The Interplay between Technology Options, Market Uncertainty, and Policy in Zero-Carbon Investment Decisions

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Abstract

Using a real-options approach, we study the decision of a private power generator considering investment in a zero-CO_2-emissions plant. Specifically, we analyze the investment decision in mutually exclusive technologies under the presence of market uncertainty, for different scenarios and under different policy regimes within each scenario. The scenarios are based on emissions targets, such as net-zero-CO_2 emissions by 2050. The policy regimes are based on whether or not the targets are binding. We find that in scenarios with fewer available zero-CO_2-technology options there is less hesitation to invest, which potentially leads to earlier investment. We also find that some policies are more effective than others in encouraging investment: incentive payments are somewhat effective, penalties for not reaching zero emissions by a specified future date are more effective; a steadily increasing CO_2-emission-allowance price also speeds up investment.

Keywords

Energy transition; CO_2-emissions targets; Investment under uncertainty; Dynamic public economics

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1. Introduction

The U.S. signed the Paris agreement and subsequently pledged to reach net-zero greenhouse gas (GHG) emissions by mid-century [27]. Several states followed with their own net-zero commitments [3].

In this paper, we study how the power grid can be decarbonized through private investments. Specifically, we analyze the investment options for a private power generator seeking to comply with a governmental goal of a net-zero electricity-generating sector as soon as possible, but not later than 2050. A relevant example is the public transit company in New Jersey who plans to outsource the building and operation of a power plant that should be capable of supplying the company's power demand for rail operations for up to two weeks in islanded mode, if needed [19]. New Jersey has a state goal of 100% clean energy by 2050 [1]. There are not currently in place incentives that would economically justify investing today in a higher-cost CO_2-neutral power plant, so any proposal of the power generator should include a transition and investment plan to become a CO_2-neutral electricity generator by 2050. In this paper, these investments are studied using a real-option approach, explicitly considering market uncertainty.

There exists a growing body of literature on investment under uncertainty in energy systems. Kozlova [16] presents an overview of 101 papers that study real options in the renewable energy sector. Around 80% of the studies focus on the power sector and just over 60% analyze an investment opportunity in an energy system, rather than, say, in R&D. This paper builds on this literature and distinguishes itself in three main ways.

First, we consider interacting investment opportunities, which Ceseña et al. [2] point out is a feature that is missing from most existing studies. Herbelot [13] does consider interacting investment opportunities, but not ones that are mutually exclusive, i.e., the power generator can invest in more than one technology and can easily switch between technologies, e.g., after paying a minimal switching cost. For the case we study, we restrict the possibility of switching and assume technologies are mutually exclusive. This could represent a situation where siting or other constraints limit the physically-feasible technology options.

Second, Décamps et al. [8] show that when two investment opportunities are similar in terms of profitability, the rational (profit-maximizing) investor will choose to wait and see how the market evolves and only invest once it becomes clear which opportunity will become more profitable. Investing early could, as indicated by Siddiqui and Fleten [24], substantially reduce the value of the investor's holdings, relative to a foregone investment. Although Siddiqui and Fleten [24] have a similar setup as ours, our study distinguishes itself by also considering different future policy regimes. As indicated by De Weerdt et al. [7], future policy regimes can have far-reaching consequences for investments made today.

Third, we extend our setup by considering an increasing CO_2-emission-allowance price and solve a two-factor real option framework. We draw on the work of Compernolle et al. [4] and Dammann and Ferrari [6] in building our solving algorithm.

The remainder of the paper is structured as follows: section 2 introduces the reader to the setup of the study, section 3 develops an investment decision framework in which the power generator aims to maximize its future profits. This framework is then applied to a hypothetical case in section 4. Section 5 studies how an increasing CO_2-emission-allowance price affects investment decisions. Section 6 discusses the research findings.

2. Setup

Assume a power generator is operating a CO_2-intensive electricity generation plant supplying firm generation, e.g., a natural gas combined cycle (NGCC). Through investment, the generator has the option to change to the use of a CO_2-reducing or CO_2-neutral technology, and incentives for doing so are provided by the state in the interest of achieving a net-zero emissions electricity sector by 2050. A relevant example is the option to change from firing the combined cycle with natural gas to firing it with CO_2-neutral hydrogen.

Many CO_2-reducing or CO_2-neutral technologies have uncertain future operating margins (i.e., revenues received minus operating costs) because of market uncertainty. The real-option approach incorporates this uncertainty into the investment decision analysis. We assume the operating margin is a stochastic variable $\{P(t) : t \geq 0\}$ with initial value P. The power generator's decision to invest in a different technology depends, *ceteris paribus*, on the value of the stochastic variable. There exists a threshold (or boundary)[1], P^*, which induces the power generator to invest in a CO_2-reducing or CO_2-neutral technology option.

In a given scenario, the threshold is either not yet reached, in which case the rational investor chooses not to exercise the option to invest in the lower-carbon alternative, or has been reached, triggering the investment. Importantly, the threshold value will depend on the technologies available to change to or from, as well as prevailing policies that may incentivize certain choices more than others. For this study, three CO_2-reducing or CO_2-neutral technology options are considered. The power generator has the option to invest in any of these at any time. However, changing back to a more CO_2-intensive technology is not allowed.

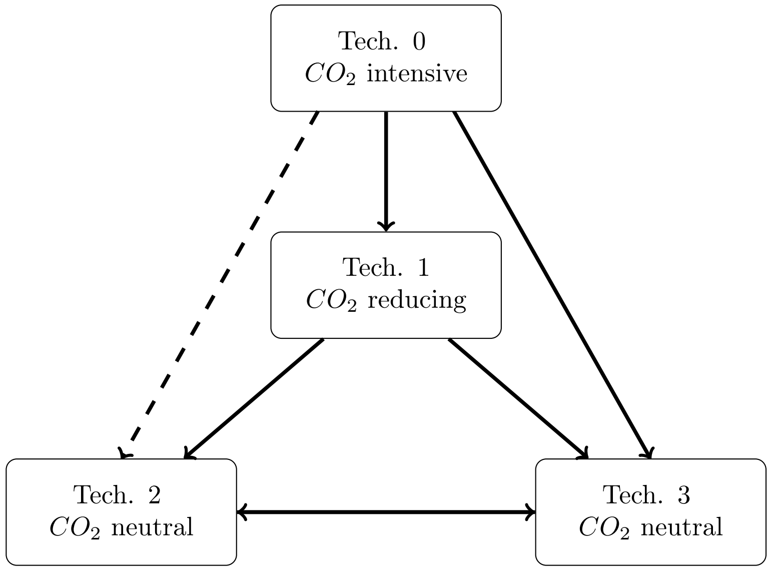
We study the decision-making for three time frames typical of corporate planning horizons. First, we analyze investment decisions driven by the goal of achieving an intermediate emissions-reduction target. Second, we study investments (after meeting the intermediate target) that further abate remaining emissions to zero. Third, we study any investment decision after reaching zero emissions. This approach is tailored to decision-making in the private sector, which typically only considers relatively short time horizons, especially in the U.S. [23, 15, 21].

The setup described above is stylized in fig. 1. The power generator has three mutually exclusive technology options. Other options are considered off the table due to siting or other constraints. We assume the incumbent technology (Tech. 0 in fig. 1) to be a CO_2-intensive NGCC. To reduce emissions, a new power plant needs to be built or a different fuel needs to be used. Solid arrows in fig. 1 indicate investment options. The power generator can choose to invest first in Tech. 1 to achieve partial emissions reductions. Here Tech. 1 represents securing access to CO_2-neutral hydrogen, e.g., by investing in a pipeline from a CO_2-neutral hydrogen producer, which then allows blending of hydrogen (25% energy ratio) into the natural gas fueling the NGCC, thereby reducing CO_2-emissions proportionately. (Tech. 1 is called CH_4/H_2 later in this paper). If the investment is made in Tech. 1, the hydrogen access facility within this investment is sized to be able to supply enough CO_2-neutral hydrogen to run the power plant entirely on hydrogen at some future point in time, if desired. This potentially makes the option profitable for the power generator to subsequently invest in replacing the NGCC with a combined cycle that can run on 100% CO_2-neutral hydrogen (HCC). This is Tech 2 in fig. 1.

The power producer who has invested in Tech. 1 has the option to invest in Tech. 3 instead of Tech. 2 to achieve CO_2-neutral generation. Tech. 3 is a geothermal energy system (GTE) for purposes of this paper. Additionally, rather than sequentially investing in Tech. 1 and then Tech. 3, the power producer may choose not to invest in Tech 1 and instead invest directly in Tech. 3 to achieve CO_2-neutral generation. Note that the pathway from Tech. 0 to Tech. 2 in fig. 1 is shown as unviable. Investing in Tech. 1 before Tech. 2 is not required, although always the cheapest pathway to reach Tech. 2.

The stochastic uncertainty that is considered in our setup is in the future operating margins associated with Tech. 1 and Tech. 2. Other parameters within the analysis are all assumed to be not uncertain. Note that all included technology options are known, even if the operating margin for Tech. 1 and Tech. 2 are uncertain. Therefore, this study is fundamentally different than, e.g., Grenadier and Weiss [11], Farzin et al. [10], and Malchow-Møller and Thorsen [17], who also study the adoption of technologies.

[1] There exists a threshold when the investment decision is driven by only one stochastic variable. Multiple stochastic variables, e.g., in case the investment costs would also be uncertain, cause the threshold to become a boundary.



(a) Full arrows represent investment options analyzed in this paper. The dashed arrow represents an existing, but always economically uninteresting option.

(b) In this study, Tech. 0 is a natural gas combined cycle, Tech. 1 represents securing of access facilities to CO_2-neutral hydrogen, e.g., a pipeline, which then allows blending of hydrogen (25% energy ratio) into the natural gas fueling the NGCC, Tech. 2 is a hydrogen combined cycle, and Tech. 3 is a geothermal energy system.

Figure 1: Investment Options

3. Framework

The power generator operates in a continuous time setting ($t \geq 0$) and generates electricity with a NGCC. We assume power is generated continuously at a fixed rate and sold under a long-term power purchase agreement at a fixed price per unit, leading to a constant cash flow, defined as:

$$\pi(t) = \delta - C, \tag{1}$$

where δ represents the incoming cash flow minus the OpEx, C represents the CO_2-emission-allowance price and is accounted for separately. After investment in any of the technology options, the emission-allowance price cancels out (partly) and the operating margin changes, e.g., to the operating margin of GTE. The latter is also constant and formalized as follows:

$$\pi(t) = \eta, \tag{2}$$

with η representing the operating margin of GTE. Alternatively, if CO_2-neutral hydrogen is blended with natural gas to fuel the NGCC, or when it is the sole fuel for the HCC, then the operating margin is uncertain. The uncertain procurement price of CO_2-neutral hydrogen is expected to decrease over time and affects the operating margin of hydrogen-fired technologies. The operating margin function for a HCC is formalized as follows:

$$\pi(t) = P(t), \tag{3}$$

where $P(t)$ is a geometric Brownian motion (GBM) with initial condition $P(0) = P$, defined as:

$$dP(t) = \mu P(t)dt + \sigma P(t)d\omega(t), \tag{4}$$

μ is the positive annualized drift rate, $d\omega(t)$ is the increment of the Wiener process, and $\sigma > 0$ is the constant volatility.

If hydrogen is blended with natural gas at a rate α by energy ratio ($\alpha \in [0, 1]$), then the operating margin function is a weighted combination of eq. (3) and eq. (1):

$$\pi(t) = (1 - \alpha)(\delta - C) + \alpha P(t) \tag{5}$$

Consequently, the operating margin function of the power generator depends on the technology used and can be summarized as follows:

$$\pi(t) = \begin{cases} \delta - C & if\ NGCC\ (Tech.0) \\ (1-\alpha)(\delta - C) + \alpha P(t) & if\ CH_4/H_2\ \text{(Tech. 1)} \\ P(t) & if\ HCC\ (Tech.\ 2) \\ \eta & if\ GTE\ (Tech.\ 3) \end{cases} \tag{6}$$

Whereas the technology used is a decision variable of the power generator, the policy regime is not. The latter can significantly affect the generator's operating margin and thus may incentivize investment in some technologies more than in others. The target to reduce CO_2 emissions, say by 25% ($\alpha \times 100$), and to reach net-zero-CO_2 emissions by $t = \zeta$ (≥ 0) and $t = \epsilon$ ($\geq \zeta$), respectively, could be linked to two possible policy regimes:

1. No consequence for not reaching targets;
2. Proportional reduction of profits to zero for not reaching targets.

The absence of any consequence, further referred to as policy regime 1, is straightforward to analyze. Profits do not change after $t = \zeta$ or $t = \epsilon$, the power generator therefore does not take these targets into account in its investment decisions. Consequently, eq. (6) remains valid throughout the entire planning horizon. However, if profits do get reduced after missing targets, further referred to as policy regime 2, the power generator's investment decisions will be affected. In fact, the opportunity cost of investing in a CO_2-reducing or zero-CO_2 technology will be reduced, incentivizing the power generator to make the investment.

In section 2 we described three investment-decision time frames to be studied. The next three subsections present the respective analyses (all derivations can be found in Appendix A). Section 3.4 introduces a numerical evaluation of the model that allows to compare policy regime 1 with policy regime 2.

3.1. Investments to reduce CO_2 emissions

The first time frame runs until the deadline for the intermediate CO_2-emissions reductions target. Two investment options are studied within this time frame, either the power generator invests in GTE or in access facilities to CO_2-neutral hydrogen[2]. We start by defining the profitability condition of GTE, which is trivial:

$$\frac{\eta}{r} - I_3 \geq \frac{\delta - C}{r}, \tag{7}$$

where I_3 is the cost to invest in Tech. 3 (GTE), and r represents the discount rate.

Proposition 1. *Let τ^*_{03} be the optimal time to invest in GTE. Then, it holds that $\tau^*_{03} = 0$ and the $NPV = \frac{\eta}{r} - I_3$ when $\frac{\eta}{r} - I_3 \geq \frac{\delta - C}{r}$. Otherwise it is never optimal to invest.*

[2]Note that investing in a HCC is not justifiable at this point for two reasons: (i) because blending CO_2-neutral hydrogen with natural gas offers enough emissions reductions to meet the first target, (ii) because the total investment cost for a HCC is high, requiring access facilities to CO_2-neutral hydrogen and requires investment in the HCC. This holds true when the cost of CO_2-neutral hydrogen is high, which is currently the case [14, 5].

If GTE is not profitable, the power generator maximizes the following value function[3]:

$$V(P) = \max_{\tau_{01}\geq 0} E\left[\int_0^{\tau_{01}} e^{-rt}\left(\delta - C\right)dt + \int_{\tau_{01}}^{\infty} e^{-rt}\left(\left(1-\alpha\right)\left(\delta - C\right) + \alpha P(t)\right)dt - e^{-r\tau_{01}}\ I_1\right]. \tag{8}$$

Equation (8) formalizes the option to fuel the NGCC with a blend of CO_2-neutral hydrogen and natural gas by paying the investment cost I_1. The aim is to find an investment time, τ^*_{01}, with a corresponding value $P^*_{\tau_{01}}$, at which it is optimal to invest in access facilities to CO_2-neutral hydrogen. Equation (8) can be rewritten as:

$$V(P) = \frac{\delta - C}{r} + \max_{\tau_{01}\geq 0} E\left[e^{-r\tau_{01}}\alpha\left(\frac{P(\tau_{01})}{r-\mu} - \frac{\delta - C}{r}\right) - e^{-r\tau_{01}}I_1\right]. \tag{9}$$

Firstly, note that the discount rate $r > \mu$. If the opposite were true, postponing the investment indefinitely would be optimal. Secondly, note that the opportunity cost of investing, $\frac{\alpha(\delta - C)}{r}$, affects the value function, and delays the investment in access facilities to CO_2-neutral hydrogen.

Proposition 2. *Assume that investing in GTE is not profitable and policy regime 1 holds. Then the following two situations can occur:*

1. *if* $\alpha\frac{C-\delta}{r} - I_1 \geq 0$, *then*

$$\tau^*_{01} = 0 \text{ and } V(P) = \frac{\alpha P}{r-\mu} + \frac{(1-\alpha)(\delta - C)}{r} - I_1$$

2. *if* $\alpha\frac{C-\delta}{r} - I_1 < 0$, *then*

$$\tau^*_{01} = inf\{t \geq 0 : P \geq P^*_{\tau_{01}}\} \text{ and}$$

$$V(P) = \begin{cases} \frac{\delta - C}{r} + A_{01}P^{\beta} & \text{if } P \leq P^*_{\tau_{01}} \\ \frac{\alpha P}{r-\mu} + \frac{(1-\alpha)(\delta-C)}{r} - I_1 & \text{if } P > P^*_{\tau_{01}} \end{cases},$$

where $A_{01} = \left(\frac{\alpha P^*_{\tau 01}}{r-\mu} - \frac{\alpha(\delta - C)}{r} - I_1\right)\frac{1}{P^{*\beta}_{\tau 01}}$, $P^*_{\tau 01} = \frac{r-\mu}{\beta\alpha - \alpha}\left(\frac{\beta\alpha(\delta-C)}{r} + \beta I_1\right)$,
and $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$.

If investing in GTE is profitable, the power generator is faced with a technology and timing decision. The following value function is maximized:

$$\begin{aligned} V(P) = \max_{\tau_{01,03}\geq 0} E\Bigg[&\int_0^{\tau_{01,03}} e^{-rt}\left(\delta - C\right)dt \\ &+ e^{-r\tau_{01,03}}\max\left(\frac{\alpha P(\tau_{01,03})}{r-\mu} + \frac{(1-\alpha)(\delta - C)}{r} - I_1,\ \frac{\eta}{r} - I_3\right)\Bigg]. \end{aligned} \tag{10}$$

Equation (10) can be rewritten as:

$$V(P) = \frac{\delta - C}{r} + \max_{\tau_{01,03}\geq 0} E\left[e^{-r\tau_{01,03}}\max\left(\alpha\left(\frac{P(\tau_{01,03})}{r-\mu} - \frac{(\delta - C)}{r}\right) - I_1,\ \frac{\eta - \delta + C}{r} - I_3\right)\right]. \tag{11}$$

Equation (11) is maximized for the operating margin P. As such the decision to invest in either technology is driven by the uncertain operating margin that is linked to using CO_2-neutral hydrogen. Following Décamps

[3] To simplify the notation we write $E[\cdot]$ instead of $E_P[\cdot]$, which represents the expected value conditional to the information that $P(0) = P$.

et al. [8], we know the investment intervals over P may be disconnected. As such, there exist the values $P^*_{\tau_{01}}$ and $P^*_{\tau_{03}}$ that indicate the boundaries of the waiting interval in-between the investment intervals. Therefore, the payoff function is not the upper envelope of the NPVs of access facilities to CO_2-neutral hydrogen or GTE. The intuition behind this waiting interval, i.e., to have disconnected investment intervals, is the following: if two technologies are very similar in terms of profitability, then the investor will be better off waiting until it becomes clear which technology is more profitable, rather than investing immediately. Consequently, the aim is to find the boundaries of the waiting interval, $P^*_{\tau_{01}}$ and $P^*_{\tau_{03}}$.

Proposition 3. *Assume the profitability condition of GTE (eq. (7)) is satisfied and policy regime 1 holds. Then the optimal time to invest is:*

$$\tau^*_{01,03} = inf\{t \geq 0 \ : \ P \leq P^*_{\tau_{03}} \ or \ P \geq P^*_{\tau_{01}}\},$$

meaning that the power generator invests in GTE when the operating margin is smaller than $P^*_{\tau_{03}}$ and invests in access facilities to CO_2-neutral hydrogen when the operating margin is larger than $P^*_{\tau_{01}}$. The value of the power generator is represented as follows:

$$V(P) = \begin{cases} \frac{\eta}{r} - I_3 & if\ P \leq P^*_{\tau_{03}} \\ \frac{\delta - C}{r} + A_{01,03}P^\beta + B_{01,03}P^\gamma & if\ P^*_{\tau_{03}} < P < P^*_{\tau_{01}} \\ \frac{\alpha P}{r-\mu} + \frac{(1-\alpha)(\delta-C)}{r} - I_1 & if\ P \geq P^*_{\tau_{01}} \end{cases}$$

Expressions for $A_{01,03}$, $B_{01,03}$, $P^*_{\tau_{03}}$, and $P^*_{\tau_{01}}$ are found numerically, $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$, and $\gamma = \frac{1}{2} - \frac{\mu}{\sigma^2} - \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$.

3.2. Investments to reach zero-CO_2 emissions

The second time frame runs from reaching the intermediate emissions target to reaching zero-CO_2 emissions. Within this time frame, we only study the case where the power generator previously invested in access facilities to CO_2-neutral hydrogen. The alternative case, i.e., the power generator previously invested in GTE, is characterized by zero-CO_2 emissions and is therefore studied in section 3.3.

We start the analysis by defining the profitability condition for investing in GTE. The power generator's current operating margin is partly driven by the uncertain operating margin P. Consequently, the profitability condition for investing in GTE is as well. We can however define when GTE will never be profitable:

$$\frac{\eta}{r} - I_3 < \frac{(\delta - C)(1 - \alpha)}{r}. \tag{12}$$

Proposition 4. *Let τ^*_{13} be the optimal time to invest in GTE. Then it holds that $\tau^*_{13} = +\infty$ (it is never optimal to invest) and the $NPV = \frac{(1-\alpha)(\delta-C)}{r} + \frac{P}{r-\mu}$ when $\frac{\eta}{r} - I_3 - \frac{(1-\alpha)(\delta-C)}{r} < 0$.*

If an investment in GTE is never profitable, the generator has a single option to invest, I_2, in a HCC. The value function for investing at τ_{12} in a HCC under policy regime 1 can be formalized as follows:

$$V(P) = \max_{\tau_{12} \geq 0} E\left[\int_0^{\tau_{12}} e^{-rt}\left((1-\alpha)(\delta - C) + \alpha P(t)\right)dt + \int_{\tau_{12}}^{\infty} e^{-rt}P(t)dt - e^{-r\tau_{12}}I_2\right] \tag{13}$$

Equation (13) can be rewritten as:

$$V(P) = \frac{(1-\alpha)(\delta - C)}{r} + \frac{\alpha P}{r - \mu} + \max_{\tau_{12} \geq 0} E\left[e^{-r\tau_{12}}\left(\frac{P(\tau_{12})}{r-\mu} - \frac{\delta - C}{r}\right)(1-\alpha) - e^{-r\tau_{12}}\ I_2\right]. \tag{14}$$

Proposition 5. *Assume that investing in GTE is never profitable and policy regime 1 holds. Then the following two situations can occur:*

1. *if* $\frac{(1-\alpha)(C-\delta)}{r} - I_2 \geq 0$, *then*

$$\tau_{12}^* = 0 \text{ and } V(P) = \frac{P}{r-\mu} - I_2$$

2. *if* $\frac{(1-\alpha)(C-\delta)}{r} - I_2 < 0$, *then*

$$\tau_{12}^* = inf\{t \geq 0 : P \geq P_{\tau_{12}}^*\} \text{ and}$$

$$V(P) = \begin{cases} \frac{\alpha P}{r-\mu} + \frac{(1-\alpha)(\delta-C)}{r} + A_{12}P^{\beta} & \text{if } P \leq P_{\tau_{12}}^* \\ \frac{P}{r-\mu} - I_2 & \text{if } P > P_{\tau_{12}}^* \end{cases},$$

where $A_{12} = \left(\frac{(1-\alpha)P_{\tau_{12}}^*}{r-\mu} - \frac{(1-\alpha)(\delta-C)}{r} - I_2\right)\frac{1}{P_{\tau_{12}}^{*\beta}}$, $P_{\tau_{12}}^* = \frac{r-\mu}{\beta(1-\alpha)}\left(\frac{\beta(1-\alpha)(\delta-C)}{r} + \beta I_2\right)$, *and* $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$.

If investing in GTE could be profitable, the power generator is faced with a different value function and needs to decide on the technology and timing. The value function is formalized by eq. (15):

$$V(P) = \max_{\tau_{12,13}\geq 0}\left[\int_0^{\tau_{12,13}} e^{-rt}\left((1-\alpha)(\delta-C) + \alpha P(t)\right)dt + e^{-r\tau_{12,13}}\max\left(\frac{P(\tau_{12,13})}{r-\mu} - I_2, \frac{\eta}{r} - I_3\right)\right] \quad (15)$$

Equation (15) can be rewritten as:

$$\begin{aligned} V(P) = {} & \frac{(1-\alpha)(\delta-C)}{r} + \frac{\alpha P}{r-\mu} + \quad (16) \\ & \max_{\tau_{12,13}\geq 0} E\left[e^{-r\tau_{12,13}}\left(\left(\left(\frac{P(\tau_{12,13})}{r-\mu} - \frac{\delta-C}{r}\right)(1-\alpha) - I_2\right), \left(\frac{\eta-(1-\alpha)(\delta-C)}{r} - \frac{\alpha P(\tau_{12,13})}{r-\mu} - I_3\right)\right)\right]. \end{aligned}$$

Similar to the analysis presented in section 3.1, investment intervals are disconnected. The aim is to find the boundaries, $P_{\tau_{12}}^*$ and $P_{\tau_{13}}^*$, of the waiting interval.

Proposition 6. *Assume that GTE can be profitable (eq. (12)) and policy regime 1 holds. Then the following two situations can occur:*

1. *if* $\frac{\eta}{r} - \frac{(1-\alpha)(\delta-C)}{r} - I_3 \leq -\frac{(1-\alpha)(\delta-C)}{r} - I_2$, *then*

$$\tau_{12}^* = 0 \text{ and } V(P) = \frac{(1-\alpha)P}{r-\mu} - \frac{(1-\alpha)(\delta-C)}{r} - I_2$$

2. *if* $\frac{\eta}{r} - \frac{(1-\alpha)(\delta-C)}{r} - I_3 > -\frac{(1-\alpha)(\delta-C)}{r} - I_2$, *then*

$$\tau_{12,13}^* = inf\{t \geq 0 : P \leq P_{\tau_{13}}^* \text{ or } P \geq P_{\tau_{12}}^*\} \text{ and}$$

$$V(P) = \begin{cases} \frac{\eta}{r} - I_3 & \text{if } P \leq P_{\tau_{13}}^* \\ \frac{(1-\alpha)(\delta-C)}{r} + \frac{\alpha P}{r-\mu} + A_{12,13}P^{\beta} + B_{12,13}P^{\gamma} & \text{if } P_{\tau_{13}}^* < P \leq P_{\tau_{12}}^* \\ \frac{P}{r-\mu} - I_2 & \text{if } P \geq P_{\tau_{12}}^* \end{cases},$$

meaning that the power generator invests in GTE when $P < P^*_{13}$ and invests in HCC when $P > P^*_{\tau_{12}}$. Expressions for $A_{12,13}$, $B_{12,13}$, $P^*_{\tau_{13}}$, and $P^*_{\tau_{12}}$ are found numerically. $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$, *and* $\gamma = \frac{1}{2} - \frac{\mu}{\sigma^2} - \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$.

3.3. Investments after reaching zero-CO_2 emissions

After reaching zero-CO_2 emissions, the power generator still has managerial flexibility to invest in a HCC or in GTE. We consider an investment instead of a switching model, changing costs are the full investment cost of a HCC or GTE.

If the power generator currently produces electricity with GTE, the decision to invest and change to using a HCC is formalized by eq. (17). Note that changing from using GTE to using a HCC requires an investment in access facilities to CO_2-neutral hydrogen as well as an investment in a HCC ($I_1 + I_2$).

$$V(P) = \max_{\tau_{32} \geq 0} E\left[\int_0^{\tau_{32}} e^{-rt}\eta dt + \int_{\tau_{32}}^{\infty} e^{-rt}P(t)dt - e^{-r\tau_{32}}(I_1 + I_2)\right] \tag{17}$$

Equation (17) can be rewritten as:

$$V(P) = \frac{\eta}{r} + \max_{\tau_{32} \geq 0} E\left[e^{-r\tau_{32}}\left(\frac{P(\tau_{32})}{r-\mu} - \frac{\eta}{r} - I_1 - I_2\right)\right]. \tag{18}$$

Proposition 7. *Assume GTE is the currently used technology. Then the power generator will invest in a HCC when:*

$$\tau^*_{32} = inf\{t \geq \tau_{32} \ : \ P \geq P^*_{\tau_{32}}\}$$

The value of the power generator is represented as follows:

$$V(P) = \begin{cases} \frac{\eta}{r} + A_{32}P^{\beta} & \text{if } P \leq P^*_{\tau_{32}} \\ \frac{P}{r-\mu} - I_1 - I_2 & \text{if } P > P^*_{\tau_{32}} \end{cases},$$

where $A_{32} = \left(\frac{\eta}{r} - \frac{P}{r-\mu} - I_1 - I_2\right)\frac{1}{P^{*\beta}_{\tau_{32}}}$, $P^*_{\tau_{32}} = \frac{r-\mu}{\beta-1}\left(\frac{\beta\eta}{r} - \beta I_1 - \beta I_2\right)$, *and* $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$.

Alternatively, the power generator has the flexibility to change to the use of GTE after having previously invested in a HCC. The decision to invest in GTE is made when P reaches low values, as formalized in eq. (19):

$$V(P) = \max_{\tau_{23} \geq 0} E\left[\int_0^{\tau_{23}} e^{-rt}P(t)dt + \int_{\tau_{23}}^{\infty} e^{-rt}\eta dt - e^{-r\tau_{23}}I_3\right] \tag{19}$$

Equation (19) can be rewritten as:

$$V(P) = \frac{P}{r-\mu} + \max_{\tau_{23} \geq 0} E\left[e^{-r\tau_{23}}\left(\frac{\eta}{r} - \frac{P(\tau_{23})}{r-\mu} - I_3\right)\right].$$

Proposition 8. *Assume a HCC is the currently used technology. Then the power generator will invest in GTE when:*

$$\tau^*_{23} = inf\{t \geq \tau_{23} \ : \ P \leq P^*_{\tau_{23}}\}$$

The value of the power generator is represented as follows:

$$V(P) = \begin{cases} \frac{\eta}{r} - I_3 & if\ P < P^*_{\tau_{23}} \\ \frac{P}{r-\mu} + A_{23}P^{\beta} & if\ P \geq P^*_{\tau_{23}} \end{cases},$$

where $A_{23} = \left(\frac{P^*_{\tau_{23}}}{r-\mu} - \frac{\eta}{r} - I_3\right)\frac{1}{P^{*\beta}_{\tau_{23}}}$, $P^*_{23} = \frac{r-\mu}{\beta-1}\left(\frac{\beta\eta}{r} + \beta I_3\right)$, *and* $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}$.

Note that the power generator is incentivized to change from a HCC to GTE when P drops below a threshold. Intuitively this corresponds to a situation characterized by high CO_2-neutral hydrogen procurement prices, which lead to a low operating margin, causing the generator to change to the only alternative technology for electricity generation.

3.4. Evaluating the investment decision under policy regime 2

Following section 3.1, 3.2, and 3.3, the investment decisions are partly driven by the opportunity cost of investing. The opportunity cost is (a fraction of) the operating margin of the currently used technology that is lost after investing. If policy regime 2 holds and the currently used technology emits CO_2, the opportunity cost is limited in time, and only has a value before the emissions targets' associated policies are implemented (at $t = \zeta$ and $t = \epsilon$). Let θ and κ represent the aggregated discounted opportunity cost in case policy regime 2 holds. Then the following holds true:

$$\theta = \alpha \int_t^{\zeta} (\delta - C)e^{-rt}dt$$
$$\kappa = (1-\alpha) \int_t^{\epsilon} (\delta - C)e^{-rt}dt$$
$$When\ t \leq \zeta.\ If\ \zeta < t \leq \epsilon\ then\ \theta = 0,\ if\ t > \epsilon\ then\ \kappa = 0$$

Since $t = \zeta$ and $t = \epsilon$ are known and do not depend on the level of P, we can find a value for θ and κ for every moment in time. Therefore, by substituting the perpetually discounted opportunity cost of investing with these values, we can re-evaluate the model, and estimate a solution that holds under policy regime 2. Note that different policy regimes do not affect the investment decision in section 3.3 because all emission targets have been reached. We refer to Appendix A.1 for the discussion on how the substitution should take place.

4. Case Study - Power Generator

A power generator set in the U.S. seeks to comply with the state's emissions targets. The generator honors a long-term power purchase agreement and needs to supply a constant load of approximately 60 MW_e. Current generation is CO_2 intensive. CO_2 emissions should be reduced by 25% by 2030 and should be zero by mid-century.

We study how the power generator transitions optimally toward becoming a zero-emissions electricity provider. The generator can invest in one of a number of mutually exclusive CO_2-neutral technology alternatives. Decision variables are the technology choice and the investment timing. Technology options are limited, since there is only access to approximately 20 acres of land, thereby excluding land-use intensive options, e.g., wind and solar. Figure 1 in section 2 illustrates the scenario with possible available technology options, including firing the existing NGCC facility with a site-blended mix of CO_2-neutral hydrogen and natural gas, a new HCC fired with CO_2-neutral hydrogen, and GTE (e.g. an organic Rankine cycle system utilizing high temperature geothermal energy [12]). The investment decision in one of these technology options is studied in three distinctly different time frames (as defined in section 2). The structure of this section is built in accordance with these three time frames.

Before starting the actual investment analysis, we introduce the set of parameter baseline values used throughout this case study (table 1). Note that these parameter values are informed fabrications for purposes of illustration. The power generator is assumed to have installed and is currently providing the 60 MW$_e$ with a NGCC and is receiving a \$0.05 operating margin per kWh$_e$. The \$0.05 operating margin assumes an electricity sale price of \$0.10 and operating expenses of \$0.05 per kWh$_e$. This operating margin is before considering the allowance price for CO_2 emissions. An allowance price of \$13 per short ton of CO_2 (the approximate current price of a RGGI CO_2-emission allowance [22]) is used throughout this case study. This equates to a cost of approximately \$0.006 per kWh$_e$ if the NGCC's emissions rate is 0.4 kg CO_2 per kWh$_e$. Expenditure on CO_2-emission allowances can be limited by investing in CO_2-reducing or CO_2-neutral technologies. To that end, the power generator has the option to use CO_2-neutral hydrogen as a fuel, or to invest in GTE. The investment cost in GTE is assumed to be \$2,500 per kW$_e$ and the operating margin is assumed to be \$0.09 per kWh$_e$.

Alternatively, the generator can reduce or neutralize its CO_2 emissions by, respectively, blending CO_2-neutral hydrogen with natural gas, or by investing in a HCC. On-site blending requires access facilities to CO_2-neutral hydrogen, e.g., a pipeline, and is technically limited to an energy ratio of 25% hydrogen and 75% natural gas, therewith reducing CO_2 emissions by 25%. We assume, for technical and cost optimization reasons, that the access facility is sized to be able to supply enough CO_2-neutral hydrogen to run the power plant entirely on hydrogen at some future point in time, if desired. The investment cost of such access facilities is assumed to be \$150 per kW$_e$. If there is access to CO_2-neutral hydrogen, the power generator can invest in a HCC, for which the investment cost is assumed to be \$1,000 per kW$_e$.

Changing to the use of CO_2-neutral hydrogen as a fuel for electricity generation means switching from a constant operating margin to an uncertain one. The uncertain operating margin is modeled with a GBM. The GBM is characterized by a constant positive annualized drift rate of 5% and a constant volatility of 0.1. All technologies are assumed to operate with a 90% capacity factor.

Table 1: Parameter Baseline Values

Parameter	**Unit**	**Value**
Operating margin NGCC (δ)	Dollar per kWh$_e$	0.05
CO_2 allowance price (C)	Dollar per kWh$_e$	0.006
Investment cost GTE (I_3)	Dollar per kW$_e$	2,500
Operating margin GTE (η)	Dollar per kWh$_e$	0.09
Investment cost access facilities (I_1)	Dollar per kW$_e$	150
Investment cost HCC (I_2)	Dollar per kW$_e$	1,000
Drift rate GBM (μ)	percentage/year	5
Volatility GBM (σ)	n.a.	0.1
Capacity factor	percentage	90

4.1. Reaching the intermediate CO_2-emissions-reduction target

The U.S. has a goal of reducing CO_2 emissions 50-52% by 2030 from 2005 levels [25]. Further, the Environmental Protection Agency (EPA) estimates that power sector GHG emissions in the US were at 73% of 2005 levels in 2020 [9]. For simplicity then, we assume CO_2-emissions follow a similar trajectory as GHG emissions, and adopt a 25% reduction in CO_2 emissions as the target for 2030 (relative to the emissions level from the power generator's NGCC).

This target could be reached by investing in any low CO_2-emitting technology. However, as we argue in section 3.1, the power generator will only consider investment in either access facilities to deliver CO_2-neutral hydrogen for on-site blending, or in GTE. The investment decision is analyzed under two policy regimes. In policy regime 1, there are no firm-level consequences for not reaching-emissions reduction targets. Particularly, in policy regime 2, the power generator's profits are taxed away after not reaching a CO_2-emissions-reduction target. Under regime 2, 25% of profits are taxed away if the 2030 target (25% reduction) is not reached and 100% of profits are taxed away if the 2050 target (100% reduction) is not reached. Under each policy regime, we consider first the case assuming GTE is not a profitable option and then the case when GTE is a profitable option.

4.1.1. Policy regime 1 and GTE is not profitable

The decision to invest in access facilities to CO_2-neutral hydrogen is based on a single investment threshold (see proposition 2), which for the baseline parameter values is found to be \$0.055 per kWh$_e$ (note that the time unit used is one year, which is then recalculated to a per hour result). Figure 2 shows how the option value is greater than the investment's NPV when the operating margin is less than the threshold. When the option value is equal to or smaller than the NPV, the power generator is incentivized to invest. This is true when the operating margin is equal to or greater than the threshold. The threshold to invest, \$0.055 per kWh$_e$, should be compared with the NGCC's operating margin after including CO_2-emission allowances, which is \$0.044 per kWh$_e$. An extra \$0.011 per kWh$_e$ of operating margin would motivate the investment in access facilities to deliver CO_2-neutral hydrogen.

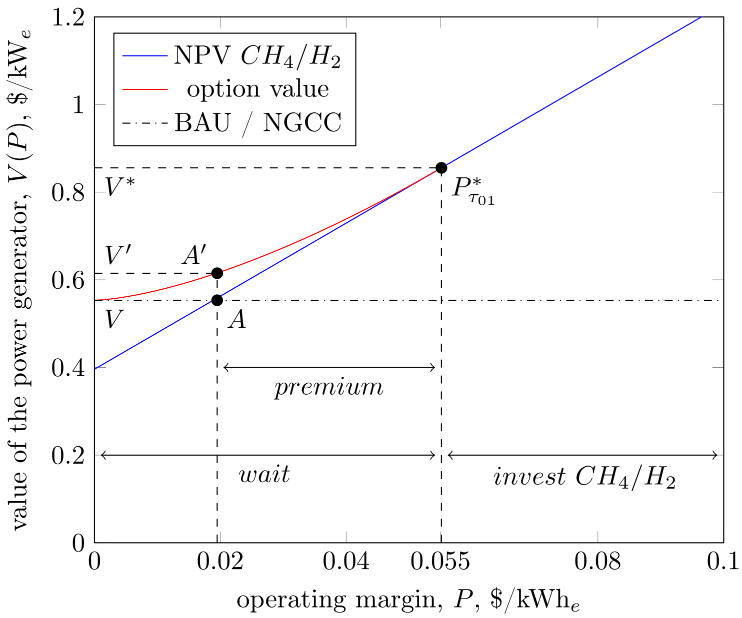


Figure 2: Optimal Investment Decision in Access Facilities to CO_2-neutral Hydrogen under Policy Regime 1 and GTE not Profitable. $P^*_{\tau01} = \$0.055$.

At point A, the NPV of an investment in access facilities to CO_2-neutral hydrogen intersects with the return function of a natural gas-fired NGCC (business as usual). Therefore, according to the NPV investment rule, a power generator should invest once the new operating margin (after blending hydrogen with natural gas) reaches the level associated with point A ($P \approx 0.02$). At this specific point, the value after investment would be V. However, the power generator has managerial flexibility to delay the investment. The ability to wait and to get new information from the market in an uncertain environment has a value, as shown by the option value curve. Therefore, at point A, a power generator with the ability to wait can move to point A', which translates to a value V'. The power generator will choose to delay an investment in access facilities to CO_2-neutral hydrogen as long as the option value exceeds the NPV. Rationally, only when the option value is equal to the value of the investment should the power generator choose to invest in access facilities to CO_2-neutral hydrogen. This equality is reached when the new operating margin reaches the investment threshold. The investment value at the threshold is greater than the value at point A. We conclude a premium is needed, indicated in the figure, to invest in an uncertain market when the option exists to wait.

The investment threshold is sensitive to the assumed investment and uncertainty parameters, as illustrated in fig. 3 and fig. 4, respectively. Figure 3 shows the relationship between the NGCC's operating margin and the assumed capital investment for access facilities to deliver CO_2-neutral hydrogen. Results are intuitive. For a given operating margin, a higher investment cost drives up the investment threshold. Similarly, a higher operating margin of the NGCC (higher opportunity cost of investing) drives up the investment threshold. Figure 3 shows that investment parameters have a significant impact on the investment decision. Therefore, policymakers could effectively speed up the investment in access facilities for CO_2-neutral hydrogen, by either reducing the NGCC's operating margin, or by subsidizing the investment in access facilities to CO_2-neutral hydrogen. A Pigouvian tax that further internalizes the NGCC's externalities would be most efficient from an economic point of view [20]. Environmental externalities of the NGCC are – to a certain extent – accounted for in the investment decision via emission allowances. However, the assumed allowance price for CO_2 emission ($13/short ton) is far below most estimates of the social cost of CO_2 that fully reflects the environmental and social external cost of emissions [26].

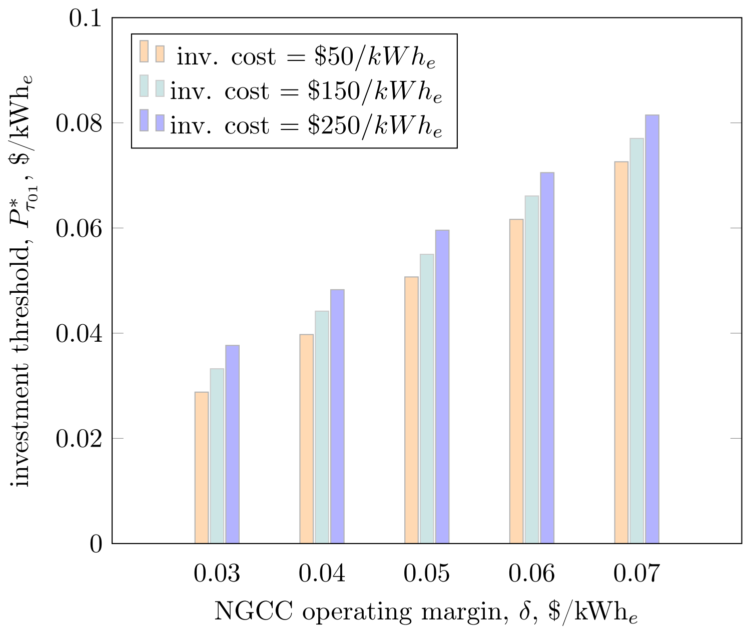


Figure 3: Sensitivity of the Investment Threshold, $P^*_{\tau_{01}}$, to Investment Parameters for an Investment in Access Facilities to CO_2-neutral Hydrogen under Policy Regime 1 and GTE not Profitable.

The uncertainty parameters, that is the drift rate and volatility, also affect the investment threshold (fig. 4). A higher positive drift rate lowers the investment threshold: if the uncertain operating margin trends upward more steeply, the power generator will be comfortable making the investment in access facilities for CO_2-neutral hydrogen at a currently-lower new operating margin. Contrarily, a higher volatility increases the investment threshold: greater uncertainty causes the power generator to want a larger buffer to hedge against a more volatile new operating margin. Consequently, policies that change the uncertainty parameter values, such as investment guarantees, also offer opportunities to steer investment behavior. Note that these policies only have a moderate impact on the investment threshold (comparing fig. 3 with fig. 4) and hence targeting investment parameters may be more efficient.

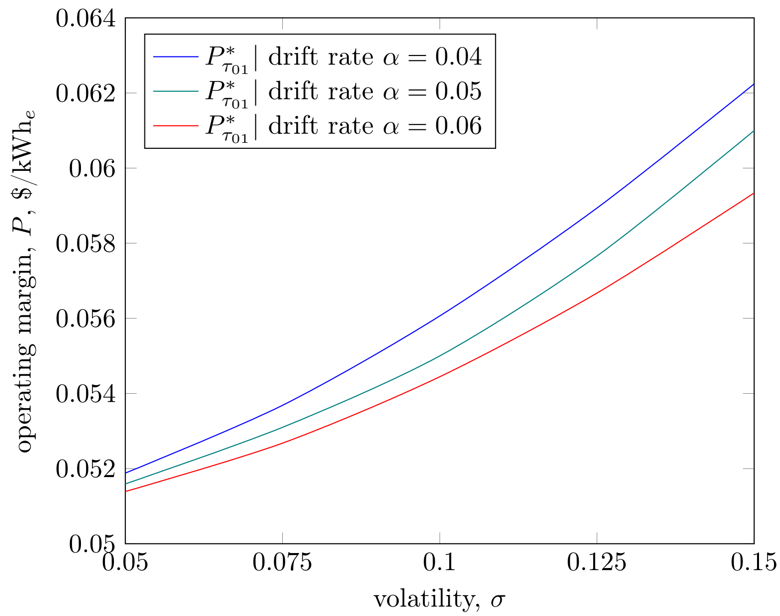


Figure 4: Sensitivity of the Investment Threshold, $P^*_{\tau_{01}}$, to uncertainty parameters for an Investment in Access Facilities to CO_2-neutral Hydrogen under Policy Regime 1 and GTE not Profitable.

4.1.2. Policy regime 1 and GTE is profitable

The above-presented analysis shows how the threshold to invest in access facilities for CO_2-neutral hydrogen behaves in the case where an investment in GTE is not profitable. If both technologies are profitable, the analysis to invest in either one must consider the option to invest in the other one. Following Décamps et al. [8], the investment region is disconnected and composed of two investment intervals, one for each technology. These two intervals are separated by an intermediate waiting interval. This is an interval during which the power generator prefers to wait and observe the market before making an irreversible investment in one of the technologies. For the baseline parameter values, we find the generator is incentivized to invest in GTE when $P \in [0, 0.045]$, wait when $P \in]0.045, 0.060[$, and invest in access facilities for CO_2-neutral hydrogen when $P \in [0.060, +\infty[$ (all expressed in Dollar per kWh$_e$). Figure 5 graphically shows the waiting interval. The intuition is simple: when the operating margin after blending hydrogen with natural gas is low, the generator is only interested to invest in the profitable GTE. This changes when the operating margin is higher but has not yet reached the threshold value for an investment in access facilities for CO_2-neutral hydrogen. In that interval, the generator prefers to wait and observe the changes in the operating margin. If it increases, it will reach the upper bound value of the waiting interval, leading to an investment in access facilities for CO_2-neutral hydrogen.

The different investment thresholds for investing in access facilities for CO_2-neutral hydrogen – depending on whether GTE is profitable or not – are \$0.060 and \$0.055 per kWh$_e$, respectively. This teaches us that, for our assumed parameter values, the investment in access facilities for CO_2-neutral hydrogen can – potentially – be brought forward in time by reducing available technologies to invest in, e.g., by not granting permits for GTE. Note that this does not necessarily mean that CO_2-emissions reductions will be reached sooner. If the operating margin after blending hydrogen with natural gas is low, and the power generator has no permits to invest in GTE, the incumbent CO_2-intensive technology will be used longer than in case when the power generator would be granted permits for investing in all available technologies.

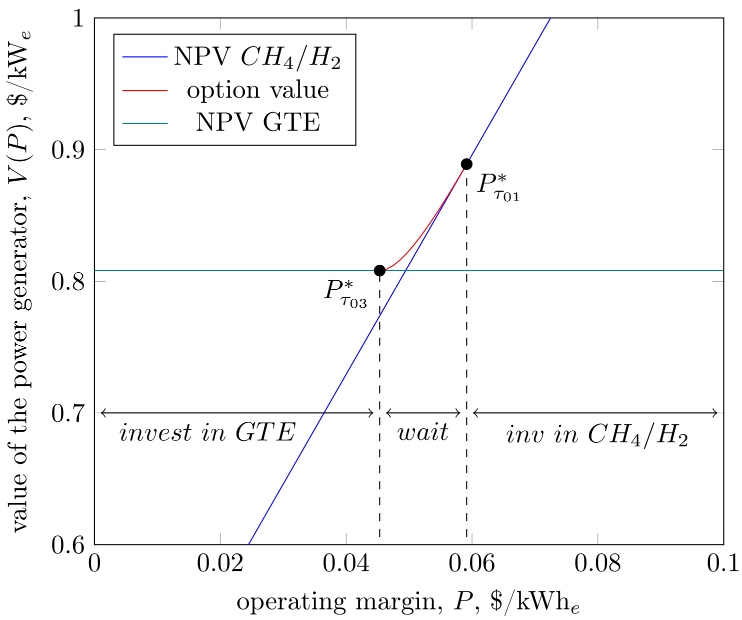


Figure 5: Optimal Investment Decision in GTE or Access Facilities to CO_2-neutral Hydrogen under Policy Regime 1, $P^*_{\tau03}$ = \$0.045, $P^*_{\tau01}$ = \$0.060.

The boundaries of the waiting interval are driven by investment and uncertainty parameters. Similar to what is shown in fig. 3, increasing investment parameters cause the boundaries to increase as well, and vice versa. The drift rate has a similar effect as when GTE is not profitable. Higher or lower drift rates broaden or decrease the waiting interval proportionately. Increased volatility also broadens the waiting interval but not proportionately (fig. Appendix B.1). A power generator that potentially faces a highly volatile operating margin after blending hydrogen with natural gas prefers to wait longer with making an investment decision.

4.1.3. Policy regime 2 and GTE is not profitable

The analyses so far considered investment decisions under policy regime 1, i.e., no firm-level consequence for not reaching CO_2-emissions targets. In this section, we study the same investment decisions, but under policy regime 2, i.e., profits are taxed away after not reaching CO_2-emissions targets. Results are different because under policy regime 2 the aggregate opportunity cost of investing decreases as time evolves: if the power generator does not undertake any investment, 25% of the NGCC's operating margin will be taxed away as of 2030. Therefore, the remaining aggregate opportunity cost of investing is always lower than under policy regime 1, where the operating margin is only affected by the CO_2-emission-allowance price.

As we did for policy regime 1, we consider two cases: one where GTE is not profitable and the second where GTE is profitable. Figure Appendix B.2 shows when GTE is profitable. The required operating margin for profitability decreases as policy implementation dates approach, after which some of the operating margin of a NGCC would be taxed away.

Under the condition that an investment in GTE is not profitable, the threshold to invest in access facilities for CO_2-neutral hydrogen decreases strongly before the 2030 target, and stabilizes thereafter (fig. 6). Before 2030 the opportunity cost of investing decreases as a result of 25% of the NGCC's operating margin being taxed away after 2030. This causes the investment threshold to decrease as well.

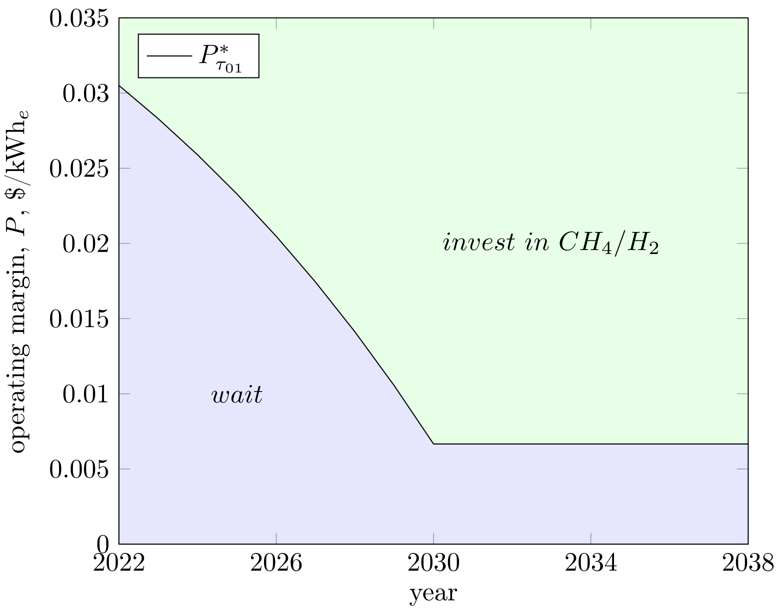


Figure 6: Optimal Investment Decision in Access Facilities to CO_2-neutral Hydrogen under Policy Regime 2 and GTE not Profitable.

4.1.4. Policy regime 2 and GTE is profitable

If investing in GTE is profitable, investment intervals are disconnected by a waiting interval. Figure 7 shows how the upper and lower boundary of the waiting interval evolve over time, as emissions targets approach (are missed) and associated policies approach (are in effect). Since the opportunity cost of investing decreases over time, investing in GTE becomes economically more interesting, and the power generator is incentivized to invest in GTE over a broader interval of P. This dynamic is translated into an increasing lower bound (fig. 7). The upper bound, indicating the threshold to invest in access facilities for CO_2-neutral hydrogen, also increases. This is because blending hydrogen with natural gas only reduces CO_2 emissions by 25%. Consequently, the NPV of 75% of the operating margin is diminishing every year as the 2050 emissions target approaches. Note that the gap between the boundaries narrows as time passes, and as waiting becomes more expensive.

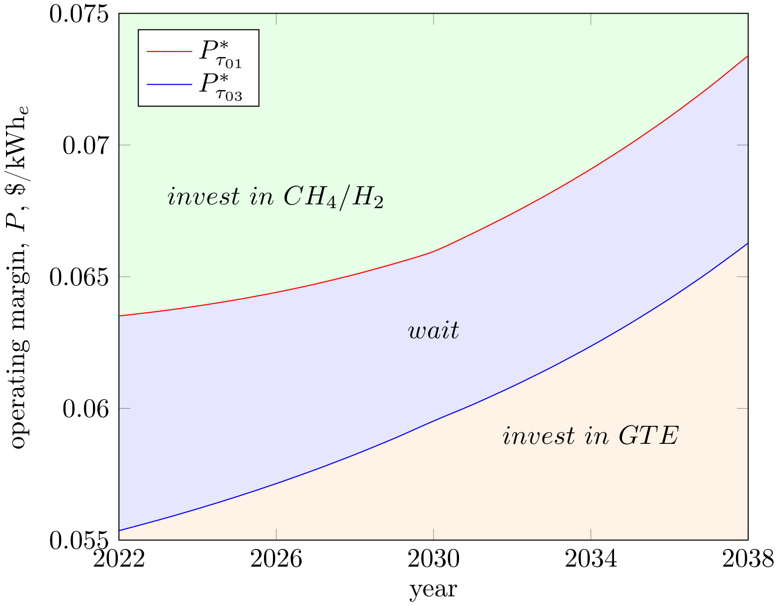


Figure 7: Optimal Investment Decision in GTE or Access Facilities to CO_2-neutral Hydrogen under Policy Regime 2.

4.2. Reaching the zero-CO_2-emissions target

Assuming the 2030 emissions target has been reached and the 2050 zero-CO_2 target is approaching, two scenarios exist: the power generator has previously invested in GTE or has previously invested in access facilities for CO_2-neutral hydrogen. The first scenario is trivial: the power generator is not confronted with the need to undertake further action since electricity generation is already CO_2-neutral. In case the second scenario holds, the power generator can either invest in a HCC or a GTE. We use a similar structure as in section 4.1 to analyze these investment options. The profitability condition of GTE now partly depends on P, and is analyzed according to proposition 4.

4.2.1. Policy regime 1 and GTE is not profitable

Figure 8 shows the analysis of the investment in a HCC under policy regime 1. The power generator has the option to invest, after which the operating margin becomes fully uncertain (100% hydrogen means the operating margin follows the stochastic variable P, unlike the case with 25% H_2 substitution). The threshold to invest in a HCC is \$0.063 per kWh$_e$ (tangent point between the option value curve and the NPV of an investment in a HCC). This threshold is \$0.008 per kWh$_e$ greater than the threshold to invest in access facilities for CO_2-neutral hydrogen (\$0.055 vs. \$0.063). The difference in thresholds is driven by the higher investment cost per kW$_e$ of a HCC compared to the investment cost of access facilities for CO_2-neutral hydrogen. As in section 4.1, the threshold to invest in a HCC is sensitive to changes in the investment and uncertainty parameters (fig. Appendix B.3 and fig. Appendix B.4).

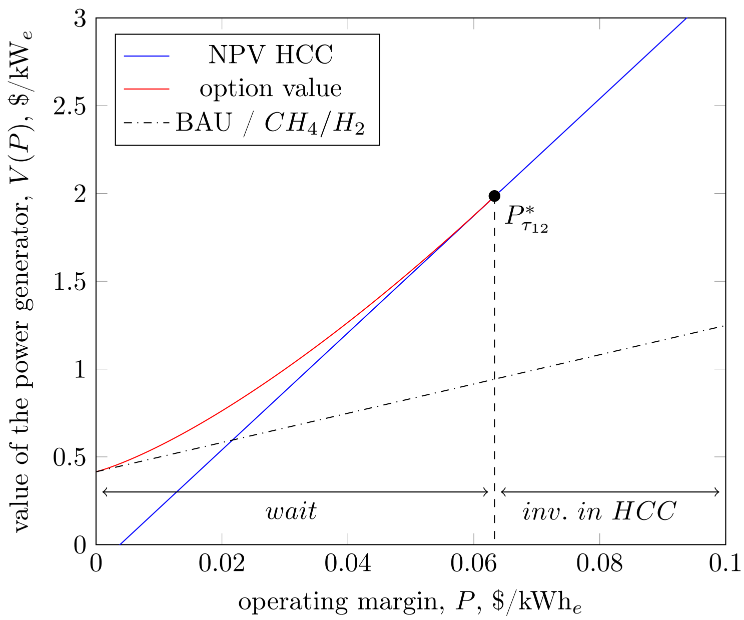


Figure 8: Optimal Investment Decision in a HCC under Policy Regime 1 and GTE not Profitable, $P^*_{\tau_{12}} = \$0.063$.

4.2.2. Policy regime 1 and GTE is profitable

If GTE is profitable there exists an interval over P during which the power generator prefers to wait before making an irreversible investment decision. Figure 9 shows how the option value is greater than the upper envelope of the NPVs when $P \in]0.020, 0.063[$. Consequently, the generator delays an investment over that interval, invests in GTE when $P \in [0, 0.020]$, and invests in a HCC when $P \in [0.063, +\infty[$ (all expressed in Dollar per kWh$_e$). The values of the boundaries are sensitive to investment and uncertainty parameters, see fig. Appendix B.4 and fig. Appendix B.5.

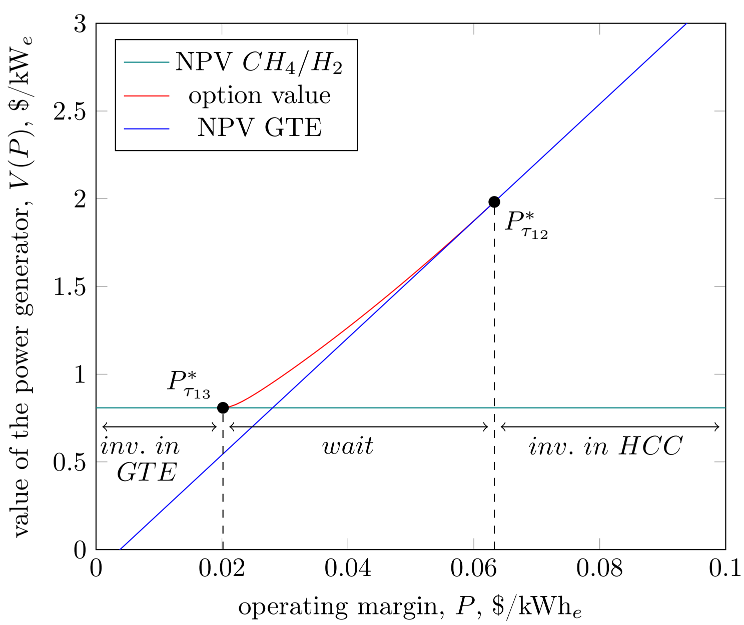


Figure 9: Optimal Investment Decision in GTE or a HCC under Policy Regime 1, $P^*_{\tau_{13}} = \$0.020$, $P^*_{\tau_{12}} = \$0.063$.

4.2.3. Policy regime 2 and GTE is not profitable

The above analyses considered policy regime 1. If, however, policy regime 2 were in place, investment thresholds shift because the opportunity cost of investing decreases. When GTE is not profitable, fig. 10 shows how the value of the threshold to invest in a HCC decreases. After 2050, the threshold is constant because the opportunity cost is zero, since the full operating margin is taxed away if CO_2 emissions are not zero at that time.

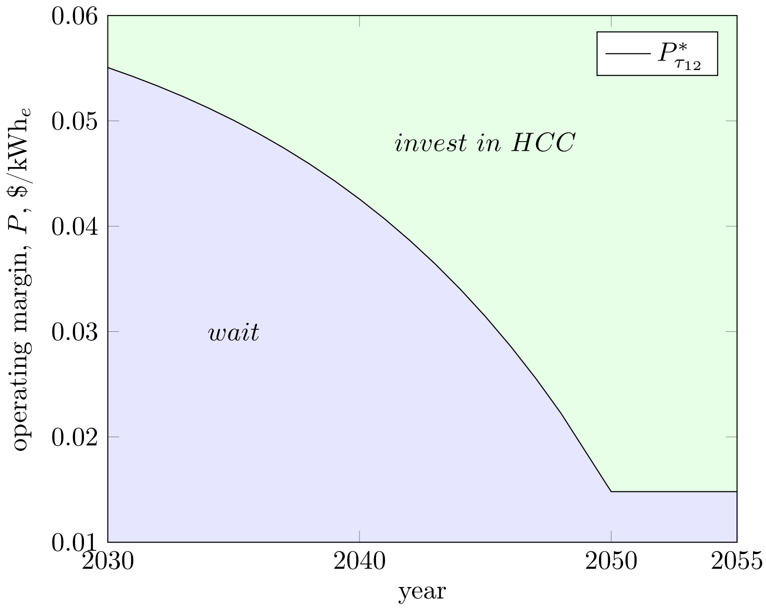


Figure 10: Optimal Investment Decision in a HCC under Policy Regime 2 and GTE not Profitable.

4.2.4. Policy regime 2 and GTE is profitable

If GTE is profitable and policy regime 2 is in place, fig. 11 shows how the boundaries of the waiting interval change over time. Like the results in fig. 7, we find that the lower bound increases, before stabilizing in 2050. The upper bound, in contrast to the result in fig. 7, now decreases. The decreasing trend is because a HCC replaces all remaining CO_2-intensive generating capacity of the NGCC, which is not the case when blending hydrogen with natural gas.

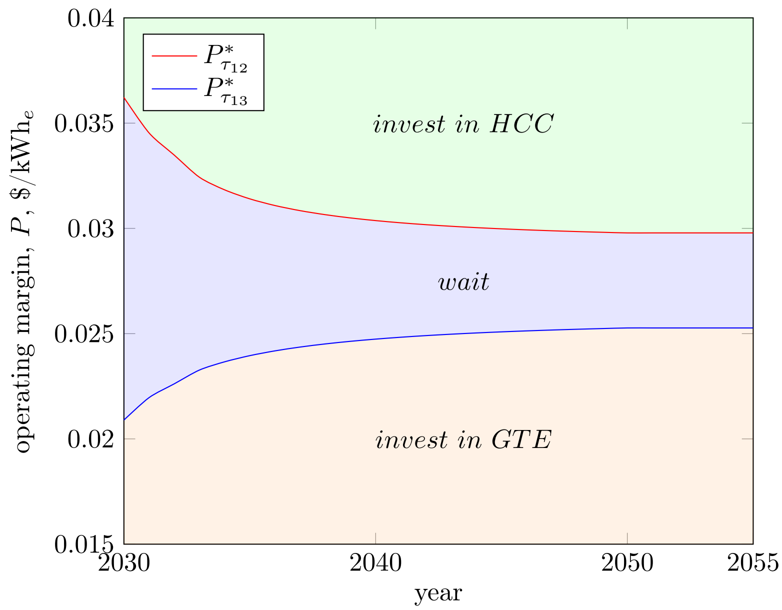


Figure 11: Optimal Investment Decision in GTE or a HCC under Policy Regime 2.

4.3. After reaching the zero-CO_2-emissions target

Once the CO_2-neutrality target has been reached, the power generator still has the option to invest in alternative CO_2-neutral electricity generating technologies. In the current setup, there is only one alternative technology and therefore, only one investment option. Moreover, the distinction between policy regime 1 and 2 does not affect the generator's decision making, since both technologies are CO_2-neutral. Consequently, the opportunity cost of investing must be fully accounted for, regardless of the policy regime. This subsection thus analyzes two scenarios in the time frame from 2050 on: the generator currently produces electricity with GTE and has the option to invest in a HCC or the generator currently operates a HCC and has the option to invest in GTE.

We proceed by analyzing the first scenario and find that the generator will only invest in a HCC if the HCC's operating margin reaches at least \$0.113 per kWh$_e$ (fig. 12). This threshold is high for two reasons. Firstly, the generator incurs a total investment cost that combines the investment cost in access facilities for CO_2-neutral hydrogen and the investment cost in a HCC. Secondly, the opportunity cost of investing, i.e., the operating margin of GTE, is high (\$0.09 per kWh$_e$). Sensitivity analyses of this threshold value indicate that, even with more extreme parameter values, the threshold value remains high (fig. Appendix B.6 and fig. Appendix B.7).

For the second scenario, we find that the generator will only invest in GTE if the HCC's operating margin drops to \$0.021 per kWh$_e$ or less (fig. 13). Note how the investment and waiting interval are mirrored, because the generator leaves the uncertain market instead of investing in it. The low value of the threshold is driven by a high opportunity cost of investing. Also in this case, the threshold value remains low for more extreme parameter values (fig. Appendix B.8 and fig. Appendix B.9).

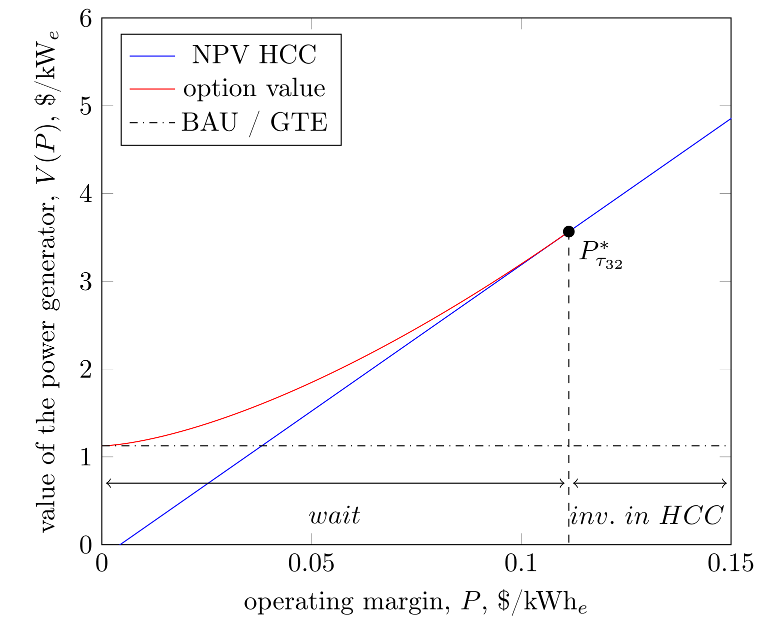


Figure 12: Optimal Investment Decision in a HCC, $P^*_{\tau_{32}} = \$0.1113$.

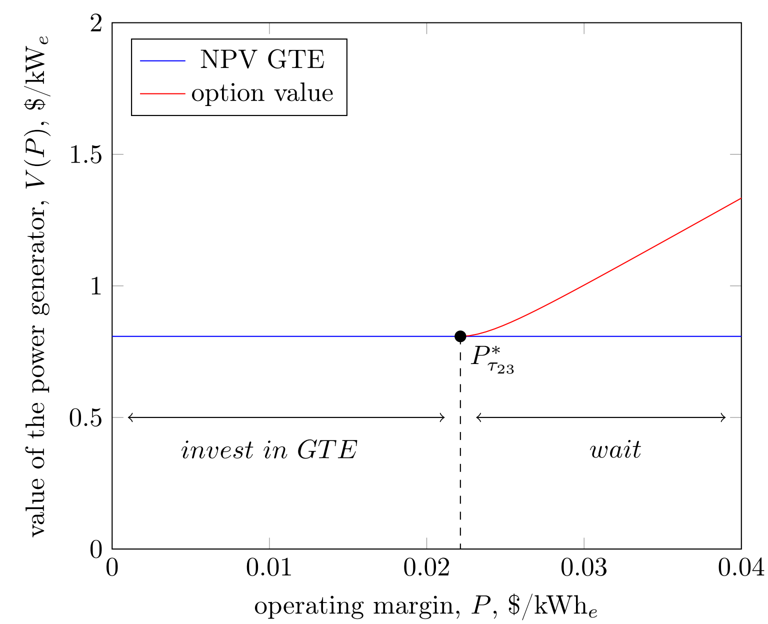


Figure 13: Optimal Investment Decision in GTE, $P^*_{\tau_{23}} = \$0.021$.

5. CO_2-Emission-Allowance Price as a Function of Time

Throughout this paper, we have assumed the CO_2-emission-allowance price, C, to be constant and equal to \$0.006 per kWh$_e$. Here, we analyze the investment decision of the power generator if the CO_2-emission-allowance price rises over time, as might occur under a cap-and-trade emissions regulatory framework[4].

If the emission allowance price is a function of time we need to revisit section 3. For simplifying the analysis in this section, we only consider the decision to invest in access facilities to CO_2-neutral hydrogen and in a HCC, both under policy regime 1 and when GTE is not profitable. The decision to blend CO_2-neutral hydrogen with natural gas, previously formalized by eq. (8), is now rewritten as:

$$V(P,C) = \max_{\tau_{01}\geq 0} E\left[\int_0^{\tau_{01}} e^{-rt}\left(\delta - C(t)\right)dt + \int_{\tau_{01}}^{\infty} e^{-rt}\left(\left(1-\alpha\right)\left(\delta - C(t)\right) + \alpha P(t)\right)dt - e^{-r\tau_{01}}\ I_1\right], \quad (20)$$

with $C(t) = Ce^{\upsilon t}$, where υ is the annual growth rate. Consequently, eq. (20) can rewritten as:

$$V(P,C) = \frac{\delta}{r} - \frac{C}{r-\upsilon} + \max_{\tau_{01}\geq 0} E\left[e^{-r\tau_{01}}\alpha\left(\frac{P(\tau_{01})}{r-\mu} - \frac{\delta}{r} + \frac{C(\tau_{01})}{r-\upsilon}\right) - e^{-r\tau_{01}}I_1\right]. \quad (21)$$

If the power generator previously invested in access facilities to CO_2-neutral hydrogen and considers investment in a HCC, eq. (13) and eq. (14) require similar rewriting:

$$V(P,C) = \max_{\tau_{12}\geq 0} E\left[\int_0^{\tau_{12}} e^{-rt}\left((1-\alpha)(\delta - C(t))dt + \alpha P(t)\right) + \int_{\tau_{12}}^{\infty} e^{-rt}\ P(t)dt - e^{-r\tau_{12}}I_2\right] \quad (22)$$

$$V(P,C) = (1-\alpha)\left(\frac{\delta}{r} - \frac{C}{r-\upsilon}\right) + \frac{\alpha P}{r-\mu} \quad (23)$$

$$+ \max_{\tau_{12}\geq 0} E\left[e^{-r\tau_{12}}\left(\frac{P(\tau_{12})}{r-\mu} - \frac{\delta}{r} + \frac{C(\tau_{12})}{r-\upsilon}\right)(1-\alpha) - e^{-r\tau_{12}}I_2\right]. \quad (24)$$

Note that if the initial value of one of the variables, $P(t)$ or $C(t)$, is zero, it will remain zero over the entire planning horizon. As such, eq. (21) and eq. (23) become one-dimensional problems and investment thresholds can be found analytically (as in section 3). Thus for eq. (21) the threshold $C^*_{\tau_{01}}$, when we fix $P=0$, is given by:

$$C^*_{\tau_{01}} = \frac{(\alpha\delta + I_1 r)}{\alpha}, \quad (25)$$

and the threshold $P^*_{\tau_{01}}$, when we fix $C=0$, is given by:

$$P^*_{\tau_{01}} = \frac{(\alpha\delta + I_1 r)}{\alpha}\frac{\beta}{\beta-1}\frac{r-\mu}{r}. \quad (26)$$

Similar expressions can be found for eq. (23):

$$C^*_{\tau_{12}} = \frac{((1-\alpha)\delta + I_1 r)}{\alpha}, \quad (27)$$

$$P^*_{\tau_{12}} = \frac{((1-\alpha)\delta + I_1 r)}{\alpha}\frac{\beta}{\beta-1}\frac{r-\mu}{r}. \quad (28)$$

Previously, the investment decision was based on the value of P, taking the form of an investment threshold that splits the investment from the waiting region. Now, the investment decision depends not only

[4]If we assume the power generator operates in a Northeastern U.S. state that is member of the Regional Greenhouse Gas Initiative (RGGI), there exists a cap-and-trade emissions framework that includes a cost containment reserve. Through this reserve, the cap is effectively increased when the allowance price reaches levels above a predetermined maximum price, set to increase every year.

on the value of P, but also on the value of C. Consequently, the threshold is a boundary in the P-C space that we designate by b. Whenever the market conditions are above the curve b, i.e., in the investment region, it is optimal to invest. The following proposition is based on Dammann and Ferrari [6] and Compernolle et al. [4].

Proposition 9. *The Boundary b_{01} (respectively b_{12}) is continuous, decreasing and convex. Additionally, $b_{01}(0) = C^*_{01}$ and $b_{01}(P^*_{01}) = 0$ (respectively $b_{12}(0) = C^*_{12}$ and $b_{12}(P^*_{12}) = 0$).*

To approximate the boundary, we use the Monte-Carlo method with a procedure described by Dammann and Ferrari [6]. We numerically evaluate our case for the baseline parameter values. For computational reasons, we set the growth rate of the CO_2-emission-allowance price to 0.05% per year. Note that this growth rate does not affect the intercept of the curve with the axes (see eq. (25), eq. (26), eq. (27), and eq. (28)), but only slightly affects the convexity of the curve (the impact is limited and does not show in a figure). However, this does not imply that different growth rates for the CO_2-emission-allowance price affect the market in the same way. Higher growth rates will cause the market to reach the boundary sooner, and will thus incentivize the power generator to invest sooner.

Figure 14 and fig. 16 show the boundary for an investment in access facilities to CO_2-neutral hydrogen and a HCC, respectively, for different drift rates of the operating margin. For high rates, the boundary has a more outspoken convexity. We can see that the curve moves down when we increase the drift rate of the operating margin, meaning that it is optimal to invest sooner. Figure 15 and fig. 17 show the sensitivity of the respective boundaries to the volatility of the operating margin, P. Higher uncertainty leads to delayed investment. This is a widely found result in real option literature.

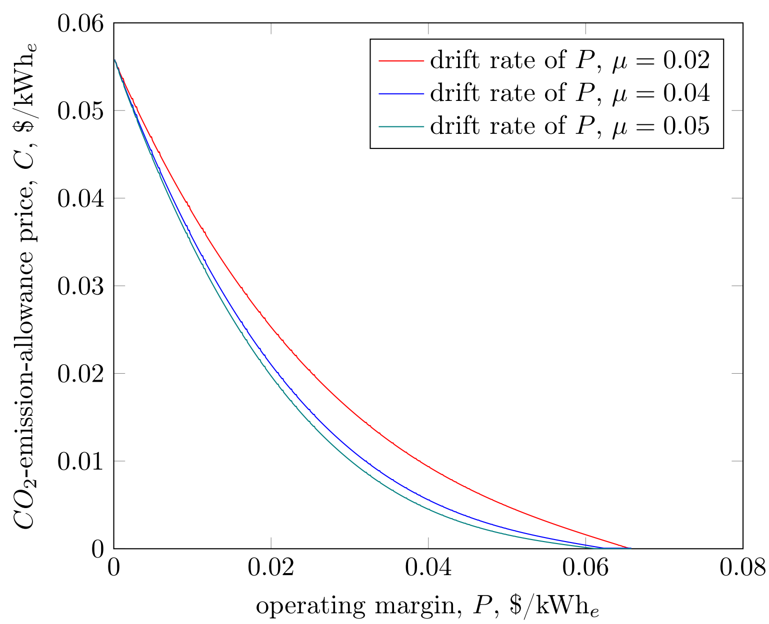


Figure 14: Sensitivity of Optimal Investment Decision in Access Facilities to CO_2-neutral Hydrogen under Policy Regime 1 and GTE not Profitable, to Drift Rate of Operating Margin.

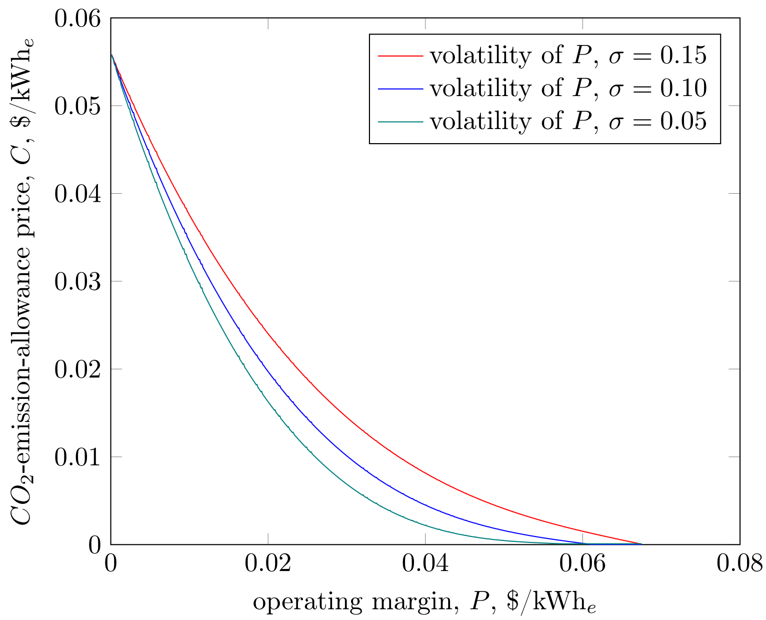


Figure 15: Sensitivity of Optimal Investment Decision in Access Facilities to CO2-neutral Hydrogen under Policy Regime 1 and GTE not Profitable, to Volatility of the Operating Margin.

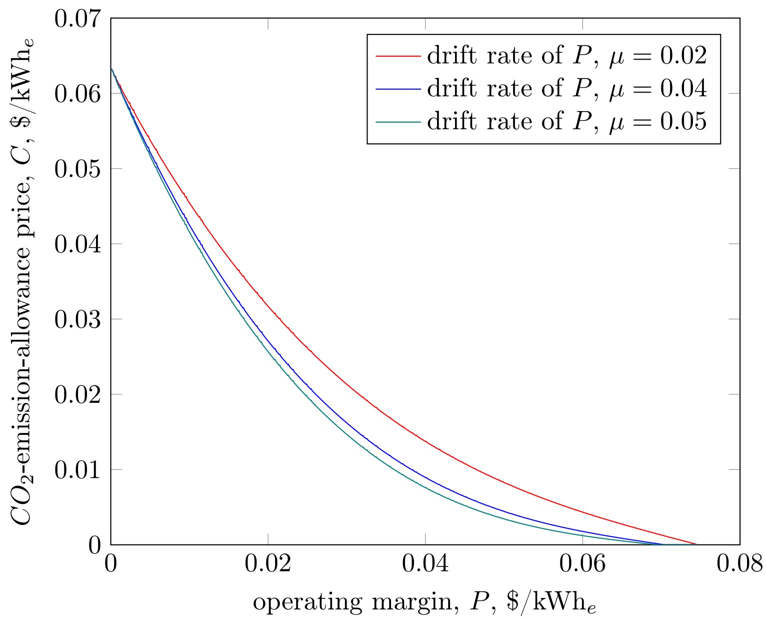


Figure 16: Sensitivity of Optimal Investment Decision in a HCC under Policy Regime 1 and GTE not Profitable, to Drift Rate of Operating Margin.

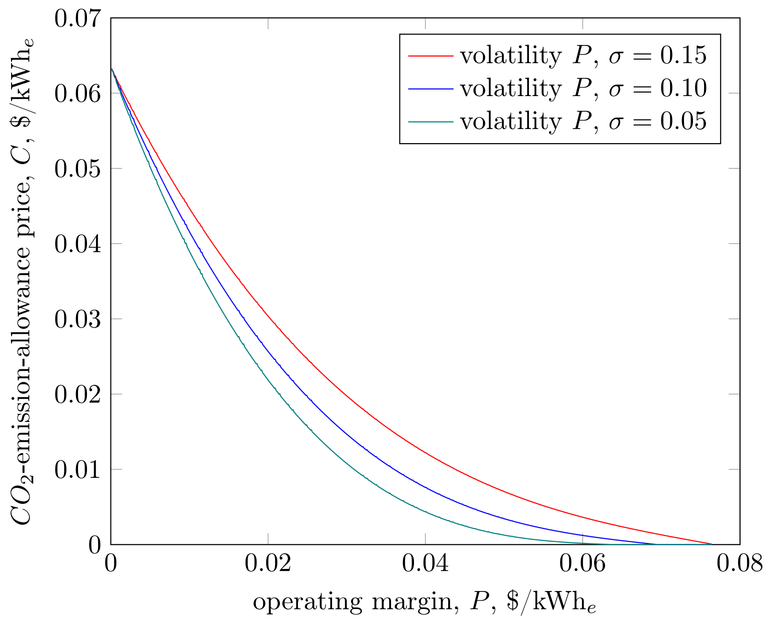


Figure 17: Sensitivity of Optimal Investment Decision in a HCC under Policy Regime 1 and GTE not Profitable, to Volatility of the Operating Margin

6. Discussion

This paper presents the analysis of investment decisions in technologies that allow a power generator to meet emissions targets. The decision to invest in these technologies is analyzed in three time frames that correspond to: (i) the time to an intermediate CO_2-emissions-reduction target, (ii) 2050 CO_2-emissions-neutrality target, and (iii) any moment in time after reaching CO_2-emissions neutrality. For the first two time frames, the decision to invest is analyzed under two possible policy regimes. Firstly, we analyze the investment decisions in the case where emissions targets are voluntary and failure to reach them has no firm-level consequences. Secondly, we analyze investment decisions in the case that the emissions targets are binding, and failing to reach them leads to a penalty of a proportional reduction of profit.

The investment decisions are studied with a real-option approach. This approach accounts for uncertainty and the irreversible nature of the investments. Results of the analyses are thresholds expressed as a minimum or maximum operating margin. The rational power generator would invest when the thresholds are attained. Investment thresholds are sensitive to the available alternative technology options, investment parameters (e.g., cost of a technology), and to uncertainty parameters, such as the volatility of the market. In specific cases, we find that the availability of multiple options could cause the power generator to delay emissions-reducing investments. Hence limiting investment options could speed up emissions reductions. When faced with fewer options the firm is less hesitant to invest in CO_2-neutral technologies. However, limiting investment options may also drastically postpone investments in CO_2-neutral technologies.

We find that the investment thresholds change significantly under different policy regimes. Therefore, the policymaker can have a significant influence over investment thresholds. A possible approach is to levy a fee on CO_2-intensive technologies (or CO_2 emissions) and / or subsidize CO_2-reducing or neutral technologies. However, policymakers typically prefer not to impose higher tax rates, and subsidizing technology investments can be expensive. Moreover, incentive payments are typically limited in time by political and budgetary reasons. The possibility of retraction can severely disrupt the market and alter intended incentives [18].

Alternatively, policymakers can define future policy regimes that tie consequences to the failure of reaching CO_2-emissions targets. We find that this approach affects investment decisions significantly. If defined unambiguously, without any uncertainty, and credibly, setting out future policy implementations could therefore be an important policy tool to facilitate a transition to zero-CO_2 emissions [7].

Essential however, to ensure the future policies in eliciting early investments in CO_2-reducing or neutral technologies, is the credibility of the policymaker in actually implementing the announced policies. Taking our case study as an example, if the power generator does not believe the second policy regime (profits taxed away) will be in effect after missing the emissions targets, announcing this future policy today will have no or minimal impact on investment thresholds.

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Appendix A. Derivations

Appendix A.1. Derivations of section 3.1

If $P = 0$, the generator is indifferent between investing in access facilities to CO_2-neutral hydrogen or waiting, when the following holds:

$$\frac{\alpha(\delta - C)}{r} = -I_1.$$

It is a matter of rewriting to find - for any level of P - that the generator invests immediately in access facilities to CO_2-neutral hydrogen if:

$$\alpha\frac{C-\delta}{r} - I_1 \geq 0,$$

and that the generator will invest later if:

$$\alpha\frac{C-\delta}{r} - I_1 < 0.$$

Before investing, the return on the value of the option, $F(P)$, over the time-interval dt is equal to the amortisation over that same interval:

$$E\left(dF(P)\right) = rF(P)dt.$$

At some level of P, $P^*_{\tau_{01}}$, it is optimal to invest in access facilities to CO_2-neutral hydrogen. At this level of P, the expected value of the investment equals the option value. The threshold value, $P^*_{\tau_{01}}$, is found by expanding dF according to Ito's Lemma:

$$E(dF(P)) = \mu PF'(P)dt + \frac{1}{2}\sigma^2 P^2 F''(P)dt.$$

Substituting yields the following differential equation:

$$\frac{1}{2}\sigma^2 P^2 F''(P) + \mu PF'(P) - rF(P) = 0.$$

The solution to this differential equation has a functional form $A_{01}P^{\beta}$, for which A_{01} and β are constants. Filling out this functional form yields a quadratic equation:

$$\frac{1}{2}\sigma^2\beta(\beta-1) + \mu\beta - r = 0.$$

The quadratic equation has two solutions for β. To avoid confusion concerning the subscript, we call the solutions β and γ. Consequently, the functional form has to be rewritten as $A_{01}P^{\beta} + B_{01}P^{\gamma}$, where B_{01} is also constant. The solution for β and γ is given by:

$$\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}};$$

$$\gamma = \frac{1}{2} - \frac{\mu}{\sigma^2} - \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}},$$

$\beta > 1$ and $\gamma < 0$.

We constrain the solution to this differential equation by setting three boundary conditions. The first condition states that the option is worth zero if P is zero (the value zero is a GBM's absorbing barrier). Condition 2 states that when $P^*_{\tau_{01}}$ is reached, the value of the option must be equal to the NPV (value-matching). The third and last condition states that an optimality is characterized by a tangent point between the option value and NPV (smooth-pasting).

1. $F(0) = 0$
2. $F(P^*_{\tau_{01}}) = \frac{\alpha P^*_{\tau_{01}}}{r-\mu} - \frac{\alpha(\delta - C)}{r} - I_1$
3. $F'(P^*_{\tau_{01}}) = \frac{\alpha}{r-\mu}$

Provided that γ is negative, the first boundary condition teaches us that B_{01} must be zero. Therefore, the simplified solution is:

$$F(P^*_{\tau_{01}}) = A_{01} P^{*\beta}_{\tau_{01}}.$$

After substituting, a solution for $P^*_{\tau_{01}}$ is found.

$$A_{01} = \left(\frac{\alpha P^*_{\tau_{01}}}{r-\mu} - \frac{\alpha(\delta - C)}{r} - I_1 \right) \frac{1}{P^{*\beta}_{\tau_{01}}}$$

$$P^*_{\tau_{01}} = \frac{r-\mu}{\beta\alpha - \alpha} \beta \left(\frac{\alpha(\delta - C)}{r} + I_1 \right)$$

We can now formulate the value of the power generator when GTE is not profitable. However, if GTE is profitable, the value is different, the investment region is disconnected and the option value no longer starts in the origin. In that case the first boundary condition does not apply and B_{01} is not per se zero. Therefore, the following system of equations represents value-matching and smooth-pasting conditions:

1. $A_{01,03} P^{*\beta}_{\tau_{01}} + B_{01,03} P^{*\gamma}_{\tau_{01}} = \alpha \left(\frac{P^*_{\tau_{01}}}{r-\mu} - \frac{\delta - C}{r} \right) - I_1$
2. $A_{01,03} \beta P^{*\beta}_{\tau_{01}} + B_{01,03} \gamma P^{*\gamma}_{\tau_{01}} = \alpha \frac{P^*_{\tau_{01}}}{r-\mu}$
3. $A_{01,03} P^{*\beta}_{\tau_{03}} + B_{01,03} P^{*\gamma}_{\tau_{03}} = \frac{\eta - (\delta - C)}{r} - I_3$
4. $A_{01,03} \beta P^{*\beta}_{\tau_{03}} + B_{01,03} \gamma P^{*\gamma}_{\tau_{03}} = 0$

The parameters $A_{01,03}$, $B_{01,03}$, $P^*_{\tau 01}$, and $P^*_{\tau_{03}}$ solve the system of equations. Although there is no analytical representation, we provide a numerical solution for the case study.

If policy regime 2 holds, the perpetual opportunity cost of investing under policy regime 1 is substituted by θ and κ. We elaborate on the investment analysis in access facilities to CO_2-neutral hydrogen if GTE is not profitable. The second boundary condition at $t \leq \zeta$ becomes:

$$F(P^*_{\tau_{01}}) = \frac{\alpha P^*_{\tau_{01}}}{r-\mu} - \theta - I_1.$$

Therefore, $A_{01,t}$ and $P^*_{\tau_{01}}$ are found to be:

$$A_{01,t} = \left(\frac{\alpha P^*_1}{r-\mu} - \theta - I_1 \right) \frac{1}{P^{*\beta}_{\tau_{01}}};$$

$$P^*_{\tau_{01}} = \frac{r-\mu}{\beta\alpha - \alpha} \beta \left(\theta + I_1 \right).$$

Note that for this specific example κ is not taken into account. That is because blending CO_2-neutral hydrogen with natural gas reduces CO_2 emissions by 25%. Therefore, after $t = \zeta$, the opportunity cost for this specific example is zero, and κ does not impact the investment decision.

Appendix A.2. Derivations of section 3.2

If an investment in GTE is never profitable, the boundary conditions to the solution of the previously introduced differential equation are:

1. $F(0) = 0$

2. $F(P^*_{\tau_{12}}) = \frac{(1-\alpha)P^*_{\tau 12}}{r-\mu} - \frac{(1-\alpha)(\delta-C)}{r} - I_2$

3. $F'(P^*_{\tau_{12}}) = \frac{1-\alpha}{r-\mu}$

A_{12} and $P^*_{\tau_{12}}$ are found similarly as in Appendix A.1.

If an investment in GTE could be profitable, the boundaries to the waiting interval $P^*_{\tau_{13}}$ and $P^*_{\tau_{12}}$ are found by numerically solving the following system of equations:

1. $A_{12,13}P^{*\beta}_{\tau_{12}} + B_{12,13}P^{*\gamma}_{\tau_{12}} = (1-\alpha)\left(\frac{P^*_{\tau 12}}{r-\mu} - \frac{\delta-C}{r}\right) - I_2$

2. $A_{12,13}\beta P^{*\beta}_{\tau_{12}} + B_{12,13}\gamma P^{*\gamma}_{\tau_{12}} = \frac{(1-\alpha)P^*_{\tau 12}}{r-\mu}$

3. $A_{12,13}P^{*\beta}_{\tau_{13}} + B_{12,13}P^{*\gamma}_{\tau_{13}} = \frac{\eta-(1-\alpha)(\delta-C)}{r} - \frac{\alpha P^*_{\tau 13}}{r-\mu} - I_3$

4. $A_{12,13}\beta P^{*\beta}_{\tau_{13}} + B_{12,13}\gamma P^{*\gamma}_{\tau_{13}} = \frac{-\alpha}{r-\mu}P^*_{\tau_{13}}$

If policy regime 2 holds, the perpetual opportunity cost of investing under policy regime 1 is substituted by θ and κ. We elaborate on the investment analysis in a HCC in case GTE is not profitable. The second boundary condition at $\zeta \leq t \leq \epsilon$ becomes:

$$F(P^*_{\tau_{12}}) = \frac{(1-\alpha)P^*_{\tau_{12}}}{r-\mu} - \kappa - I_2.$$

Therefore, $A_{t_{12}}$ and $P^*_{\tau_{12}}$ are found to be:

$$A_{t_{12}} = \left(\frac{(1-\alpha)P^*_{\tau_{12}}}{r-\mu} - \kappa - I_2\right)\frac{1}{P^{*\beta}_{\tau_{12}}};$$

$$P^*_{\tau_{12}} = \frac{r-\mu}{\beta(1-\alpha)-(1-\alpha)}\beta\left(\kappa + I_2\right).$$

Note that $A_{t_{12}}$ is now also time-dependent. For this specific example θ is not taken into account. That is because blending CO_2-neutral hydrogen with natural gas reduces CO_2 emissions by 25%. Therefore, when $\zeta \leq t \leq \epsilon$, the opportunity cost for this specific example is zero, and only κ impacts the investment decision.

Appendix A.3. Derivations of section 3.3

Boundary conditions to the solution of the previously introduced differential equation when switching to a HCC are:

1. $F(0) = 0$

2. $F(P^*_{32}) = \frac{P^*_{\tau 32}}{r-\mu} - \frac{\eta}{r} - I_1 - I_2$

3. $F'(P^*_{\tau_{32}}) = \frac{1}{r-\mu}$

Boundary conditions to the solution of the differential equation when switching to GTE are:

1. $F(0) = 0$

2. $F(P^*_{23}) = \frac{\eta}{r} - \frac{P^*_{\tau 23}}{r-\mu} - I_3$

3. $F'(P^*_{\tau_{23}}) = \frac{-1}{r-\mu}$

Appendix B. Supplemental Sensitivity Results

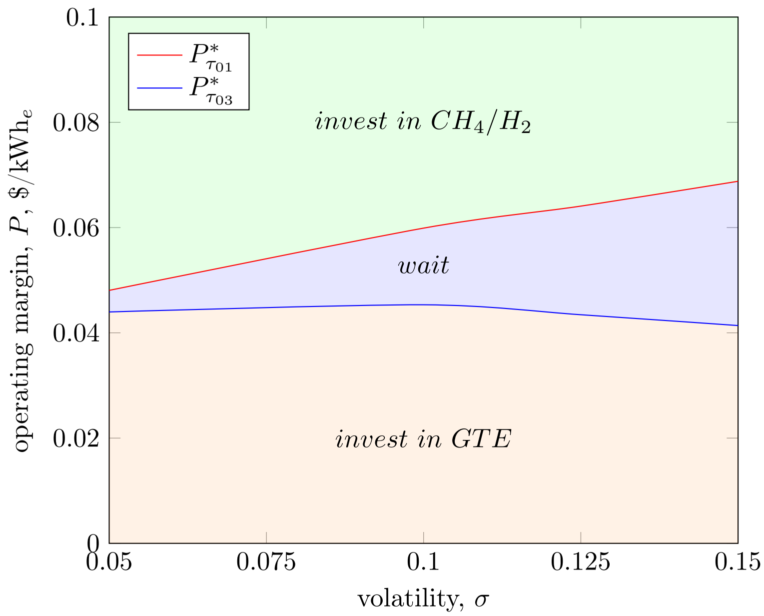

Figure Appendix B.1: Sensitivity Optimal Investment Decision in GTE or in Access Facilities to CO_2-neutral Hydrogen under Policy Regime 2. (Relates to fig. 5.)

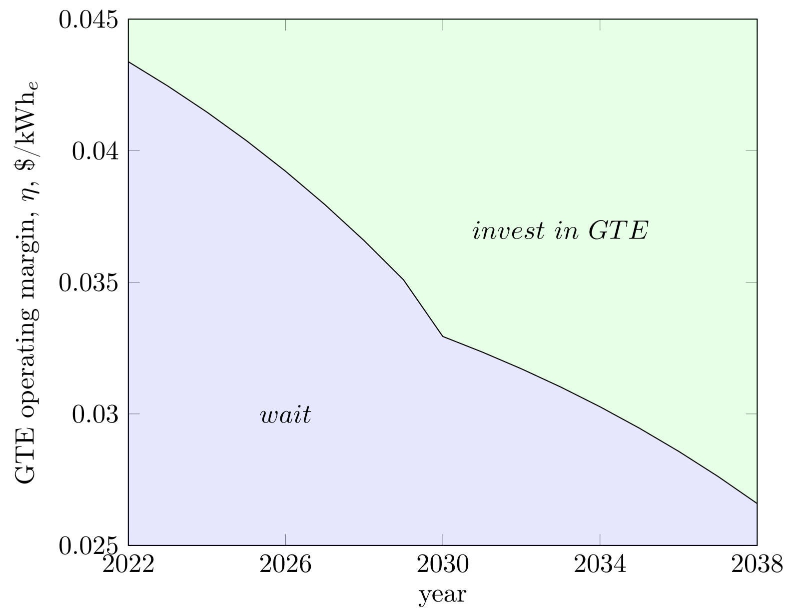

Figure Appendix B.2: Required Operating Margin for GTE to be Profitable.

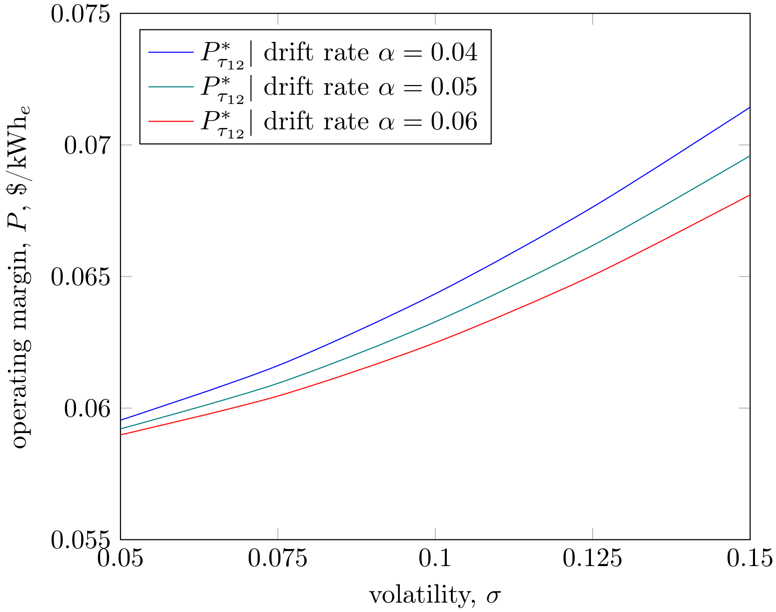

Figure Appendix B.3: Sensitivity of the Investment Threshold, $P^*_{\tau_{01}}$, to Uncertainty Parameters for an Investment in a HCC under Policy Regime 1 and GTE not Profitable. (Relates to fig. 8.)

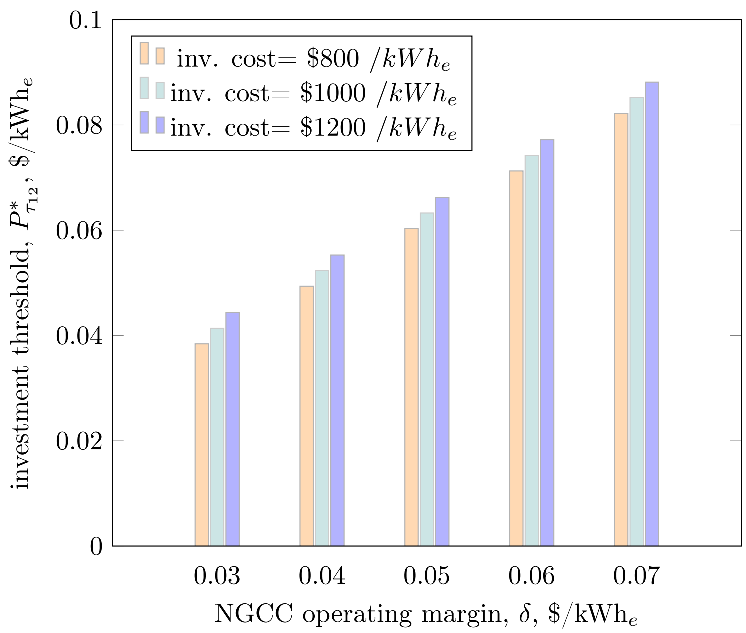

Figure Appendix B.4: Sensitivity of the Investment Threshold, $P^*_{\tau_{12}}$, to Investment Parameters for an Investment in a HCC and GTE not Profitable. (Relates to fig. 8.)

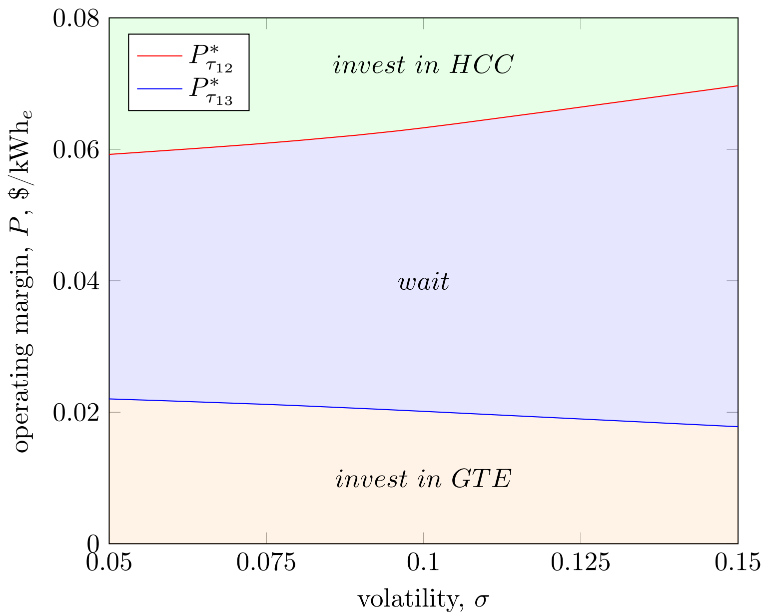

Figure Appendix B.5: Sensitivity Optimal Investment Decision in GTE or a HCC under Policy Regime 2. (Relates to fig. 9.)

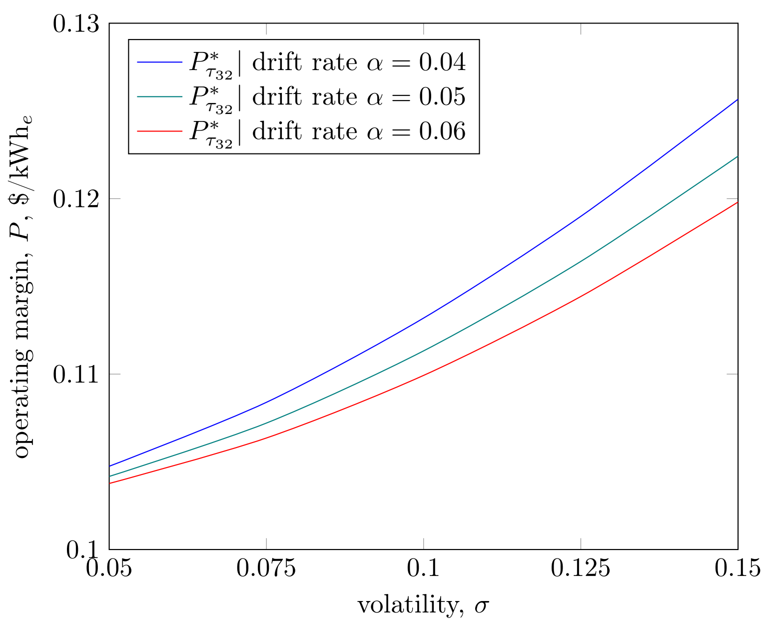

Figure Appendix B.6: Sensitivity of the Investment Threshold, $P^*_{\tau_{32}}$, to Uncertainty Parameters for an Investment in a HCC (and Access Facilities to CO_2-neutral Hydrogen). (Relates to fig. 12.)

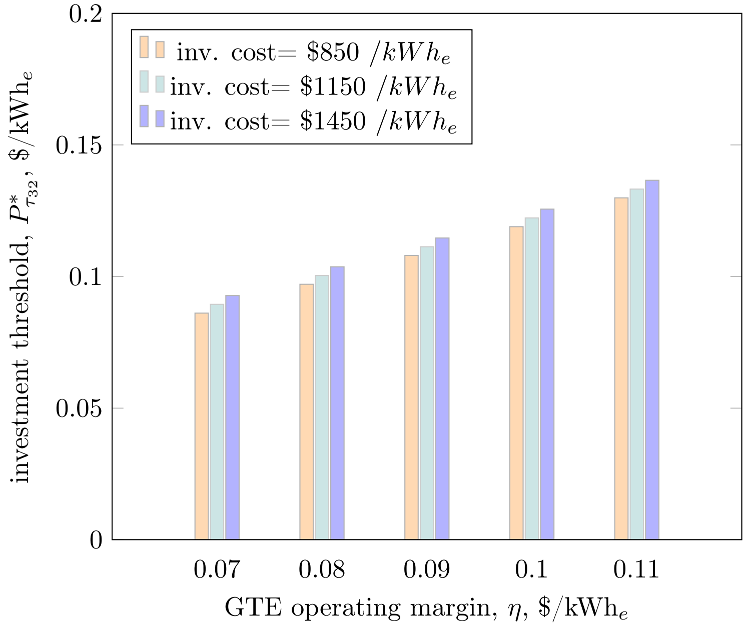

Figure Appendix B.7: Sensitivity of the Investment Threshold, $P^*_{\tau_{32}}$, to Investment Parameters for an Investment in a HCC (and Access Facilities to CO_2-neutral Hydrogen). (Relates to fig. 12.)

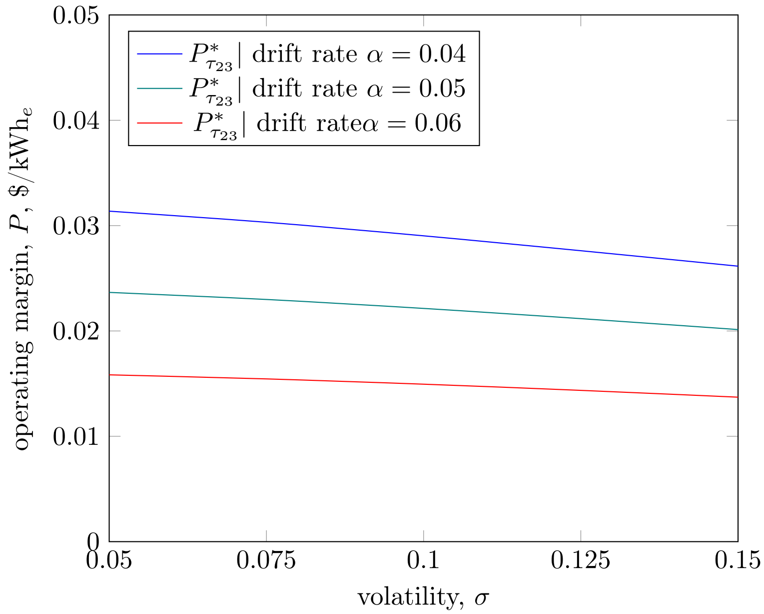

Figure Appendix B.8: Sensitivity of the Investment Threshold, $P^*_{\tau_{23}}$, to Uncertainty Parameters for an Investment in GTE. (Relates to fig. 13.)

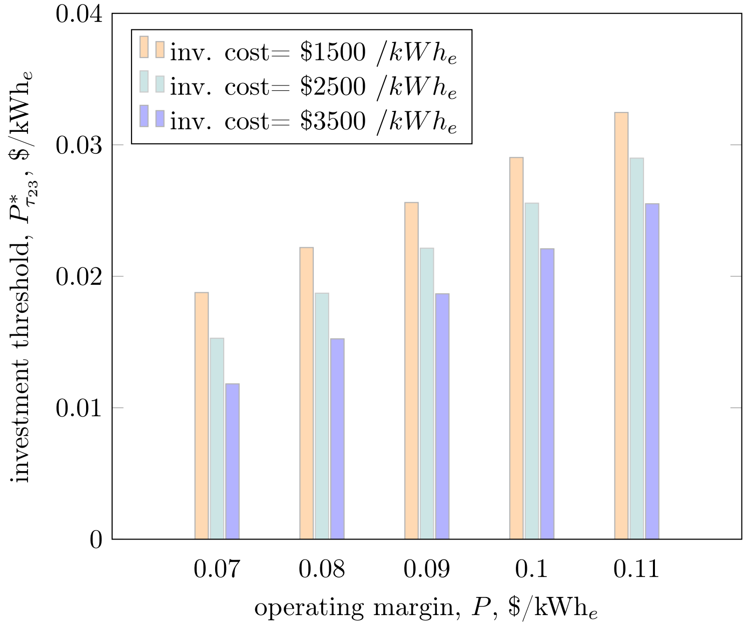

Figure Appendix B.9: Sensitivity of the Investment Threshold, $P^*_{\tau_{23}}$, to Investment Parameters for an Investment in GTE. (Relates to fig. 13.)