

Barriers to efficient carbon pricing: policy risk, myopic behaviour, and financial constraints

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Abstract

We investigate the limitations of cap-and-trade systems as a tool for driving investments in low-carbon industrial technologies. Investments may be delayed, and suboptimal technology choice may result from myopic behaviour, financial constraints, and policy risk. We develop a partial equilibrium model that explicitly incorporates such imperfect behaviour in cap-and-trade systems. We evaluate how these imperfections influence the carbon price signal and their subsequent impact on irreversible investment decisions of industries. We find that such imperfections can distort carbon price trajectories, leading to suboptimal technology choice and delayed investments in low-carbon technologies. Vice versa, imperfect behaviour of investors due to other external factors may influence the carbon price trajectory if the group of affected agents is sufficiently large to influence carbon prices. The results indicate a need for complementary policy instruments to address these carbon market imperfections. To better align model outcomes with the reality of carbon markets, we advocate that modellers use techniques that capture imperfect market behaviour.

Keywords: Emission trading, EU ETS, Rolling horizon, Myopic behavior, Decarbonization, Liquidity constraint, Industrial investments

1. Introduction

Carbon pricing is a necessary component in environmental policy, designed to internalise the social costs of carbon emissions by making polluters pay for the damage they cause (Stavins, 2022). Although the principle of carbon pricing is widely accepted, its implementation remains a topic of considerable debate and continues to be a central question in climate policy.

In theory, emission prices in a cap-and-trade system follow Hotelling's rule, which describes the optimal price and extraction path of a finite resource. (Hotelling, 1931) Because emission trading schemes usually allow for banking— that is, saving unused emission allowances for future use— participants can arbitrage the use of emission certificates over time. This implies that market participants estimate long-term abatement costs and plan their emissions accordingly over time to maximise value (Perino and Willner, 2016; Bruninx et al., 2020). They weigh the benefit of emitting less today against the expected future value of unused allowances, which is discounted at their cost of capital. In equilibrium, this intertemporal optimisation leads to a price path that increases at

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the discount rate, eventually converging toward the expected long-term marginal abatement cost. Long-term emission price models such as Perino and Willner (2016); Bruninx et al. (2020) assume rational behaviour and perfect foresight on future abatement costs.

However, empirical evidence suggests that short-term fluctuations in emission prices tend to reflect short-term effects rather than long-term abatement costs and that banking does not occur at the cost-optimal level (Bastianin et al., 2024; Sitarz et al., 2024). The disconnect between empirical observations and long-term models may be attributed to several imperfections in emission trading schemes that hinder their effectiveness. Investors are likely myopic and focus on short-term price signals rather than long-term expectations and may delay investments in low-carbon technologies (Sitarz et al., 2024). Furthermore, financial constraints can limit the ability of industrial actors to purchase emission allowances in advance for their planned emissions. Risk markets for emission allowances could be incomplete due to financial constraints (e.g., insufficient cash reserves) that limit the risk-taking ability of financial institutions (Tietjen et al., 2021; Acharya et al., 2013). These factors create inefficiencies that challenge the optimal functioning of carbon pricing mechanisms and will be further discussed in Section 2

To investigate how such imperfections might affect the efficiency of the carbon market, we develop and employ a partial equilibrium model that captures this imperfect behaviour in the EU Emission Trading Scheme (EU ETS), namely myopic behaviour and financial constraints. Furthermore, we consider the impact of increased policy risk on carbon markets. These effects may lead to a carbon price that fails to minimise abatement costs over the scheme’s duration. We refer to this deviation from a cost-minimising price trajectory as an *imperfect carbon price*. Abatement costs can be decreased by alleviating financial constraints or by complementing the imperfect carbon price with other instruments. We evaluate the *carbon price efficiency*, which we define as how well the price trajectory, if followed, minimises abatement costs compared to perfect foresight.

In the second part of the paper, we analyse the impact that the imperfections have on investment decisions in industrial investments, which have to be based on the imperfect carbon price. Specifically, we will explicitly represent investment decisions in zero-emission industrial technologies, which will be referred to as *green industrial investments* throughout this paper. This representation is necessary to capture the persistent, often irreversible nature of industrial investments and the potential for technological lock-in. We will conduct a case study on the decarbonisation of the EU steel industry to illustrate these effects.

We contribute to this body of literature by showing how imperfect behaviour leads to suboptimal banking and can deter the efficiency of emission trading schemes. Furthermore, we quantitatively assess how imperfect behaviour of industrial investors can lead to the postponing of investments and suboptimal technology choice, and consequently, how this changes the demand for emission allowances.

The remainder of the paper is structured as follows. In Section 2, we summarise the criticisms on cap-and-trade systems related to the topic at hand. We cover regulatory uncertainty and imperfect economic behaviour in cap-and-trade systems. Subsequently, the methodology is described in Section 3. In Section 5, the results are shown, and in Section 6, they are discussed. Section 7 concludes.

2. Relevant literature

This work connects to three strands of literature. First, it builds on contributions highlighting how regulatory uncertainty undermines the credibility of carbon pricing and creates commitment problems that deter low-carbon investments. Second, it engages with research on the behavioural limitations of market actors in cap-and-trade systems, which affect trading behaviour and market outcomes. Third, it relates to literature on irreversible industrial investment decisions.

2.1. *Regulatory uncertainty affects carbon pricing*

Although carbon pricing is often seen as the theoretical benchmark, it has been criticised as an imperfect climate policy for various reasons. A first group of criticisms relates to the dynamic that carbon pricing creates between the policymaker and the regulated entities. Firstly, there is a perceived lack of credible commitment of policymakers to their climate ambition, which is needed to trigger the required investments (Chiappinelli and Neuhoff, 2020). Investment hold-up is a risk in the absence of a persistent commitment to the set climate policy.¹ In essence, policymakers only need to create expectations of a high carbon price to increase emissions abatement, but are incentivised to back down after investment has occurred. Industrial investors would tend to discount the carbon price due to this risk, leading to delays in investments. According to Stiglitz (2019), this time-inconsistency is one of the reasons why it can be beneficial to complement a carbon price with additional policies. However, there is a trade-off between the need to create a persistent commitment and allowing flexibility to change the policy to potential learning in abatement technologies and climate damages (Brunner et al., 2012).

Secondly, carbon pricing is susceptible to failure of collective action in the common interest, since it is harder for the large group of beneficiaries of the policy – society – to organise against the concentrated entities that will bear the consequences. This makes it easier for the latter to influence policymakers in their interest (Tvinnereim and Mehling, 2018; Olson, 1965). Furthermore, carbon pricing is susceptible to regulatory capture (Tvinnereim and Mehling, 2018; Stigler, 1971).²

2.2. *Imperfect behaviour of actors in cap-and-trade systems*

A second strand of literature relates to behavioural aspects of the regulated entities. Financial and compliance actors active in cap-and-trade systems tend to show myopic behaviour (Sitarz et al., 2024), in part as a consequence of the aforementioned regulatory uncertainty, but also due to shareholder pressure and management structure (Agarwal et al., 2018). Quemin and Trotignon (2021) present evidence suggesting that compliance actors on cap-and-trade systems indeed have limited foresight. One example is a 2014 survey in which 30% of correspondents expected the EU ETS to no longer exist in 2020 (Nordeng et al., 2014). Compliance actors consider their cap-and-trade system activities as an operational expense: they hedge by banking emission allowances for production sales they already committed to, but tend to decrease that activity for sales further in the future. For example, power companies typically cover about 80% of next year's forward

¹The hold-up problem refers to a situation in which two parties are committing to a contract that requires a high up-front investment by one party, and the other has the incentive to renegotiate that contract for the value of that commitment.

²Regulatory capture refers to a situation in which regulatory agencies serve the interests of the industry they are meant to oversee, rather than the public interest. This can result from lobbying, revolving-door employment, or information asymmetries that give regulated entities influence over policy outcomes.

electricity sales with banked allowances, but this coverage drops to around 20% for sales more than two to three years ahead (Quemin and Trotignon, 2021).

Financial actors may also be restricted in how much capital they are able to allocate to emission trading due to financial constraints (Tietjen et al., 2021; Acharya et al., 2013). To our knowledge, no quantitative work has investigated how such financial constraints affect emissions and prices in emission trading schemes.

2.3. Imperfect decision making in industrial investments

A sufficiently high carbon price – even an imperfect one – should attract investments in green industrial investments. However, the decisions of these investors might in themselves also be imperfect, potentially postponing investments. One crucial factor is uncertainty and how it interacts with the irreversible nature of investments. McDonald and Siegel (1986) shows how irreversibility and uncertainty interact to shape investment timing. Using a continuous-time stochastic model, they let both expected revenues and upfront costs follow random processes and derive a simple investment threshold rule. They show that when investment is irreversible, it can be optimal to delay until expected benefits substantially exceed costs – often by a factor of two – because waiting preserves the option to invest later when uncertainty has resolved. Dixit and Pindyck (1994) uses real-options theory to describe investments under uncertainty. Lamberts-Van Assche et al. (2023) applies real options theory to investments in carbon capture and storage (CCS) and carbon capture, utilisation and storage (CCUS). Bloom et al. (2007) test these ideas empirically using firm-level data from manufacturing. They find that heightened uncertainty significantly dampens firms’ immediate investment response to demand changes. Specifically, they show that firms in the top uncertainty quartile respond to demand shocks at roughly half the rate of those in the bottom quartile.

Besides rational economic reasons, there are behavioural effects which likely play a role in practice. Benartzi and Thaler (1995) describe how loss aversion may manifest as myopic behaviour. Specifically, they highlight how frequent performance assessment amplifies managers’ sensitivity to short-term losses. Though their study is rooted in financial markets, the same psychological mechanism can deter industrial decision-makers from committing to long-horizon, risky investment: short-term setbacks loom disproportionately larger than future gains. This bias can thus create under-investment in transformative – but initially uncertain – green technologies.

3. Methodology

We develop and apply a partial equilibrium model that shows investors’ decision-making in emission-reduction projects, based on an imperfect carbon price. The model captures two carbon market imperfections: financial constraints and myopic foresight. A rolling horizon optimisation is implemented to capture myopic foresight, and constraints on the banking behaviour are used to represent financial constraints. The third – increased policy risk – is captured by increasing the discount rate. An emission trading scheme is endogenously considered, consisting of one representative compliance actor (b_y^{Comp}) and a financial actor (b_y^{Fin}) that compete for a supply of emissions allowances (S_y) that decreases linearly over the years (y), as illustrated in Figure 1a. The model also allows for a particular sector to be explicitly modelled by considering industrial production agents that invest irreversibly in a set of technologies (Figure 1b). Production agents participate in the emission trading scheme, where they buy allowances for their emissions ($b_{a,y}^{\text{Prod}}$). The agents’

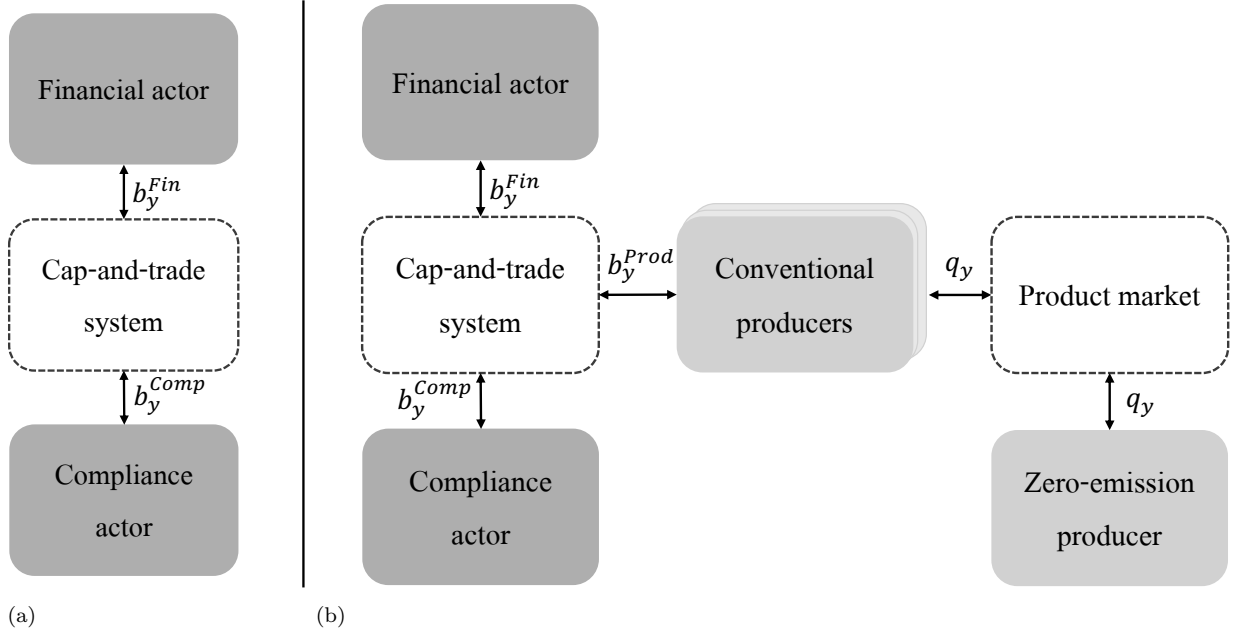


Figure 1. Model variants where (a) the compliance agent represents the entire abatement effort and (b) an industrial sector is explicitly modelled

actions on the cap-and-trade system are coordinated through the market coupling constraint (1) in every year y in the optimisation window \mathcal{Y} .

$$\forall y \in \mathcal{Y} : b_y^{\text{Comp}} + b_y^{\text{Fin}} + \sum_{\forall a \in \mathcal{A}_G} b_{a,y}^{\text{Prod}} = S_y \quad (p_y^{\text{ETS}}) \quad (1)$$

3.1. Compliance actors

All compliance actors are represented by a single representative agent with a quadratic abatement cost curve. In every optimisation window of the rolling horizon approach it minimises the discounted cost (at rate r with $A_y = (1+r)^{-y}$) of buying emission allowances b_y^{Comp} at a price of p_y^{ETS} for its emissions and bearing the abatement cost for its reductions in emissions with respect to its baseline emissions E_{ref}^{Comp} , as in Eq. (2). Banking is assumed to be prohibited for the compliance actors for interpretability, such that the banking function is exclusively assigned to the financial agent. This modelling choice does not influence the results. In reality, compliance actors might bank as well and take a role as financial actors.

$$\text{Min.}_{b_y^{\text{Comp}}} \sum_{y \in \mathcal{Y}} A_y \cdot p_y^{\text{ETS}} \cdot b_y^{\text{Comp}} + A_y \cdot \beta \cdot (E_{ref}^{\text{Comp}} - b_y^{\text{Comp}})^2 \quad (2)$$

s.t.

$$\forall y \in \mathcal{Y} : b_y^{\text{Comp}} \geq 0 \quad (3)$$

3.2. Financial actors

All allowance demand for hedging and long-term arbitrage on the EU ETS is represented as a single agent, which we refer to as *financial agent*. This agent is without actual emissions, yet has the ability to buy and sell emission allowances (b_y^{Fin}). It arbitrages by holding emission allowances in advance for years with higher carbon prices. The amount of allowances it holds, or total number of allowances in circulation (TNAC) in any given year, is described as in Eq. (5), where $TNAC_0$ accounts for allowances that are already in circulation at the start of the first optimisation window.³

It minimises the discounted cost of buying emission allowances as in Eq. (4), in every rolling horizon window. This actor's banking constraint, Eq. (5), is alleviated with the current TNAC value to account for allowances that are already in circulation. Borrowing is not allowed (Eq. (6)). The agents' limited capital is represented using Eq. (7), constraining the monetary value of its bank in all future years to that of the initial year. γ is a parameter that will be used to control the financial constraint.

$$\text{Min.}_{b_y^{\text{Fin}}} \sum_{y \in \mathcal{Y}} A_y \cdot p_y^{\text{ETS}} \cdot b_y^{\text{Fin}} \quad (4)$$

s.t.

$$\forall y \in \mathcal{Y} : TNAC_y = TNAC_0 + \sum_{y^*=1}^y b_{y^*}^{\text{Fin}} \quad (5)$$

$$\forall y \in \mathcal{Y} : TNAC_y \geq 0 \quad (6)$$

$$\forall y \in \mathcal{Y} : TNAC_y \cdot p_y^{\text{ETS}} \leq TNAC_0 \cdot p_0^{\text{ETS}} \cdot \gamma \quad (7)$$

$$\forall y \in \mathcal{Y} : b_y^{\text{Fin}} \text{ is free} \quad (8)$$

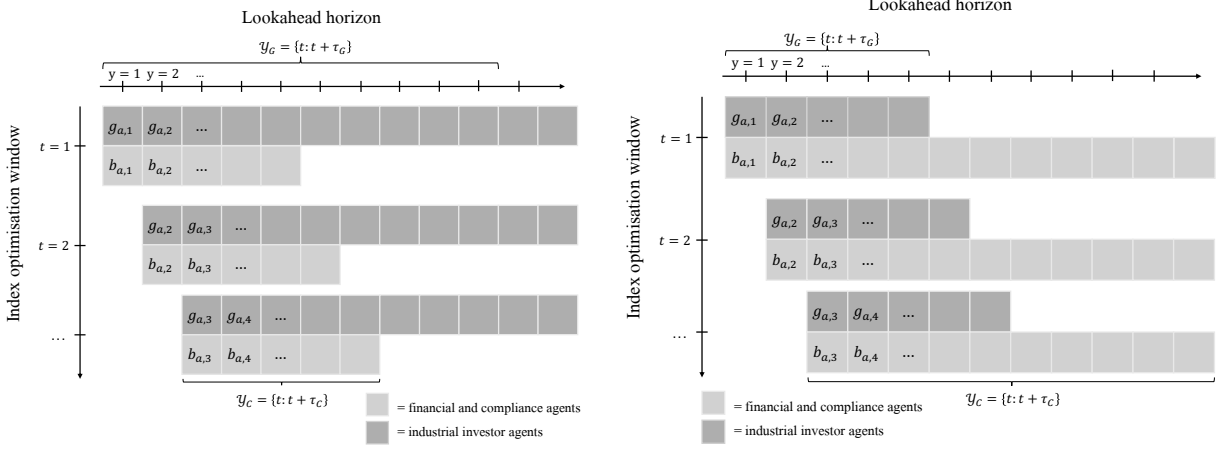
3.3. Industrial investors

In the second part of the paper, we extend the model to include industrial investors who have to base investment decisions on an uncertain and imperfect carbon price. Multiple agents ($\forall a \in \mathcal{A}_G$) compete in a market for a product (e.g., steel), each representing a single technology. The coupling constraint Eq. (9) determines the price for the considered final product p_y^G in each considered year for an inelastic demand D_y .

$$\forall y \in \mathcal{Y} : \sum_{a \in \mathcal{A}_G} q_{a,y} = D_y \quad (9)$$

Industrial investor agents make capital investments in production capacity $cap_{a,y}$. Each agent $\forall a \in \mathcal{A}_G$ maximises profit by producing a quantity $q_{a,y}$ of an industrial good, factoring in variable production costs $vc_{a,y}$, according to Eq. (10), in every optimisation window of the rolling horizon approach. Emission allowances are purchased ($b_{a,y}^{\text{Prod}}$), for the resulting emissions, based on the carbon intensity CI of the technology (Eq. (11)), but they cannot bank. Production $q_{a,y}$ is limited

³Since this agent represents all banking behaviour in the cap-and-trade system, its bank corresponds to the TNAC



(a) Imperfect carbon price

(b) Imperfect investments

Figure 2. Rolling horizon implementation with different lookahead in different markets

to the available installed capacity (Eq. (12)) and $cap_{a,y}$ and $q_{a,y}$ are non-negative (Eqs. (13),(14)).

$$\begin{aligned} \forall a \in \mathcal{A}_G : \quad & \text{Max.} && - \sum_{y \in \mathcal{Y}} A_y \cdot IC \cdot cap_{a,y} \\ & q_{a,y}, b_{a,y}^{\text{Prod}}, cap_{a,y} && \\ & + \sum_{y \in \mathcal{Y}} A_y ((p_y^G - vc_{a,y}) \cdot q_{a,y} - p_y^{\text{ETS}} \cdot b_{a,y}^{\text{Prod}}) && \end{aligned} \quad (10)$$

s.t.

$$\forall a \in \mathcal{A}_G, \forall y \in \mathcal{Y} : b_{a,y}^{\text{Prod}} \geq q_{a,y} \cdot CI \quad (11)$$

$$\forall a \in \mathcal{A}_G, \forall y \in \mathcal{Y} : q_{a,y} \leq \sum_{y^*=1}^y cap_{a,y^*} \quad (12)$$

$$\forall a \in \mathcal{A}_G, \forall y \in \mathcal{Y} : q_{a,y} \geq 0 \quad (13)$$

$$\forall a \in \mathcal{A}_G, \forall y \in \mathcal{Y} : cap_{a,y} \geq 0 \quad (14)$$

3.4. Rolling horizon

To model imperfect foresight, we implement a rolling horizon approach in which agents optimise their decisions over a limited forward-looking window—referred to as their lookahead horizon—which is shifted forward in time as the optimisation progresses. This allows us to model imperfect foresight, where agents do not plan over the full horizon but instead re-optimize sequentially based on updated information. Figure 2 illustrates this setup, showing how decision variables are optimised over overlapping time windows that roll forward by one year per optimisation window. Different agent types are assigned their lookahead horizon: τ_G for industrial producers and τ_C for financial and compliance actors. As shown in Figure 2, this means that at each time step t , industrial investors solve their optimisation problems over the window $\{t, : t + \tau_G\}$, while ETS participants optimise over $\{t : t + \tau_C\}$. Decisions for the current period are then fixed, and the window advances by one period. Note that agents that are more forward-looking need to make assumptions about

the decisions of the other, more myopic agents. We assume they have perfect foresight over the actions that the other agents end up making. How this is achieved is outlined in Appendix A.

3.5. Solution strategy

To solve this mixed complementarity problem, we use a price search algorithm based on Alternating Direction Methods of Multipliers (ADMM), following the approach of Boyd (2010), Höschle et al. (2018), and Bruninx et al. (2020). This algorithm iteratively determines the equilibrium prices for the emission and steel markets. We apply it using a rolling horizon approach inspired by Quemin and Trotignon (2021). The details on how we applied ADMM in a rolling horizon are described in Appendix A.

4. Case study

4.1. Overview cases

Table 1 shows an overview of the different cases considered. The first three cases serve as baseline variations to illustrate the individual effects of increased risk (through a higher discount rate), financial constraints (by restricting the capital available to financial actors via γ), and limited foresight (by shortening the lookahead horizon τ in the cap-and-trade system). Each of these cases includes only compliance and financial actors, and isolates one behavioural dimension while keeping others at their idealised levels.

The fourth case introduces a parametric sweep over different levels of capital availability ($\gamma \in [0.4, \infty]$), under a fixed myopic lookahead of 10 years in the emissions trading system. This allows investigation into how the strength of the financial constraint interacts with forward-looking behaviour. Similarly, changes to the foresight level while actors are constrained in capital are investigated in the fifth case.

In the final three cases, the steel sector is represented explicitly rather than as part of the aggregate compliance actor. This disaggregation is necessary to capture the persistent, often irreversible nature of capital investment decisions in hard-to-abate sectors, as well as the potential for technological lock-in. By modelling investment decisions directly, we can assess how imperfect foresight and distorted price signals affect long-term investment trajectories and their impact on the decarbonisation path. The *both imperfections* case combines limited foresight in both the carbon market (τ_C) and product market (τ_P), and is intended to reflect a more realistic industrial setting. However, because the results of this scenario reflect the interaction of multiple mechanisms, we also consider two isolating cases—one with imperfect carbon pricing only, and one with imperfect investment foresight only. These help disentangle the individual contributions of each imperfection and clarify how their combination gives rise to the observed behaviour under more realistic assumptions.

4.2. Data & assumptions

All cases have the following data regarding the emission trading system in common. The emission trading system resembles EU ETS. Emission trading is modelled from 2025 to 2060. In line with the current proposal, the emission supply linearly decreases with a linear reduction factor (LRF) of 4.3% until 2028 and 4.4% thereafter. We extrapolate the latter LRF beyond, reaching zero in 2039, although future reforms can change this value. Baseline emissions were based on verified 2023 emissions, which are the most recent officially released numbers at the time of writing. The

Table 1. Overview of the different cases. γ represents the level of financial restriction and τ the lookahead horizon in years in the steel and cap-and-trade systems.

Case	Param. values				Actors considered			Results Section
	γ	τ_C	τ_P	r	Compl. actor	Financial actor	Ind. actors	
Increased risk	∞	∞		9%	✓	✓		5.1
Financial constraint	1	∞		7%	✓	✓		5.1
Myopic foresight	∞	10		7%	✓	✓		5.1
Interactions with γ	[0.4.. ∞]	10		7%	✓	✓		5.2
Interactions with τ	1	[3.. ∞]		7%	✓	✓		5.2
Steel case - Imperfect carbon price	∞	[6.. ∞]	∞	7%	✓	✓	✓	5.3
Steel case - Imperfect investments	∞	∞	[6.. ∞]	7%	✓	✓	✓	5.3
Steel case - Both imperfections	∞	[6.. ∞]	[6.. ∞]	7%	✓	✓	✓	5.3

abatement cost curve was calibrated such that it results in an 80 EUR/tCO₂ for 2025.⁴ The initial TNAC is based on the reported 2023 value of 1111.7 Mt (EC, 2024). The functioning of the Market Stability Reserve (MSR) is not considered in this paper.

Finally, the case study on the steel industry considers industrial investors, comparing various emission-reducing technologies to the conventional blast furnace (BF) process: blending natural gas (NG) or hydrogen gas into existing blast furnaces, various CCS solutions, natural gas-based direct reduction of iron (NG-DRI), and hydrogen-based direct reduction of iron (H-DRI) technologies.

Each technology has different emission intensities and associated costs, as detailed in Table 2. We assume a virgin steel demand of 107 Mt/y that remains constant, based on European steel production in 2023, a recycling rate of 40% (EC, 2025), and sufficient blast furnace legacy capacity to produce these volumes.

We assume gas prices of 40 EUR/MWh, baseload electricity prices of 60 EUR/MWh, hydrogen prices of 166 EUR/MWh and iron ore prices of 100 EUR/t (Vogl et al., 2018). The blending technologies were assumed to have relatively low capital expenditures (CAPEX) because they represent retrofitting solutions; the CAPEX of the H-DRI route was based on Hüttel and Lehner (2024).

5. Results

The structure of the results section follows the case-study setup (Section 4.1). In Section 5.1, we analyse the impact of different behaviours of the financial actor on the carbon price in a case where only the compliance and financial actor are considered, hence, we do not consider investments. First, we analyse how financial constraints, myopic behaviour or increased risk limit the ability of financial actors to bank emission allowances, and how that affects the carbon price efficiency. In Section 5.2, we analyse the interactions when actors, in addition to being financially constrained, are myopic. The former four cases highlight how imperfect price signals are formed. We then move on to a case study in Section 5.3, which investigates what happens if industrial investors act upon an imperfect carbon price. The case considers steel manufacturers that have to base investment decisions on the imperfect carbon price and might be myopic themselves.

⁴We iteratively determined that $\beta = 0.1448$ results in current EU ETS prices for the steel sector cases and $\beta = 0.0989$ when the compliance agent represents all emissions.

Table 2. Emissions & energy requirements steel-making routes. *Retrofits: cost taken as 10% of the CAPEX of new blast furnaces

Technologies	BF	BF + H2 blending	BF + NG blending	BF + CCS	NG-DRI	NG-DRI + CCS	H-DRI
Coal (MWh/t _{steel})	5.2	4.485	4.32	5.2	0	0	0
Nat Gas (MWh/t _{steel})	0	0	1.005	0	2.37	2.37	0
H2 (MWh/t _{steel})	0	0.91	0	0	0	0	1.73
Electricity (MWh/t _{steel})	0.2	0.2	0.2	0.81	0.34	0.45	0.62
Iron Ore (t/t _{steel})	1.37	1.37	1.37	1.37	1.363	1.363	1.4
Scrap (t/t _{steel})	0.125	0.125	0.125	0.125	0.17	0.17	0.10
Direct Emissions (t _{CO2} /t _{steel})	1.7	1.36	1.59	0.51	0.80	0.22	0
CAPEX (EUR/t _{steel} /y)	1100	*110	*110	*128	870	1020	870
Legacy capacity (Mt _{steel} /y)	107	0	0	0	0	0	0

5.1. Imperfect behaviour on cap-and-trade systems

Recall from the introduction that long-term abatement models prescribe cap-and-trade systems to have an exponential price path following Hotelling’s rule. We use such a case under perfect foresight as the reference in this section. To illustrate the sensitivity of our results, we show the results for a central scenario and their range if we consider the baseline emissions Gaussian ($\sigma = 100$ Mt).

Figure 3 shows in the top row the results when a risk premium is introduced in the banking decision by the financial agent, reflecting increased policy risk. With a higher discount rate of 9%—compared to 7% in the benchmark—the agent requires a greater return to justify holding allowances. As a result, banking is reduced, and the bank depletes four years earlier. Emission prices are somewhat lower in the near term compared to the benchmark, and rise higher in the long term. As a result of this, the compliance actor’s (red) timing of the abatement deviates from the cost-optimal path (red dashed), leading to a 3.9% increase in total system costs compared to no risk premium (not shown in the Figure). This demonstrates that policy risk introduces efficiency losses due to the shift in the timing of emissions.

The second row of Figure 3 shows the model results when the look-ahead horizon is reduced to 10 years ($\tau_C = 10$) and banking is not constrained (solid line) with respect to the perfect foresight case (dotted line). The results show similar behaviour: banking will again not happen to the socially optimal amount, resulting in imperfect carbon prices. In this case, the resulting uncertainty on the bought emission certificates is smaller and hence also on the banked amount of certificates. This is because if agents are not sufficiently forward-looking, they do not react to the variations in the level of baseline emissions. Myopic behaviour effectively makes the market outcomes less sensitive with respect to long-term uncertainty. In the central scenario, emission prices are 15.5% lower in 2025 than in the perfect foresight case. The total abatement cost is 0.1% higher.

The third row of Figure 3 shows the model results when the financial actors are constrained such that the value of their banked emission allowances does not exceed the current monetary value of the TNAC ($\gamma = 1$) with an infinite horizon (solid line), with respect to the reference where capital is unconstrained (dotted line).

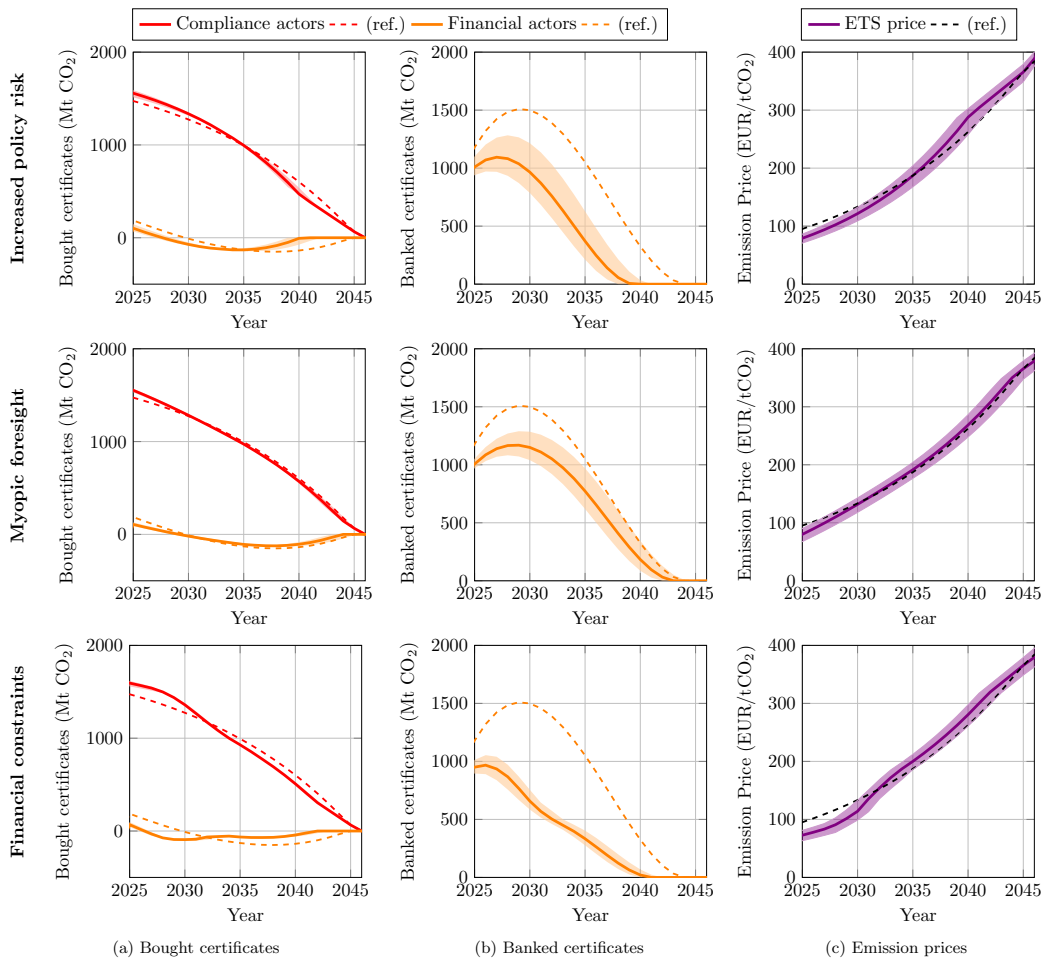


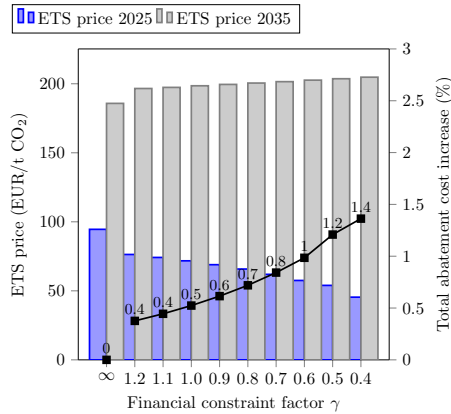
Figure 3. (a) shows the emission allowances bought by compliance and financial actors in three cases: increased policy risk (+2%), myopic foresight ($\tau_C = 10$) and financial constraint ($\gamma = 1$); for compliance actors, this equals their emissions. All cases reduce banking by financial actors (b) compared to the unconstrained case (dotted line), resulting in lower prices in 2025–2029 and higher prices after 2030 (c). Shaded areas reflect uncertainty from Gaussian baseline emissions.

5.2. Interactions of myopic behaviour and financial constraints

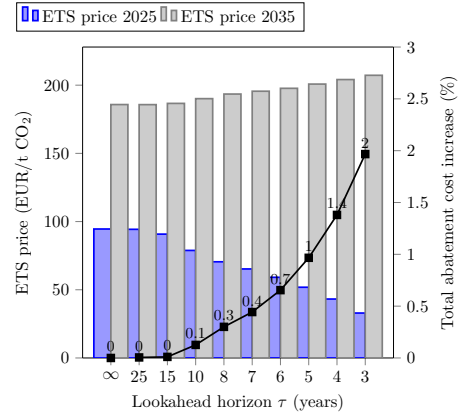
Figure 4a and 4b show the sensitivity to the financial constraints and lookahead horizon, when each is considered in isolation. Both effects can make actors underestimate the optimal carbon price in 2025 and consequently increase abatement costs by up to 2%.

Next, we will analyse the interactions between the different imperfect behaviours mentioned above. We will use an illustrative example that is calibrated on the assumption that the current value of the TNAC will not increase in the future – in other words, we assume banking is currently constrained ($\gamma = 1$). After that, we'll assume agents to have a lookahead horizon of $\tau = 10$ years. Abatement costs are calibrated such that they produce an emission allowance price of 80 EUR/tCO₂. We will then relax either one of those constraints to illustrate the impact that policies could have that either affects myopicness or financial constraints.

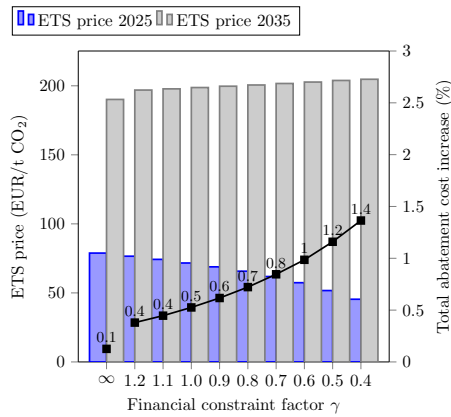
Figure 4c quantifies the impact of financial constraints in the presence of myopic behaviour. As financial constraints become less strict (γ increases), ETS prices align closer to the optimal



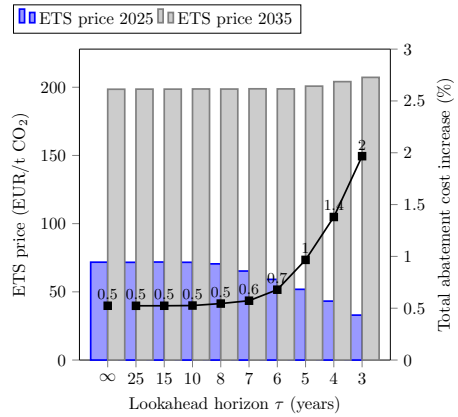
(a) Impact of financial constraints and $\tau = \infty$



(b) Impact of lookahead horizon and $\gamma = \infty$



(c) Impact of financial constraints and $\tau = 10$



(d) Impact of lookahead horizon and $\gamma = 1$

Figure 4. Impact of financial constraints and myopic behaviour on carbon pricing efficiency. It compares scenarios with (a) financial constraints, (b) myopic behaviour ($\tau = 10$), and their (c-d) combination, against idealised cases without such constraints and perfect foresight. Short-term price suppression leads to higher long-term prices and increased total abatement costs.

trajectory. Higher financial constraints (lower γ values) result in lower emission prices in 2025 but higher prices in 2035, and hence in increased total abatement costs over time. The non-linear relationship between γ and abatement costs underlines the impact of financial barriers on carbon price efficiency.

Figure 4d illustrates the impact of myopic behaviour in the presence of financial constraints. Our results underscore how myopia can decrease the efficiency of carbon pricing systems. Agents that become myopic can increase abatement costs, for example, a decrease in the look-ahead horizon from 5 to 3 years increases the abatement cost from 1.0% to 2.0%. The decrease in short-term prices can be rather significant with such a change in the lookahead horizon (-40%).

Current carbon prices would, in this specific situation, not be impacted by increasing the foresight of participants, since the financial constraint they face still prohibits them from banking more. Therefore, no improvement in the carbon price signal efficiency can be obtained in this case. This result emphasises that when multiple constraints influence banking behaviour, all must

be addressed to achieve efficiency improvements. This also explains the similarity between panel (a) and (c), since the availability of capital constrains the banking behaviour, the carbon price efficiency is not affected by whether the foresight level is (c) limited to 10 years or (a) perfect.

5.3. Postponement of industrial investments

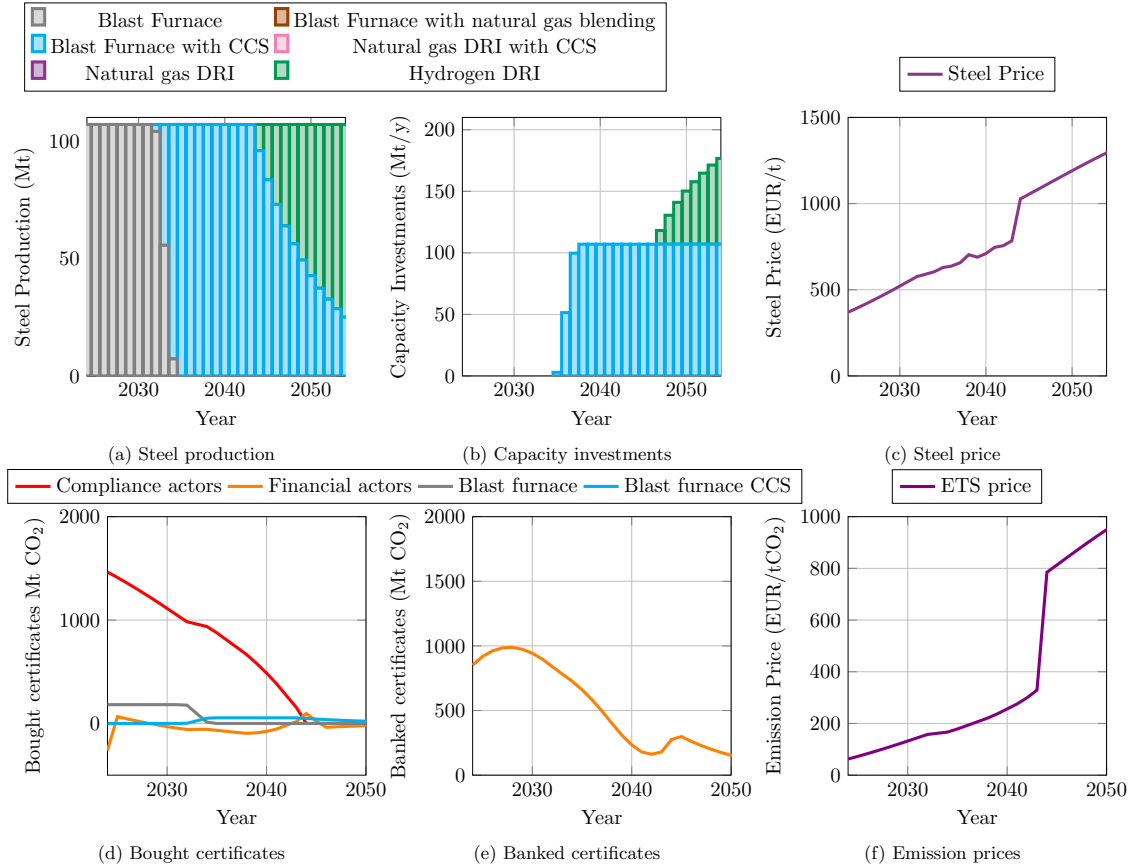


Figure 5. Steel industry with myopic investments. (a) displays annual steel production; (b) shows the cumulative capacity investments; (c) presents the resulting steel price (d) illustrates the emission certificates bought by compliance, financial, and emitting steel agents.

We now consider cases where investments in the steel industry are based on an imperfect carbon price signal and where steel investors themselves may be myopic. From this point forward, we will disregard any financial constraints. Figure 5 illustrates an example of such a case, where both the steel investors and financial agents act myopically ($\gamma = \infty, \tau_C = 10, \tau_P = 10$). Panel 5a shows how the annual steel production is replaced by H-DRI, driven by the rising carbon price (Figure 5f), and the role of the CCS solution as a transition technology in this case, while in the perfect foresight case, the BF technology is immediately replaced with H-DRI (not shown in Figure 5). Figure 5b shows the timing of the capacity investments to decarbonise the steel sector. The jump in the carbon price visible in Figure 5f can be explained by the CCS technology becoming price-setting in the EU ETS, this is however, a rather case-specific effect.

Figure 5d illustrates the emission certificates purchased by the financial actor and the emissions from steel technologies when banking by the financial actors is lowered (see Figure 5e). This exerts

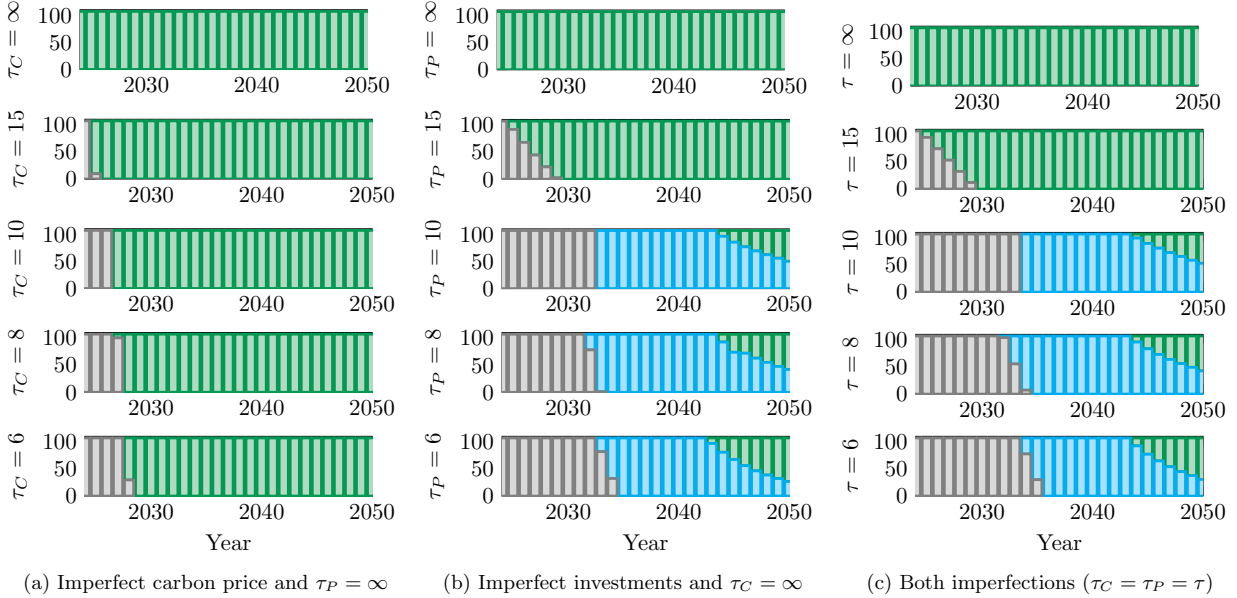
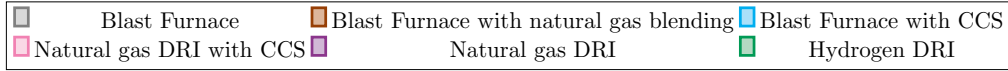


Figure 6. Steel production in Mt under (a) imperfect carbon prices, (b) myopic steel sector investments, and (c) both imperfections. Myopic investment decisions drive prolonged blast furnace use and lead to CCS adoption, which does not occur under perfect foresight.

downward pressure on emission prices in the early years by reducing demand for allowances and delays investments in H-DRI and extends the use of emission-intensive steel technologies (not shown in the Figure).

Next, we analyse perfect industrial investments on an imperfect price path, imperfect investment behaviour, whilst foresight is perfect in the cap-and-trade system, and a case with both imperfections. The top row in Figure 6 shows the reference case under perfect foresight for all actors. In this case, the model opts to invest immediately in H-DRI because in such a case where banking occurs to the optimal amount, emission prices are higher. All agents have foresight over the limited availability of emission allowances beyond 2040 and invest accordingly. In the first column, Figure 6 shows the cases where carbon prices are imperfect due to myopic behaviour by financial agents. Since this leads to lower price signals in the early years, it delays investment in low-carbon technologies. Conventional blast furnaces remain in use longer, even when cleaner alternatives would be cost-effective under perfect foresight. The effect is robust across different foresight levels within the steel sector, indicating that carbon price imperfections alone already skew investment away from the optimal path. Appendix B contains additional sensitivities to the input cost data that confirm this.

Figure 6b assumes perfect foresight for financial agents but myopic behaviour by steel producers. Here, the financial agent still arbitrages with perfect foresight, but steel investors fail to anticipate high future carbon prices. As a result, the shift away from blast furnaces is delayed, and CCS—absent in the perfect foresight case—enters the technology mix. This suggests that short-term outlooks can lead to the adoption of costlier or less effective technologies.

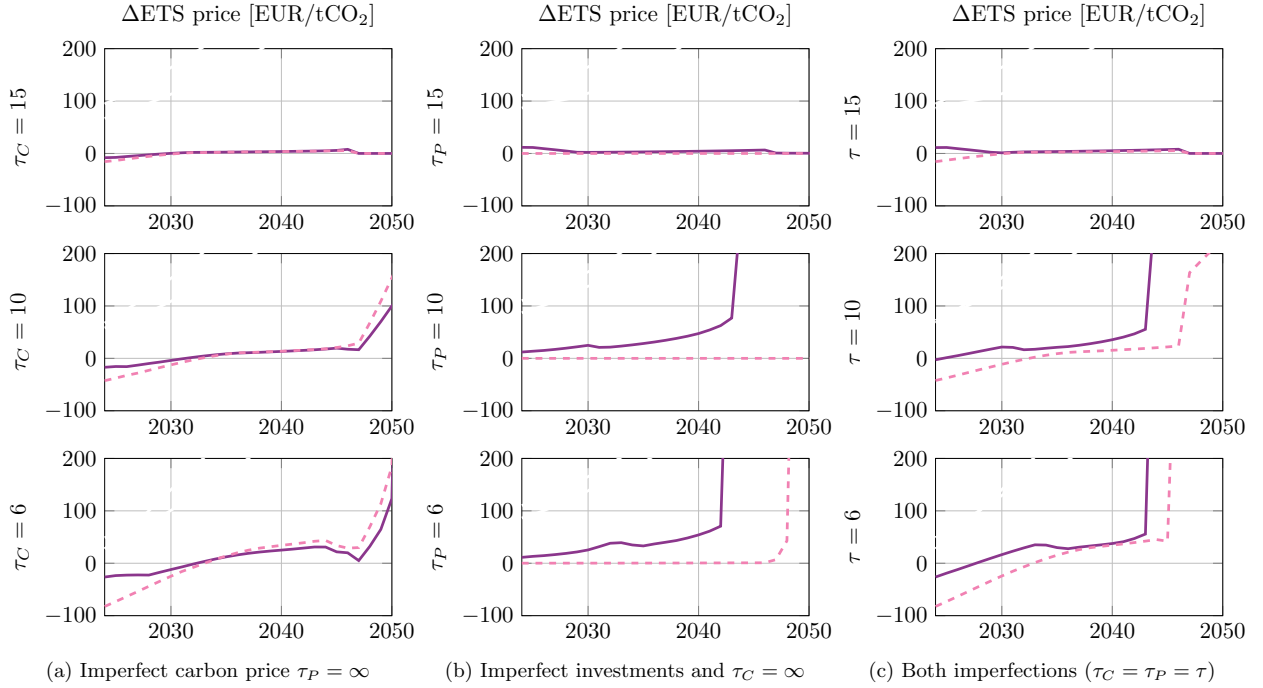


Figure 7. Changes in EU ETS prices w.r.t. perfect foresight under (a) imperfect carbon pricing, (b) myopic steel sector investments, and (c) both imperfections. Solid lines show the main case; dashed lines show a sensitivity with a small steel sector (1Mt/year). Myopic steel investments drive system-wide price effects only when the sector is large enough to impact allowance demand.

In Figure 6c both imperfections are combined. While outcomes deteriorate further, the effect is only marginally worse than in panel (b), indicating that investment myopia plays a larger role for the steel sector.

Knowing that myopic behaviour by industrial investors can lead to additional emissions in that sector, it raises the question to what degree it impacts the carbon price signal. Figure 7 follows the same structure (and imperfections as Figure 6), but now shows differences in price trajectories under imperfect carbon pricing, where financial agents are myopic (w.r.t. perfect foresight). Solid lines represent the main model run; dashed lines reflect a sensitivity in which the steel sector is small (1Mt/year). We add the latter to illustrate the outcome when the set of myopic investors is too small to have an effect on the carbon price itself. As discussed earlier, myopic behaviour depresses carbon prices in the early years and raises them in later years. The lowering is, however, more profound in the case of a small steel sector. This is because the steel sector is able to move its investments and, as such, move its demand for emission allowances more substantially when it is larger. It is incentivised to do so in a way that compensates for the inefficient behaviour of the financial actor.

Figure 7b assumes perfect foresight for financial agents but myopic investment in the steel sector. In the small-sector case (dashed), prices remain unchanged because the actor's increased demand for emission allowances is not significant enough to increase EU ETS prices (except for lookahead horizons ≤ 6). When the steel sector is large, these suboptimal decisions lead the sector to emit more relative to the reference and drive up prices. After 2045, the EU ETS price spikes as CCS-equipped blast furnaces become the marginal abatement option. Note that this is case-

sensitive and that different cases in Appendix B do not show this behaviour. It is also because of this effect that even for the small steel sector, EU ETS prices spike in 2048 for lookahead horizons ≤ 6 .

The trajectory in Figure 7c combines both imperfections. It shows a muted early price signal followed by a sharper increase later, driven by both financial and investment myopia. While myopic financial agents distort the price path of allowances, it is myopic investment behaviour that contributes most to the system-wide price effects. Both imperfections are mutually reinforcing in the later years, where carbon prices are significantly higher when foresight is imperfect.

6. Discussion

6.1. Recommendations

Policies could aim to promote long-term planning in emission trading schemes by providing greater predictability about the long-term system’s design and avoiding ad-hoc adjustments. Periodic rule-setting in emission trading schemes compounds these challenges by discouraging market participants from looking beyond the time frame in which rules are defined. This regulatory uncertainty might undermine the credibility of long-term carbon price signals, which could delay critical investments in low-carbon technologies or lock in transition technologies. Addressing these limitations might enhance the efficiency of carbon pricing mechanisms. However, when different limitations interact, as shown in Figure 4c, it might require the elimination of multiple imperfections for the changes to take effect.

Our results underscore that a decrease in available capital to bank emission allowances decreases efficiency. This underscores what previous work warned about – that restricting financial institutions’ access to emission trading schemes can deter their efficiency (Quemin and Pahle, 2023). Financial constraints, which restrict banking, may become a more pressing issue as we approach net-zero and certificate prices rise. Policy measures might be needed to ensure sufficient capital in emission allowance markets to maintain their effectiveness. These could be achieved directly by reducing barriers to entry for financial institutions, or indirectly by making emission allowance trading more attractive by ensuring stability through price caps, for example.

Attributing price evolutions in real-world emission trading schemes to regulation and behavioural changes remains inherently difficult. As shown in this paper, different behaviours on emission trading schemes can lead to similar changes in prices. The interactions between different limitations might hamper efforts aimed at improving the efficiency of carbon pricing, as illustrated in Section 5.2.

Finally, we encourage the use of rolling horizons when studying complementary policies to emission trading schemes. This approach might reflect market behaviour better, as it accounts for the limited foresight of participants and the constraints they face.

6.2. Limitations & areas for future work

This paper’s partial equilibrium model was set up to resemble the EU ETS, yet it remains limited in complexity. We emphasise that the numeric results of our case study of the steel sector are not a projection, but are contingent on evolving factors such as technology development, investment costs, carbon prices, and fuel costs. Our stylised approach allows us to maintain interpretability and reveal the fundamental interactions. More complex models could, e.g., introduce markets for hydrogen and electricity, and hedging in those markets. This would, e.g., enable exploring how different sources of risk affect the decision-making of industrial investors.

As detailed in Section 2.3, one reason for imperfect decision-making by industrial actors is the uncertainty of how technology evolves. Because knowledge about a technology is gradually revealed, it can be beneficial to wait to invest. This option-value is not well represented in our model.

Additionally, future research could explore the performance of complementary climate policies in a model setting where an imperfect carbon price is present.⁵ Evaluating their effectiveness in rectifying imperfect decisions would be valuable.

Finally, our findings underscore the need for empirical research into how ETS-governed companies make investment and operational decisions. Understanding the behavioural drivers, risk perceptions, and internal decision processes of firms could help validate or challenge the stylised assumptions used in models like ours. Such empirical insights would be crucial to assess whether policy instruments designed to compensate for imperfect decision-making – such as carbon contracts for difference – are targeting real-world frictions effectively.

7. Conclusions

This paper investigates the causes and consequences of imperfect carbon pricing in emission trading schemes, focusing on the effects of myopic behaviour, increased policy risk, and financial constraints. Using a partial equilibrium model, we demonstrate how these market imperfections lead to inefficient carbon price trajectories that fail to achieve the lowest abatement cost over the duration of the scheme. Limited availability of capital restricts actors' ability to bank emission allowances optimally, resulting in lower carbon prices in the short term and higher prices in the long term. This leads to suboptimally timed abatement and consequently increases total abatement costs. Myopic behaviour further increases these inefficiencies, as participants with limited foresight overspend the carbon budget in the early years. Policy risk affects banking behaviour similarly and may further deteriorate the efficiency of carbon pricing.

Furthermore, the imperfect behaviour of investors due to external factors could influence the carbon price trajectory if the concerned market has a significant share of total emissions, as we observed in our case study on the steel industry. However, the extent to which steel investors actually exhibit the modelled behaviour remains unknown. Complementary policy instruments may be needed to correct for these inefficiencies, as any carbon pricing instrument operates in a second-best world with imperfections.

Our results reveal how these imperfections impact investment decisions in novel, low-emission technologies. The inefficiency introduced by imperfect pricing leads to delays and suboptimal technology choices. The impact of rolling horizons on the efficiency of the carbon price signal indicates their importance in future analyses. To better align market models with reality, we argue that researchers should test the robustness of their conclusions to alternative assumptions about market participant behaviour, including myopic behaviour and financial constraints.

CRediT authorship contribution statement

Alexander Hoogsteyn: Conceptualisation, Modelling, analysis, writing – original draft, **Jelle Meus:** Conceptualisation, Writing – review. **Kenneth Bruninx:** Conceptualisation, Modelling, writing - review, **Erik Delarue:** Writing – review, supervision.

⁵For example, carbon contracts for difference aim to reduce the risk of industrial investors and reduce their carbon price risk, but there is a lack of research quantifying their effectiveness (Richstein et al., 2024; Hoogsteyn et al., 2025).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

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Data availability

The output data required to reproduce the above findings is available to download from <https://github.com/AlexanderHoogsteyn/GreenIndustrialProduction>, along with the source code of the used Julia implementation of the optimisation models.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT-4.1 in order to improve the structure and proofread the written work of the authors. After using this tool/service, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Appendix A. ADMM-based rolling horizon approach

Algorithm 1 presents the pseudo-code for implementing the ADMM approach within a rolling horizon optimisation framework. This method employs a standard rolling-horizon strategy, where an optimisation problem is solved iteratively over a limited lookahead window of length τ (inner loop). After each iteration, the decision variables corresponding to the initial segment of the lookahead window are fixed. Subsequently, the lookahead window is extended by one year, advancing the simulation. This process is repeated (outer loop) until the entire modelled time frame has been covered.

We first describe the standard rolling horizon implementation used to coordinate investment and market decisions of multiple agents under an EU ETS. The algorithm iterates over two indices: t , the index of the rolling horizon window, and i , the iteration index of the ADMM procedure used to reach equilibrium between agents at each time step.

At each time step t , a subset of the full time horizon is optimised. This subset corresponds to the lookahead horizon of each agent type: τ_P for industrial producers and τ_C for financial and compliance actors. The respective optimisation windows are defined as $\mathcal{Y}_G = \{t : t + \tau_G\}$ and $\mathcal{Y}_C = \{t : t + \tau_C\}$. Prices p_y^G (for goods) and p_y^{ETS} (for EU ETS allowances) are initialised to zero and updated iteratively within their respective horizon based on the residuals from the decentralised optimisation problems solved by each agent.

Within each window t , the algorithm performs inner ADMM iterations indexed by i . In each iteration, agents solve their independent optimisation problems given the current prices. Primal and dual residuals are computed to quantify imbalances and mismatches in shared variables. Prices

(1) *Initialise prices over the full horizon:*
Set $\forall y \in \{1 : \text{end}\} : p_y^{ETS}, p_y^G = 0$

(2) *Initialise optimisation window to first horizon:*
Set $t = 1, \mathcal{Y}_G = \{t : t + \tau_P\}, \mathcal{Y}_C = \{t : t + \tau_C\}$

while $t + \tau_P \leq \text{end}$ or $t + \tau_C \leq \text{end}$ **do**

$i = 1$

while $\|r_y^{G,1}\| \geq \epsilon$ or $\|r_y^{C,1}\| \geq \epsilon$ or $\|\delta_{a,y}^{G,i}\| \geq \epsilon$ or $\|\delta_{a,y}^{C,i}\| \geq \epsilon$ or $i = 1$ **do**

(3) *Solve agents problems, based on p_y^{ETS}, p_y^G :*
 $b_y^{\text{Comp},i} = \text{argmin}((2) \text{ s.t. } (3)) \text{ over } \mathcal{Y}_C$
 $s \ b_y^{\text{Fin},i} = \text{argmin}((4) \text{ s.t. } (6) - (8)) \text{ over } \mathcal{Y}_C$
 $\forall a \in \mathcal{A}_G : q_{a,y}^i, b_{a,y}^{\text{Prod},i}, \text{cap}_{a,y}^i = \text{argmin}((10) \text{ s.t. } (11) - (14)) \text{ over } \mathcal{Y}_G$

(4) *Update primal residuals $r_y^{G,i}, r_y^{C,i}$:*
 $r_y^{G,i} = D_y - \sum_{\forall a \in \mathcal{A}_G} q_{a,y}^i$
 $r_y^{C,i} = S_y - \sum_{\forall a \in \mathcal{A}_{ETS}} b_{a,y}^{\text{Prod},i}$

(5) *Update dual residuals $\delta_{a,y}^{G,i}, \delta_{a,y}^{C,i}$:*
 $\delta_{a,y}^{G,i} = \rho \cdot ((q_{a,y}^i - \sum_{\forall a \in \mathcal{A}_G} q_{a,y}^i) - (q_{a,y}^{i-1} - \sum_{\forall a \in \mathcal{A}_G} q_{a,y}^{i-1}))$
 $\delta_{a,y}^{C,i} = \rho \cdot ((b_{a,y}^{\text{Prod},i} - \sum_{\forall a \in \mathcal{A}_{ETS}} b_{a,y}^{\text{Prod},i}) - (b_{a,y}^{\text{Prod},i-1} - \sum_{\forall a \in \mathcal{A}_{ETS}} b_{a,y}^{\text{Prod},i-1}))$

(6) *Update prices: p_y^{ETS} over \mathcal{Y}_C, p_y^G over \mathcal{Y}_G :*
 $\forall y \in \mathcal{Y}_G : p_y^G = p_y^G - \rho \cdot r_y^{G,i-1}$
 $\forall y \in \mathcal{Y}_C : p_y^{ETS} = p_y^{ETS} - \rho \cdot r_y^{C,i-1}$

$i = i + 1$

end

(7) *Add constraints on decision variables:*
 $b_t^{\text{Comp}} = b_t^{\text{Comp},i}, b_t^{\text{Fin}} = b_t^{\text{Fin},i}$
 $\forall a \in \mathcal{A}_G : q_{a,t} = q_{a,t}^i, b_{a,t}^{\text{Prod}} = b_{a,t}^{\text{Prod},i}, \text{cap}_{a,t} = \text{cap}_{a,t}^i$

(8) *Move lookahead window by one:*
 $t = t + 1$
 $\mathcal{Y} = \{t : t + \tau\}$

end

Algorithm 1: Pseudo-code of the rolling horizon optimisation where the financial and compliance actors have a lookahead horizon τ_C and industrial investors τ_P where the ADMM algorithm is used to find the equilibrium between industrial investors, financial actors and compliance actors under the EU ETS, based on Höschle et al. (2018).

are then updated accordingly, and the procedure repeats until all residuals fall below a tolerance threshold ϵ .

Once convergence is reached for window t , constraints are imposed to fix the variables at time t . The window is then shifted by one period ($t \leftarrow t + 1$) and the process repeats until the end of the full planning horizon is reached.

Algorithm 2 presents a variant of Algorithm 1, in which the industrial producers can have a longer horizon than emission trading actors, denoted by τ_P (for industrial producers) and τ_C (for EU ETS market participants). This extension requires the industrial investors to base their decisions on expectations of the carbon price. Since the industrial investors may look further into the future

(1) Initialise prices over the full horizon:
Set $j = 1, \forall y \in \{1 : \text{end}\} : p_y^{ETS,j}, p_y^{G,j} = 0$
while $j = 1$ or $\|p_y^{ETS,j} - p_y^{ETS,j-1}\| \geq \epsilon$ **do**
 (2) Initialise optimisation window to first horizon:
Set $t = 1, \mathcal{Y}_G = \{t : t + \tau_P\}, \mathcal{Y}_C = \{t : t + \tau_C\}$
while $t + \tau_P \leq \text{end}$ or $t + \tau_C \leq \text{end}$ **do**
 Set $i = 1$
while $\|r_y^{G,1}\| \geq \epsilon$ or $\|r_y^{C,1}\| \geq \epsilon$ or $\|\delta_{a,y}^{G,i}\| \geq \epsilon$ or $\|\delta_{a,y}^{C,i}\| \geq \epsilon$ or $i = 1$ **do**
 (1) Solve agents problems, based on p_y^{ETS}, p_y^G :
 $b_y^{\text{Comp},i} = \text{argmin}((2) \text{ s.t. } (3))$ over \mathcal{Y}_C
 $b_y^{\text{Fin},i} = \text{argmin}((4) \text{ s.t. } (6) - (8))$ over \mathcal{Y}_C
 $\forall a \in \mathcal{A}_G : q_{a,y}^i, b_{a,y}^{\text{Prod},i}, \text{cap}_{a,y}^i = \text{argmin}((10) \text{ s.t. } (11) - (14))$ over \mathcal{Y}_G
 (2) Update primal residuals $r_y^{G,i}, r_y^{C,i}$:
 $r_y^{G,i} = D_y - \sum_{\forall a \in \mathcal{A}_G} q_{a,y}^i$
 $r_y^{C,i} = S_y - \sum_{\forall a \in \mathcal{A}_{\text{ETS}}} b_{a,y}^{\text{Prod},i}$
 (3) Update dual residuals $\delta_{a,y}^{G,i}, \delta_{a,y}^{C,i}$:
 $\delta_{a,y}^{G,i} = \rho \cdot ((q_{a,y}^i - \sum_{\forall a \in \mathcal{A}_G} q_{a,y}^i) - (q_{a,y}^{i-1} - \sum_{\forall a \in \mathcal{A}_G} q_{a,y}^{i-1}))$
 $\delta_{a,y}^{C,i} = \rho \cdot ((b_{a,y}^{\text{Prod},i} - \sum_{\forall a \in \mathcal{A}_{\text{ETS}}} b_{a,y}^{\text{Prod},i}) - (b_{a,y}^{\text{Prod},i-1} - \sum_{\forall a \in \mathcal{A}_{\text{ETS}}} b_{a,y}^{\text{Prod},i-1}))$
 (4) Update prices: p_y^{ETS} over \mathcal{Y}_C, p_y^G over \mathcal{Y}_G :
 $\forall y \in \mathcal{Y}_G : p_y^G = p_y^G - \rho \cdot r_y^{G,i-1}$
 $\forall y \in \mathcal{Y}_C : p_y^{ETS} = p_y^{ETS} - \rho \cdot r_y^{C,i-1}$
 $i = i + 1$
 end
 (5) Add constraints on decision variables:
 $b_t^{\text{Comp}} = b_t^{\text{Comp},i}, b_t^{\text{Fin}} = b_t^{\text{Fin},i}$
 $\forall a \in \mathcal{A}_G : q_{a,t} = q_{a,t}^i, b_{a,t}^{\text{Prod}} = b_{a,t}^{\text{Prod},i}, \text{cap}_{a,t} = \text{cap}_{a,t}^i$
 (6) Move lookahead window by one:
 $t = t + 1$
 $\mathcal{Y} = \{t : t + \tau\}$
end
 $p_y^{ETS,j} = p_y^{ETS}$
 $j = j + 1$
end

Algorithm 2: Pseudo-code of the rolling horizon optimisation where the financial and compliance actors have a lookahead horizon τ_C and industrial investors τ_P where the ADMM algorithm is used to find the equilibrium between industrial investors, financial actors and compliance actors under the EU ETS, based on Höschle et al. (2018).

than EU ETS market participants ($\tau_G > \tau_C$), the optimisation problems of the former depend on EU ETS price expectations beyond the actual horizon of financial and compliance actors. This is addressed using a nested iteration scheme—indexed by j , where industrial investors first assume zero carbon prices beyond τ_C . In subsequent outer iterations, they update their decisions based on the EU ETS price trajectory produced in the previous run. This procedure enables convergence

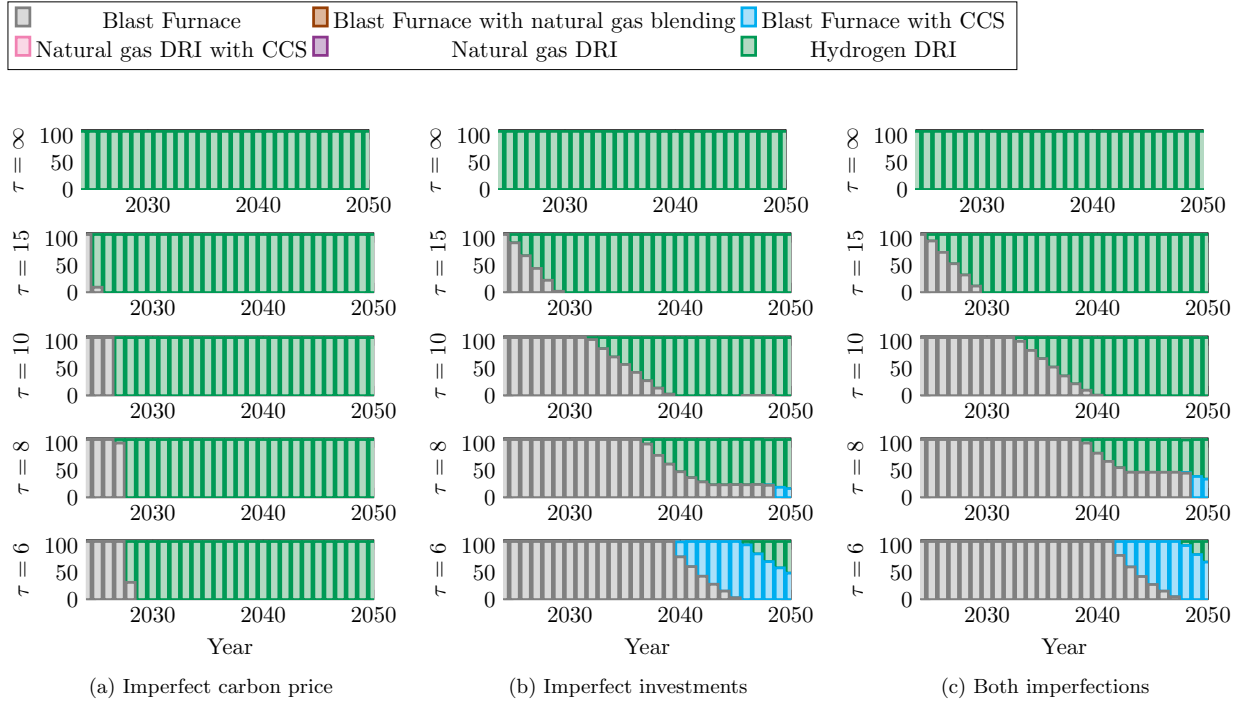


Figure B.8. Sensitivity to a 100% increase to carbon disposal costs for CCS.

between expectations and market outcomes across mismatched planning horizons.

Let us revisit the case in which $\tau_C > \tau_G$. This case requires an outer loop as well. In that case, EU ETS prices are calculated over a longer horizon than investment decisions are made—yet those EU ETS prices depend on the decisions of the investors, more specifically, on the demand for emission allowances by the producers. We will give the ETS agents foresight over the decisions by the industrial producers by iteratively updating the supply based on the used emission budget by the industrial producers. The financial actor can then adjust its banking strategy based on the updated emission supply (not shown in the algorithm description). Using such an approach, we implicitly assume that the financial agent has perfect foresight over the imperfect actions of the steel sector.

Appendix B. Supplementary results

Figure B.8 shows the sensitivity in which carbon capture disposal costs for CCS are doubled. The fundamental dynamics observed in the reference case persist: imperfect carbon pricing delays the shift away from conventional technologies (panel a), while myopic investment in the steel sector leads to overreliance on suboptimal CCS-equipped blast furnaces (panel b). When both imperfections are combined (panel c), the delayed transition and reliance on CCS remain, though the higher disposal cost makes the inefficiencies less pronounced. The results confirm that the core interactions between myopic behaviour and technology choice are robust to higher CCS costs.

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