Beyond Carbon Pricing: Quantifying Transition Risks for Climate Stress Testing when Firms Differ in Climate Ambitions*

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Abstract

Climate stress testing aims to assess firm-level transition risks and how these propagate to financial institutions and the financial system. We examine how climate stress-testing scenario design affects the quantification and comparability of firm-level transition risks under a common transition shock. We develop a stylized model of firm-level investment in low-carbon production capacity under climate policy uncertainty, applied to the European steel sector. Two identical firms differ only in their expectations about future climate policy scenarios, capturing belief-driven early- and late-mover behavior in low-carbon production investment. Firm cash flows depend on investment timing, capital and operating costs, policy support, carbon pricing, carbon product requirements and demand for primary steel. We show that stress-testing scenarios based primarily on carbon pricing generate broad and overlapping valuation outcomes for the early and late mover firm, reflecting uncertainty in cost pass-through and carbon leakage protection. By contrast, an accelerated policy-mix scenario combining price incentives with binding product bans and demand reductions produces a sharper transition shock, leading to a clear differentiation between early and late movers. Overall, the results show that the use of a sufficiently stringent transition scenario is critical for ensuring the comparability and informativeness of firm-level climate stress tests for financial risk management.

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1 Introduction

Since Marc Carney's landmark speech "Breaking the Tragedy of the Horizon" in his former role as Governor of the Bank of England (Carney, 2015), it has become widely acknowledged that climate change poses a systemic risk to the financial system. These risks arise both from the physical impacts of a warming climate and from transition dynamics related to changes in policies, technologies or preferences, particularly when economic structures and financial portfolios remain misaligned with low-carbon pathways (Battiston et al., 2017; Espinoza et al., 2020; Dietz et al., 2016). This implies that financial and economic assets may undergo changes in value (Reinders, Schoenmaker, and M. A. Van Dijk, 2023; Campiglio et al., 2023). While governments and legislators are primarily responsible for implementing climate policies, central banks and financial supervisors also play a crucial role within the scope of their mandate. They have to capture climate-related risks and be able to quantify their impacts (NGFS, 2024). As a consequence, forward-looking climate stress testing and climate-related scenario analysis has been established as a key analytical tool to capture those risks at the financial institution level (Acharya et al., 2023; BIS, 2021; Jobst and Ong, 2020; Reinders, Schoenmaker, and M. A. Van Dijk, 2023; Alessi et al., 2024). A central objective of these exercises is to identify which firms are most exposed to adverse transition scenarios and to translate this exposure into meaningful risk signals as a basis for the determination of capital allocation for financial stability.

Yet, despite rapid methodological progress (Acharya et al., 2023), current climate stress testing practices often struggle to deliver clear and comparable firm-level risk assessments. This paper asks whether alternative scenario designs can improve the quantification and comparability of firm-level transition risks under a common transition shock. Specifically, we examine whether accelerated policy-mix scenarios that combine carbon pricing with binding regulatory constraints, such as bans on emissions-intensive products and demand-side adjustments, generate clearer differentiation between early and late movers a in a market, and hence more actionable firm-level risk signals.

We motivate this question by two main short-comings in current climate stress testing exercises. First, many stress tests encounter difficulties in measuring financial risk at company level from a transition as they often rely on a combination of historical and sectoral data Dikau et al. (2024) and Baer et al. (2022). For example, in its second economy-wide climate stress test, the European Central Bank (ECB), forward-looking firm-level emissions were estimated using historical firm emission data that are projected according to NGFS-implied emissions growth rates derived through sectoral downscaling (Emambakhsh et al., 2023). This approach has two limitations. On the one hand, it is unable to capture forward-looking strategies of individual corporates and on the other hand, this approach is insufficient to capture within sector heterogeneity of firms (Baer et al., 2022; Hüttl et al., 2022).

Second, most stress tests rely on carbon pricing as the primary climate policy transmission mechanism (Lorans, Priol, and Bouchet, 2025). Established in 2017, the scenarios of the Network for Greening the Financial System (NGFS) have become the cornerstone for climate stress testing, used both by companies for strategic planning and by financial institutions for risk assessment. The framework distinguishes scenarios across three categories: orderly transitions with early and gradual policy tightening; disorderly transitions with delayed action followed by abrupt adjustment; and "hot house world" scenarios with limited policy action and escalating physical risks. Across all pathways, carbon pricing serves as a central policy transmission mechanism. Most institutional stress testing exercises have adopted this carbon-price-focused approach, closely following the NGFS framework (Table 1). Of the four major European supervisory exercises conducted since 2021, three rely primarily on carbon prices as the transmission mechanism, while only the "Fit-for-55 exercise" by the European Supervisory Authorities (ESAs) introduces alternative policy shocks such as the "run on brown" scenario (ECB, 2022; ESAs and ECB, 2024; Dunz et al., 2021; England, 2022). While carbon pricing is a central element of climate policy frameworks, its firm-level transmission in climate stress-testing depends critically on a firm's ability to pass higher costs on to customers (Reinders, Schoenmaker, and M. Van Dijk, 2025; Evdokimova and

Millischer, 2025; Desnos et al., 2023; Lorans, Priol, and Bouchet, 2025) and on the extent of carbon leakage protection through free the allocation of free allowances or border adjustment measures. Cost-pass-through substantially differs across firms and sectors and is difficult to observe or forecast ex ante (Neuhoff and Ritz, 2019). As a result, even firms within the same sector may experience very different valuation responses to identical carbon price paths (Evdokimova and Millischer, 2025).

Taken together, these features generate stress test results that are aggregated at sectoral-level and sensitive to contested parameter assumptions about carbon price transmissions, limiting their usefulness for firm-level quantification and differentiation of transition risks and ultimately supervisory decision-making. In supervisory practice, this uncertainty has contributed to climate stress tests being used primarily as exploratory or learning exercises, with limited implications for capital requirements or risk weights (ECB, 2022; England, 2021; Reinders, Schoenmaker, and M. A. Van Dijk, 2023; Dikau et al., 2024).

To isolate the role of scenario design in firm-level climate stress testing, we develop a stylized microeconomic model of low-carbon ("green") capacity investment under policy uncertainty. Two otherwise identical firms differ only in their beliefs about future climate policy. An early-mover firm anticipates an accelerated transition with binding product bans on emission-intensive materials and adjusts its investment strategy accordingly, while a late-mover firm expects policy continuity and delays investment. Investment decisions are irreversible and determine firms' ability to access markets when stringent policies materialize. While the model abstracts from macroeconomic feedbacks and financial sector amplification, it constitutes a structural firm-level valuation framework (Reinders, Schoenmaker, and M. Van Dijk, 2025) in which transition scenarios affect discounted cash flows through investment timing, operating costs, demand, and market access.

We illustrate these challenges using the steel sector as a canonical example of a hard-to-abate industry facing profound transition risk. As of 2024, the production of iron and steel accounted for around 19 percent of the total 493 million tonnes of CO_2 euquivalent emit-

ted by all industrial installations covered by the EU Emissions Trading System (Agency, 2025). Conventional primary steelmaking relies on coal-intensive blast furnaces to reduce iron ore, making the Blast Furnace Basic Oxygen Furnace (BF BOF) route one of the most emissions-intensive industrial processes, with emissions of around two tonnes of CO_2 per tonne of steel (Vogl, Åhman, and Nilsson, 2018). While low-carbon alternatives exist, most prominently hydrogen-based direct reduced iron combined with electric arc furnaces (DRI EAF), their deployment requires large, irreversible investments and, in practice, the replacement or substantial retrofitting of existing assets (Wang et al., 2021; Hüttel and Lehner, 2024). Furthermore, the growing availability of secondary steel from recycling is expected to reduce demand for primary steel over time, although the magnitude and timing of this shift remain uncertain (Vogl, Åhman, and Nilsson, 2021). These features make the steel sector particularly sensitive to the design of transition scenarios, as firm-level outcomes depend not only on carbon prices, but also on regulatory constraints, demand-side adjustments, and firms' expectations about the pace and credibility of climate policy.

We consider four discrete climate policy scenarios that vary along two dimensions: policy ambition (baseline versus accelerated) and policy instrument choice (carbon pricing only versus a broader policy mix). For the policy-mix scenarios, in addition to carbon pricing, we specify assumptions on policy support via Carbon Contracts for Differences (CCfDs), product carbon requirements (PCRs, including bans on emissions-intensive products), and reduced demand. Importantly, the definition of such an accelerated climate policy scenario is not about making a statement about the likelihood of such a scenario being realized. But given that the very essence of climate stress testing lies at exploring how a sudden shift in climate policy, aimed at aligning the economy with a certain ambition level - affect assets, firms and ultimately banks differently, an accelerated climate policy scenarios should generate transmission shock mechanisms that benefits firms aligned with the transition pathway, while disadvantaging those that remain misaligned with the trajectory. Against this background, instruments like CCfDs play a key role in supporting low-carbon investment by

reducing uncertainty about future carbon price developments and compensating firms for the incremental costs of clean technologies (Richstein, Anatolitis, et al., 2024; Richstein and Neuhoff, 2022). Product carbon requirements further strengthen decarbonisation incentives by restricting the market access of emissions-intensive products and, once climate-neutral production technologies are available at sufficient scale, by creating credible long-term planning incentives for firms to prepare for a full transition (Gerres et al., 2021; Neuhoff, Chiappinelli, et al., 2019). Finally, reduced demand assumptions capture the growing importance of demand-side adjustments in climate transitions, reflecting shifts in consumption patterns and lower demand for carbon-intensive goods. The importance of demand-side adjustments is increasingly recognised, notably through the NGFS Low Demand scenario and recent stress-testing work that explicitly incorporates revenue-side transmission channels beyond carbon pricing (NGFS, 2024; Lorans, Priol, and Bouchet, 2025). For each scenario, we compute firm-level net present values under varying levels of carbon price pass-through and carbon leakage protection. We further evaluate downside risk by comparing expected net present value and conditional value-at-risk (CVaR).

The analysis yields three main insights. First, when transition scenarios are based on carbon prices, but pass-through capacity and leakage protection are uncertain and hence subject to further assumptions, carbon price shocks generate wide and overlapping valuation distributions for early and late movers. Second, accelerated policy-mix scenarios, combining carbon pricing with binding product carbon requirements, demand reductions, and targeted support instruments, produce substantially clearer firm-level differentiation. By operating through demand and product constraints rather than prices alone, these scenarios generate a sharp transition shock independent of further assumptions. It is thereby possible to better differentiate between firms with heterogeneous transition strategies as late movers risk losing market shares. Third, policy-mix scenarios thereby compress the gap between expected outcomes and tail risks, making them better suited for identifying firms with material downside exposure in a stress testing context.

We study this question in the context of transition plans, which are increasingly mandated disclosures intended to reveal firms' forward-looking decarbonization strategies (J. Bingler et al., 2023; Caldecott and Shrimali, 2023; EBA, 2025). Transition plans have the potential to introduce forward-looking information into climate risk assessment, but their informativeness depends critically on the benchmark scenario against which they are evaluated (Committee, 2021; Schütze et al., 2024). When firms assess their strategies relative to current-policy baselines, plans may appear viable even if they are misaligned with climate targets consistent with the Paris Agreement. Evaluating transition plans against a sufficiently stringent stress test scenario, by contrast, can reveal material differences in firms' exposure to transition risk.

These findings contribute to the growing literature on forward-looking climate risk measurement and stress testing (Baer et al., 2022; Cormack et al., 2020; Evdokimova and Millischer, 2025). Rather than proposing a more comprehensive or granular stress-testing framework, the paper shows that scenario design itself is a first-order determinant of whether firm-level stress tests deliver informative and robust risk differentiation, building on earlier work that documents (i) the quantitative relevance of demand-side transmission channels beyond carbon pricing (Lorans, Priol, and Bouchet, 2025) and (ii) the strong dependence of transition risk metrics on scenario narratives and modelling assumptions in general (Campiglio et al., 2023; J. A. Bingler, Colesanti Senni, and Monnin, 2022; Acharya et al., 2023; Tang et al., 2024). In this sense, accelerated policy-mix scenarios provide a more appropriate benchmark for evaluating transition plans and for distinguishing early and late movers in prudential risk assessment.

The remainder of the paper is structured as follows. Section 2 presents the scenario design and the investment model. Section 3 discusses investment behavior, valuation outcomes, and downside risk across scenarios. Section 4 concludes with implications for climate stress testing and supervisory practice.

Stress test	**Type**	**Horizon**	**Balance sheet assumption**	**Scenarios**	**Ambition**	**Key transition risk / stress feature**
ECB 2022 climate risk stress test (ECB, 2022)	Bottom-up	LT: 30 years (to 2050); ST: 3 years (to 2030)	Long-term: Dynamic; Short-term: Static	Long-term: (i) Orderly transition; (ii) delayed, disorderly transition; (iii) "hot house world" (NGFS); Short-term: (iv) Baseline; (v) Stress	Long-term (i) = 1.5°C; (ii) = below 2°C; (iii) = current policies, 3°C	Carbon price (USD/tCO_2) across all scenarios
ESAs and ECB 2024 Fit-for-55 climate scenario analysis (ESAs and ECB, 2024)	Top-down	8 years (to 2030)	Static; Dynamic in an extension	(i) Fit for 55 Baseline; (ii) Fit for 55 Adverse I ("Run on brown"); (iii) Fit for 55 Adverse II	(i) = smooth implementation of Fit for 55 package, in line with EU 2030 targets and Paris Agreement; (ii) & (iii) = Abrupt policy implementation with adverse shocks	"Run on brown" via exogenous shock to the financial constraints of firms based on degree of brownness; sector-specific policy shocks
ECB economy-wide climate stress-test (Dunz et al., 2021)	Top-down	30 years (to 2050)	Static	Long-term: (i) Orderly transition; (ii) delayed, disorderly transition; (iii) "hot house world" (NGFS)	Long-term (i) = 1.5°C; (ii) = below 2°C; (iii) = current policies, 3°C	Flat carbon tax applied to direct emissions and energy prices (also a function of climate policy)
Bank of England's 2021 Climate Biennial Exploratory Scenario (CBES) (England, 2022)	Bottom-up	30 years (to 2050)	Static	(i) Early Action; (ii) Late Action; (iii) No Additional Action	(i) Global warming is limited to 1.8°C by the end of 2050; (ii) Same as above, but transition delayed until 2031; (iii) global warming reaches 3.3°C by 2050	(i) & (ii) carbon price as shadow price of all GHG emissions (summary incorporating a range of different climate policies)

Table 1: Overview of selected transition risk stress scenarios and their key features

2 Model and data

2.1 Stylized Model for Investment Decisions by Firms

We develop a stylized microeconomic model to study low-carbon ("green") investment decisions by steel firms under climate policy uncertainty. Two representative firms operate identical emission-intensive ("brown") steelmaking capacity and compete in a homogeneous product market over two production periods. Each firm is endowed with an initial brown production capacity K_{i0}.

The timing of decisions is as follows (see Figure 1). In period 0, firms simultaneously decide how much of their existing emission-intensive ("brown") capacity to convert by investing in low-carbon ("green") steel-making technology. This decision is irreversible and measured by the amount of converted capacity $g_i \in [0, \frac{1}{2}K_{i0}]$. Firms can convert at most one half of their initial production capacity. Converted capacity becomes operational in period 1 (2028-2034), during which firms produce at full capacity, with green output $q_{i1,\text{green}} = g_i$ and brown output $q_{i1,\text{brown}} = K_{i0} - g_i$.

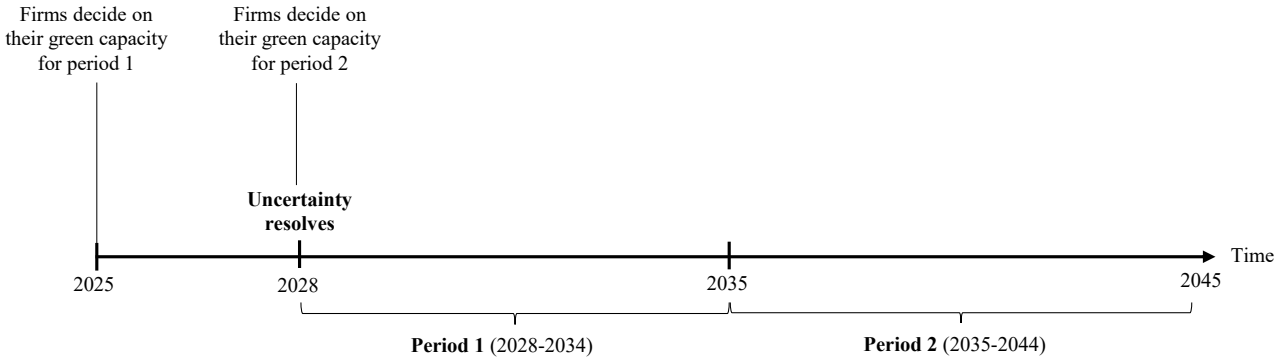


Figure 1: Investment timeline for firms.

At the beginning of period 1, uncertainty over future climate policy and market conditions is resolved. Uncertainty is represented by a finite set of scenarios that differ in their level of carbon prices, financial support for the incremental costs of green investment, regulatory

restrictions on brown products, and the demand for primary steel in period 2 (2035-2044). In scenarios where brown steel products are banned, firms optimally shut down brown production and may convert additional capacity, subject to the maximum level of capacity that can be converted per period. If demand for primary steel in period 2 is sufficiently low, aggregate desired production may exceed market demand. In such cases, firms are rationed and total output is allocated according to a priority rule that depends on relative early green investment, creating a first-mover advantage for firms that converted more capacity in period 0. Total green capacity in period 2 is therefore constrained by early investment decisions, reflecting irreversibility in capacity conversion.

Firms are identical in technology and costs but differ in their subjective beliefs over policy scenarios. The "early mover firm" assigns higher probability to accelerated transition scenarios, while a "late mover firm" places greater weight on the continuation of current policies. These belief differences affect expected profits and generate heterogeneous investment choices ex ante, while realized scenarios determine production, market access, and profits ex post.

While traditional stress tests typically rely on time horizons of 3–5 years, climate risks compel credit institutions to adopt horizons of up to 30 years to better capture their long-term effects (Auzepy and Bannier, 2025). Such longer horizons have also been adopted by most climate stress testing exercises conducted by central banks (see Table 1).

Model formulation. Firm i takes output prices as given and maximizes a mean–variance objective over a finite set of S scenarios.[1]

$$\max_{g_i \in [0, \frac{1}{2}K_{i0}]} J_i = \sum_{s=1}^{S} \pi_i^s \Pi_i^s(g_i, g_j) - \lambda \sum_{s=1}^{S} \pi_i^s \big(\Pi_i^s(g_i, g_j) - \bar{\Pi}_i\big)^2, \tag{1}$$

where π_i^s denotes firm i's subjective probability of scenario s, $\Pi_i^s(g_i, g_j)$ denotes scenario-specific discounted profits as a function of both firms' period 0 investments, $\bar{\Pi}_i = \sum_s \pi_i^s \Pi_i^s$ is expected profit, and $\lambda \geq 0$ measures risk aversion.

Scenario-specific profits. Scenario-specific profits consist of discounted operating cash flows in both production periods:

$$\begin{aligned}\Pi_i^s(g_i, g_j) = &\sum_{t=2028}^{2034} \frac{1}{(1+r_i)^{t-2025}} \left[(K_{i0} - g_i)(\bar{p}_{1t}^s - \bar{c}_{1t,\text{brown}}^s) + g_i(\bar{p}_{1t}^s - \bar{c}_{1t,\text{green}}^s)\right] \\ &+ \sum_{t=2035}^{2044} \frac{1}{(1+r_i)^{t-2025}} \left[q_{i2,\text{brown}}^s(g_i, g_j)(\delta^s \bar{p}_{2t}^s - \bar{c}_{2t,\text{brown}}^s) + q_{i2,\text{green}}^s(g_i, g_j)(\bar{p}_{2t}^s - \bar{c}_{2t,\text{green}}^s)\right],\end{aligned} \tag{2}$$

where period 1 production is mechanically determined by period 0 investment ($q_{i1,\text{green}} = g_i$ and $q_{i1,\text{brown}} = K_{i0} - g_i$), and period 2 production quantities $q_{i2,\text{brown}}^s(g_i, g_j)$ and $q_{i2,\text{green}}^s(g_i, g_j)$ are determined by constraints (C1)–(C6), the policy indicator δ^s, and the market allocation rule that depends on both firms' period 0 investments. In period 2, firms convert brown capacity into green capacity only up to the level of production they expect to realize given market-wide rationing, so that green capacity is never installed but left idle; any remaining unconverted brown capacity becomes idle when $\delta^s = 0$. Expected profits are given by $\bar{\Pi}_i = \sum_{s=1}^{S} \pi_i^s \Pi_i^s(g_i, g_j)$.

[1] While mean–variance penalizes dispersion symmetrically, it provides a tractable reduced-form representation of policy-risk exposure and suffices for our purpose of comparing early- and late-mover investment incentives under common shocks. Annex E discusses robustness to alternative downside-risk measures (e.g., CVaR).

Policy restrictions and stranded assets. The indicator $\delta^s \in \{0, 1\}$ captures whether steel from brown production can be sold in period 2. When $\delta^s = 1$, brown steel generates revenue as in period 1. When $\delta^s = 0$, brown steel cannot be sold due to regulatory product bans. In this case, brown production yields no revenue but still incurs unavoidable fixed costs, implying negative operating profits. Firms therefore optimally set $q^s_{i2,\text{brown}} = 0$ and convert brown capacity into green only up to the level of green production they expect to realize given market access in period 2. However, if period 0 investment was insufficient, some brown capacity remains unconverted and idle in period 2, even after optimal conversion conditional on expected market access. This stranded capacity incurs costs $c^s_{\text{stranded}} = c^{\text{ann}}_{x,\text{brown}} + c^{\text{ann}}_{\ell,\text{brown}}$, where $c^{\text{ann}}_{x,\text{brown}}$ denotes annualized capital costs and $c^{\text{ann}}_{\ell,\text{brown}}$ fixed labour costs that may persist in the medium run due to employment protection. Each unit of green capacity deployed in period 0 reduces potential stranded assets one-for-one, creating a positive marginal benefit of early green investment when steel from brown production is banned.

Constraints. The optimization problem is subject to:

$$q_{i1,\text{brown}} + q_{i1,\text{green}} = K_{i0}, \tag{C1}$$

$$q^s_{i2,\text{brown}} + q^s_{i2,\text{green}} \leq K_{i0}, \tag{C2}$$

$$g_i \leq \tfrac{1}{2} K_{i0}, \tag{C3}$$

$$q^s_{i2,\text{green}} \leq g_i + \tfrac{1}{2} K_{i0}, \tag{C4}$$

$$q^s_{i2,\text{brown}} + q^s_{j2,\text{brown}} + q^s_{i2,\text{green}} + q^s_{j2,\text{green}} \leq \overline{S}^s_2, \tag{C5}$$

$$q^s_{ip,\cdot} \geq 0. \tag{C6}$$

Constraint (C1) ensures full capacity utilization in period 1. Constraint (C3) limits the maximum conversion per period to 50% of total initial capacity. Constraint (C4) captures the irreversibility of capacity conversion: period 2 green production is bounded by period 0

investment plus the maximum feasible period 2 conversion. When market-wide rationing binds, actual green production may be strictly lower than this upper bound. Firms anticipate such rationing when deciding how much remaining brown capacity to convert, ensuring that green capacity is converted only up to realized production, while the maximum feasible level of green production remains constrained by period 0 investment. Constraint (C5) introduces a scenario-specific cap on total primary steel production in period 2, reflecting reduced demand in accelerated transition scenarios due to material efficiency improvements and increased secondary steel production.

Market-wide rationing and allocation. The scenario-specific demand $\overline{S}_2^s$ on total primary steel production in period 2 ranges from K_{i0} to $2K_{i0}$, reflecting different demand levels across scenarios. Firms anticipate this rationing when deciding how much remaining brown capacity to convert in period 2, ensuring that green capacity is never installed but left unused. Allocation follows a smooth priority rule based on relative period 0 investment:

$$w_i(g_i, g_j) = \frac{1}{1 + \exp\{-k(g_i - g_j)\}}, \tag{3}$$

where $k > 0$ governs the strength of first-mover advantage. The full allocation mechanism maps period-0 investments (g_i, g_j) and the market cap $\overline{S}_2^s$ into realized period-2 production quantities through this priority weighting (formal derivation in Appendix Annex A). For our optimization problem, we summarize the effect of period-0 investment on period-2 market access by the marginal allocation parameter $\theta_i^s := \frac{\partial q_{i2,\text{total}}^s}{\partial g_i} \in [0, 1]$, where $q_{i2,\text{total}}^s = q_{i2,\text{brown}}^s + q_{i2,\text{green}}^s$. When combined production does not exceed the cap, $\theta_i^s = 1$: period 0 investment translates one-for-one into period 2 capacity. When the cap is strictly binding, $\theta_i^s \in (0, 1)$ depends smoothly on relative investment through the priority rule, creating a first-mover advantage that ensures differentiability of the firm's optimization problem.

Symbol	Description
$i, j \in \{\text{early mover}, \text{late mover}\}$	Firm indices (Early mover and late mover firm).
$p \in \{1, 2\}$	Period index: $p = 1$ (2028–2034), $p = 2$ (2035–2044).
$s \in \{1, \ldots, S\}$	Scenario index capturing alternative climate policy realizations.
g_i	Period 0 green capacity investment by firm i (decision variable).
$q^s_{ip,\text{brown}}$	Quantity of brown steel produced by firm i in period p, scenario s.
$q^s_{ip,\text{green}}$	Quantity of green steel produced by firm i in period p, scenario s.
K_{i0}	Initial production capacity of firm i (constant).
$\overline{S}_2^s$	Scenario-specific demand on total primary steel production in period 2: $q^s_{i2,\text{brown}} + q^s_{j2,\text{brown}} + q^s_{i2,\text{green}} + q^s_{j2,\text{green}} \leq \overline{S}_2^s$.
$\bar{p}^s_{pt}$	Market price in period p, year t, scenario s. Prices are determined at the industry level by the unit costs of the price-setting technology, augmented by a small exogenous margin μ. When brown steel production is permitted, the brown technology is price-setting; when brown steel is banned, the green technology sets the market price. Firms take prices as given and do not engage in price setting.
$\bar{c}^s_{pt,\text{brown}}$	Unit operating cost of brown steel in period p, year t, scenario s (see Appendix Annex B for detailed cost calculations).
$\bar{c}^s_{pt,\text{green}}$	Unit operating cost of green steel in period p, year t, scenario s (see Appendix Annex B for detailed cost calculations).
δ^s	Policy indicator for period 2: $\delta^s = 1$ if brown steel can be sold, $\delta^s = 0$ if brown steel is banned.
c^s_{stranded}	Annualized stranded asset cost per unit of idle brown capacity in scenario s.
π_i^s	Subjective probability assigned by firm i to scenario s, $\sum_s \pi_i^s = 1$.
Π_i^s	Scenario-specific discounted profit of firm i.
$\bar{\Pi}_i$	Expected profit of firm i, $\bar{\Pi}_i = \sum_s \pi_i^s \Pi_i^s$.
λ	Risk aversion parameter in the mean–variance objective.
r_i	Firm-specific discount rate (WACC).[2]
$w_i(\cdot)$	Smooth priority weight (sigmoid) determining market access under rationing.
k	Steepness parameter governing first-mover advantage in the priority rule.
θ_i^s	Marginal allocation parameter linking period 0 investment to period 2 market access under scenario s.

Table 2: Key variables and parameters used in the model.

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Marginal benefit and optimal investment. The marginal benefit of early green investment reflects three channels. In period 1, substituting brown with green capacity generates operating gains whenever green production is less costly. In period 2, early investment increases expected profits and reduces exposure to stranded asset costs in scenarios where brown steel sales are restricted. In addition, when the market-wide cap on production binds, early investment improves a firm's access to scarce market share, creating a first-mover advantage. Formally, letting $\Pi_i^s(g_i, g_j)$ denote discounted profits in scenario s, the scenario-specific marginal benefit of early investment is

$$MB_i^s(g_i, g_j) \equiv \frac{\partial \Pi_i^s(g_i, g_j)}{\partial g_i} = B_1^s + B_2^s(g_i, g_j), \tag{4}$$

where B_1^s captures period 1 operating cost savings and $B_2^s(g_i, g_j)$ captures period 2 operating gains, avoided stranded asset costs, and when total capacity exceeds the demand the marginal effect of early investment on access to constrained market share. Firms differ in their subjective beliefs over policy scenarios, and these beliefs determine the expected marginal benefit $\sum_s \pi_i^s MB_i^s(g_i, g_j)$. For risk-averse firms, the optimal investment trades off this belief-weighted expected marginal benefit against the dispersion of profits across scenarios, yielding an interior solution whenever uncertainty is material. By contrast, risk-neutral firms invest fully whenever the expected marginal benefit is positive and do not invest otherwise. Formal derivations and closed-form solutions are provided in Annex A.

[2]The discount rate here is the Weighted Average Cost of Capital (WACC) which is given by WACC = $w_e \cdot R_e + w_d \cdot R_d$, where w_e and w_d are the shares of equity and debt in the firm's capital structure, and R_e and R_d are the cost of equity and cost of debt, respectively; see also Table 4

2.2 Data for Numerical Simulation

We apply the model using technology cost data, emission intensities, and financing parameters for the European steel industry. Table 4 summarizes the key input values. To explore how investment decisions respond to climate policy uncertainty, we define four scenarios that vary along two dimensions: policy ambition (baseline versus accelerated transition) and policy instrument choice (mixed policy portfolio versus carbon pricing alone). Table 3 details the scenario specifications. The policy mix scenarios (1 and 3) combine carbon pricing with targeted support through Carbon Contracts for Differences (CCfDs), which guarantee green steel producers a stable operating margin by compensating for the cost differential between brown and green production. In Scenario 1 (Baseline - Policy mix), CCfDs cover half the necessary support volume ($\beta = 0.5$); in Scenario 3, full coverage is provided ($\beta = 1$). The carbon pricing scenarios (Scenarios 2 and 4) rely exclusively on emissions pricing without complementary support instruments. Scenario 3 (Accelerated -Policy mix) additionally imposes a binding product carbon requirement that bans brown steel products in period 2 ($\delta = 0$). Further, aggregate demand for primary steel falls from 12 to 9 Mt, below the combined capacity of both firms (12 Mt)[3]. This creates rationing in period 2, with allocation determined by the priority rule defined in Section 2.1. Across all scenarios, we vary two parameters: the carbon cost pass-through rate $\rho \in [0, 1]$, where $\rho = 1$ indicates full pass-through to output prices and $\rho = 0$ indicates full internalization, and the carbon leakage protection parameter $\alpha \in [0, 1]$, which governs the degree to which free allowances compensate for costs that cannot be passed through.[4] The interaction between these parameters determines the effective carbon price faced by producers and the strength of investment incentives. Formal definitions and implementation details are provided in Annex B. Finally, we model

[3] As discussed in Vogl, Åhman, and Nilsson (2018), substantial uncertainty remains regarding the future availability of secondary steel and the resulting displacement of primary production. To account for this, we also report results for a more severe demand contraction scenario in which period-2 demand falls to 6 Mt instead of 9 Mt (see Annex D).

[4] We abstract here from additional features of the EU ETS leakage protection framework, such as the output-based benchmarking system, under which free allowances are granted only up to the benchmark emissions intensity rather than fully offsetting firms' marginal carbon costs.

heterogeneous beliefs by assigning different subjective probabilities over the four scenarios (Table 5). The early mover firm expects stringent action, placing 70% probability on the accelerated policy-mix scenario ($\pi^3_{\text{early mover}} = 0.70$). The late mover firm expects policy continuity, assigning 70% probability to the baseline carbon-pricing scenario ($\pi^2_{\text{late mover}} = 0.70$). An equal-probability benchmark serves as a reference case. This scenario design allows us to assess how different stress-testing narratives affect the comparability of firm-level transition risk assessments under a common policy shock.

Table 3: Scenario elements and assumptions

Elements	Baseline – Limited ambition		Accelerated – Increased ambition	
	Policy mix (1)	**Carbon prices** (2)	**Policy mix** (3)	**Carbon prices** (4)
Scenario-specific				
Carbon prices	*moderately increase over time:* • Period 1 (2028–2034): 70–170 €/tCO_2 (Pahle et al., 2022; IEA, 2023) • Period 2 (2035–2044): 180–280 €/tCO_2 (IEA, 2023; Pahle et al., 2022)			*increase sharply over time:* • Period 1 (2028–2034): 70–270 €/tCO_2 (Dietz et al., 2018) • Period 2 (2035–2044): 280–480 €/tCO_2 (Dietz et al., 2018)
Carbon Contracts for Differences (CCfDs)	✓, although not the full volume covered (implemented through β, $\beta = 0.5$ (Annex B/Annex C)	×	✓, full volume covered (implemented through β, $\beta = 1$ (Annex B/Annex C)	×
Demand	12 MT	12 MT	9 MT	12 MT
Product carbon requirements	×	×	✓, brown steel products may not be sold anymore in the market (implemented through δ, $\delta = 0$)	×
Sensitivities across models				
Carbon cost pass-through	Testing different specifications, from 0–1 (implemented via parameter ρ in the model, $\rho = 1$ = full pass-through, $\rho = 0$ = full internalization, see Annex B).			
Free allowances	Depends on pass-through, see Annex B).			
Carbon leakage protection	Degree to which free allowances correct for what can be passed through. Testing different specifications, from 0–1 (implemented through parameter $\alpha = 1$ in the model, $\alpha = 1$ = fully protected, 0 = zero protection), see Annex B).			

Table 4: Cost input factors

Element	Technology	Value	Unit	Reference
Opex	BF-BOF - total	≈ 415.00	€/ton annual steel production capacity	Mayer, Bachner, and Steininger (2019)
	BF-BOF - labour costs	≈ 50	€/ton annual steel production capacity	Ebd.
	H-DRI-EAF - total	≈ 625.00	€/ton annual steel production capacity	Ebd.
Capex	BF-BOF relining	≈ 50	€/ton annual steel production capacity	Vogl, Åhman, and Nilsson (2018)
	BF-BOF investment (brownfield)	≈ 170	€/ton annual steel production capacity	Ebd.
	BF-BOF investment (greenfield)	≈ 440	€/ton annual steel production capacity	Ebd.
	DRI-EAF investment (greenfield)	≈ 630	€/ton annual steel production capacity	Ebd. & Richstein and Neuhoff (2022)
Emission Intensities	BF-BOF	≈ 2	t CO_2/ton steel	Vogl, Åhman, and Nilsson (2018)
	H-DRI-EAF	≈ 0.05	t CO_2/ton steel	Ebd.
Financing Assumptions	Share of debt (w_d)	≈ 0.6	share	Richstein and Neuhoff (2022)
	Share of equity (w_e)	≈ 0.4	share	Calculated: $w_e = 1 - w_d$
	Cost of debt (i)	≈ 0.03	share	Ebd.
	Cost of equity (i_{eq})	≈ 0.1	share	Ebd.
	Depreciation (n)	20	years	Ebd.
	Annuity factor debt (AF_d)	≈ 0.07	share	Calculated: $\frac{i}{1-(1+i)^{-n}}$
	Annuity factor equity (AF_{eq})	≈ 0.12	share	Calculated: $\frac{i_{eq}}{1-(1+i_{eq})^{-n}}$
	Annuity under financing mix	≈ 0.1	share	Calculated: $w_d \cdot AF_d + w_e \cdot AF_{eq}$

Table 5: Potential belief profiles of firm i

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Equal	0.25	0.25	0.25	0.25
Early mover	0.05	0.05	0.7	0.2
Late mover	0.2	0.7	0.05	0.05

3 Results

3.1 Marginal benefit and optimal investment decision

Figure 2 shows the discounted marginal benefit per scenario and period as a function of carbon leakage protection and the pass-through rate of carbon prices across policy scenarios. The black contour marks the zero-marginal-benefit frontier separating regions where early green investment yields a positive marginal profit for firms.[5]

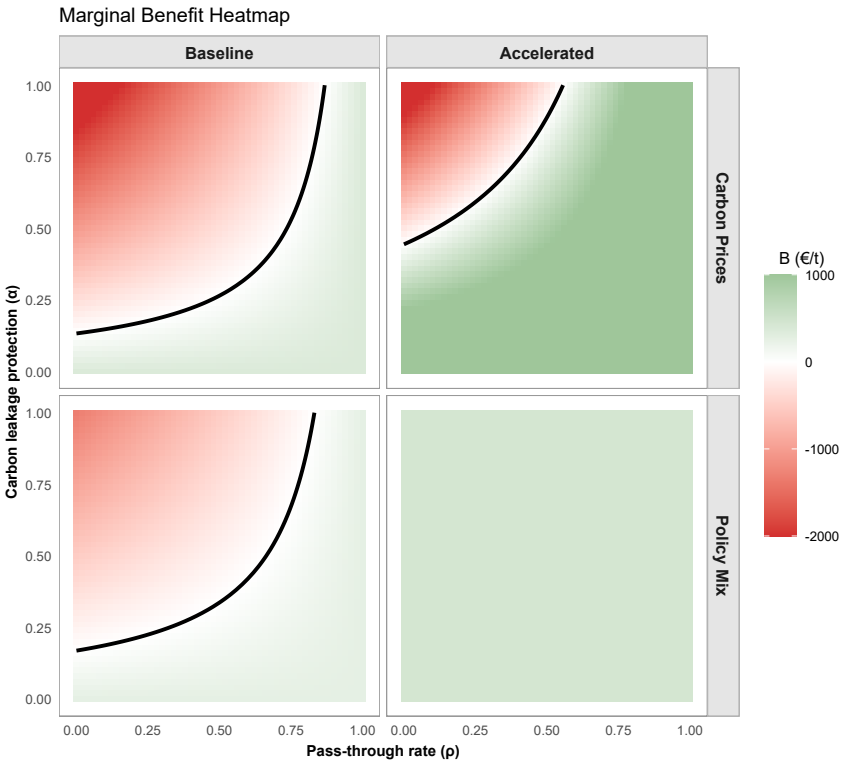


Figure 2: Discounted marginal benefit (MB) per scenario and period

The effect is strongest under the accelerated policy-mix scenario, where a contraction in period-2 primary steel demand and binding capacity rationing make early green investment

[5] Annex A reports robustness results for a more stringent market-wide capacity constraint in period 2 (total demand shrinks 6 Mt). As a benchmark for brown capital expenditure, we assume brownfield investment costs. This is realistic because incumbent steel producers typically operate existing blast furnace infrastructure, and decarbonization decisions often involve retrofitting or incremental upgrades rather than entirely new greenfield construction.

profitable in 100% of the (α, ρ) space. In this case, profitability is independent of carbon cost pass-through and leakage protection, as investment returns are dominated by avoided stranded costs and priority access to a shrinking market. Under the baseline policy mix, positive marginal benefits arise in 47% of cases. By contrast, under carbon-price-only designs, early green investment yields positive marginal benefits in 40% of cases under the baseline scenario, increasing to 80% under accelerated carbon pricing, indicating a strong sensitivity of investment incentives to net carbon prices.

Figure 3 shows how beliefs, risk preferences, and strategic interaction jointly determine optimal first-period green capacity conversion across the (α, ρ) space.

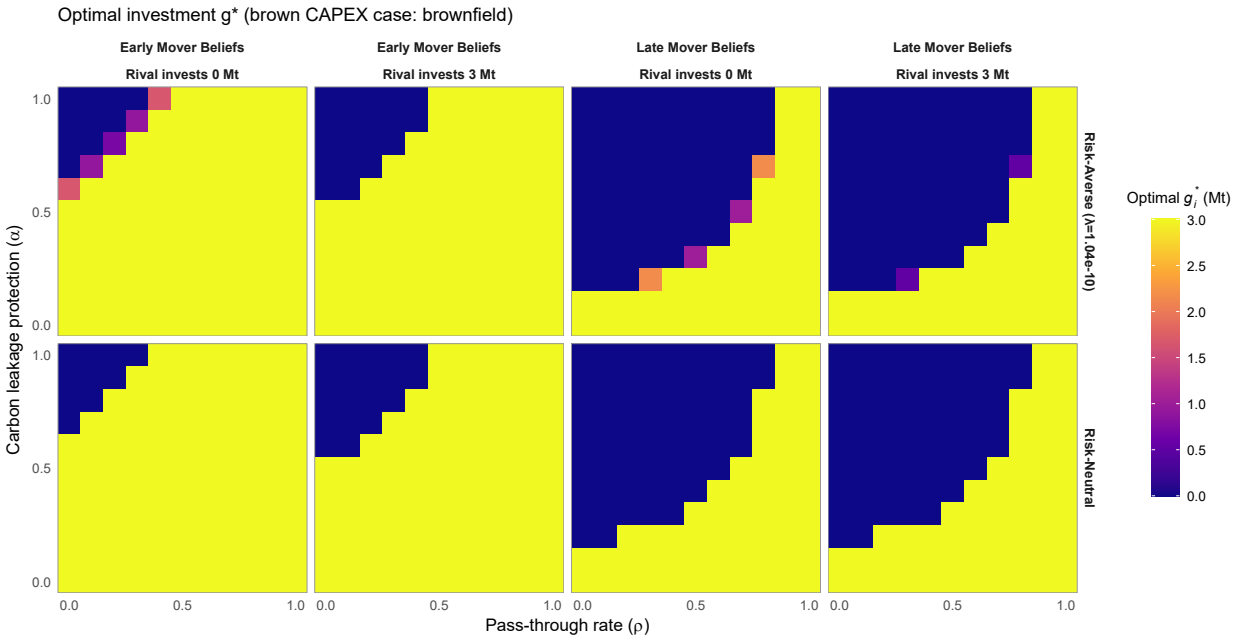


Figure 3: Optimal level of green investment for risk-neutral and risk-averse firms under different belief profiles

Under early-mover beliefs, which assign high probability to the accelerated policy-mix scenario with a ban on products from brown production, firms invest early in a large majority of the parameter space. When the rival does not invest, positive first-period green investment arises in about 92% of the (α, ρ) space, both under risk neutrality and risk aversion. When the rival invests early, this share remains high at about 84%, again essentially unchanged between

risk-neutral and risk-averse preferences. The main difference is that risk aversion leads to interior investment solutions, rather than corner outcomes, without materially affecting the extensive margin of investment.[6]

By contrast, under late-mover beliefs, which place greater weight on baseline and carbon-price-only scenarios, early green investment is substantially less prevalent. When the rival does not invest, firms invest positively in about 49% of the (α, ρ) space under risk neutrality and about 46% under risk aversion. When the rival invests early, the risk-neutral share remains around 49%, while the risk-averse share declines slightly to about 45%. In these states, higher carbon-cost pass-through and stronger leakage protection dampen the effective carbon-cost differential, reducing the marginal benefit of early conversion and sustaining large regions in which zero green investment remains optimal.

Relative to the risk-neutral benchmark, introducing risk aversion leads to a modest contraction of the region of early investment, particularly under late-mover beliefs. This asymmetry reflects downside exposure under the accelerated policy-mix scenario: late movers face stranded-asset losses and quantity rationing when brown production is banned, while early investment primarily truncates upside gains. A mean–variance objective therefore places greater weight on low-profit realizations, shifting optimal investment toward more conservative positions even when expected profits from early conversion remain positive.

3.2 Cash flow analysis

Figures 4 and 5 map policy-parameter uncertainty into firm-level cash-flow outcomes relevant for climate stress testing. Each panel reports mean annual cash flows (solid line) together with the min–max envelope across the (α, ρ) grid (shaded band). Columns correspond to policy scenarios; rows vary rival early investment (0 vs. 3 Mt). The dashed vertical line marks the transition from period 1 to period 2.

[6]We calibrate λ such that the variance penalty in the mean–variance objective implies a risk premium equal to 3% of expected profits at the reference point $(\alpha, \rho) = (0.5, 0.5)$. This yields $\lambda = k\,E[\Pi]/\mathrm{Var}(\Pi)$ with $k = 0.03$.



Figure 4: Cash flow over time for early mover

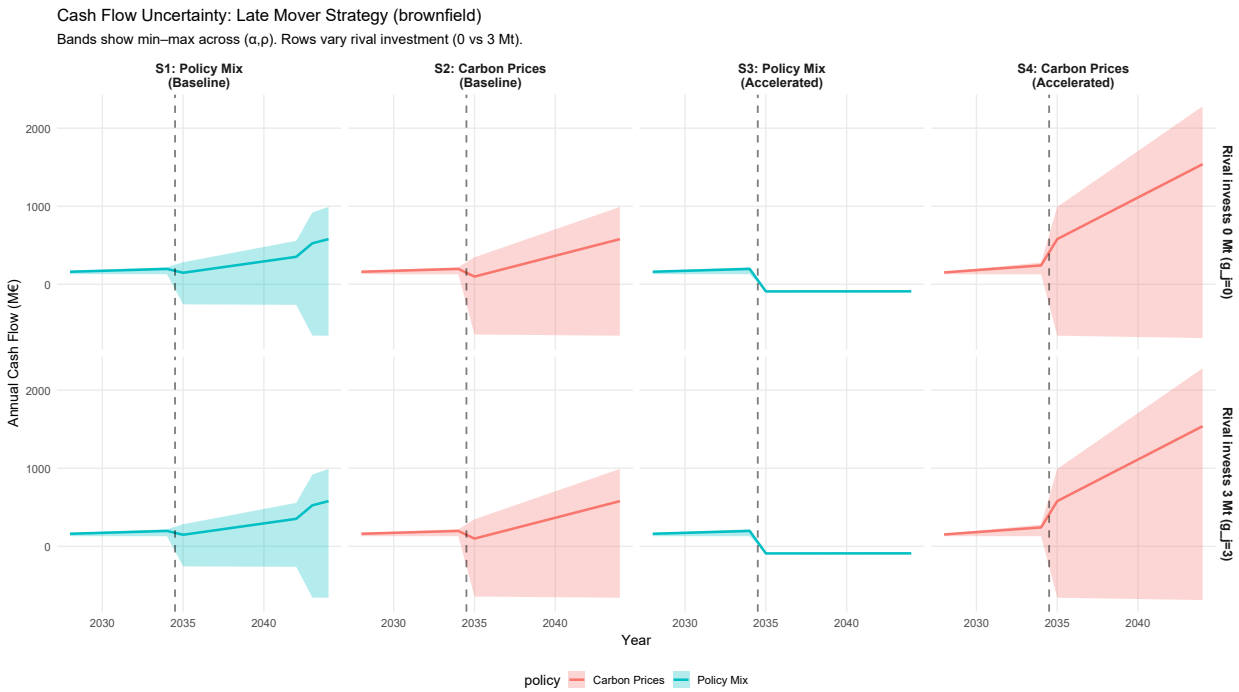


Figure 5: Cash flow over time for late mover

Under carbon-price-only designs (S2 and S4), the stress-test signal is dominated by assumptions on cost pass-through and leakage protection. In period 2, average annual cash flows vary widely across (α, ρ), with standard deviations of approximately 360 M€ for the late mover and 690 M€ for the early mover in the baseline carbon-price scenario (S2), and rising to over 650 M€ and 1,240 M€, respectively, under the accelerated carbon-price regime (S4). As a result, the same firm may appear resilient or fragile depending on policy design assumptions rather than underlying transition exposure. As the demand remains unchanged for these scenarios and firms do not compete over market shares, rival investment has no effect on the cash flows.

The accelerated policy-mix scenario (S3) yields a qualitatively different stress-test signal. Cash flows become tightly distributed and sharply state-dependent, as the dominant shock operates through reduce demand and first mover advantage rather than prices. In period 2, dispersion across (α, ρ) collapses: the standard deviation of annual cash flows falls below 0.5 M€ for both early and late movers, indicating near-deterministic outcomes conditional on the policy regime. This generates a clear separation between firm types. The early mover maintains positive and relatively stable period 2 cash flows, averaging about 207 M€ when the rival does not invest and around 58 M€ when the rival invests early. By contrast, the late mover experiences a discrete drop to negative cash flows of approximately -91 M€, largely invariant to rival behavior.

From a stress-testing perspective, S3 therefore provides a sharper identification environment. It produces a robust ranking of early and late movers that is largely insensitive to contested (α, ρ) assumptions and instead directly linked to transition readiness under an accelerated, demand- and emission-intensive product constrained regime. In contrast, carbon-price-only environments generate wide cash-flow distributions that obscure firm-level vulnerability, weakening their informational content for forward-looking climate stress tests. Figure 6 illustrates this result by showing how the degree of overlap in period-2 cash flow distributions collapses in S3 relative to the carbon-price-only scenarios.

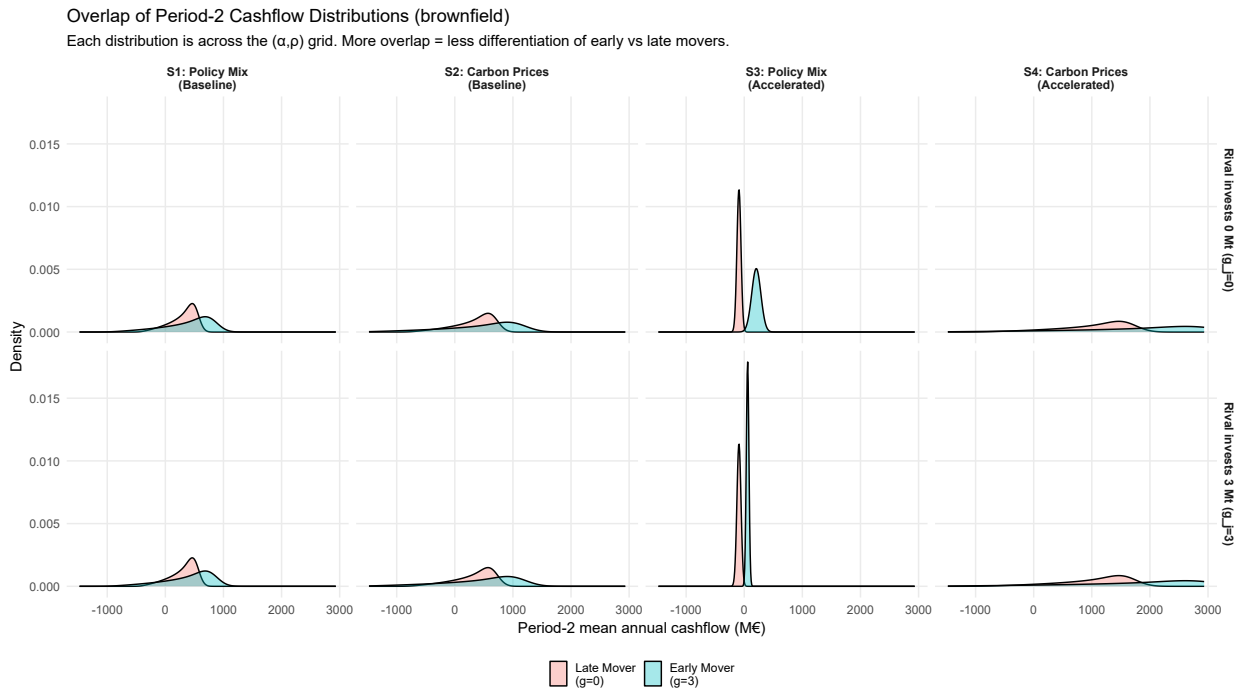


Figure 6: Overlap of period-2 mean annual cash flow distributions across policy scenarios (brownfield case).

Figure 7 quantifies the trade-off between average performance and downside exposure under joint scenario and policy-design uncertainty (uniform over the (α, ρ) grid). For the brownfield case, the wedge between expected NPV and CVaR(5%), $\Delta \equiv E[\text{NPV}] - \text{CVaR}(5\%)$, is large in absolute terms but highly belief-dependent. Under early-mover beliefs, the early investment strategy yields a high expected NPV (about 3,042 M€ when the rival invests 0 Mt and 2,575 M€ when the rival invests 3 Mt), but remains exposed to severe left-tail outcomes with CVaR(5%) $\approx -3{,}187$ M€ in both rival configurations, implying $\Delta \approx 6{,}229$ M€ (rival 0) and $\Delta \approx 5{,}762$ M€ (rival 3). By contrast, the late investment strategy under the same beliefs has a much smaller downside wedge ($\Delta \approx 1{,}752$ M€) and a lower probability of negative NPV (1.8% versus 5.0% for early investment).

Under late-mover beliefs, downside risk becomes markedly more pronounced for early investment: CVaR(5%) falls to about $-6{,}955$ M€ (rival 0) and $-6{,}955$ M€ (rival 3), while expected NPV remains positive (1,762 M€ and 1,728 M€, respectively). This raises the downside wedge to $\Delta \approx 8{,}716$–$8{,}683$ M€ and increases the probability of losses to roughly

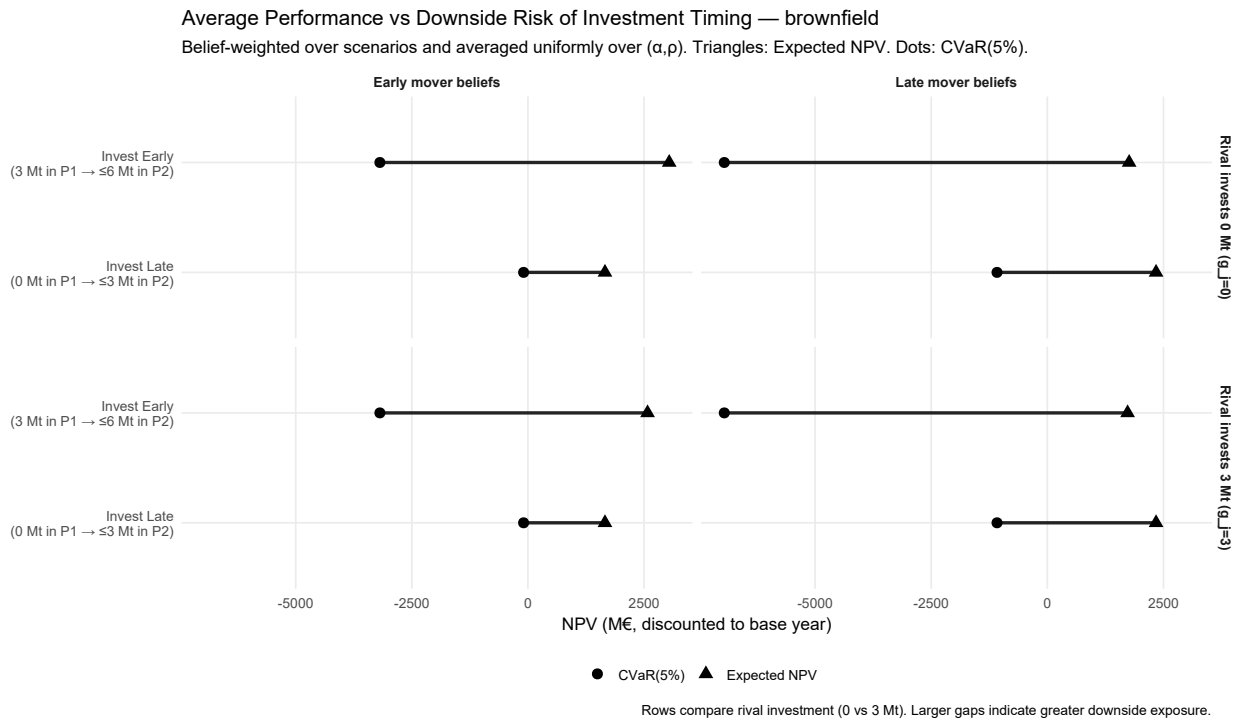


Figure 7: NPV vs. CVAR

26% for early investment, compared with about 8.8% for late investment. Rival early investment primarily shifts expected returns for the early mover (e.g., from 3,042 to 2,575 M€ under early-mover beliefs, and from 207 to 58 M€ in the accelerated policy-mix cash-flow results), but does not materially change tail risk in the joint distribution, consistent with the interpretation that left-tail outcomes are driven by the accelerated transition state rather than marginal parameter variation in (α, ρ).

4 Conclusion

Climate stress testing is intended to assess transition risks at both the firm and financial system levels, yet current practices often obscure the very heterogeneity they aim to capture. By relying on sectoral emission pathways and carbon pricing as the primary policy lever, traditional approaches struggle to differentiate firms within sectors and generate highly dispersed valuation outcomes. This paper demonstrates that forward-looking firm-level data, for example captured through transition plans, can address this limitation, but only when evaluated against scenarios that provide a clear and non-contingent transition or policy shock.

We use a stylized microeconomic model of green capacity investment under policy uncertainty, parameterized using data from the European steel sector, to compare how different scenario designs affect firms' strategic decisions and valuation outcomes. Two otherwise identical firms differ only in their subjective beliefs about climate policy trajectories: the early mover assigns high probability to accelerated transitions, while the late mover expects policy continuity. Firms choose irreversible green capacity investment in period 0 before uncertainty about future policy is resolved. Investment incentives depend on three channels: period-1 operating cost savings, avoided stranded asset costs when brown steel is banned in period 2, and preferential market access when shrinking demand for primary steel creates binding capacity constraints in accelerated transition scenarios.

Our results show that scenario design fundamentally shapes the informativeness of firm-level analysis. Under carbon-price-only scenarios (Scenarios 2 and 4), investment incentives depend heavily on three parameters: the carbon price level, the carbon cost pass-through rate (ρ), and the degree of carbon leakage protection (α). Over the full (α, ρ) grid, cash flow projections exhibit wide ranges, reflecting uncertainty about how carbon costs transmit to firms' effective burden. This policy design uncertainty compounds the effects of heterogeneous beliefs and investment strategies, producing overlapping NPV distributions for early and late mover that obscure heterogeneity. By contrast, the accelerated policy-mix

scenario (Scenario 3) delivers a non-contingent transition shock through three complementary instruments: a binding product standard that bans brown steel products in period 2, a reduce demand for primary steel reflecting material efficiency improvements and increased secondary production that reduce demand for primary steel, and CCfDs that offer financial support for green steel producers. This mix operates independently of pass-through rates, allowance allocation, or carbon price levels, creating a clear and predictable shock. The reduced demand falls below the combined initial capacity of both firms, triggering rationing that rewards early investment through priority allocation. Under this scenario, early investors capture substantially more period-2 output. Late movers face severe downside risk: when they invest minimally in period 0 and the accelerated scenario materializes, they face both stranded asset costs and quantity rationing in period 2, creating large gaps between expected NPV and worst-case outcomes. The policy-mix scenario thus generates sharper differentiation between firms and substantially less dispersion in valuations.

These findings address the two alignment challenges raised in our introduction. First, regarding firm-to-policy alignment, transition plans reveal whether firms anticipate current policy continuity or prepare for accelerated transitions. When evaluated against a common accelerated scenario, these plans become comparable across firms and portfolios, enabling credible assessment of strategic positioning. Second, regarding policy-to-Paris alignment, our accelerated policy-mix scenario shows that binding regulatory constraints combined with demand reductions create clearer differentiation between early and late mover than carbon pricing alone. This suggests that current stress testing practices, which rely primarily on carbon price scenarios, may fail to capture the full range of firm-level vulnerabilities under stringent transition pathways.

Our stylized model has clear limitations. With two firms, four scenarios, and exogenous policy parameters, we illustrate mechanisms rather than propose a comprehensive stress testing framework. In particular, we abstract from an explicit mapping of firm-level valuation outcomes to financial sector exposures, for example through structural credit risk

models linking changes in firm value to equity and debt losses in the spirit of Merton-type frameworks (Reinders, Schoenmaker, and M. A. Van Dijk, 2023). Nevertheless, the core insight remains: firm-level transition plans, when evaluated against a sufficiently stringent and clearly specified accelerated transition scenario, provide the forward-looking and granular information that climate stress testing currently lacks. As transition plans become increasingly standardised through sustainability reporting standards and risk management frameworks, integrating them into stress testing exercises using accelerated policy-mix benchmarks would substantially strengthen climate risk assessment in the financial sector.

Annex A Marginal Benefit Derivation

This appendix derives the marginal benefit of period-0 green investment and characterizes the optimal investment decision under risk neutrality and risk aversion.

A.1 Period-2 Production Quantities

Period-2 production depends on the policy regime.

Case $\delta^s = 1$ (brown allowed). When brown steel can be sold in period 2, market demand is sufficiently large that firms can operate at full capacity. Firms therefore convert brown capacity into green up to the technically feasible level and produce at full capacity:

$$q^s_{i2,\text{green}} = g_i + \tfrac{1}{2}K_{i0}, \qquad q^s_{i2,\text{brown}} = \tfrac{1}{2}K_{i0} - g_i. \tag{A.1}$$

Production quantities coincide with maximum feasible capacity and are deterministic functions of the period-0 investment g_i.

Case $\delta^s = 0$ (brown banned). When brown steel is banned, firms set $q^s_{i2,\text{brown}} = 0$ since brown production yields no revenue but incurs operating costs. Green output is determined by the market-wide size constraint and an allocation rule (derived in Section A.3):

$$q^s_{i2,\text{green}} = \tilde{g}^s_i(g_i, g_j) \in [0, K_{i0}], \qquad q^s_{i2,\text{brown}} = 0. \tag{A.2}$$

The allocation function $\tilde{g}^s_i(g_i, g_j)$ depends on both firms' period-0 investments. When combined feasible capacity does not exceed the demand ($\hat{g}_i + \hat{g}_j \leq \overline{S}^s_2$, where $\hat{g}_i := g_i + \frac{1}{2}K_{i0}$), both firms produce at their maximum feasible levels: $\tilde{g}^s_i = \hat{g}_i$. When the cap binds ($\hat{g}_i + \hat{g}_j > \overline{S}^s_2$), production is allocated according to a priority rule that favors firms with greater period-0 investment.

Define the marginal allocation parameter:

$$\theta_i^s(g_i, g_j) := \frac{\partial \tilde{g}_i^s(g_i, g_j)}{\partial g_i} \in [0, 1]. \tag{A.3}$$

This measures how an additional unit of period-0 investment translates into period-2 green production under scenario s.

Idle brown capacity incurs stranded asset costs:

$$c^s_{\text{stranded}} := c^{\text{ann}}_{x,\text{brown}} + c^{\text{ann}}_{\ell,\text{brown}}, \tag{A.4}$$

where $c^{\text{ann}}_{x,\text{brown}}$ denotes annualized capital costs and $c^{\text{ann}}_{\ell,\text{brown}}$ denotes fixed labour costs that persist in the short to medium run even when capacity is idle.

A.2 Marginal Benefit of Early Investment

We now derive the marginal benefit of period-0 investment: $MB_i^s(g_i, g_j) := \frac{\partial \Pi_i^s(g_i, g_j)}{\partial g_i}$.

Period 1 marginal benefit. Using $q_{i1,\text{brown}} = K_{i0} - g_i$, the first part of equation (1) can be rewritten as:

$$\Pi^s_{i1}(g_i) = \sum_{t=2028}^{2034} \frac{1}{(1+r_i)^{t-2025}} \Big[K_{i0}(\bar{p}^s_{1t} - \bar{c}^s_{1t,\text{brown}}) + g_i(\bar{c}^s_{1t,\text{brown}} - \bar{c}^s_{1t,\text{green}}) \Big]. \tag{A.5}$$

Differentiating with respect to g_i:

$$B^s_1 := \frac{\partial \Pi^s_{i1}}{\partial g_i} = \sum_{t=2028}^{2034} \frac{1}{(1+r_i)^{t-2025}} (\bar{c}^s_{1t,\text{brown}} - \bar{c}^s_{1t,\text{green}}). \tag{A.6}$$

This captures the period-1 operating cost savings from substituting brown with green production capacity. When green production is less costly, $B^s_1 > 0$.

Period 2 marginal benefit, $\delta^s = 1$ (brown allowed). Using equation (A.1):

$$\Pi^s_{i2}(g_i) = \sum_{t=2035}^{2044} \frac{1}{(1+r_i)^{t-2025}} \Big[K_{i0} \Big(\bar{p}^s_{2t} - \tfrac{1}{2}\bar{c}^s_{2t,\text{brown}} - \tfrac{1}{2}\bar{c}^s_{2t,\text{green}} \Big) + g_i(\bar{c}^s_{2t,\text{brown}} - \bar{c}^s_{2t,\text{green}}) \Big]. \quad \text{(A.7)}$$

Differentiating:

$$B^s_2 = \frac{\partial \Pi^s_{i2}}{\partial g_i} = \sum_{t=2035}^{2044} \frac{1}{(1+r_i)^{t-2025}} (\bar{c}^s_{2t,\text{brown}} - \bar{c}^s_{2t,\text{green}}). \quad \text{(A.8)}$$

The marginal benefit is constant in g_i, reflecting the simple cost differential between technologies.

Period 2 marginal benefit, $\delta^s = 0$ (brown banned). With $q^s_{i2,\text{green}} = \tilde{g}^s_i(g_i, g_j)$ and $q^s_{i2,\text{brown}} = 0$:

$$\Pi^s_{i2}(g_i, g_j) = \sum_{t=2035}^{2044} \frac{1}{(1+r_i)^{t-2025}} \Big[\tilde{g}^s_i(g_i, g_j) \big(\bar{p}^s_{2t} - \bar{c}^s_{2t,\text{green}} + c^s_{\text{stranded}} \big) - K_{i0} c^s_{\text{stranded}} \Big]. \quad \text{(A.9)}$$

The term c^s_{stranded} appears with a positive sign because each additional unit of green production reduces idle brown capacity by one unit, avoiding stranded asset costs. Differentiating:

$$B^s_2(g_i, g_j) = \frac{\partial \Pi^s_{i2}}{\partial g_i} = \theta^s_i(g_i, g_j) \sum_{t=2035}^{2044} \frac{1}{(1+r_i)^{t-2025}} \big(\bar{p}^s_{2t} - \bar{c}^s_{2t,\text{green}} + c^s_{\text{stranded}} \big). \quad \text{(A.10)}$$

The marginal benefit now depends on $\theta^s_i(g_i, g_j)$, which determines how period-0 investment translates into period-2 production under the allocation rule.

Total marginal benefit. Combining both periods:

$$MB^s_i(g_i, g_j) = B^s_1 + B^s_2(g_i, g_j). \quad \text{(A.11)}$$

When brown production remains allowed in all scenarios ($\delta^s = 1$), the marginal benefit MB_i^s is constant in g_i and depends only on the cost differentials between brown and green production.

When brown production is banned in some scenarios ($\delta^s = 0$), early green investment yields additional benefits by reducing stranded brown capacity and the associated fixed costs. Moreover, if aggregate demand is constrained, the marginal benefit also depends on the allocation parameter $\theta_i^s(g_i, g_j)$, which governs priority access to the shrinking market. In this case, marginal incentives become state-dependent and strategic interdependence arises through firms' relative investment timing.

A.3 Allocation Rule Under Demand Constraint

We now derive the allocation rule that determines period-2 production when brown is banned and the demand constraint binds.

Setup. When brown steel is banned in period 2 ($\delta^s = 0$) and the demand for primary steel is reduced, total production across both firms is capped at $\overline{S}_2^s$. Each firm has maximum feasible green capacity:

$$\hat{g}_i = g_i + \tfrac{1}{2}K_{i0}, \qquad \hat{g}_j = g_j + \tfrac{1}{2}K_{i0}. \tag{A.12}$$

If combined capacity $\hat{g}_i + \hat{g}_j$ exceeds the demand $\overline{S}_2^s$, the market must be rationed between firms.

Case 1: No rationing ($\hat{g}_i + \hat{g}_j \leq \overline{S}_2^s$). Both firms can produce at their maximum feasible levels:

$$\tilde{g}_i^s = \hat{g}_i = g_i + \tfrac{1}{2}K_{i0}. \tag{A.13}$$

The marginal effect of period-0 investment on period-2 production is:

$$\theta_i^s = \frac{\partial \tilde{g}_i^s}{\partial g_i} = 1. \tag{A.14}$$

Each unit of period-0 investment translates one-for-one into period-2 green capacity.

Case 2: Rationing binds ($\hat{g}_i + \hat{g}_j > \overline{S}_2^s$). The market must be split between firms. We use a smooth priority rule that favors the firm with greater period-0 investment. Define firm i's priority weight:

$$w_i(g_i, g_j) = \frac{1}{1 + \exp\{-k(g_i - g_j)\}}, \qquad k > 0, \tag{A.15}$$

where k controls the strength of first-mover advantage. When $g_i > g_j$, firm i receives higher priority ($w_i > 0.5$); when $g_i < g_j$, firm i receives lower priority ($w_i < 0.5$). By construction, $w_j(g_j, g_i) = 1 - w_i(g_i, g_j)$.

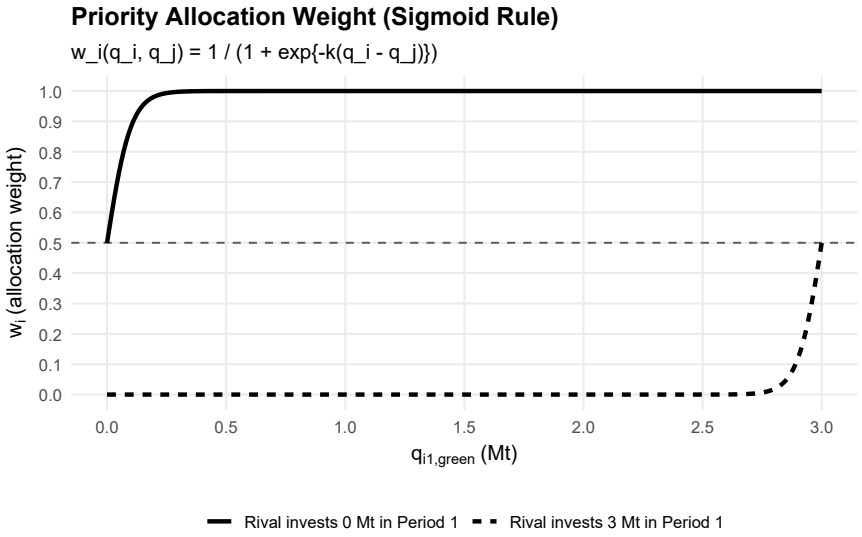


Figure 8: Priority allocation weight w_i as a function of firm i's period-0 investment g_i for two rival strategies: $g_j = 0$ (solid line) and $g_j = 3$ Mt (dashed line). The sigmoid shape reflects smooth first-mover advantage. When $g_i > g_j$, firm i receives higher priority ($w_i > 0.5$); when $g_i < g_j$, firm i receives lower priority ($w_i < 0.5$). The steepness parameter $k = 20$ creates a sharp transition around the point where both firms invest equally.

Firm i's actual production combines two extreme outcomes weighted by priority:

$$\tilde{g}_i^s(g_i, g_j) = w_i(g_i, g_j) \cdot \min\{\hat{g}_i, \overline{S}_2^s\} + \big(1 - w_i(g_i, g_j)\big) \cdot \max\{0, \overline{S}_2^s - \hat{g}_j\}. \tag{A.16}$$

The first term represents the high-priority outcome: if firm i has very high priority, it

produces as much as it wants (limited by its own capacity or the entire market). The second term represents the low-priority outcome: if firm i has very low priority, firm j produces first and firm i gets only the residual.

To find the marginal allocation parameter, differentiate equation (A.16) with respect to g_i. Since $\frac{\partial w_i}{\partial g_i} = kw_i(1-w_i)$ and $\hat{g}_i < \overline{S}_2^s$ for feasible investments:

$$\theta_i^s(g_i, g_j) = w_i + kw_i(1-w_i)\big[\hat{g}_i + \hat{g}_j - \overline{S}_2^s\big]. \tag{A.17}$$

The first term (w_i) captures the direct effect of priority on allocation. The second term ($kw_i(1-w_i)[\cdot]$) captures the strategic effect: how increasing g_i improves firm i's priority position. This strategic effect is strongest when firms are evenly matched ($w_i \approx 0.5$) and proportional to the degree of rationing ($\hat{g}_i + \hat{g}_j - \overline{S}_2^s > 0$).

Application to period-2 quantities. The allocation parameter θ_i^s directly determines how period-0 investment affects period-2 production. From equation (A.3):

$$\frac{\partial q_{i2,\text{green}}^s}{\partial g_i} = \frac{\partial \tilde{g}_i^s(g_i, g_j)}{\partial g_i} = \theta_i^s(g_i, g_j). \tag{A.18}$$

When the demand does not bind, $\theta_i^s = 1$ and each unit of period-0 investment translates one-for-one into period-2 green capacity. When the cap binds, $\theta_i^s \in (0,1)$ and the translation is less than one-for-one due to rationing. The exact value depends on both firms' investment choices through equations (A.15) and (A.17), creating strategic complementarity: if rival j invests heavily, firm i must also invest to maintain priority and secure period-2 market access.

A.4 Optimal Investment

Having characterized production quantities and marginal benefits, we now solve for optimal period-0 investment.

First-order condition. The first-order condition for the optimization problem (1) is:

$$\frac{dJ_i}{dg_i} = \sum_{s=1}^{S} \pi_i^s MB_i^s(g_i, g_j) - 2\lambda \sum_{s=1}^{S} \pi_i^s \big(\Pi_i^s(g_i, g_j) - \bar{\Pi}_i(g_i, g_j)\big) MB_i^s(g_i, g_j) = 0, \tag{A.19}$$

with solution projected onto the feasible set $[0, \frac{1}{2}K_{i0}]$.

Risk-neutral case ($\lambda = 0$). When firms are risk-neutral, the solution is bang–bang:

$$g_i^* = \begin{cases} \frac{1}{2}K_{i0} & \text{if } \overline{MB}_i > 0, \\ 0 & \text{if } \overline{MB}_i < 0, \end{cases} \qquad \overline{MB}_i := \sum_{s=1}^{S} \pi_i^s MB_i^s(g_i, g_j). \tag{A.20}$$

Firms invest fully if the expected marginal benefit is positive and do not invest otherwise.

Closed form (no rationing, $\lambda > 0$). When the demand does not bind in any scenario ($\theta_i^s = 1$ for all s), the marginal benefit MB_i^s is constant in g_i and profits are linear: $\Pi_i^s(g_i, g_j) = A_i^s + MB_i^s \cdot g_i$. In this case, the first-order condition (A.19) yields an interior solution:

$$g_i^* = \frac{\overline{MB}_i - 2\lambda \operatorname{Cov}(A_i^s, MB_i^s)}{2\lambda \operatorname{Var}(MB_i^s)}, \tag{A.21}$$

with bounds $[0, \frac{1}{2}K_{i0}]$ enforced.

Numerical solution (rationing binds). When the demand binds in some scenarios, $\theta_i^s(g_i, g_j) < 1$ makes $MB_i^s(g_i, g_j)$ depend on g_i, and equation (A.19) must be solved numerically by grid search over the feasible set.

A.5 Comparative Statics

With an interior solution and constant marginal benefits (no rationing):

$$\frac{\partial g_i^*}{\partial \lambda} = -\frac{\overline{MB}_i}{2\lambda^2 \operatorname{Var}(MB_i^s)} < 0 \quad \text{if } \overline{MB}_i > 0. \tag{A.22}$$

Risk aversion reduces investment. Lower variance in marginal benefits across scenarios ($\text{Var}(MB_i^s)$) increases investment, while higher covariance between the intercept and marginal benefit ($\text{Cov}(A_i^s, MB_i^s)$) reduces investment.

Annex B Details of Unit Costs

To clarify the cost structure of brown and green steel, we decompose the unit costs into operating expenditures, capital expenditures, net carbon costs (after free allocation), and potential subsidies such as CCfDs (see also Table 6 for a summary of variables and parameters).

B.1 Brown steel.

The unit costs of producing one tonne of brown steel in period $p \in \{1, 2\}$, year t, and scenario s are given by:

$$\bar{c}^s_{pt,\text{brown}} = \bar{ox}^s_{pt,\text{brown}} + \bar{cx}^s_{pt,\text{brown}} + \left(\bar{ei}^s_{pt,\text{brown}} - \underbrace{\bar{ei}^s_{pt,\text{brown}} \cdot (1-\rho)\,\alpha}_{\bar{fa}^s_{pt,\text{brown}}} \right) \bar{cp}^s_{pt}, \tag{A.23}$$

where $\bar{fa}^s_{pt,\text{brown}}$ represents free allowances.[7]

B.2 Green steel.

The unit costs of producing one tonne of green steel in the same period and scenario are:

$$\bar{c}^s_{pt,\text{green}} = \bar{ox}^s_{pt,\text{green}} + \bar{cx}^s_{pt,\text{green}} + \left(\bar{ei}^s_{pt,\text{green}} \cdot \bar{cp}^s_{pt} \right) - \beta^s \cdot \bar{cc\bar{f}d}^s_{pt,\text{green}}. \tag{A.24}$$

[7]The parameters α and ρ do not carry scenario- or time-specific indices, as they are used as general sensitivities in our model.

B.3 Stranded asset costs (Scenario 3, Period 2).

When brown steel is banned ($\delta^s = 0$), idle brown capacity incurs stranded asset costs:

$$c^s_{\text{stranded}} = c^{\text{ann}}_{x,\text{brown}} + c^{\text{ann}}_{\ell,\text{brown}}, \tag{A.25}$$

where $c^{\text{ann}}_{x,\text{brown}}$ represents annualized capital obligations on brown capacity and $c^{\text{ann}}_{\ell,\text{brown}}$ represents fixed labour costs that persist in the short to medium run even when capacity is idle. These costs are incurred on capacity ($K_{i0} - q^s_{i2,\text{green}}$) that cannot produce due to the brown steel ban.

Table 6: Cost-related variables and policy parameters for brown and green steel.

Symbol	**Description**
$\bar{ox}^s_{pt,\cdot}$	Average operating expenditures (Opex) per unit of steel in period p, year t, scenario s
$\bar{cx}^s_{pt,\cdot}$	Average annualized capital expenditures (Capex) per unit of steel in period p, year t, scenario s, given by the annuity factor under the assumed financing mix (see Table 4).
c^s_{stranded}	Stranded asset costs per unit of idle brown capacity in scenario s, equal to $c^{\text{ann}}_{x,\text{brown}} + c^{\text{ann}}_{\ell,\text{brown}}$ (annualized capital obligations plus fixed labour costs). Applied only when brown steel is banned ($\delta^s = 0$).
$\bar{ei}^s_{pt,\cdot}$	Average emission intensity (tCO_2 per tonne) in period p, year t, scenario s
$\bar{cp}^s_{pt}$	Average carbon price in period p, year t, scenario s
$\bar{fa}^s_{pt,\cdot}$	Free allowances in tonnes of emissions per unit of steel, period p, year t, scenario s
ρ	Cost pass-through rate (share of carbon costs shifted to consumers); $\rho = 1$ = full pass-through, $\rho = 0$ = full internalization
α	Protection factor (extent of shielding via free allocation or CBAM); $\alpha = 1$ = full protection, $\alpha = 0$ = no protection
$\bar{ccfd}^s_{pt,\text{green}}$	Average CCfD payout per unit of green steel, period p, year t, scenario s
β^s	CCfD volume factor in scenario s ($\beta^s = 1$ implies the full green steel volume is covered, $\beta^s = 0$ implies no volume is covered)

Annex C Calculation of Payments for Carbon Contracts for Difference (CCfDs)

In the scenarios that include Carbon Contracts for Difference (CCfDs), we estimate annual payment flows based on the relative costs and emissions savings of green versus conventional (brown) steelmaking. CCfDs are awarded for a duration of 15 years, starting from the year the green steel plant becomes operational. These contracts subsidize the incremental operating expenditures (OPEX) and capital expenditures (CAPEX) of green steel production, compared to traditional methods. Each year, the CCfD payment is calculated as the difference between a fixed strike price and the effective carbon price, multiplied by the emissions avoided (in tonnes of CO_2). If the carbon price is higher than the strike price, the producer pays back the difference; if it is lower, the contract pays out the gap. The formula follows the methodology proposed by Lösch et al. (2022), and does not incorporate potential green premiums that steel producers may receive. The annual per-tonne support is given by:

$$\bar{ccfd}^{s}_{pt,\text{green}} = \left\{ \underbrace{\frac{(\bar{ox}^{s}_{pt,\text{green}} - \bar{ox}^{s}_{pt,\text{brown}}) + (\bar{cx}^{s}_{pt,\text{green}} - \bar{cx}^{s}_{pt,\text{brown}})}{\bar{ei}^{s}_{pt,\text{brown}} - \bar{ei}^{s}_{pt,\text{green}}}}_{\text{(1) Strike Price}} - \underbrace{\bar{cp}^{s}_{pt} \cdot \frac{(\bar{ei}^{s}_{pt,\text{brown}} - \bar{fab}^{s}_{pt,\text{brown}}) + (\bar{fab}^{s}_{pt,\text{green}} - \bar{ei}^{s}_{pt,\text{green}})}{\bar{ei}^{s}_{pt,\text{brown}} - \bar{ei}^{s}_{pt,\text{green}}}}_{\text{(2) Effective } CO_2 \text{ Price}} \right\} \cdot \underbrace{\left(\bar{ei}^{s}_{pt,\text{brown}} - \bar{ei}^{s}_{pt,\text{green}}\right)}_{\text{(3) Avoided Emissions}}$$

Annex D Results with smaller demand in period 2 in accelerated policy scenario

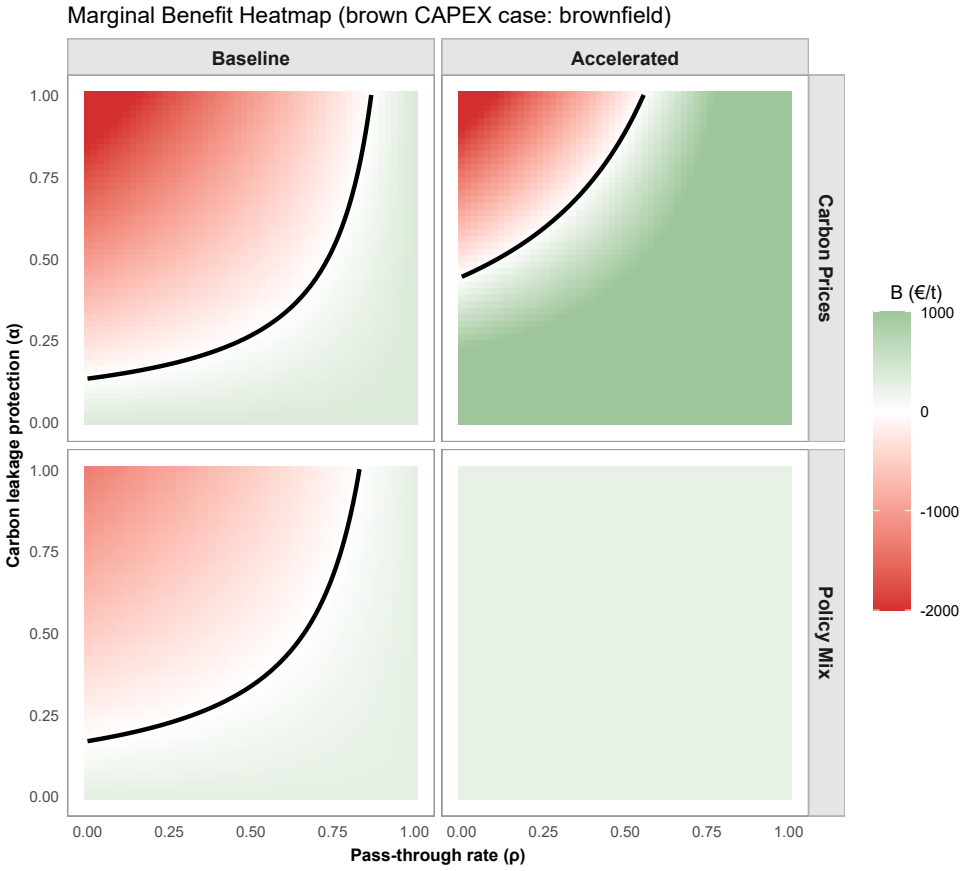


Figure 9: Discounted Marginal benefit (MB) per scenario and period

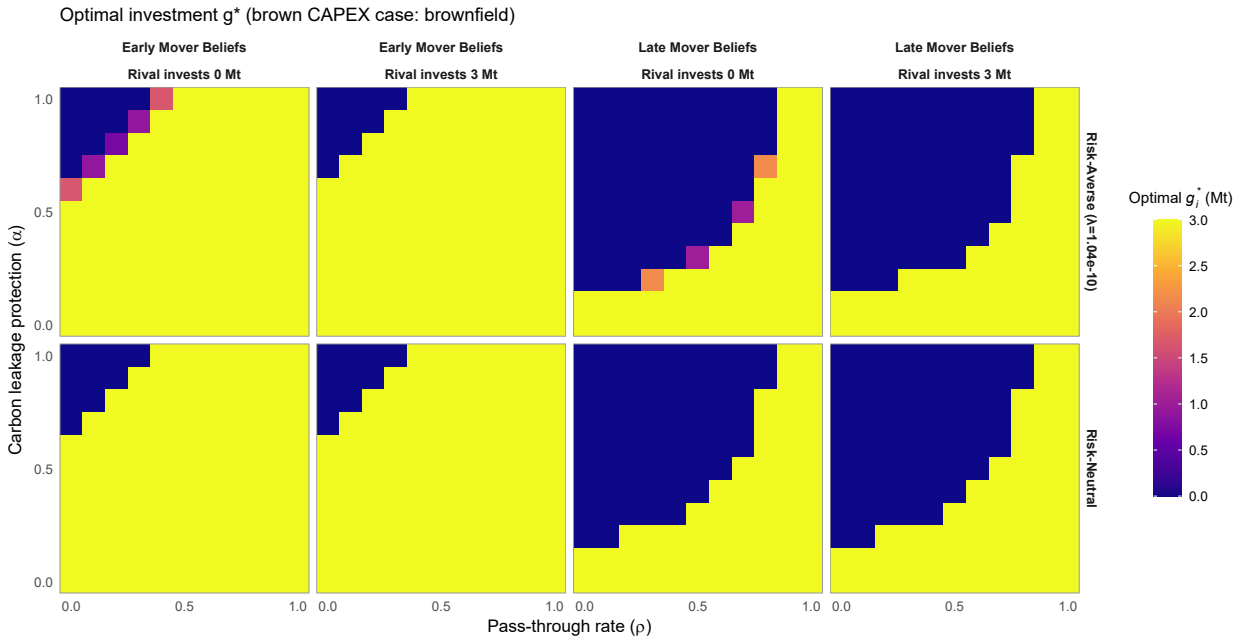


Figure 10: Optimal level of green investment for risk neutral and risk averse case for different belief profiles



Figure 11: Cash flow over time for early mover

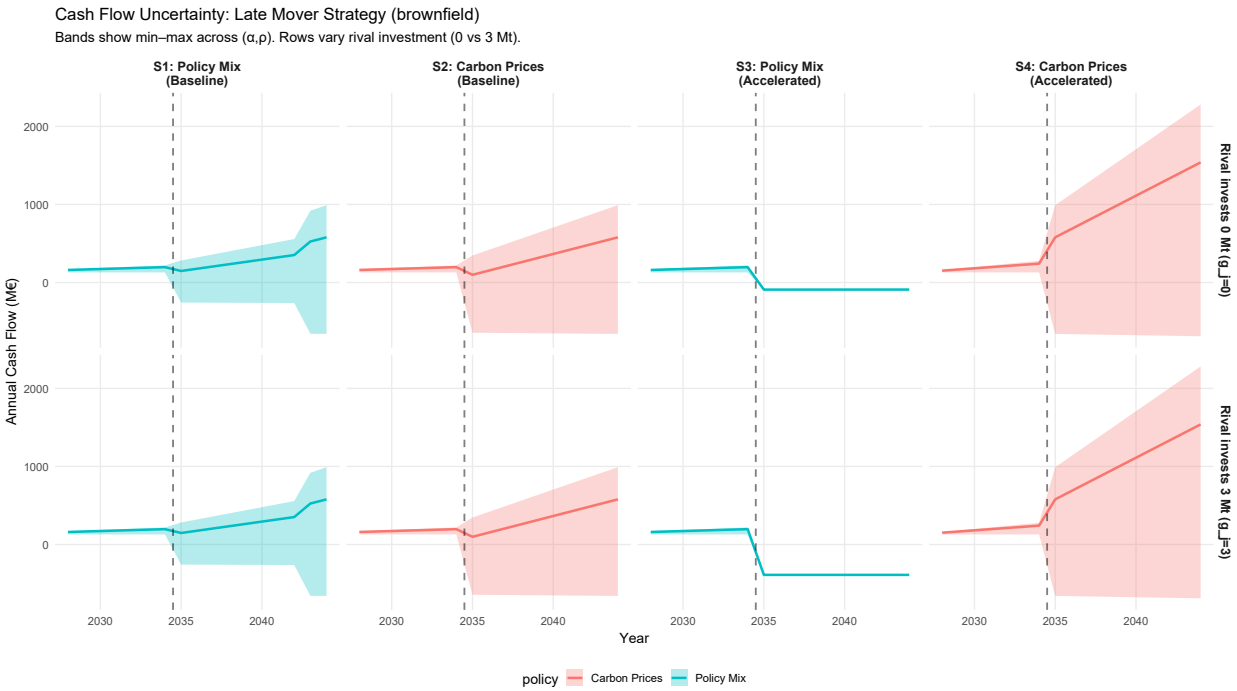


Figure 12: Cash flow over time for late mover

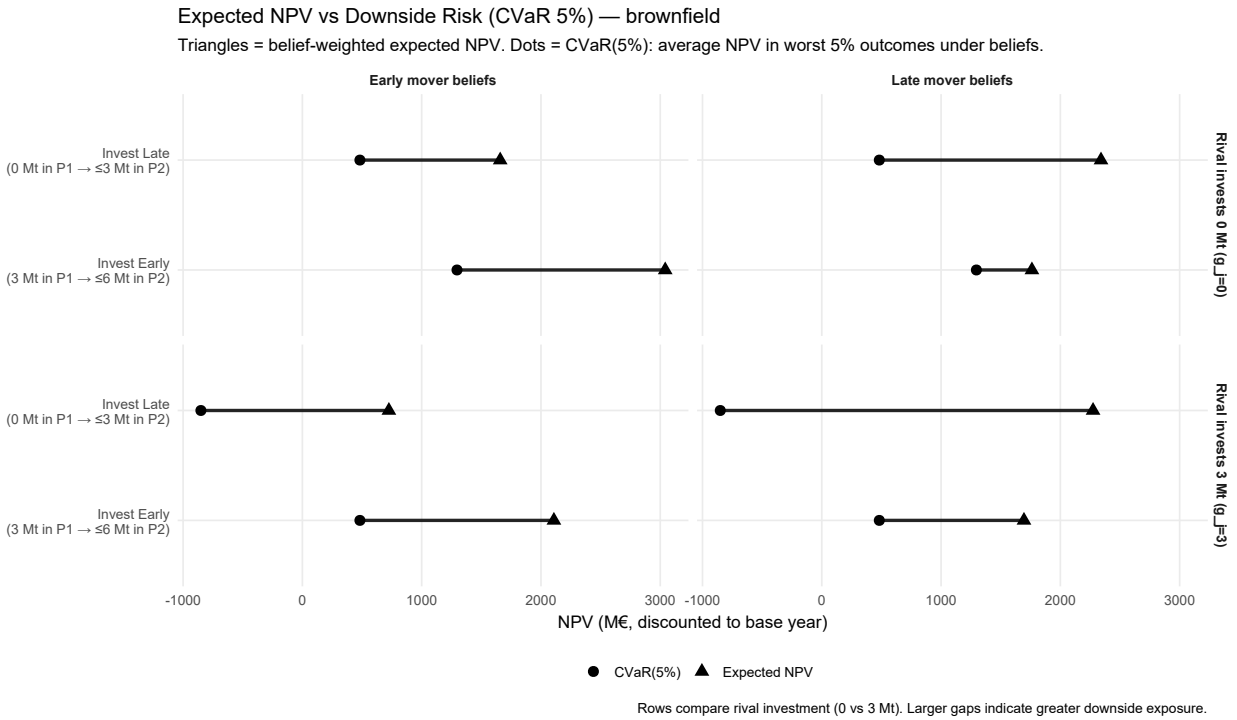


Figure 13: NPV vs. CVAR

Annex E Results with CVAR as risk aversion

Figure 14 reports the optimal period-0 green investment decision when firms evaluate downside risk using a CVaR-based objective rather than mean–variance preferences. The figure mirrors the structure of the baseline optimal investment heatmaps in Section 3, but replaces the variance penalty with a Conditional Value-at-Risk criterion.

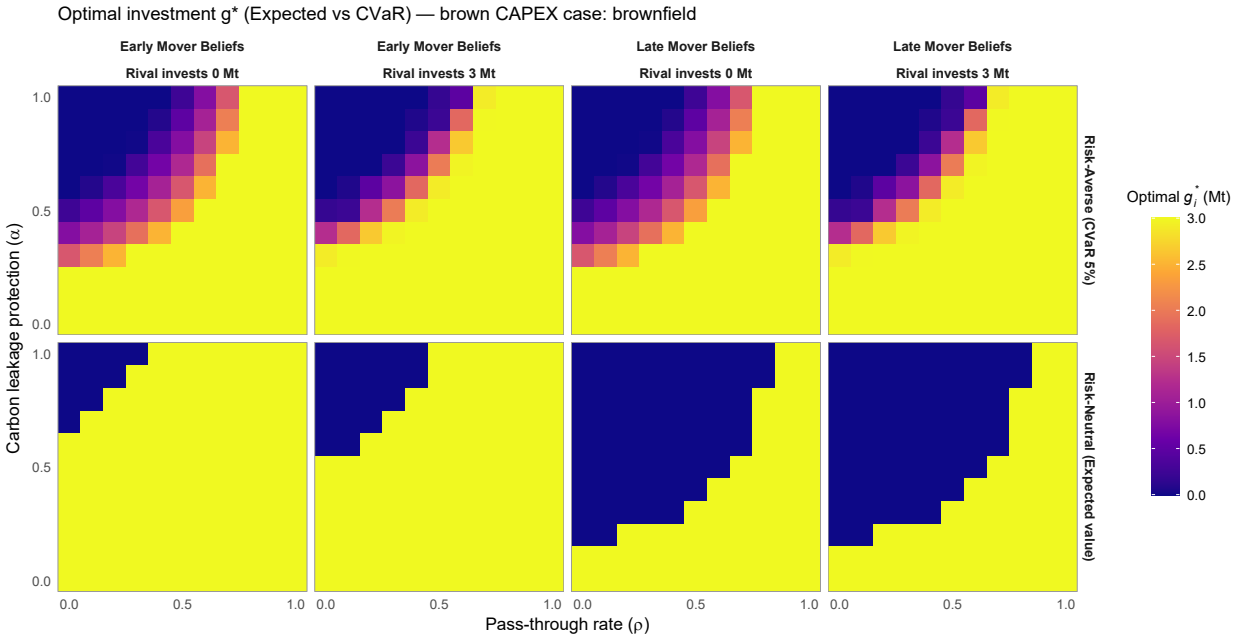


Figure 14: Optimal first-period green capacity conversion under CVaR-based downside-risk aversion.

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