces the additional output. Its investment problem is formalized as follows:

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

Downstream firm: oil producer

The value of the downstream firm is

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

where

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

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

$$Q_D(\beta) \equiv \frac{1}{2}\sigma_D^2 \beta(\beta - 1) + \alpha_D \beta - r = 0.$$

The downstream firm could use the waste flow of the upstream firm as an input to its production process. As a result, a cost saving is made:

$$K < K_U + K_D.$$

The NPV for the joint venture is:

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

CCS & EOR

CCS now, EOR later

EOR now, CCS later

Joint Venture

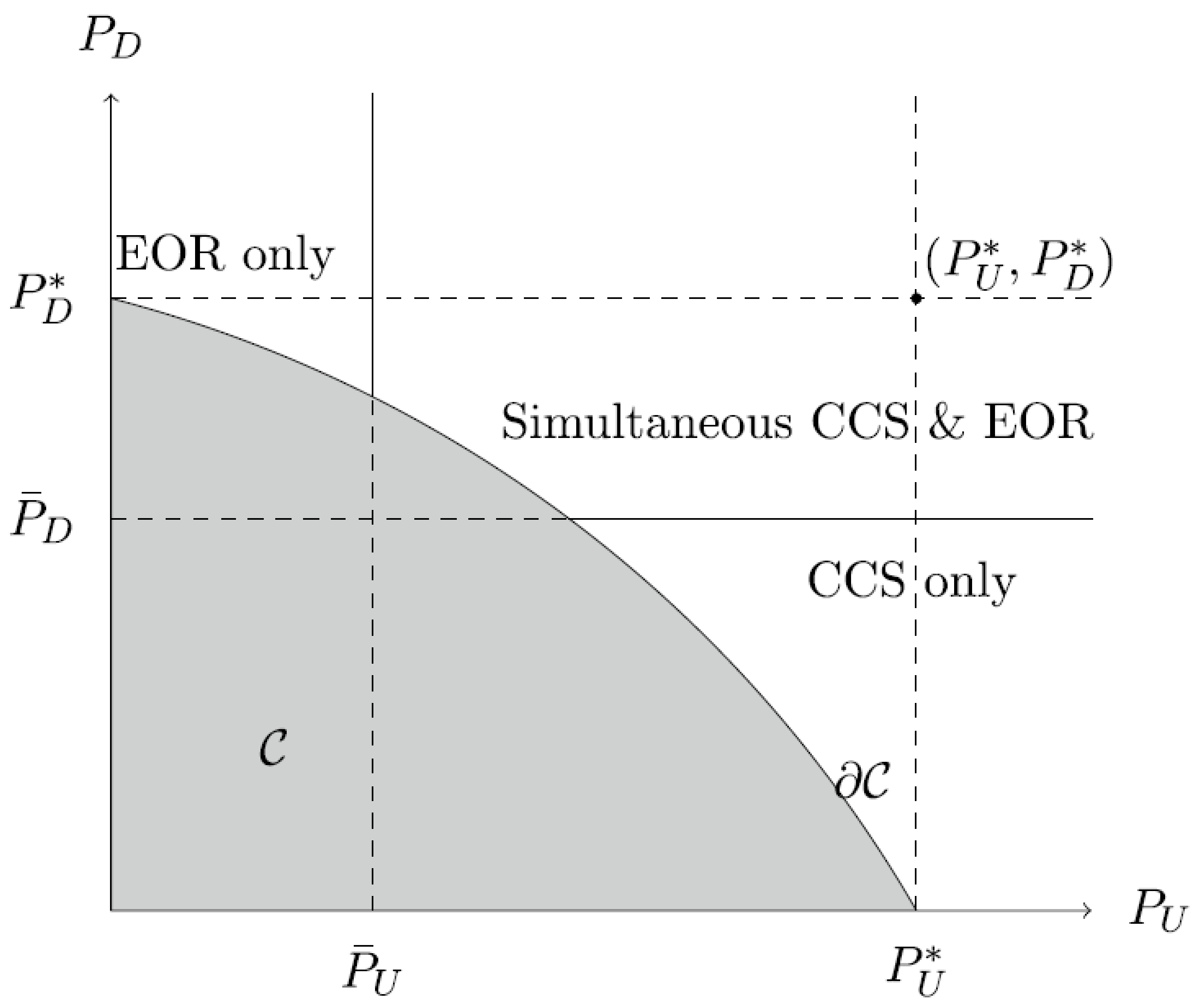
The value function of JV is:

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

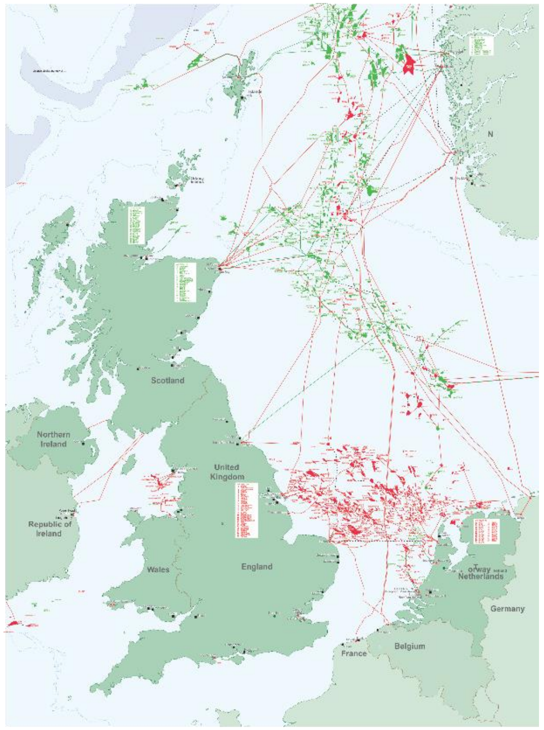
No known analytical solution, but can be solved using finite difference method. However:

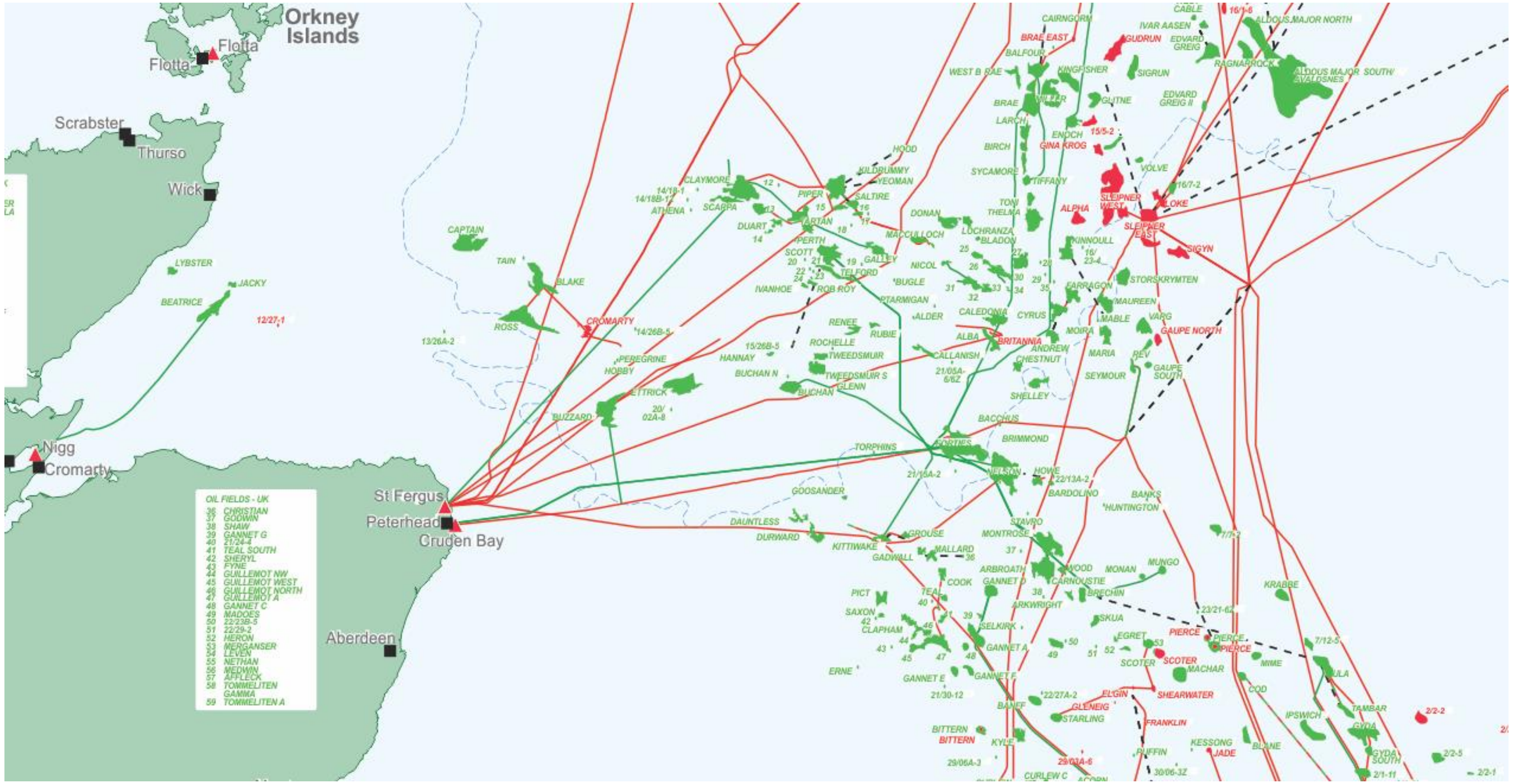
Proposition 1 *There exists a non-increasing and continuous mapping* $P_U \mapsto b(P_U)$ *on* $(0, P_U^*)$ *that describes the boundary* ∂C*, i.e., for all* $P_U \in (0, P_U^*)$ *it holds that* $(P_U, b(P_U)) \in \partial \mathcal{C}$ *and for all* $(P_U, P_D) \in \partial \mathcal{D}$ *it holds that*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

Exercise Regions

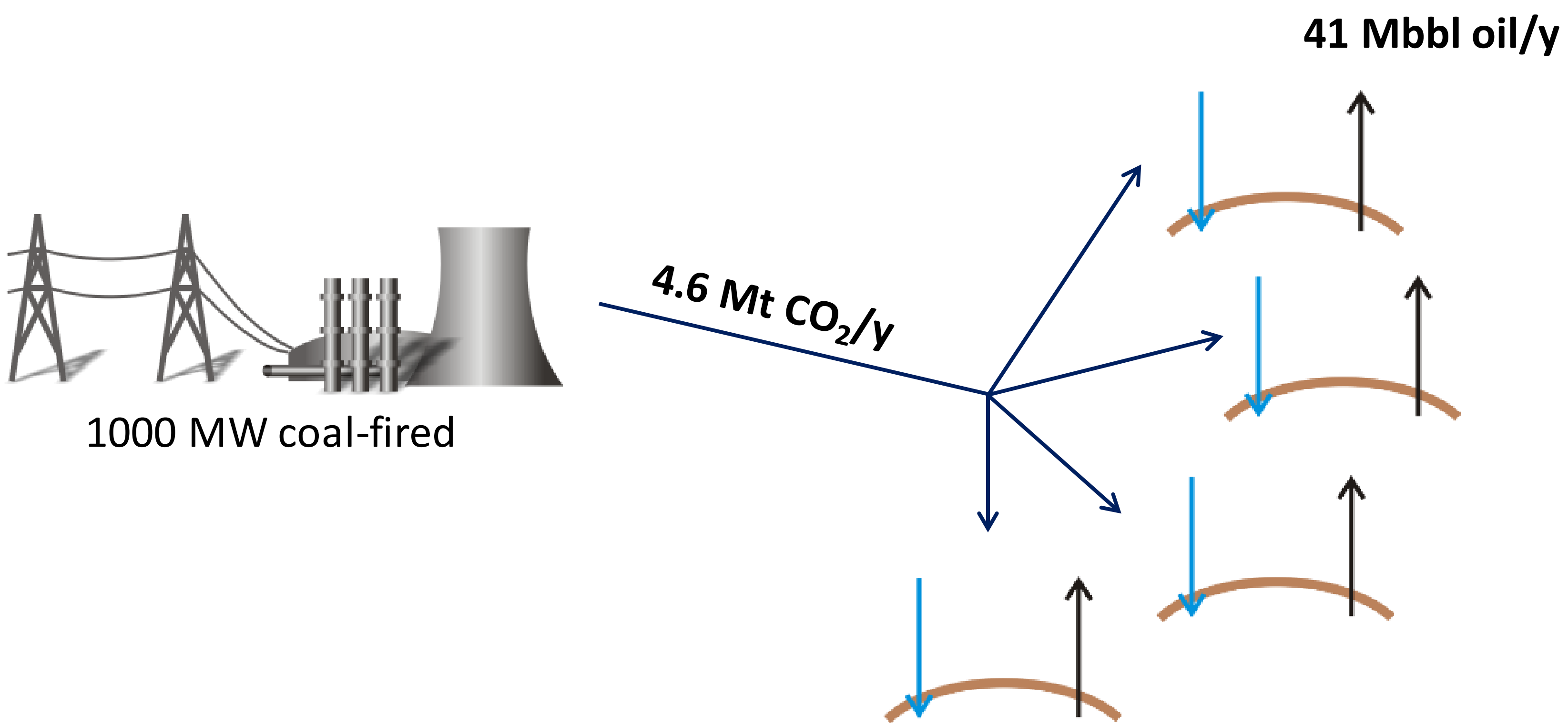


Application





Application



Application

Table 1 Total cost calculation of the CCS investment in case the electricity company operates as a single investor

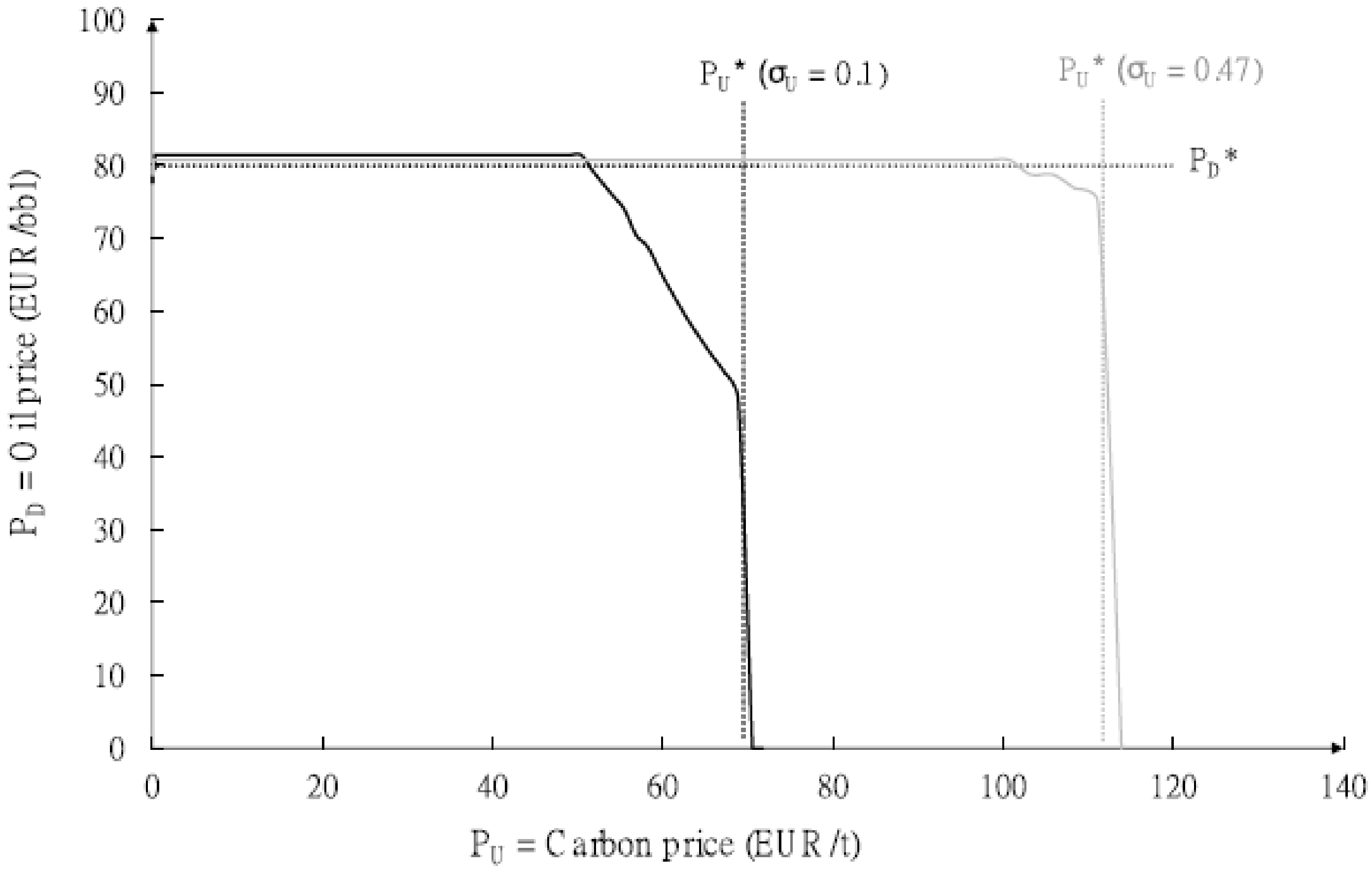
Description	Value	Unit
Capital expenditure	1040	Mln €
Operational expenditure	7.22	€/t CO_2
CO_2 transport and storage	14.97	€/t CO_2
Quantity of CO_2 emitted (Q_U)	4.59	Mln t/y
Discount rate (r)	0.15	–
Total discounted cost CCS (K_U)	1719	Mln €

See Compernolle et al. (2017) for further cost details

Table 2 Total cost calculation of the EOR investment in case the oil company operates as a single investor

Description	Value	Unit
Capital expenditure	1543	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)	1924	Mln €

Exercise boundary



Exercise regimes

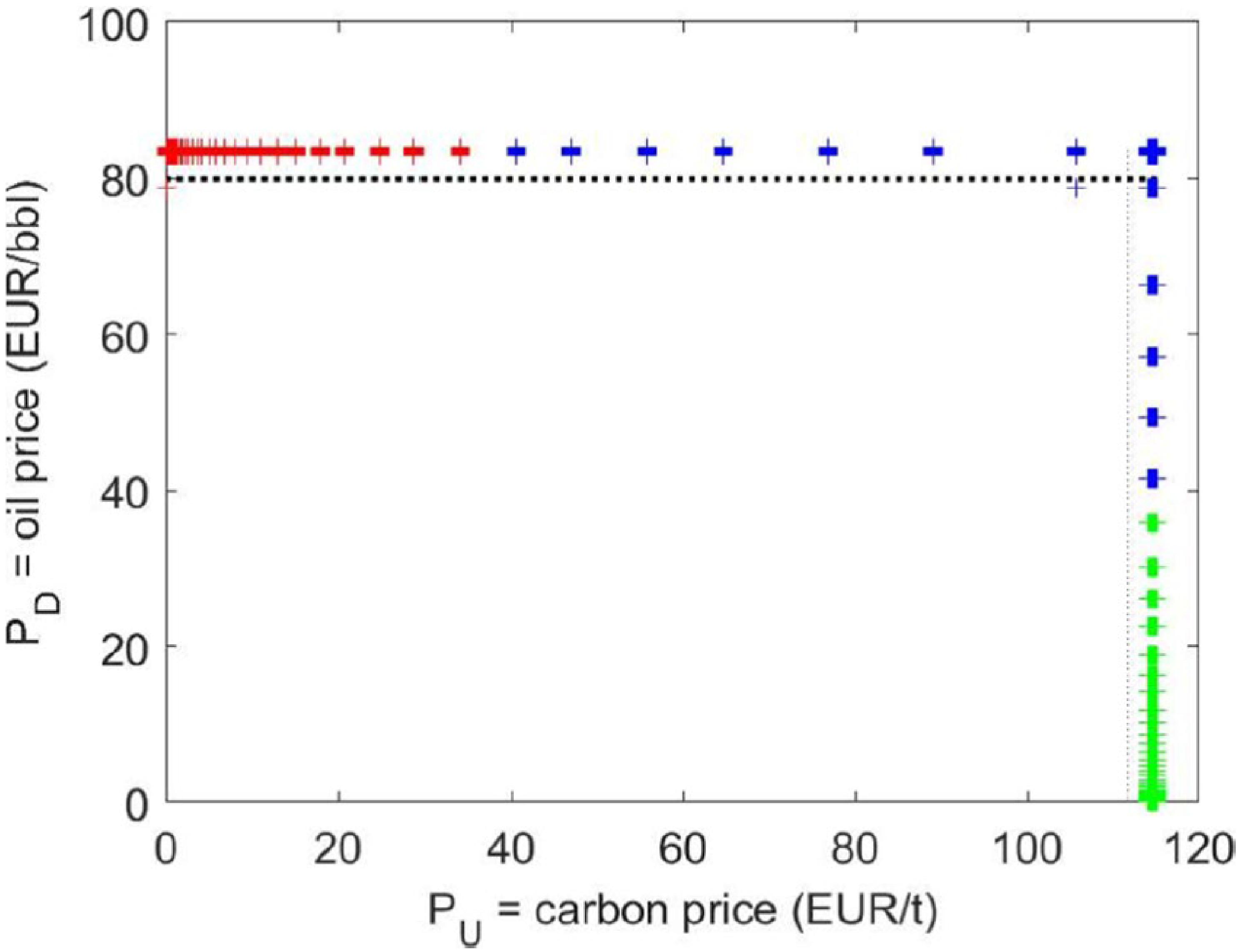
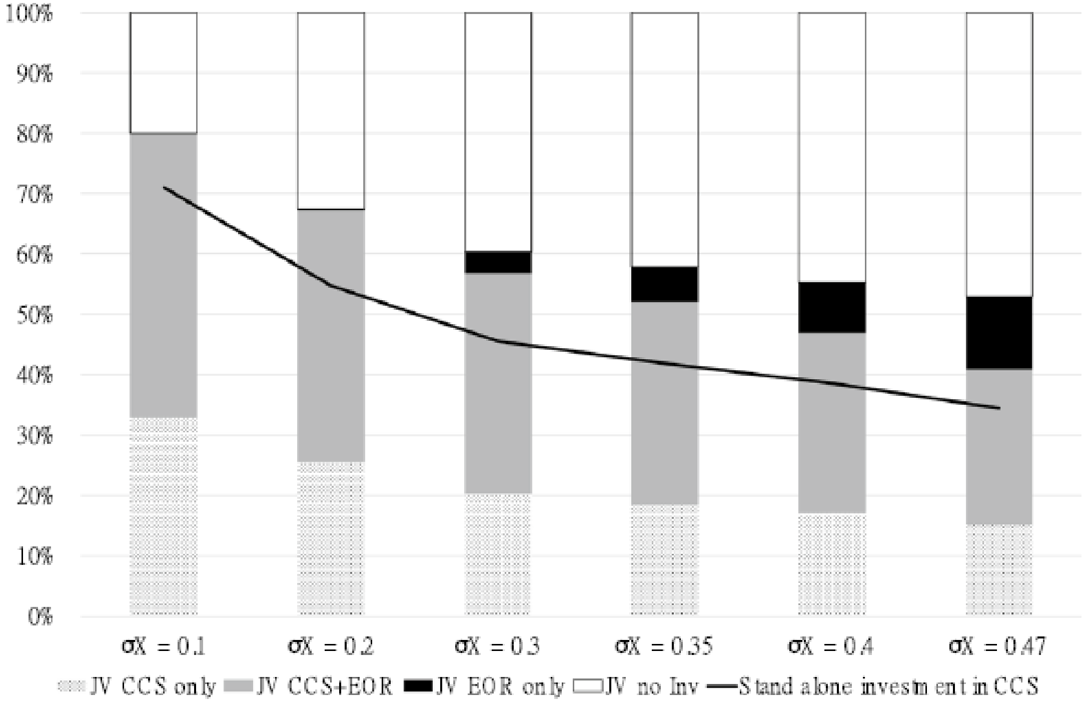
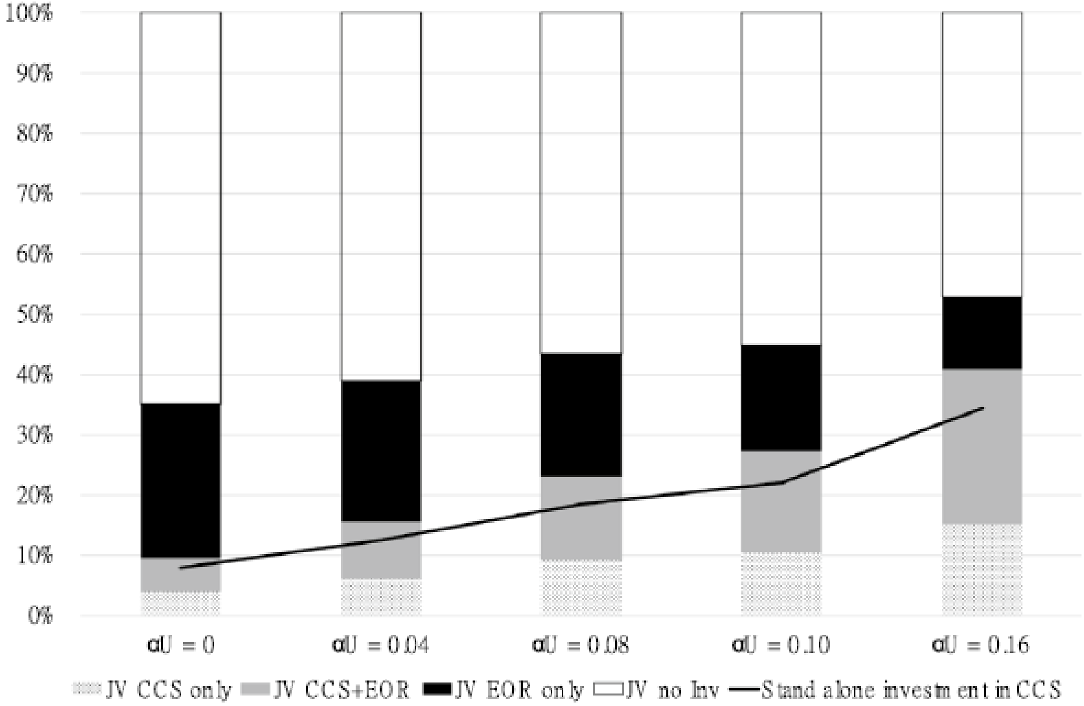


Fig. 5 Investment choice of the joint venture. Red area: region where the joint venture only invests in EOR; bleu area: region where the joint venture invests in both CCS and EOR; green area: region where the joint venture only invests in CCS

Likelihood of investment within 5 years





CO_2 Reduction over 50 years

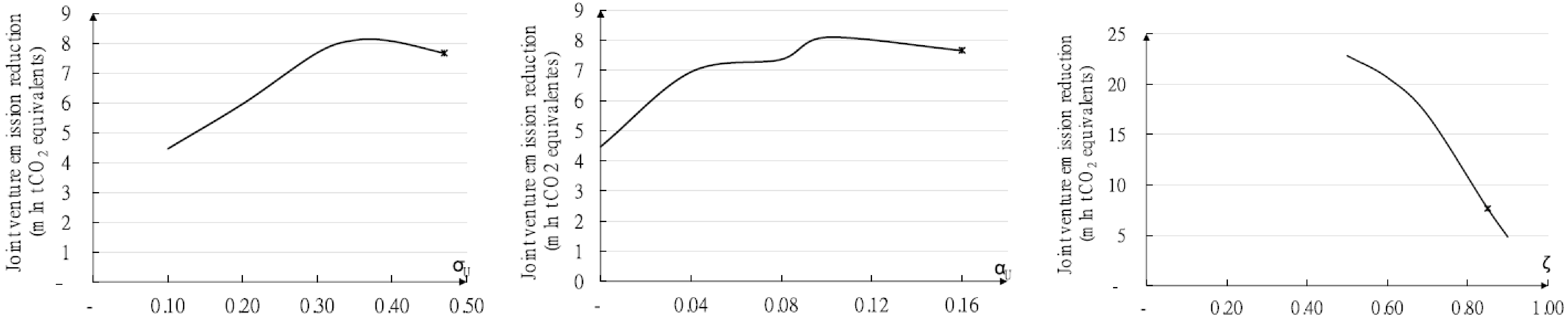


Fig. 8 Average CO_2 emission reduction realized by the joint venture, for different values of σ_U, α_U, and $\zeta = \frac{K}{K_U+K_D}$

CO_2 Reduction over 50 years

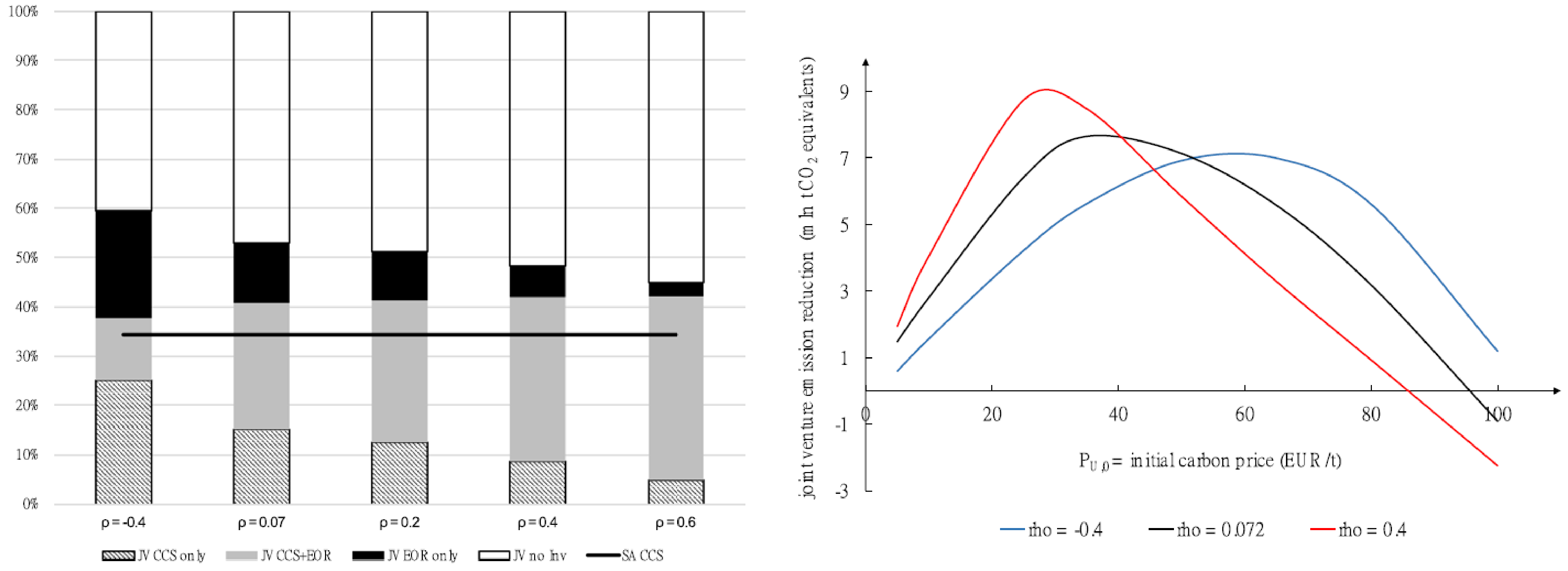


Fig. 10 Left panel: choice of the joint venture for $P_{U,0}$ = 35 EUR/t. Right panel: average carbon emission reduction realized by the joint venture in case of positively and negatively correlated price processes and for increasing carbon price levels

Conclusions

- Cooperation between firms can lead investment in carbon reduction to
  - Taking place sooner and
  - Having a higher environmental impact
- As well as increasing firm value along the value chain.

- Can we have our cake and eat it?