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The effectiveness of carbon pricing: the role of diversification in a firm's investment decision*

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Abstract

It is often argued that compared to a carbon tax, a volatile carbon price under an emissions trading system poses a problem in the transition towards a low carbon economy. However, this paper shows that, when sufficiently positively correlated with the electricity price, carbon price uncertainty diminishes overall volatility because of a diversification effect. To get this result, we develop a dynamic real options model to analyze the impact of positively correlated price uncertainty on the timing of an investment decision. In contrast to static models, we show that even when the carbon price is initially the same under both policy instruments, the timing of the investment decision will typically be different. More importantly, we find that multiple correlated price uncertainties under an emissions trading system encourages investment more than less uncertainty under a carbon tax. Hence, to stimulate a low carbon (or discourage a carbon intensive) investment, an emissions trading system (carbon tax) is preferred. The policy reverts for higher levels of uncertainty and low correlations.

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1 Introduction

Managing climate change is one of the most challenging environmental problems humanity has ever faced. To keep global warming below 1.5°C and enhance the capacity to adapt to climate risks require large increases of investments in low-emission infrastructure and buildings, along with a redirection of financial flows towards low-emission investments. Enabling these investments requires policy instruments which aim to shift market preferences away from fossil fuel based technologies (IPCC, 2018). There is broad acceptance among economists that carbon emissions should be priced. However, the choice between a CO_2 tax, a cap and trade, or a cap and auction system is much debated in the literature. Even 45 years after the seminal Weitzman (1974) paper, the debate is still ongoing and - also given this contribution - it is becoming clear that there is no exact answer to the question "Cap or Tax?". Weitzman (1974) showed that under marginal abatement cost uncertainty the resulting emission abatement under a cap or a tax is not the same. Furthermore, he finds that uncertainty in the marginal benefit curve has no implication with regard to choosing the preferred policy instrument. Later, Stavins (1996) showed that uncertainty in the marginal benefits should not be neglected when it is correlated with the marginal costs. The choice of policy instrument reverts from a tax system to a cap and trade system when the correlation between the marginal cost and the marginal benefits is positive. The literature building on this work primarily discusses the choice between quantity and price based instruments from a welfare perspective, focusing on uncertainty on the part of the regulatory agency. However, firms that are regulated are also likely to be uncertain about the costs of control and the realized benefits, which will affect their investment behavior.

To capture the fact that the costs and revenues associated with an investment are built up over several years and are subject to price processes that fluctuate in time, we use a real options approach. This provides a dynamic framework to analyze how the investment behavior of a firm is different for policy instruments that differ in terms of the uncertainty that they generate. In fact, while Weitzman (1974) and Stavins (1996) take a static approach to uncertainty by omitting the time component, the real options approach is dynamic and can, therefore, take into account the stochastic evolution of costs and benefits over time. The inclusion of a time component in analyses that evaluate policy measures is highly relevant because environmental policy objectives are very often set to be reached within specific long and short term time frames. For instance, the 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). Hence, to determine which instrument is most optimal to reach the objectives within time it is important to understand how different policy measures affect the timing of the investment decision.

A carbon tax and a cap and trade system differ in terms of the uncertainty that they create, in that a carbon tax results in an uncertain aggregate emission level but fixes the price of carbon, whereas an emissions trading system fixes the aggregate emission level, but leaves the carbon price uncertain. Nordhaus (2007) states that because the supply of allowances is inelastic under a cap and trade system, shifts in demand can cause significant price changes. He argues that carbon price volatility created by an emissions trading market is a reason to favor carbon taxes over cap and trade. Carbon price stability is also one of the main policy objectives of the EU while reforming its emissions trading system (European Parliament and the Council, 2015, 2018). Multiple strands of literature study mechanisms on how to reduce volatility including intertemporal banking and borrowing of allowances (see, e.g., Leard, 2013), the introduction of options (Chevallier et al., 2011), the incorporation of price floors/ceilings (see, e.g., Perkis et al., 2016; Brauneis et al., 2013), or the impact of the market stability reserve (Perino and Willner, 2016). Hence, there seems to be agreement among policy makers and scientists in the field of environmental economics that carbon price volatility under an emissions trading system poses a problem in making the transition towards a low carbon economy. In these lines of reasoning however, the diversification effect resulting from the correlation between stochastic price processes tends to be overlooked.

Walsh et al. (2014) also conclude that a tax is always preferred to stimulate investment in low carbon technologies. However, they analyze a tax system in a deterministic framework. For the emissions trading model they assume a single stochastic cost flow that stands for the carbon price set by the market. Although a tax set by the government is indeed constant, a firm regulated under a tax system still has to make an investment decision under the uncertainty that is present in the future demand for energy. The present paper takes into account this revenue uncertainty and considers the effects of its (positive) correlation with cost price uncertainty. Empirical research provides evidence that the gas price and the CO_2 price are indeed positively correlated with electricity price (see e.g. Hintermann, 2016; Hammoudeh et al., 2015; and Chernyavs'ka and Gullì, 2008). Since the majority of CO_2 emissions in the EU emissions trading system result from electricity generation, and fuel prices and carbon prices are production costs of electricity, an increase in these costs are passed through to the electricity price.

We present a real options model that takes into account this positive correlation. Also Boomsma and Linnerud (2015) and Rohlfs and Madlener (2014) have previously shown that correlation between the prices underlying the investment options allows investors to diversify and thus reduce the overall risk. To analyze the impact of the different policy measures on the timing of the investment decision, we do not present the results in the usual way, i.e. in terms of the electricity price trigger at which it is optimal to invest. Rather, given the investment trigger and initial price levels, we calculate the probability that the investment will take place within a certain time frame. In this way we make explicit the effect of a carbon tax or a market-based carbon price on the timing of investment decisions.

We make a distinction between the policy instruments discouraging an investment in a carbon intensive, gas-fired power plant and the same policy instruments encouraging investment in the same power plant, but equipped with a CO_2 capture unit. We first analyze to what extent a carbon tax and an emission trading system are able to postpone investment in a carbon intensive power plant. We find that correlated uncertainty in the carbon cost and revenue flow under an emissions trading system stimulates investment. Hence, opposite to the conclusions by Walsh et al. (2014), we find that if price processes are strongly correlated under an ETS, a tax system is preferred to postpone investment in carbon intensive technologies. Furthermore, we show that a tax on CO_2 has a different impact on the probability that investment takes place than the same carbon price set by an emissions trading market. This result contradicts the usual conclusion in the field of environmental economics that the price level of a carbon tax has the same impact as the same carbon price set by an emissions trading market (see, e.g., Stavins, 1996). A crucial feature of this literature is that the models are static. Therefore, while the price level may be the same, this literature ignores that investment timing decisions may be different. The main reason for our result is the impact of the correlation between the price processes and their level of uncertainty. If this positive correlation and its diversification effect are taken into account, our analyses show that despite the same initial carbon price level, investment in carbon intensive technologies is less likely under a tax system than under an emissions trading system. Furthermore, the result that less uncertainty leads to later investment also does not correspond to the traditional conclusions in the real options literature and shows the importance of recognizing multiple (correlated) sources of uncertainty. In addition, we show that our conclusions do not hold in highly uncertain environments. We also analyze how these results apply to a firm which could either exercise an option to invest in a gas-fired power plant or exercise an option to invest in the same gas-fired power plant equipped with a CO_2 capture unit. We find that under an emission trading system with strongly correlated price uncertainty and a growing CO_2 price, the option to invest in a gas-fired power plant with a CO_2 capture unit will be exercised earlier and at a lower CO_2 price level than when a tax system with a constant CO_2 price would be put in place. If the price processes are weakly correlated under an ETS, then carbon price volatility does pose a problem in the sense that the option to invest in the low carbon technology will be exercised earlier under a tax system, where carbon price volatility plays no role. If the tax is constant over time, the carbon price level at which the option to invest in the low carbon technology is exercised, is higher than under an ETS with a reducing cap and a growing carbon price. Hence, when correlation is weak, an ETS with a dampened carbon price volatility and a growing CO_2 price is preferred.

We start with a simplified analytical model in which all costs are considered volatile under an emissions trading system. Then we extend this model by keeping the levelized cost of energy production constant while the firm faces a volatile cost of carbon. We find an analytic expression of the investment boundary and run a simulation to discuss policy relevant implications of this model result. We show that the conclusions drawn from the simplified analytical model remain valid in the more extended and realistic model. The analytical model then forms a sound basis to intuitively explain the interactions between the level of correlation and the level of uncertainty, and the impact of these interactions on the probability that investment takes place within a specified time frame.

The paper is organized as follows. In the next section, we present our model where we theoretically show how correlated uncertainty affects the investment threshold boundary. Then, in Section 3, we analyze which policy instrument is most preferred to postpone investment in a carbon intensive technology taking into account the diversification effect of correlated stochastic price processes. We also present an in-depth analysis of the interactions between the level of correlation and the level of uncertainty. In Section 4 we summarize the main conclusions following from our results.

2 Basic Model

First we present a basic real options model in which we assume no differentiation in costs. Either all costs, i.e. carbon price, investment and operational costs are constant (tax system) or volatile (emission trading system). We calculate the investment boundary, i.e. the cost and electricity price combinations for which it is optimal for a firm to invest. We use this simplified model to analytically show how the level of uncertainty and the diversification effect resulting from correlated stochastic prices processes impact this threshold boundary. Then, we present a more realistic model in which the carbon pricing scheme is analyzed separately from the other costs. We find an analytic expression for the investment boundary and run a simulation to understand the implications of this result.

2.1 Simplified model without cost differentiation

We consider a firm that can invest in a new electricity-generating facility that will produce Q MWh of power per year. The emission factor is η, so that ηQ tons of CO_2 are emitted due to this process. Since all revenues and costs are linear in Q, we shall use the normalization $Q = 1$. The cost of carbon is C_{carbon} per ton of CO_2. In addition, there are investment and operational costs, which are considered as the levelized costs of electricity, equal to C_{LCOE} per MWh. It follows that the firm's total unit costs are given by

$$C := C_{LCOE} + C_{carbon}\eta.$$

We keep our initial model as simple as possible, and we model C as one stochastic process that follows a GBM[1]

$$\frac{dC}{C} = \alpha_C dt + \sigma_C dB_C,$$

[1]In Section 2.2, we model C_{LCOE} and C_{carbon} as separate stochastic processes.

where $(B_{C,t})_{t\geq 0}$ is a Wiener process. The price of electricity, P, is stochastic and follows the geometric Brownian motion (GBM)

$$\frac{dP}{P} = \alpha_P dt + \sigma_P dB_P,$$

where $(B_{P,t})_{t\geq 0}$ is a Wiener process. The expectation operator and probability measure for the process $(P_t, C_t)_{t\geq 0}$, starting at (P, C) are denoted by $\mathsf{E}_{(P,C)}$ and $\mathsf{P}_{(P,C)}$, respectively. The process B_P is (imperfectly) correlated with B_C, i.e. $\mathsf{E}_{(P,C)}[dB_P dB_C] = \rho dt$, for some $|\rho| < 1$. Since a tax system is in principal deterministic and an ETS system generates future uncertainty regarding CO_2 prices, a tax system corresponds to a situation with $\sigma_C = 0$, whereas an ETS has $\sigma_C > 0$. Finally, we assume that cash flows are discounted at the (constant) rate $r > \max\{\alpha_P, \alpha_C\}$.

The firm's problem is now to solve the following optimal stopping problem:

$$\begin{aligned} V(P,C) &= \sup_{\tau} \mathsf{E}_{(P,C)} \left[\int_{\tau}^{\infty} e^{-rt} \left(P_t - C_t \right) dt \right] \\ &= \sup_{\tau} \mathsf{E}_{(P,C)} \left[e^{-r\tau} \left(\frac{P_\tau}{r - \alpha_P} - \frac{C_\tau}{r - \alpha_C} \right) \right], \end{aligned} \tag{1}$$

where finiteness of the improper integral is guaranteed by our assumption on the discount rate.

A standard argument based on Girsanov's theorem (see, e.g., Øksendal, 2000) now shows that there exists a probability measure $\tilde{\mathsf{P}}$, equivalent to P, such that the value function can be written as

$$V(P,C) = C \sup_{\tau} \tilde{\mathsf{E}}_{(P,C)} \left[e^{-r_Z \tau} \left(\frac{Z_\tau}{r - \alpha_P} - \frac{1}{r - \alpha_C} \right) \right], \tag{2}$$

where $Z_\cdot := P_\cdot / C_\cdot$ and $r_Z = r - \alpha_C > 0$. A straightforward application of Itô's lemma shows that Z follows the GBM

$$\frac{dZ}{Z} = \alpha_Z dt + \sigma_Z d\tilde{B}, \tag{3}$$

where $\tilde{B}$ is a standard Brownian motion (under $\tilde{\mathsf{P}}$),

$$\alpha_Z = \alpha_P - \alpha_C, \quad \text{and} \tag{4}$$

$$\sigma_Z^2 = \sigma_P^2 + \sigma_C^2 - 2\rho\sigma_P\sigma_C. \tag{5}$$

Equation (5) shows that on the one hand, the additional uncertainty under an emissions trading system ($\sigma_C > 0$) increases the overall uncertainty (σ_Z), but that on the other hand, a positive correlation between the two price processes results in a diversification effect, reducing the overall uncertainty. Hence, to understand the full impact of different policy instruments, all market intricacies (the level of uncertainty and the diversification effect) and their interactions need to be incorporated in their evaluation.

Some further simplifications imply that

$$\begin{aligned}V(P,C) &= C \sup_{\tau} \tilde{\mathsf{E}}_Z \left[e^{-r_Z \tau} \left(\frac{Z_\tau}{r-\alpha_P} - \frac{1}{r-\alpha_C} \right) \right] \\ &= \frac{C}{r-\alpha_P} \sup_{\tau} \tilde{\mathsf{E}}_Z \left[e^{-r_Z \tau} \left(Z_\tau - \frac{r-\alpha_P}{r-\alpha_C} \right) \right].\end{aligned}$$

This final optimal stopping problem can be solved using standard methods, which shows that the optimal policy is to invest as soon as the trigger

$$Z^* = \frac{\beta_Z}{\beta_Z - 1} \frac{r-\alpha_P}{r-\alpha_C},$$

is reached from below, where $\beta_Z > 1$ is the positive root of the quadratic equation

$$\mathscr{Q}(\beta) \equiv \frac{1}{2}\sigma_Z^2 \beta(\beta-1) + \alpha_Z \beta - r_Z = 0.$$

The following proposition states that, in contrast to standard real options theory as covered in, e.g., Dixit and Pindyck (1994), the investment trigger can be decreasing in uncertainty, depending on the level of uncertainty and the level of correlation.

Proposition 1 *The optimal investment trigger Z^* is decreasing in σ_C if and only if, $\sigma_C < \rho\sigma_P$.*

Proof. The result follows from some straightforward calculus. First note that

$$\frac{\partial Z^*}{\partial \sigma_C} = \underbrace{\frac{\partial Z^*}{\partial \beta_Z}}_{>0} \frac{\partial \beta_Z}{\partial \sigma_C},$$

so, the sign of $\partial Z^*/\partial \sigma_C$ is determined by the sign of $\partial \beta_Z/\partial \sigma_C$. It holds that

$$\frac{\partial \beta_Z}{\partial \sigma_C} = \underbrace{\frac{\partial \beta_Z}{\partial \sigma_Z}}_{>0} \frac{\partial \sigma_Z}{\partial \sigma_C},$$

and

$$\frac{\partial \sigma_Z}{\partial \sigma_C} = 2\sigma_C(\sigma_C - \rho\sigma_P).$$

Therefore,

$$\frac{\partial Z^*}{\partial \sigma_C} < 0 \iff \sigma_C < \rho\sigma_P.$$

■

Note that the trigger Z^*, when written in terms of P and C, describes the optimal exercise *boundary*, which can be expressed as a ray through the origin:

$$P^*(C) = \frac{\beta_Z}{\beta_Z - 1} \frac{r-\alpha_P}{r-\alpha_C} C, \tag{6}$$

so that the stopping set (the set of all points in the state space where investment is optimal) is given by

$$S = \left\{ (C, P) \in \mathbb{R}_+^2 \;\middle|\; P \geq P^*(C) \right\}.$$

The firm's value function is then given by

$$V(P, C) = \begin{cases} \left(\frac{P/C}{Z^*}\right)^{\beta_Z} \frac{1}{\beta_Z - 1} \frac{C}{r - \alpha_C} & \text{if } P < P^*(C) \\ \frac{P}{r - \alpha_P} - \frac{C}{r - \alpha_C} & \text{if } P \geq P^*(C) \end{cases}.$$

For further reference, let $\tau^* := \inf\{t \geq 0 | Z_t \geq Z^*\}$ be the first hitting time (from below) of the investment trigger Z^*. As long as $P < P^*$, the electricity price is not high enough to justify investment. For $P > P^*$ the firm will invest immediately. Depending on the initial carbon price level, and the policy system under consideration (tax or emission trading system), the electricity price at which it is optimal for a firm to invest, will differ. If the objective of the policy is to introduce a carbon price in order for investment in carbon intensive technologies to be postponed, a policy resulting in a higher P^* is preferred. We assess the impact of tax and emissions trading systems on the optimal investment decision in two different ways. In the EU, policy objectives regarding the mitigation of climate change are formulated in terms of target dates. For example, to meet its commitments under the Paris Agreement, the EU has set binding greenhouse gas emissions reduction goals in the 2020 Climate and Energy Package (European Commission, 2009) and the 2030 Climate and Energy Framework (European Commission, 2014). For all greenhouse gas emissions under the EU emissions trading system (ETS), a 20% and a 43% reduction compared to 2005 levels needs to be reached in 2020 and 2030 respectively (European Commission, 2017). For non-ETS emissions, country specific reduction targets are set (European Commission, 2018). One way to judge the consequences of uncertainty in the energy market and the carbon market on the timing of investment decisions is to study the expected time to invest. For a given initial electricity and carbon price level, the higher P^*, the longer the expected time to invest. As long as $\alpha_Z > \sigma_Z^2/2$, it holds that (see, e.g., Øksendal, 2000),

$$\tilde{\mathsf{E}}_Z[\tau^*] = \frac{\log(Z^*/Z)}{\alpha_Z - \sigma_Z^2/2}. \tag{7}$$

In Proposition 2 it is shown that the level of uncertainty and the diversification effect resulting from the positive correlation between the two stochastic price processes impacts the expected time to invest. For low levels of carbon price uncertainty and a sufficiently high correlation factor, the expected time to invest will decrease with increasing uncertainty and hence, investment will be stimulated instead of postponed.

Proposition 2 *Provided that $\alpha_Z > \sigma_Z^2/2$, the expected time to invest is decreasing in σ_C if, and only if, $\sigma_C < \rho\sigma_P$.*

Proof. The result follows from observing that

$$\frac{\partial \tilde{\mathsf{E}}_Z[\tau^*]}{\partial \sigma_C} \propto \Big(\underbrace{\frac{Z}{Z^*}\frac{\partial Z^*}{\partial \sigma_Z}(\alpha_Z - \sigma_Z^2/2)}_{>0} + \underbrace{\log(Z^*/Z)\sigma_Z}_{>0} \Big) \frac{\partial \sigma_Z}{\partial \sigma_C}$$

$$\propto \sigma_C - \rho\sigma_P,$$

where we have used the result from Proposition 1 in the last step. ■

The difference in results between our model and the model by Walsh et al. (2014) can be explained by taking a closer look at eq. (5), which shows that including revenue uncertainty and the correlation between the price and cost processes affects the overall uncertainty (σ_Z^2). If, for an investment decision under an emissions trading system, only uncertainty in the CO_2 price is considered, like in the model of Walsh et al. (2014), then $\sigma_Z = \sigma_C$. By adding revenue uncertainty, σ_Z^2 increases because σ_P^2 is added to σ_C^2. However, because revenue uncertainty diversifies cost uncertainty when a cost and a revenue process are positively correlated, σ_Z^2 is also reduced by $2\rho\sigma_P\sigma_C$ and hence, $\sigma_Z^2 = \sigma_C^2 + \sigma_P^2 - 2\rho\sigma_P\sigma_C$. For the tax system, Walsh et al. (2014) assume all cash flows deterministic. In our model we assume all costs constant and add a stochastic process regarding the revenue flow. Hence, under a tax system, $\sigma_Z^2 = \sigma_P^2$, and under an emissions trading system, $\sigma_Z^2 = \sigma_C^2 + \sigma_P^2 - 2\rho\sigma_P\sigma_C$. From the latter expression it follows that for a positive correlation coefficient large enough, the total uncertainty σ_Z decreases with σ_C and σ_P.

2.2 Extended model with cost differentiation

To make the model more realistic, we split the total production costs into levelized costs and carbon costs, so that uncertainty in the carbon pricing schemes can be analyzed separately from the uncertainty in the levelized costs of production, which may include, for example, wholesale prices of gas or coal.

To build the model, let $B = (B_P, B_L, B_C)$ be three correlated Brownian motions, with

$$\mathsf{E}_{(P,L,C)}[dB_P dB_L] = \rho_{PL}dt, \quad \mathsf{E}_{(P,L,C)}[dB_P dB_C] = \rho_{PC}dt, \quad \text{and} \quad \mathsf{E}_{(P,L,C)}[dB_L dB_C] = \rho_{LC}dt,$$

with $|\rho_{PL}| < 1$, $|\rho_{PC}| < 1$, and $|\rho_{LC}| < 1$.

As before, let the electricity price P, killed at the discount rate r, follow the GBM[2]

$$\frac{dP}{P} := -\mu_P dt + \sigma_P dB_P,$$

[2]It turns out to be technically easier to bring the discount rate inside the stochastic processes.

where $\mu_P = -(\alpha_P - r)$ is the killed growth rate of the electricity price. Similarly, the processes for the (killed) LCOE and the (killed) CO_2 price are given by the GBMs

$$\frac{dL}{L} = -\mu_L dt + \sigma_L dB_L, \quad \text{and} \quad \frac{dC}{C} = -\mu_C dt + \sigma_C dB_C,$$

respectively, where $\mu_L := -(\alpha_L - r)$ and $\mu_C := -(\alpha_C - r)$. We assume that the problem is not degenerate in the sense that it does not simultaneously hold that $\sigma_P = \sigma_L = \sigma_C$ and $\rho = 1$. The firm's investment problem (per MWh) can now be written as the optimal stopping problem:

$$V(P, L, C) = \sup_{\tau} \mathsf{E}_{(P,L,C)} \left[\frac{P_\tau}{r - \alpha_P} - \frac{L_\tau}{r - \alpha_L} - \frac{\eta C_\tau}{r - \alpha_C} \right]. \tag{8}$$

For $i = L, C$, let $\beta_{Pi} > 1$ be the positive root of the quadratic equation

$$\mathcal{Q}_{Pi}(\beta) \equiv \frac{1}{2}(\sigma_P^2 + \sigma_i^2 - 2\rho_{Pi}\sigma_P\sigma_i)\beta(\beta - 1) - \mu_P\beta + \mu_i(\beta - 1) = 0.$$

Adapting the results from Hu and Øksendal (1998) to our case we now get the following proposition.

Proposition 3 *Suppose that for $i = L, C$ it holds that*

$$\mu_P < \frac{\beta_{Pi} - 1}{\beta_{Pi}} \left[\mu_i + \tfrac{1}{2}(\sigma_P^2 + \sigma_i^2 - 2\rho_{Pi}\sigma_P\sigma_i) \right]. \tag{9}$$

Then the optimal time to invest is the first hitting time of the stopping set

$$S = \left\{ (P, L, C) \in \mathbb{R}_+^3 \;\middle|\; P \geq \frac{\beta_{PL}}{\beta_{PL} - 1} \frac{r - \alpha_P}{r - \alpha_L} L + \eta \frac{\beta_{PC}}{\beta_{PC} - 1} \frac{r - \alpha_P}{r - \alpha_C} C \right\}. \tag{10}$$

The condition in (9) is of a similar nature as the usual "growth rate should not exceed discount rate" assumption that is made in one-dimensional GBM-driven real options model. There, as here, its role is to ensure finite firm value: if the growth rate of free cash flows is higher than the discount rate, then expected discounted future cash flows are growing without bound over time. In our case, the picture is more complicated because of the presence of two stochastic cost components. Roughly speaking, one can think of the right-hand side of (9) as a "cost-adjusted discount rate". Given that we have two correlated cost processes, there are two such, related, adjusted discount rates. The revenue growth rate should not exceed either of them for the usual reason.

There are no known analytical expressions for $\mathsf{E}_{(P,L,C)}[\tau_S]$, where τ_S is the first hitting time of S, nor of the probability that S is hit within T years. These quantities can, however, easily be approximated via simulations.

3 Results and Discussion

In this section, we analyze how different policy instruments impact the postponement of carbon intensive technologies. By putting a price on carbon, the cost of CO_2 emissions is internalized in the firm's profit function, whereas otherwise it would remain an external cost carried by all of society. As an illustration, we consider a firm that has the option to invest in a Natural Gas Combined Cycle (NGCC) plant in Belgium. In real options theory, the irreversibility of the investment is taken into account by considering a lump sum investment cost which is sunk after the investment has been made. In this model, the total cost to produce a unit of electricity is the sum of the levelized cost of electricity (LCOE) and the cost of emitting CO_2. The LCOE is the unit cost of electricity, in which the lump sum investment cost is amortized and hence, also considered sunk after the investment has been made. The LCOE also includes all operational expenditures and is calculated as follows:

$$LCOE = \frac{FCF * CAP + FIXOM}{CF * 8766 * Q} + VAROM + HR * FUEL, \tag{11}$$

with CAP, the capital expenditure of the NGCC, FIXOM and VAROM, the fixed and variable operational and maintenance costs, CF, the capacity factor, Q, the power plant size, HR, the heat rate, i.e. the amount of energy used to produce 1MWh of electricity, and FUEL the natural gas price in EUR/MWh.The Fixed Charge Factor (FCF) annualizes the capital cost and is calculated as follows:

$$FCF = r + \frac{r}{(1+r)^T - 1}, \tag{12}$$

with r the discount rate and T the life-time of the plant.

Description	Parameter	Value	Unit	Ref
Capital cost	CAP	790	EUR/kW	
Fixed OM	$FIXOM$	9	EUR/y	
Variable OM	$VAROM$	2.8	EUR/MWh	
2018 average gas price	$FUEL$	23.68	EUR/MWh	–
Size	Q	800	MW	–
Capacity factor	CF	0.85	–	
Heat rate	HR	1.92	–	
Life time	T	30	years	
Discount rate	r	0.12	–	
Fixed Charge Factor	FCF	0.1241	–	
Levelized Cost of electricity	$LCOE$	62.70	EUR/MWh	
Emission factor	η	0.37		

Table 1: Parameter values to determine the LCOE of the NGCC.

The LCOE determined in Table 1 is used as the initial LCOE in the simulation (L_0). Because the

LCOE is linear in the gas price, the LCOE is assumed to fluctuate in time accordingly. We estimate the GBM parameter values for the gas and electricity price processes using the Belgian monthly wholesale prices for the period 2008-2018 as reported by the European European Commission (2020). A firm regulated under a tax system faces a constant cost per tonne of CO_2 emitted. If a cap-and-trade system is put in place, the price of carbon is set by the market and evolves over time. We estimate the GBM parameter values for the carbon price process under an ETS using the monthly ECX EUA (European Union Allowance) futures prices for the period 2008-2018 (Quandl, 2021).

The GBM parameter values of the price process i are estimated based on Eqs. 13-16, with $X_{i,t}$ the price level of process i at time t and $\bar{X}_i$ the sample mean of the normal distribution. To estimate the diffusion parameters, we used data containing the monthly average price of the corresponding process ($n = 127$).

$$\alpha_i = \bar{X}_i + \frac{\sigma_i}{2}, \tag{13}$$

with

$$\bar{X}_i = \frac{1}{n} \sum_{t=1}^{n} \log\left(\frac{X_{i,t}}{X_{i,t-1}}\right), \tag{14}$$

and

$$\sigma_i = \sqrt{\frac{1}{n-1} \sum_{t=1}^{n} \left(\log\left(\frac{X_{i,t}}{X_{i,t-1}}\right) - \bar{X}_i\right)^2}, \tag{15}$$

The correlation coefficient between two price processes i and j is determined as follows:

$$\rho_{i,j} = \frac{1}{n-1} \sum_{t=1}^{n} \frac{\log\left(\frac{X_{i,t}}{X_{i,t-1}}\right) - \bar{X}_i}{\sigma_i} \frac{\log\left(\frac{X_{j,t}}{X_{j,t-1}}\right) - \bar{X}_j}{\sigma_j}. \tag{16}$$

Table 2 shows the parameter values used to analyze a firm's decision to invest in a gas fired power plant in Belgium[3]. In line with empirical evidence (see, e.g., Hintermann, 2016), the correlation between the price processes is positive.

[3]Given that we work with GBMs, the parameters are assumed to be constant over time.

Description	Parameter	Value	Unit
Electricity price growth rate	α_P	0.11	
Electricity price volatility	σ_P	0.58	
2018 electricity price	P_0	59.65	EUR/MWh
Gas price growth rate	α_L	0.04	
Gas price volatility	σ_L	0.36	
2018 LCOE	L_0	62.70	EUR/MWh
Carbon price growth rate	α_C	0.11	
Carbon price volatility	σ_C	0.52	
2018 EU ETS price	C_Carbon	24.73	EUR/t
Gas and electricity price correlation	ρ_{PL}	0.66	
Carbon and electricity price correlation	ρ_{PC}	0.07	
Carbon and gas price correlation	ρ_{CL}	0.11	

Table 2: GBM parameter values.

3.1 Further insights into the calculation of the expected time to invest

For illustration purposes, we first present the results of the simplified model to get a feeling of the randomness that is inherent in our model. Figures 1A-C show simulated sample paths for the costs and prices under a tax system, an emissions trading system without considering correlation and an emission trading system with a correlation of 0.8 between the cost and price processes, respectively. Under a tax system the costs are constant, which results in a constant investment threshold level $P^*_{Tax,t}$ (Figure 1D). In case of an ETS, the price threshold level at time t depends on the cost level at time t. The reason is that if costs are stochastic, the price level at which it is optimal to invest, also changes in time. Figure 1E shows that whereas at $t = 0$, $P^*_{ETS} = 97.37$ EUR/MWh, at the time of investment ($t = 4.18$), $P_t = P^*_{ETS,t} = 124.39$ EUR/MWh, given the simulated sample path. Note that as P and C evolve, the expected time to invest, $\tilde{\mathsf{E}}_{(P,C)}[\tau^*]$, also evolves over time. The expected time to invest at time t depends on the cost and price levels at time t. Whereas at $t = 0$, $\tilde{\mathsf{E}}_{(P,C)}[\tau^*]$ is 3.9 years under a tax system (Figure 1G) and 7.00 years under an emissions trading system (Figure 1H), for the simulated sample paths investment is made after 2.97 years in case of a tax system and 4.18 years in case of an emissions trading system. When the carbon price and the electricity price are highly correlated, the diversification effect is notable. Because total uncertainty is reduced, the investment threshold at time $t = 0$ is lower and investment is expected to take place more early.

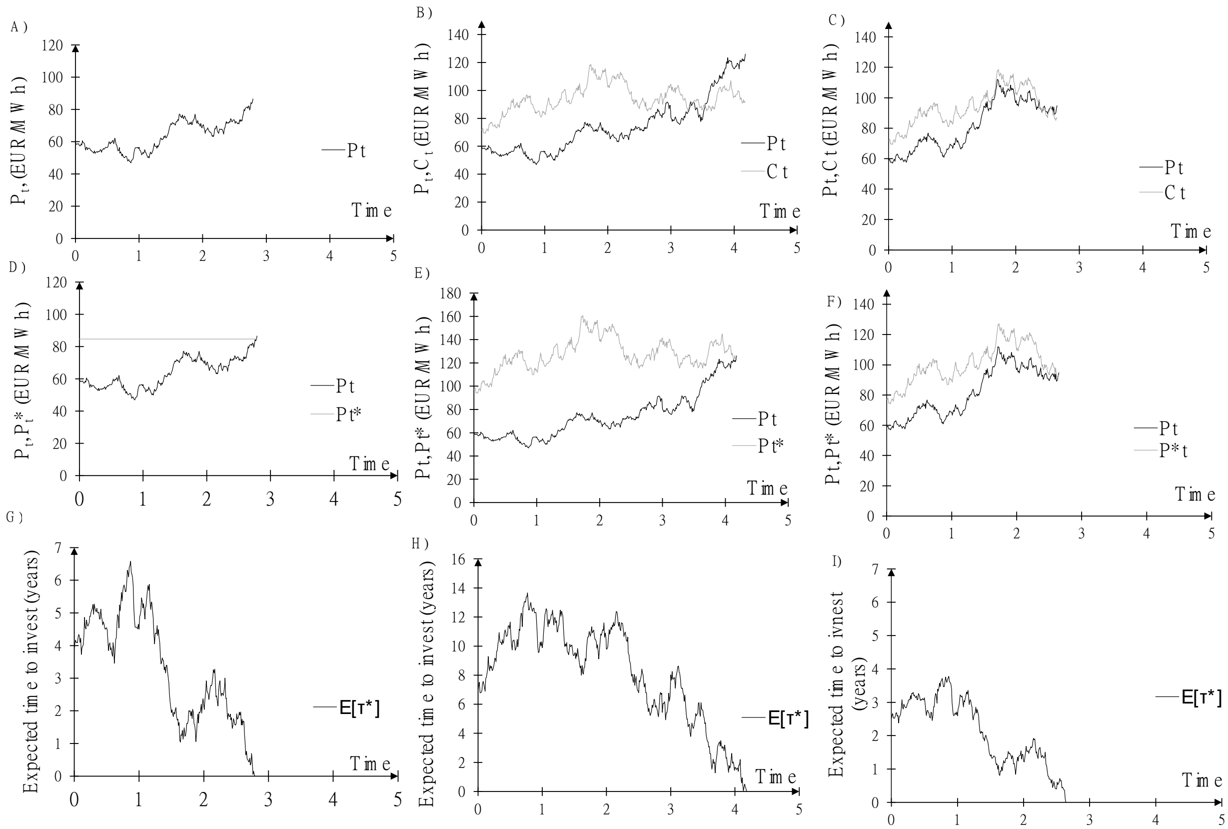

Figure 1: Simplified model results. *A/B/C*: sample paths for the cost and price process under a tax, an ETS with $\rho = 0$, and an ETS with $\rho = 0.8$ respectively. *D/E/F*: sample path for the price level and trigger price level under a tax, ETS ($\rho = 0$), and ETS ($\rho = 0.8$) respectively. *: G/H/I*: expected time to investment under a tax, ETS ($\rho = 0$), and ETS ($\rho = 0.8$). $\sigma_P = 0.2, \alpha_P = 0.11, \sigma_C = 0.2$ in case of ETS, $\sigma_C = 0$ in case of tax, $\alpha_C = 0, r = 0.12, P_0 = 59.65$ EUR/MWh, $C_0 = 71.85$ EUR/MWh.

Expressed in terms of electricity prices, under a tax system the investment threshold is fixed and under an emissions trading system the investment threshold fluctuates because it is directly affected by a fluctuating cost. Figure 2 shows the probability density of τ^*. The vertical, dashed line indicates the expected time that the investment will take place ($\tilde{\mathsf{E}}_{(P,C)}[\tau^*]$). This value corresponds to the value of $\tilde{\mathsf{E}}_{(P,C)}[\tau^*]$ at $t = 0$, depicted in Figure 1H and Figure 1I for $\rho = 0$ and $\rho = 0.8$ respectively. Furthermore, the probability density function of τ^* has a long tail and when the cost and price process are highly correlated, the distribution of τ^* is skewed further to the left (see Figure 2).[4]

[4]The first-passage time density f can be obtained from the distribution function of the supremum process of Z; see, e.e., Harrison (2013):

$$f(t) = \varphi(d_+)\frac{\partial d_+}{\partial t} + \left(\frac{Z^*}{Z_0}\right)^{2\alpha_Z/\sigma_Z^2 - 1} \varphi(d_-)\frac{\partial d_-}{\partial t},$$

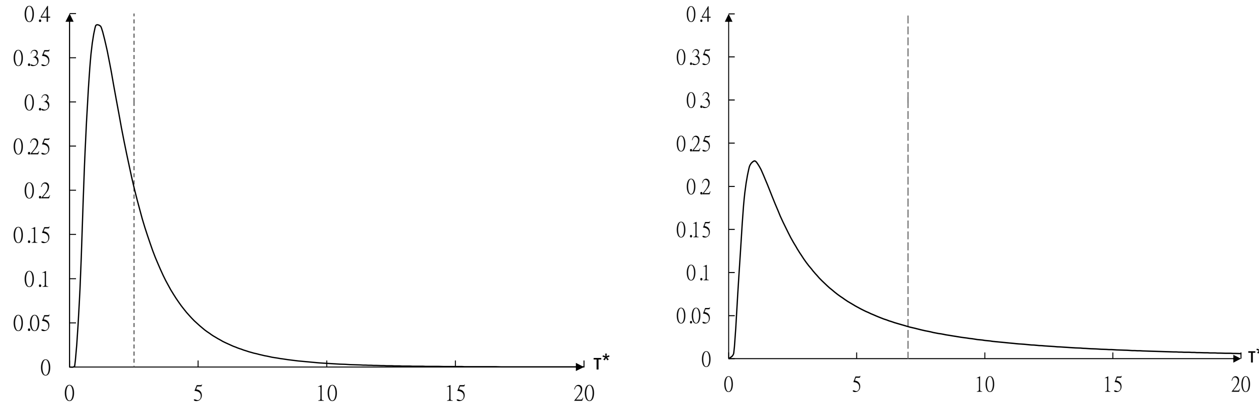

Figure 2: probability density function of τ^*. $\sigma_P = 0.2, \alpha_P = 0.11, \sigma_C = 0.2$ in case of ETS, $\sigma_C = 0$ in case of tax, $\alpha_C = 0, r = 0.12, P_0 = 59.65$ EUR/MWh, $C_0 = 71.85$ EUR/MWh. Left panel: $\rho = 0$. Right panel: $\rho = 0.8$. The dashed vertical line indicates the expected time to invest ($\tilde{\mathsf{E}}_{(P,C)}[\tau^*]$).

Therefore the expected time to invest is not necessarily a good summary measure for the distribution of investment times. We prefer not to present our results in terms of the investment triggers as these metrics are not one-to-one comparable because of the non-monotonic effects of the parameters driving uncertainty (volatility and correlation) on the likelihood of investment. We, therefore, express the results in terms of the probability that investment takes place within 5 years from now. We use the more realistic, extended model to present the results and we show that the intuition from the simplified model remains valid in the extended model. The result of the analytical model is hence independent of the strong assumptions that are made. We use the propositions from the simplified model to explain the interactions between the level of uncertainty, the correlation factor, and the probability of investment.

3.2 Impact of correlated price processes on the selection of a carbon pricing instrument

In this section, we take an investor's perspective and analyze how effective the different policy instruments are in limiting the probability to invest in a gas fired power plant without carbon capture and storage. We show the importance of taking into account multiple volatile price processes and

where

$$d_{\pm}(t) = \frac{\log(Z_0/Z^*)}{\sigma_Z\sqrt{t}} \pm \frac{\alpha_Z - \sigma_Z^2/2}{\sigma_Z}\sqrt{t},$$

and φ is the density function of the standard normal distribution.

their correlation when analyzing the investment decision.

We show the results considering only the volatility and correlations between the price processes as reported in Table 2. The growth rates are set to zero such that the effects of the volatility rates and correlation coefficients are isolated. We simulate a tax system by setting $\sigma_C = 10^{-10}$.

The left panel of Figure 3 shows the results for the simplified model, where there is no differentiation between the total costs (LCOE and the carbon cost). The black solid line shows that under a CO_2 tax of 24.73 EUR/t, there is a probability of about 13% that investment in a gas-fired power plant takes place within 5 years. The orange lines on the left panel of Figure 3 show the results for $\sigma_L = \sigma_C$ and for $\rho_{LC} = 0.99$. The probability to invest in a carbon intensive technology is higher than under a tax system and is increasing with increasing cost volatility as long as the correlation between the carbon price and the electricity price is rather low ($\rho_{PC} = 0.07$). This result is, while surprising, not new within the real options theory. In the case of a low-growth, low-risk firm, a moderate increase in uncertainty, increases the probability to invest because of the possibility of higher shocks in the price processes (Sarkar, 2000). An increase in volatility consequently increases the probability to invest. The shocks in the cost processes are needed to stimulate investment. Because of the high correlation between the carbon price and the LCOE this effect is further amplified. The total uncertainty increases and hence, also the probability to invest increases. Also the diversification effect resulting from a correlation between the carbon price and the electricity price is shown. A positive correlation between the electricity price and the cost processes ($\rho_{PC} = \rho_{PL} = 0.8$) diversifies the effect, reduces the overall uncertainty and hence, reduces the probability to invest as well (the dashed orange line). For higher levels of carbon price uncertainty, the probability of investment decreases. Hence, the left panel of Figure 3 shows that there are two opposing effects when the correlation between the carbon price and the electricity price is larger. On the one hand, total volatility increases and the probability of investment increases with increasing carbon price volatility. The additional uncertainty dominates the diversification effect. For higher levels of carbon price uncertainty on the other hand, total volatility decreases because of a diversification effect induced by ρ_{PC}. The probability of investment then decreases with increasing carbon price volatility and for $\sigma_C \geq 0.7$, an emissions trading system is preferred over a tax system to postpone investment in a carbon intensive technology.

On the right panel of Figure 3, we show the results when the costs are differentiated. Adopting the data of Table 2, the volatility in the LCOE is fixed to $\sigma_L = 0.36$, the correlation between the LCOE and the carbon price is relatively low ($\rho_{CL} = 0.11$) and the correlation between the LCOE and the electricity price is relatively large ($\rho_{PL} = 0.66$). The results are different from the results on the left panel and in accordance with the traditional real options results: the probability of investment decreases with increasing uncertainty and the correlation between the cost and price process has a diversifying effect. The reduction in the total uncertainty increases the probability of investment.

The volatility in the LCOE and the correlation between the LCOE and the electricity price impact the probability of investment under a carbon tax. Because the correlation is relatively high, the total uncertainty is reduced and the probability of investment is increased (compared to the left panel).

We show that if the correlation between the price processes is neglected, an ETS would wrongly be preferred over a tax system to limit investment in a carbon intensive technology. Under an ETS, when the correlation coefficients would be neglected, the probability of investment would slightly decrease for increasing carbon price uncertainty (blue solid line) and the ETS would be the preferred policy to limit the investment in the carbon intensive technology. However, when the correlation between the different price processes are considered, the diversification effect dominates the presence of additional uncertainty and the probability to invest increases with increasing uncertainty. This effect is further amplified when $\rho_{PC} = 0.8$.

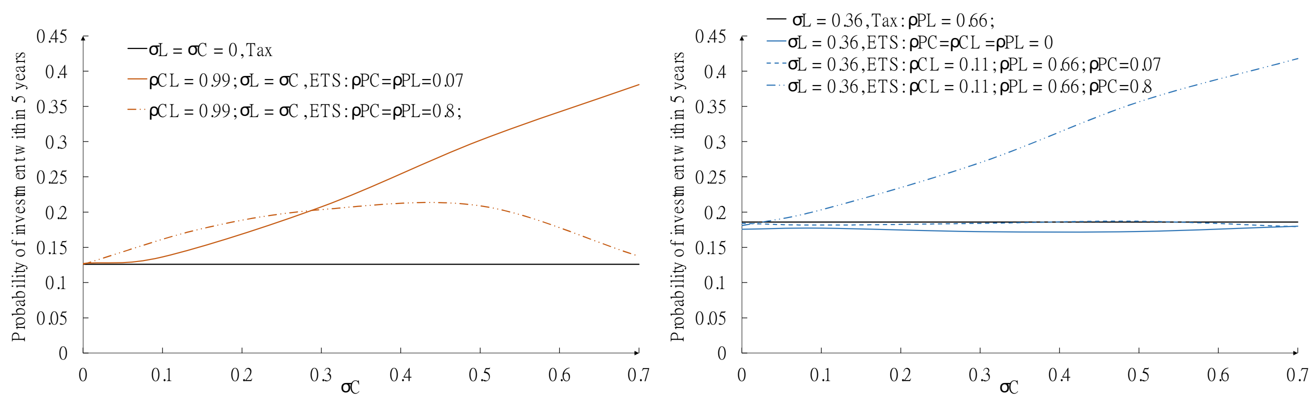

Figure 3: Probability of investment within 5 years for increasing levels of carbon price volatility. All growth rates are set to 0, $\sigma_P = 0.6$. The left panel represents the more simplified model without cost differentiation. In the right panel, the price processes of the carbon price and the LCOE are disentangled.

3.3 Carbon pricing

The results of Section 3.2 have direct policy implications with regard to the level at which a CO_2 tax should be set. Currently, carbon prices are not uniform across different countries. Carbon taxes range between a level as low as 2 EUR/t CO_2 in Estonia and 120 EUR/t CO_2 in Sweden (Speck and Paleari, 2016). Also, the main problem faced by the EU emissions trading system is a too low CO_2 market price. Therefore, different reforms are implemented to tighten the allowance supply and increase the carbon price (European Parliament and the Council, 2018).

First we present a case where the LCOE is considered constant ($\sigma_L = 10^{-10}$). We find that when the LCOE is assumed to be constant, an ETS is always the preferred policy instrument to keep the probability of investment in the carbon intensive technology limited. Nevertheless, the diversification effect resulting from the positive correlation between the carbon cost and the electricity price process is notable. If the correlation coefficient would be larger (grey solid line), then the probability to invest would be higher because the diversification effect dominates the volatility. If the carbon price volatility would be higher (dashed grey line), the probability of investment decreases as the diversification effect is dominated by the large uncertainty. Furthermore, the left panel of Figure 4 shows that in order for a tax to limit the probability to invest to 20%, a carbon tax of about 90 EUR/t is required, whereas under an ETS system with $\sigma_C = 0.52$ and low (high) levels of correlation between the electricity and carbon price, a carbon price level of about 8 EUR/t (18 EUR/t) is sufficient.

The right panel of Figure 4 shows the results when also the LCOE is considered volatile and an additional stochastic process is added to the analysis ($\alpha_L = 0.04$, $\sigma_L = 0.36$, $\rho_{PL} = 0.66$, $\rho_{LC} = 0.11$). Comparing the right panel of Figure 4 to the left panel, the probability of investment decreases a bit under a tax system. This is different from the results on the right panel of Figure 3 where the probability to invest increases under a tax when $\sigma_L = 0.36$ is included. This difference can be explained by the positive growth rate of the LCOE considered in the results of Figure 4. Also under an ETS with a rather low correlation between the carbon price and the electricity price ($\rho_{PC} = 0.07$), the probability to invest decreases. Hence, the additional source of uncertainty dominates the diversification effect and the ETS remains the preferred policy instrument to limit the probability of investment in carbon intensive technologies. However, if the correlation coefficient is higher ($\rho_{PC} = 0.8$), then the level of carbon price volatility does impact the decision on the optimal policy instrument and a tax system is preferred over an ETS for carbon price levels below 20 EUR/t. Whereas under a tax, a carbon price of 72 EUR/t is sufficient to limit the probability of investment to 20%, under an ETS with a strong correlation between the carbon and electricity price, a carbon price of about 29 EUR/t is required to have the same impact. If the correlation and hence the diversification effect would be limited ($\rho_{PC} = 0.07$) or not be accounted for, then a CO_2 market price level of 6 EUR/t would be considered sufficient to limit the probability to invest within 5 years in a gas-fired power plant to 20%.

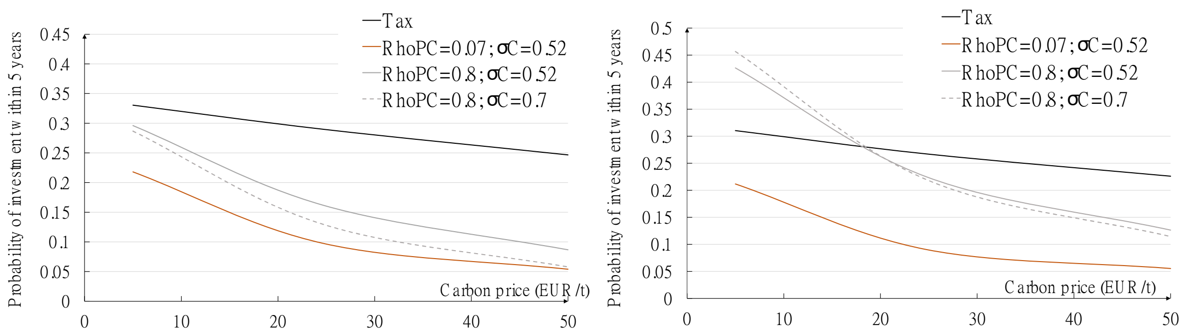

Figure 4: A specific carbon tax does not have the same impact as the same carbon price established under an ETS. The left panel only considers carbon price volatility and electricity price volatility: $\sigma_L = 10^{-10}$, $\rho_{PL} = 0$, $\rho_{LC} = 0$. The right panel also considers gas price volatility: $\alpha_L = 0.04$, $\sigma_L = 0.36$, $\rho_{PL} = 0.66$, $\rho_{LC} = 0.11$.

We conclude that, although a uniform carbon price seems to be appealing in theory (Weitzman, 2014), a specific carbon tax does not have the same impact on postponement of investment in carbon intensive technologies as the same carbon price established indirectly by a CO_2 market. In fact, we show that finding the optimal carbon price level is only part of the problem. The impact of the carbon price on the timing of the investment decision is highly sensitive to the carbon price volatility and its correlation with other volatile cash flows, which are country specific. Individual nations should therefore establish carbon pricing policies independently, with prices that vary across systems and are tailored to the prevailing dynamics in their energy market. These results add another argument to conclusions made previously by McEvoy and McGinty (2018) who highlight that the efficiency gains from a uniform tax are overstated. Tackling climate change is a problem of collective action and an international environmental agreement in which a uniform emission tax is adopted is not expected to motivate meaningful participation.

3.4 The type of technology matters

Policy instruments that internalize the cost of carbon into a firms' investment decision have the aim to postpone investments in carbon-intensive technologies. However, these policy instruments are also designed to stimulate firms to invest in low-carbon technologies. In this section, we compare the option to invest in a carbon-intensive gas-fired power plant with the option to invest in a gas-fired power plant, which limits its emissions by adopting carbon capture and storage (CCS).

First, we show that for the option to invest in a gas-fired power plant with carbon capture and storage (CCS) to be exercised before the option to invest in a carbon intensive, gas-fired power plant, the price on CO_2 needs to be sufficiently high. Because under an ETS the carbon price grows in time, the minimum carbon price level required for a plant with CCS to become the preferred investment option, is lower than under a tax system for which the carbon price is assumed to be constant in time. If the CO_2 price is not sufficiently high and there would be a substantial correlation between the revenue and the cost flows, a CO_2 tax would be preferred to delay the investment in the gas-fired power plant, as discussed in the previous section. However, if the CO_2 price is sufficiently high to justify investment in the gas-fired power plant with CCS, the choice of policy instrument reverts from a tax system to an emissions trading system.

Consider a firm which has the option to invest in a gas-fired power plant, which is equipped with an installation that captures CO_2 emissions that are transported to and stored in a geological reservoir (CCS, Carbon Capture and Storage). The cost of the investment and its operations are higher compared to a plant without CCS. As a result of the CCS investment, however, only a small amount of CO_2 is released into the atmosphere. The parameter values to determine the initial LCOE for an NGCC with carbon capture and storage are listed in Table 3.

Description	Parameter	Value	Unit	Ref
Capital cost	CAP	1490	EUR/kW	
Fixed OM	$FIXOM$	17	EUR/y	
Variable OM	$VAROM$	5.9	EUR/MWh	
2018 average gas price	$FUEL$	23.68	EUR/MWh	–
Size	Q	800	MW	–
Capacity factor	CF	0.85	–	
Heat rate	HR	2.13	–	
Life time	T	30	years	
Discount rate	r	0.12	–	
Fixed Charge Factor	FCF	0.1241	–	
Levelized Cost of electricity	$LCOE$	89.02	EUR/MWh	
Emission factor	η	0.05		

Table 3: Parameter values to determine the LCOE of the NGCC with carbon capture and storage.

The left panel of Figure 5 shows that to stimulate investment in CCS, a CO_2 tax of at least 75 EUR/t is needed. Under an emission trading system, the cap needs to be continuously reduced such that carbon prices grow in time, discouraging investment in carbon intensive gas fired power plants at CO_2 market prices as low as 5 EUR/t. This is also in line with the results of Mo et al. (2015) who find that a CCS retrofit investment becomes more valuable with a higher carbon price drift rate as it means higher CO_2 emission costs in the future.

The left panel of Figure 5 shows that for low-carbon technologies, a limited correlation between the carbon cost and the electricity revenues influences the choice between policy instruments. If $\rho_{PC} = 0.07$,under an emissions trading system, the probability to invest in CCS within 5 years is always lower than under a tax system. Under an emissions trading system, investment in CCS is expected to take place sooner if the carbon and electricity price are positively correlated (right panel of Figure 5). Under a tax system, the probability that investment in CCS takes place within 5 years is about 21%, regardless of the carbon price level. Under an emissions trading system with positively correlated cost and revenue flows, the probability to invest in CCS is about 40% for low carbon price levels.

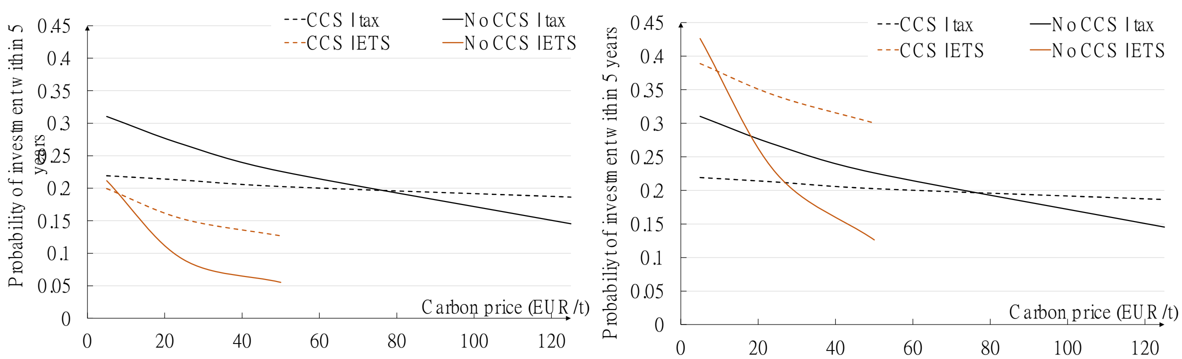

Figure 5: The impact of a carbon pricing instrument on the probability of investment in CCS. The left panel considers a $\rho_{PC} = 0.07$ and $\sigma_C = 0.15$. The right panel considers a $\rho_{PC} = 0.8$ and $\sigma_C = 0.4$.

In Section 3.2 we found that correlated costs and revenue flows under an emissions trading system stimulate investment. To discourage investment in carbon-intensive technologies such as a gas-fired power plant, an ETS is preferred when the correlation between the electricity price and the carbon price is limited. If there would be a large and positive correlation, then a tax system becomes the preferred policy instrument. In contrast, if we expand the analysis and add an option to invest in a gas-fired power plant with CO_2 capture, we find that a tax system is the preferred policy option if under an emission trading system the correlation between the electricity price and the carbon price is weak. However, considering that the CO_2 price will grow in time, the option to invest in a gas-fired power plant with a CO_2 capture unit will be exercised at a lower CO_2 price level compared to a tax system with a constant CO_2 price. With these results, we show that the correlation coefficient, volatility rates and carbon price growth rates should not be neglected as this could result in significant differences in model conclusions.

4 Conclusion

A carbon tax and an emissions trading system differ in terms of the uncertainty that they generate on the profitability of energy investments and, thus, impact on the investment decision of firms. We have shown that carbon price volatility under an emissions trading system does not necessarily lead to a delay of the investments necessary for the transition towards a low carbon economy. Firms make investment decisions under multiple sources of uncertainty. By considering the positive correlation between prices set in the energy and carbon market, we find that additional uncertainty can stimulate investment, due to the diversification effect generated by these different sources of uncertainty. **The optimal choice of policy instrument depends on the volatility of the market prices and the correlation level as well as the targeted technology. We find that when volatile price processes are weakly correlated under an ETS, investment is more postponed compared to a tax. If under an ETS, the correlation between the volatile price processes is strong and the volatility not too large, the diversification effect dominates and the probability of investment increases.**

Hence, in the case of weakly correlated price processes, an emission trading system is desirable to discourage investment in carbon intensive technologies. The multitude of uncertainties does not pose a problem and dominates the diversification effect. Investments will be less likely than when a tax system were in place. However, to stimulate investment in low carbon technologies, an ETS with weakly correlated, volatile price processes is less desirable and a tax system is the preferred policy instrument. In contrast, if the volatile price processes are strongly correlated, an emission trading system is less desirable to discourage investment in carbon intensive technologies. If policy makers aim to stimulate investment in low carbon technologies, an emission trading system with strongly correlated price processes will be preferred over a tax. The diversification effect dominates the multitude of uncertainties resulting in an increased likelihood that investment will take place.

Furthermore, by analyzing the problem in a dynamic real options framework, we find that the price signal of a carbon tax does not have the same impact as the price signal of the same carbon price set by an emissions trading system. While the price signal is the same, the timing of the investment decision, and hence the timing of the emission reduction is different for both policy instruments. Our analysis suggests that the effect of policies on the *timing* of investment decisions should not be neglected.

As a final remark, note that we only showed results for cases that satisfy the conditions of Proposition 3. For cases where these conditions are not met, the stopping set is potentially larger than the one we specify. To analyze such cases, tailor-made numerical schemes need to be developed, because no known analytical expressions for the investment region then exist. Currently there is no 'off-the-shelf' method available and we leave its development as an interesting avenue for future research. We show that neglecting other stochastic processes that impact an investment's profitability for analytical tractability can lead to qualitatively erroneous conclusions.

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