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

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Abstract

Climate stress testing has become a key tool to assess firm-level transition risks and how these propagate to financial institutions and the financial system. Yet, current practices often rely on historical and sector-averaged data that obscure firm-level ambition and within sector heterogeneity.

We develop a stylized model of irreversible firm-level investment to simulate belief-driven early- and late-mover behavior in low-carbon production investment and apply it to the European steel sector. We show stress-testing scenarios based primarily on carbon pricing generate broad and overlapping valuation outcomes for the early and late mover firm, even when forward-looking firm strategies are taken into account, reflecting uncertainty in cost pass-through and carbon leakage protection. By contrast, an accelerated policy-mix scenario combining price and policy incentives with primary demand reductions produces a sharper transition shock, leading to a clear differentiation between aligned and non-aligned firms with the transition. Overall, the results show that the use of forward-looking firm data is as critical as the choice of a sufficiently stringent transition scenario. The latter ensures that climate stress test results are informative for financial risk management or capital allocation and pricing.

Keywords: Transition Risks, Energy-intensive Industry, Climate Stress-testing, Transition plans, Policy Uncertainty
JEL Codes: Q54, Q58, G18; G32, D21, E37, O33, H23

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1 Introduction

Since Mark 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, Bowen, et al., 2016). This implies that financial and economic assets may undergo changes in value (Reinders, Schoenmaker, and M. A. Van Dijk, 2023; Campiglio, Daumas, 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 have to 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 pricing and 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 the combination of both, forward-looking firm-level data and 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 and other policy incentives with 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 the second economy-wide climate stress test by 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 a central limitation: As it does not capture forward-looking strategies of individual firms, it is insufficient to capture within sector heterogeneity. Firm heterogeneity within a sector thereby only arises due to diverging current emission intensities 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. Across all NGFS pathways, ranging from orderly transitions and "hot house world" scenarios, carbon pricing serves as a central policy transmission mechanism (NGFS, 2023). 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). It should be noted that carbon prices under the NGFS frameworks do not merely refer to observed market prices, e.g. the carbon price under the EU Emission Trading system (EU-ETS), but are used as a proxy for other climate policy instruments and thereby reflect the overall ambition of a policy scenario. While carbon pricing is a central element of climate policy frameworks, from a stress-testing perspective, its firm-level transmission in climate stress-testing, hence it's ability to shock a firm's cashflow or financial performance, is often not well understood (Ostrovnaya et al., 2026) and 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. When the statutory incidence of a carbon price falls on the producer (Musgrave, 1959), its economic incidence - the extent to which costs are passed through rather than absorbed - varies across firms and sectors and is difficult to observe or estimate (Neuhoff and Ritz, 2019; Cludius et al., 2020). 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 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, the uncertainty surrounding those exercises 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 using forward-looking firm-level data and 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 in their beliefs about future climate policy. An early-mover firm anticipates an accelerated transition with a policy mix benefiting firms aligned with such pathway and demand reductions, while a late-mover firm expects policy continuity. Investment decisions are irreversible and determine firms' ability to convert in the future. 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 equivalent emitted 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 (Campiglio, Lamperti, and Terranova, 2024).

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). 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. 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, support instruments like Carbon Contracts for Differences (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). Hence, for the policy-mix scenarios, in addition to carbon pricing, we specify assumptions on policy support - here implemented via CCfD) - and reduced demand for primary steel.

The latter assumption captures 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 cannot only be ackowledged for the steel sector (Vogl, Åhman, and Nilsson, 2021), but is also increasingly recognised in the context of climate stress testing, 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.

The analysis yields two 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, a carbon price shock generates wide and overlapping valuation distributions for early and late movers despite their diverging investment strategies. Second, the accelerated policy-mix scenario, combining carbon pricing, demand reductions, and targeted support instruments, produces substantially clearer firm-level differentiation. By covering the incremental costs of the green technology and operating through demand constraints rather than prices alone, the scenario generates a sharp transition shock that mainly hurts the later mover that risks losing market shares.

We study this question in the context of the growing importance of forward-looking reporting, for example in the form of transition plans, which are increasingly mandated 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 crucial 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, Daumas, et al., 2023; J. A. Bingler, Colesanti Senni, and Monnin, 2022; Acharya et al., 2023; Tang et al., 2024). In this sense, an accelerated policy-mix scenario provides 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 and valuation outcomes under varying investment strategies and and stress testing approaches. 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	Long-term: 30 years (to 2050); Short-term: 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_0.

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 the green steel-making technology. This decision is irreversible and measured by the amount of converted capacity $g_i \in [0, \frac{1}{2}K_0]$. Within a single period 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 $q_{i1,\text{brown}} = K_0 - g_i$.

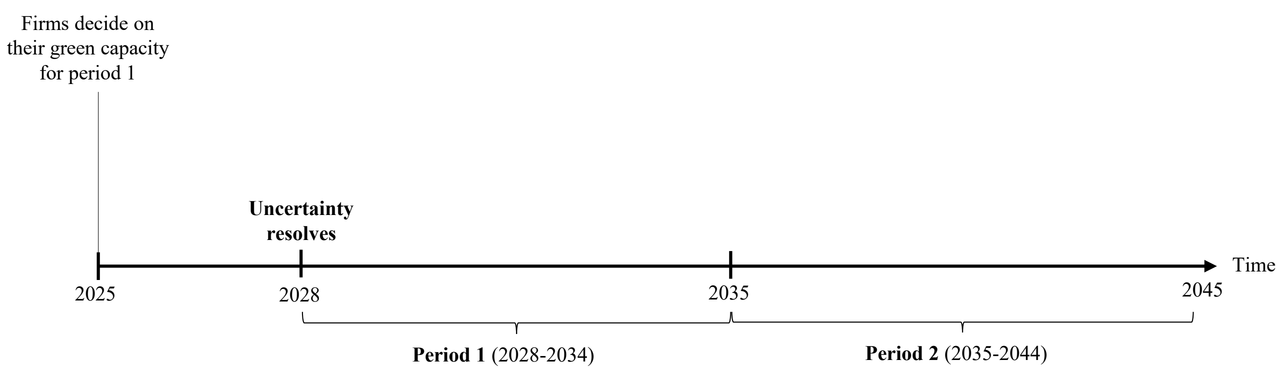

Figure 1: Investment timeline for firms.

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, the financial support provided for the incremental costs of green investment (here implemented as a Carbon Contract for Difference, CCfD, see Appendix C), and the demand for primary steel in period 2 (2035–2044). If demand for primary steel in period 2 falls below aggregate installed capacity, firms compete for available demand 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. Capacity left idle by rationing is stranded and continues to incur fixed costs. Total green capacity in period 2 is 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 the 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. Moreover, 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. Each firm takes output prices as given and chooses its green investment g_i ex ante to maximize a mean–variance objective over a finite set of S scenarios, taking the rival's investment g_j as given.[1]

$$\max_{g_i \in [0, \frac{1}{2}K_0]} J_i(g_i, g_j) = \sum_{s=1}^{S} \pi_i^s \Pi_i^s(g_i, g_j) - \lambda \sum_{s=1}^{S} \pi_i^s \left(\Pi_i^s(g_i, g_j) - \bar{\Pi}_i\right)^2, \tag{1}$$

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. Because period-2 market access depends on both firms' investments, (1) defines a game. Its Nash equilibrium is characterized at the end of this section.

Scenario-specific profits. Scenario-specific profits consist of discounted operating cash flows in both production periods and stranded-asset costs due to competition for market access when demand for primary steel declines:

$$\begin{aligned} \Pi_i^s(g_i, g_j) = &\sum_{t=2028}^{2034} \frac{1}{(1+r)^{t-2025}} \left[(K_0 - g_i)(\bar{p}_{1t}^s - \bar{c}_{1t,\text{brown}}^s) + g_i(\bar{p}_{1t}^s - \bar{c}_{1t,\text{green}}^s)\right] \\ &+ \sum_{t=2035}^{2044} \frac{1}{(1+r)^{t-2025}} \Big[q_{i2,\text{brown}}^s(\bar{p}_{2t}^s - \bar{c}_{2t,\text{brown}}^s) + q_{i2,\text{green}}^s(\bar{p}_{2t}^s - \bar{c}_{2t,\text{green}}^s) \\ &\qquad - c_{\text{stranded}}^s \left(K_0 - q_{i2,\text{total}}^s\right)\Big], \end{aligned} \tag{2}$$

where $q_{i2,\text{total}}^s = q_{i2,\text{brown}}^s + q_{i2,\text{green}}^s$. Unit costs $\bar{c}_{pt,\tau}^s$ include operating costs, annualized capital costs, and carbon costs (net of support). Period-1 production is determined by period-0 investment ($q_{i1,\text{green}} = g_i$ and $q_{i1,\text{brown}} = K_0 - g_i$), while period-2 production quantities are determined by constraints (C1)–(C7) and the market allocation rule described below. In period 2, firms convert brown capacity into green only up to the level of production they expect to realize given market-wide rationing, so that green capacity is never installed and left idle. Any capacity not allocated to production under rationing is stranded. Expected profits are given by $\bar{\Pi}_i = \sum_{s=1}^{S} \pi_i^s \Pi_i^s(g_i, g_j)$.

Stranded assets under demand-side rationing. When period-2 demand falls below installed capacity, market-wide rationing leaves part of a firm's capacity or both firm's capacity idle. Idle capacity continues to incur the annualized cost $c_{\text{stranded}}^s = c_{x,\text{brown}}^{\text{ann}} + c_{\ell,\text{brown}}^{\text{ann}}$, where $c_{x,\text{brown}}^{\text{ann}}$ denotes

[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. **??** discusses robustness to alternative downside-risk measures (e.g., CVaR).

annualized capital costs and $c^{\text{ann}}_{\ell,\text{brown}}$ fixed labour costs that may persist in the medium run due to employment protection. Because the priority rule allocates a larger share of scarce demand to firms with more green capacity, each unit of early green investment raises the firm's allocated production and reduces idled (stranded) capacity at the margin, creating a positive marginal benefit of early investment when the demand cap binds.

Constraints. The optimization problem is subject to:

$$
\begin{aligned}
q_{i1,\text{brown}} + q_{i1,\text{green}} &= K_0, && \text{(C1)}\\
q^s_{i2,\text{brown}} + q^s_{i2,\text{green}} &\le K_0, && \text{(C2)}\\
g_i &\le \tfrac{1}{2}K_0, && \text{(C3)}\\
q^s_{i2,\text{green}} &\le g_i + \tfrac{1}{2}K_0, && \text{(C4)}\\
q^s_{i2,\text{brown}} &\le K_0 - g_i, && \text{(C5)}\\
q^s_{i2,\text{brown}} + q^s_{j2,\text{brown}} + q^s_{i2,\text{green}} + q^s_{j2,\text{green}} &\le \overline{S}^s_2, && \text{(C6)}\\
q^s_{ip,\cdot} &\ge 0, && \text{(C7)}
\end{aligned}
$$

Constraint (C1) ensures full capacity utilization in period 1. Constraint (C3) limits the maximum conversion per period to half of 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 production may be strictly lower than this upper bound, and firms anticipate such rationing when deciding how much remaining brown capacity to convert, ensuring that green capacity is converted only up to realized production. Constraint (C5) ensures that already converted capacity cannot be operated as brown. Constraint (C6) 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 $\overline{S}^s_2$ on total primary steel production in period 2 ranges from K_0 to $2K_0$, reflecting different demand levels across scenarios. Let $\hat{g}_i \equiv g_i + \frac{1}{2}K_0$ denote firm i's "green-ready capacity" (capacity already converted plus the maximum still convertible in period 2). When demand for primary steel falls below aggregated installed capacity, total period-2 output is allocated in proportion to green-ready capacity:

$$
q^s_{i2,\text{total}} = \begin{cases} K_0, & \overline{S}^s_2 \ge 2K_0, \\ \min\left\{ \dfrac{\overline{S}^s_2\, \hat{g}_i}{\hat{g}_i + \hat{g}_j},\ K_0 \right\}, & \overline{S}^s_2 < 2K_0. \end{cases} \tag{3}
$$

This proportional rule captures the first mover advantage as it channels scarce demand toward firms with more green-ready capacity and thereby reward early conversion. We summarize the effect of period-0 investment on period-2 market access by the marginal allocation parameter:

$$\theta_i^s := \frac{\partial q^s_{i2,\text{total}}}{\partial g_i} = \begin{cases} 0, & \overline{S}_2^{\,s} \geq 2K_0, \\ \dfrac{\overline{S}_2^{\,s}\,\hat{g}_j}{(\hat{g}_i+\hat{g}_j)^2} \in (0,1), & \overline{S}_2^{\,s} < 2K_0. \end{cases} \tag{4}$$

When combined production does not exceed the demand cap, $\theta_i^s = 0$: early investment does not buy future market access. When the cap is strictly binding, $\theta_i^s \in (0,1)$ and is "strictly decreasing" in own investment, the marginal return to early conversion diminishes resulting in interior optima. The rule is smooth and bounded, ensuring differentiability of the firm's optimization problem.

Symbol	**Description**
$i, j \in \{1,2\},\ i \neq j$	Firm indices
$p \in \{1,2\}$	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).
$\hat{g}_i = g_i + \frac{1}{2}K_0$	Green-ready capacity of firm i: converted plus maximum still convertible in period 2.
$q^s_{ip,\text{brown}}$	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.
$q^s_{i2,\text{total}}$	Total period-2 output of firm i in scenario s, $q^s_{i2,\text{brown}} + q^s_{i2,\text{green}}$.
K_0	Initial production capacity, identical across firms (constant).
$\overline{S}_2^{\,s}$	Scenario-specific demand cap on total primary steel production in period 2.
$\bar{p}^s_{pt}$	Market price in period p, year t, and scenario s. Prices are set at the industry level by the unit cost of the price-setting (brown) technology, including partial carbon pass-through ρ, augmented by a small exogenous markup μ. Firms take prices as given and do not engage in strategic price setting.
$\rho \in [0,1]$	Share of the carbon cost passed through to output prices.
$\alpha \in [0,1]$	Degree of carbon leakage protection.
$\bar{c}^s_{pt,\text{brown}}$	Unit cost of brown steel in period p, year t, scenario s (see Appendix Appendix B).
$\bar{c}^s_{pt,\text{green}}$	Unit operating cost of green steel, net of CCfD support, in period p, year t, scenario s (see Appendix Appendix B).
c^s_{stranded}	Annualized stranded-asset cost per unit of capacity left idle by rationing 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	Discount rate (WACC), identical across firms.[2]
θ_i^s	Marginal allocation parameter linking period-0 investment to period-2 market access under scenario s, defined in (4).

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

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, when the demand cap binds, early investment improves a firm's access to scarce market share and reduces the capacity left idle and

[2]The discount rate here is the Weighted Average Cost of Capital (WACC), 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 5.

stranded; when the cap does not bind, early investment simply substitutes cheaper green for brown production at full capacity. Formally, letting $\Pi_i^s(g_i, g_j)$ denote discounted profits in scenario s, the scenario-specific marginal benefit of early investment is

$$MB_i^s(g_i, g_j) \;\equiv\; \frac{\partial \Pi_i^s(g_i, g_j)}{\partial g_i} = B_1^s + B_2^s(g_i, g_j), \tag{5}$$

where B_1^s captures period-1 operating cost savings and $B_2^s(g_i, g_j)$ captures period-2 operating gains together with, when the cap binds, the marginal value of additional market access and the associated reduction in stranded-asset costs, scaled by θ_i^s. Firms differ in their subjective beliefs, and these beliefs determine the expected marginal benefit $\sum_s \pi_i^s MB_i^s(g_i, g_j)$. Because θ_i^s is strictly decreasing in own investment in rationed scenarios, when the firm assigns a positive probability to at least one scenario where scarced demand is rationed, the belief-weighted marginal benefit declines in g_i , and the optimum can be interior even for risk-neutral firms. The risk aversion parameter that penalizes the dispersion of profits across scenarios, further dampens investment. Formal derivations and closed-form expressions for B_1^s and B_2^s are provided in Appendix A.

Best response and equilibrium. Since each firm's payoff depends on the rival's investment decision through the allocation rule (3), the model is a two-player game in period-0 investments. Firm i's best response is

$$g_i^*(g_j) = \arg \max_{g_i \in [0, \frac{1}{2}K_0]} J_i(g_i, g_j), \tag{6}$$

and a (pure-strategy) Nash equilibrium is a pair (g_i^*, g_j^*) that are mutual best responses, with each firm evaluating (1) under its "own beliefs". The game is therefore asymmetric: an early mover and a late mover differ only in π_i^s. The strategic interaction of the two firms only operates through the rationed scenarios and its sign follows from

$$\frac{\partial \theta_i^s}{\partial g_j} = \frac{\overline{S}_2^{\,s}\,(\hat{g}_i - \hat{g}_j)}{(\hat{g}_i + \hat{g}_j)^3}, \qquad \text{sign}\left(\frac{\partial MB_i^s}{\partial g_j}\right) = \text{sign}(g_i - g_j). \tag{7}$$

By contrast, in non-rationed scenarios $\theta_i^s = 0$ and the MB_i^s is independent of the rival's investment decision g_j. Green investments are thus strategic complements for a firm that leads $(g_i > g_j)$ and strategic substitutes for a firm that lags. Because best responses are continuous on the compact and convex interval $[0, \frac{1}{2}K_0]$, an equilibrium exists. [3]

[3] A unique equilibrium and existence in pure strategies is not guaranteed globally, hence we show both numerically.

2.2 Data for Numerical Simulation

We apply the model using technology cost data, emission intensities, and financing parameters to the European steel industry. Table 5 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 4 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 only on emissions pricing without complementary policy support instruments for the green technology. In scenario 3 (Accelerated -Policy mix), total demand for primary steel additionally falls from 12 to 9 Mt, below the combined capacity of both firms (12 Mt)[4]. 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.[5] 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 Appendix B. Finally, we model this with heterogeneous beliefs by assigning different subjective probabilities over the four scenarios (Table 3). The early mover firm expects stringent action, placing 85% probability on the accelerated policy-mix scenario ($\pi^3_{\text{early mover}} = 0.85$). The late mover firm expects policy continuity, assigning 85% probability to the baseline carbon-pricing scenario ($\pi^2_{\text{late mover}} = 0.85$). An equal-probability benchmark serves as a reference case. This scenario design allows us to assess how different stress-testing designs affect the comparability of firm-level transition risk assessments under a common policy shock.

Table 3: 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	0.85	0.05
Late mover	0.05	0.85	0.05	0.05

[4]This reduction is approximated based on the Langfristszenarien for Germany (Sensfuß et al., 2021) using the O45-Strom scenario . As discussed in Vogl, Åhman, and Nilsson (2021), 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 scenario in which period-2 demand falls to 8 Mt instead of 9 Mt (see Appendix D).

[5]In the steel sector a great variability of pass-through rates can be observed, see (Ostrovnaya et al., 2026). 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.

Table 4: Scenario elements and assumptions

Elements	Baseline – Limited ambition: Policy mix (1)	Baseline – Limited ambition: Carbon prices (2)	Accelerated – Increased ambition: Policy mix (3)	Accelerated – Increased ambition: Carbon prices (4)
Scenario-specific				
Carbon price	*Moderate:* 70–150 (P1), 150–250 (P2) (Pahle et al., 2022; IEA, 2023)			*Sharp:* 50–250 (P1), 250–450 (P2) (Dietz, Fruitiere, et al., 2018)
Carbon Contracts for Differences (CCfDs)	✓ partial ($\beta = 0.5$) (Richstein and Neuhoff, 2022)	×	✓ full ($\beta = 1$)	×
Demand in the second period	12 Mt	12 Mt	9 Mt (Sensfuß et al., 2021)	12 Mt
Sensitivities across models				
Pass-through	Ranges from 0–1 via ρ: $\rho = 1$ full pass-through, $\rho = 0$ full internalization, Appendix B. For the steel sector, such a wide range can be observed, see (Ostrovnaya et al., 2026)			
Free allowances	Depends on pass-through, see Appendix B			
Leakage protection	Degree to which free allowances correct for what cannot be passed through. Tested from 0–1 via α: $\alpha = 1$ fully protected, $\alpha = 0$ unprotected.			

Notes: P1 = 2028–2034, P2 = 2035–2044. Carbon prices in €/tCO_2.

Table 5: Cost input factors

Element	Technology	Value	Unit	Reference
Opex	BF-BOF, total	415	€/t capacity	Mayer, Bachner, and Steininger (2019)
	BF-BOF, labour	50	€/t capacity	ibid.
	H-DRI-EAF, total	625	€/t capacity	ibid.
Capex	BF-BOF relining	50	€/t capacity	Vogl, Åhman, and Nilsson (2018)
	BF-BOF brownfield	170	€/t capacity	ibid.
	BF-BOF greenfield	440	€/t capacity	ibid.
	DRI-EAF greenfield	630	€/t capacity	ibid.; Richstein and Neuhoff (2022)
Emission intensity	BF-BOF	2.00	tCO_2/t steel	Vogl, Åhman, and Nilsson (2018)
	H-DRI-EAF	0.05	tCO_2/t steel	ibid.
Financing	Share of debt (w_d)	0.60	share	Richstein and Neuhoff (2022)
	Share of equity (w_e)	0.40	share	$w_e = 1 - w_d$
	Cost of debt (i)	0.03	share	ibid.
	Cost of equity (i_{eq})	0.10	share	ibid.
	Depreciation (n)	20	years	ibid.
	Annuity factor, debt	0.07	share	$i/[1 - (1 + i)^{-n}]$
	Annuity factor, equity	0.12	share	$i_{eq}/[1 - (1 + i_{eq})^{-n}]$
	Annuity, financing mix	0.09	share	$w_d AF_d + w_e AF_{eq}$
Sectoral path	Primary intensity	1.81 / 0.12	tCO_2/t steel	Climate Bonds (2024)

Notes: All values are approximate. Capacity costs are per tonne of annual steel production capacity. Sectoral path values are for 2030 and 2050 respectively.

3 Results

3.1 Marginal benefit and optimal investment decision

The results of the marginal benefit analysis highlight that the benefit of early green investment varies significantly by scenario. Figure 2 shows the discounted marginal benefit per scenario as a function of carbon leakage protection and the pass-through rate of carbon prices across policy scenarios and periods. The black contour marks the zero-marginal-benefit frontier separating regions where early green investment yields a positive marginal profit for firms.[6]

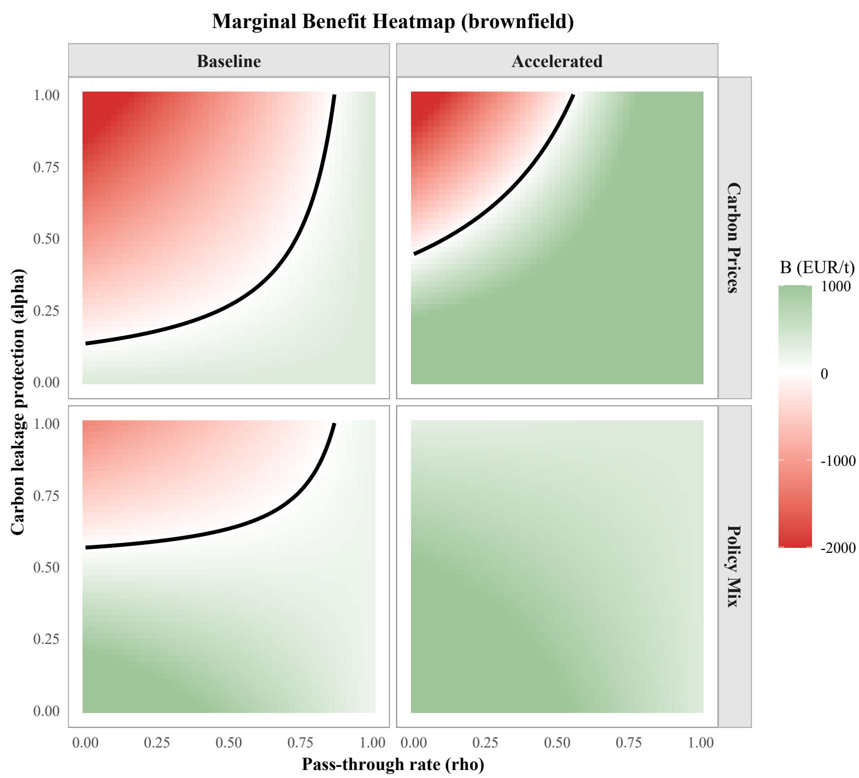

Figure 2: Discounted marginal benefit (MB) per scenario and period

As it can be seen, the marginal benefit of early green investment is consistently positive only under the accelerated policy-mix scenario (positive in 100% of the (α, ρ) space). In this case, the sign of the marginal benefit is independent of carbon cost pass-through and leakage protection due to the support with Carbon Contracts for Difference (CCfDs) which fully corrects for incremental costs. Instead, investment returns are driven by avoided stranded costs and priority access to a

[6] Appendix D reports robustness results for a more stringent market-wide capacity constraint in period 2 (total demand shrinks 8 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.

shrinking market. Under the baseline policy mix, positive marginal benefits arise in around 70% of cases, indicating that investment incentives are already strong even without accelerated policy tightening, but still depend on assumptions about pass through,carbon leakage protection and the size of policy support. By contrast, under carbon-price-only designs, early green investment yields positive marginal benefits in 41% of cases under the baseline scenario, increasing to slightly over 80% under accelerated carbon pricing, highlighting the strong sensitivity of firm cashflows to net carbon prices in the absence of complementary policy instruments.

Given the belief of profiles defined in section of the two heterogeneous firms when solving for the optimized level of green investment in the first period, the optimal solution of the decision problem of the two firms yields two profiles. Figure 3 shows how beliefs, risk preferences, and strategic interaction jointly determine the optimal level of green capacity conversion across the (α, ρ) space.

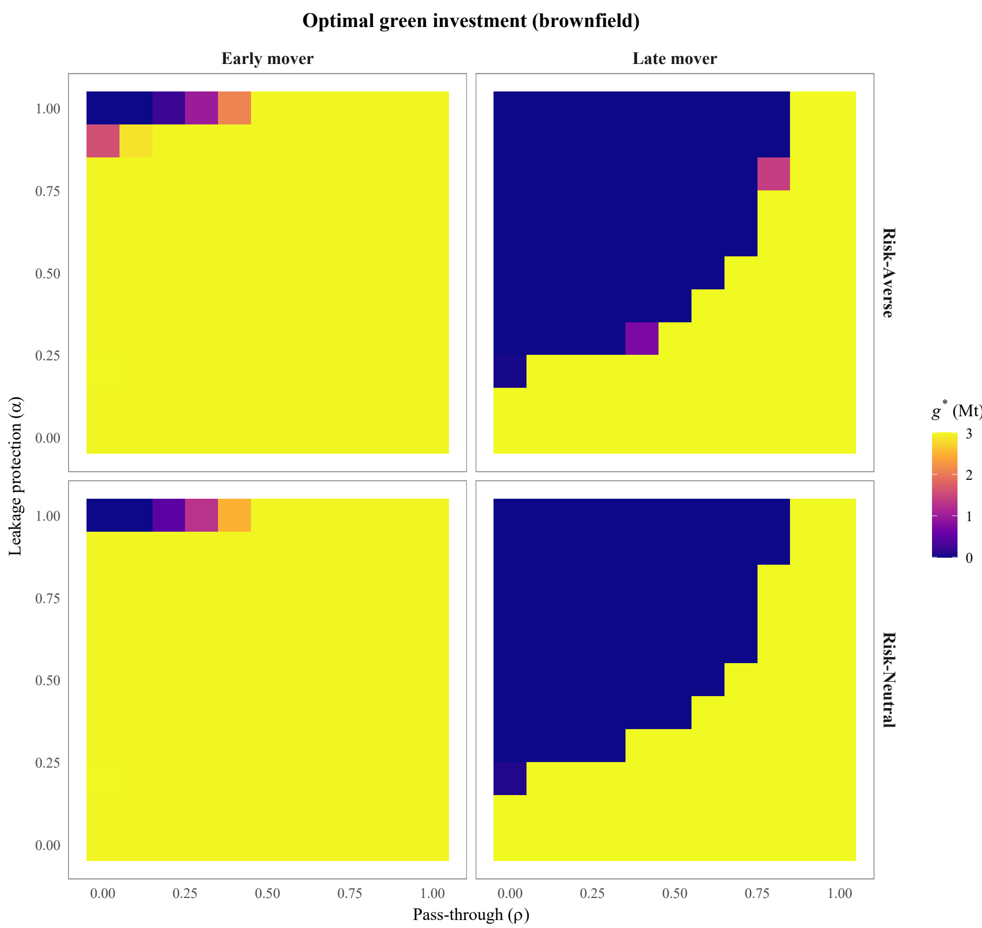

Figure 3: Optimal level of green investment for risk-neutral and risk-averse firms under different belief profiles

Under early-mover beliefs, which assign high probability to the accelerated policy-mix scenario with shrinking demand for primary steel, firms invest early in a large majority of the parameter space (98% of the cases shown on the figure). In the case of high carbon leakage protection and low pass-through, it is also optimal for an early mover belief profile to invest zero or only partially. Under later-mover beliefs, however, a firm is divided between investing and no investing: In about 51% of the (α, ρ) space), a firm would invest, and hence in 49% of the space would invest nothing. High carbon-cost pass-through or strong leakage protection reduce the carbon cost differential between green and brown and hence the marginal benefit of early investment. Furthermore, investment decision are robust to risk aversion. The split between positive and zero investment is almost identical for both belief profiles, except that for the later mover interior solutions vanish in the risk neutral case.

3.2 Cash flow analysis

After having motivated why diverging investment strategies can be rational, this part of the analysis now gives insights into the range and potential shocks to the cashflows of the firms given under different strategies and scenarios. Figures 4 and 5 map the policy-market-parameter uncertainty into firm-level cash-flow outcomes relevant for climate stress testing. Each panel reports the discounted mean annual cash flows (solid line) together with the min–max envelope across the (α, ρ) grid (shaded band). Columns correspond to policy scenarios and rows vary rival early investment (0 vs. 3 Mt). The dashed vertical line marks the transition from period 1 to period 2.[7]

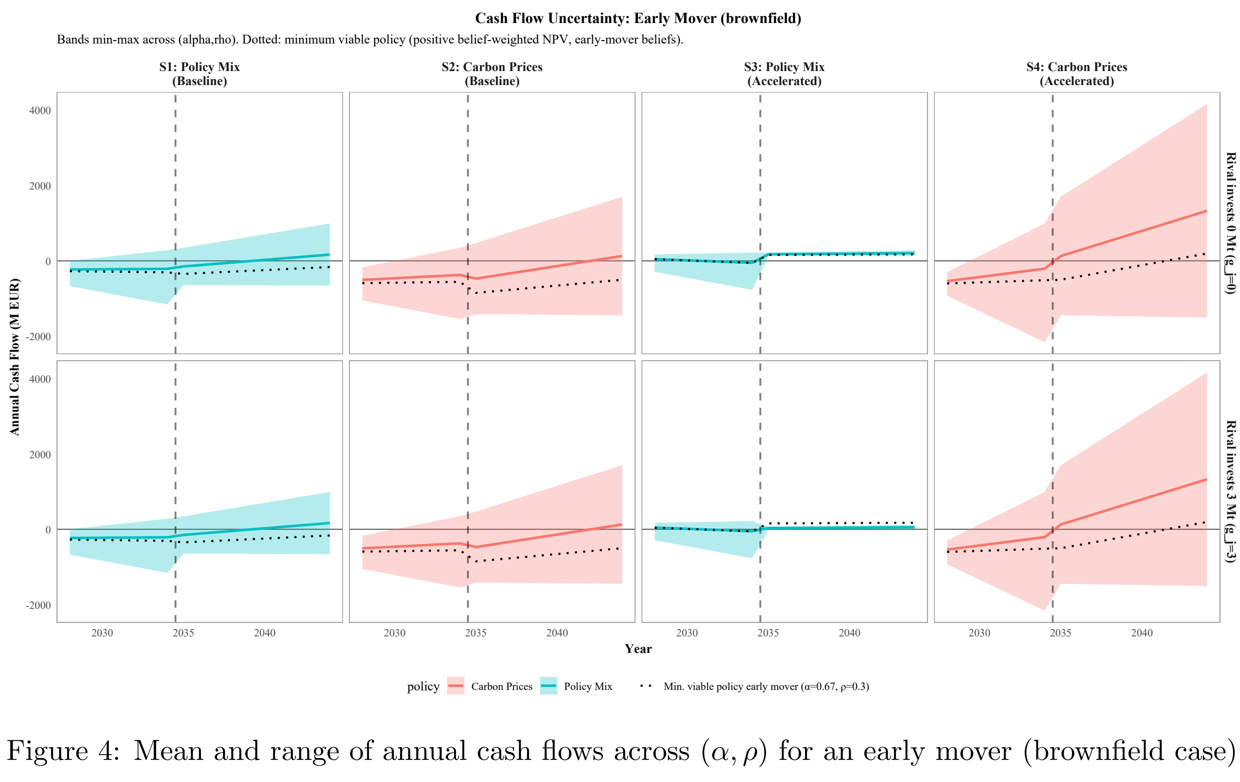

Figure 4: Mean and range of annual cash flows across (α, ρ) for an early mover (brownfield case).

Under carbon-price-only designs (S2 and S4), the stress-test signal is dominated by assumptions

[7]The black dotted line plots the NPV for the baseline or "minimum" (α, ρ) combination which is required for the firm's strategy to be rational given its beliefs

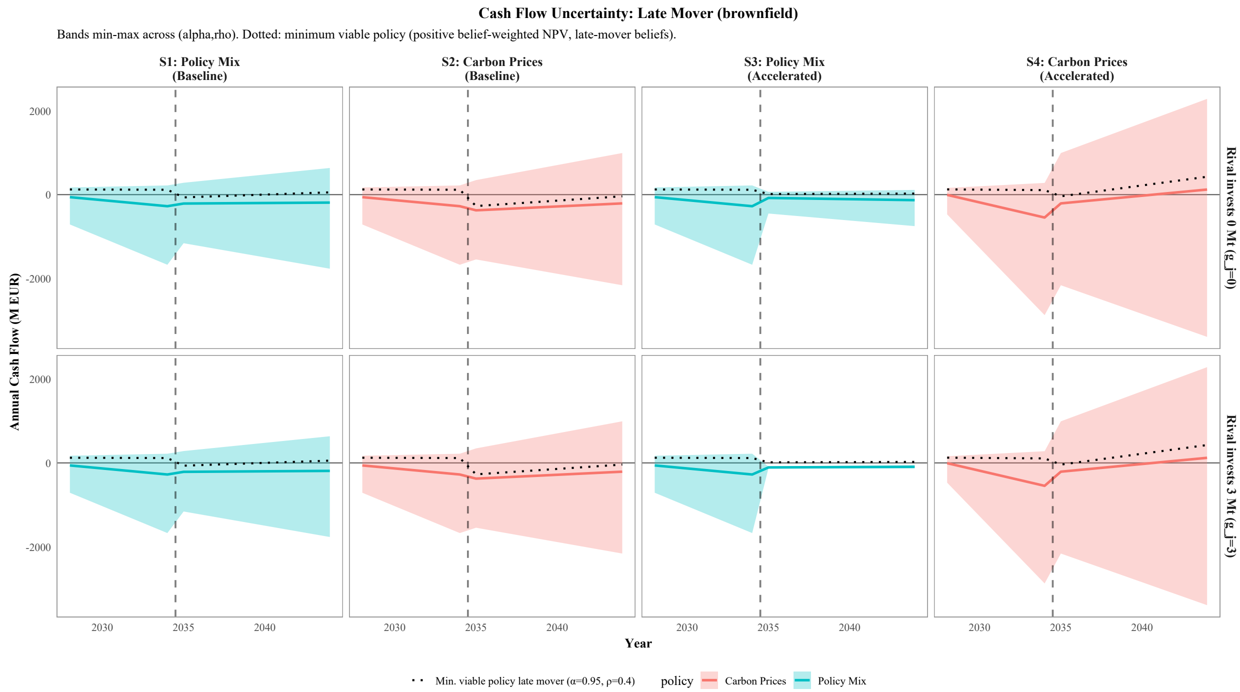

Figure 5: Mean and range of annual cash flows across (α, ρ) for a late mover (brownfield case).

on cost pass-through and leakage protection. In both periods, average annual cash flows vary widely across (α, ρ), with standard deviations of approximately 658 M€ for the late mover and 830 M€ for the early mover in the baseline carbon-price scenario (S2), and rising to about 1,157 M€ and 1,469 M€, respectively, under the accelerated carbon-price regime (S4). As a result, the same firm may appear resilient or fragile depending on market and policy design assumptions rather than underlying transition exposure. As demand remains unchanged in these scenarios and firms do not compete over market shares, rival investment has no effect on 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 reduced demand and first-mover advantage rather than prices. In period 2, dispersion across (α, ρ) collapses: the standard deviation of annual cash flows falls to roughly 20–170 M€ for both early and late movers, indicating narrower outcomes conditional on the policy scenario. This generates a clear separation between firm types. The early mover maintains positive and stable period 2 cash flows, averaging about 188 M€ when the rival does not invest and 44 M€ when the rival invests early.

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 assumptions about (α, ρ). In contrast, carbon-price-only environments generate wide cash-flow distributions that obscure firm-level vulnerability, weakening the informational value 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.

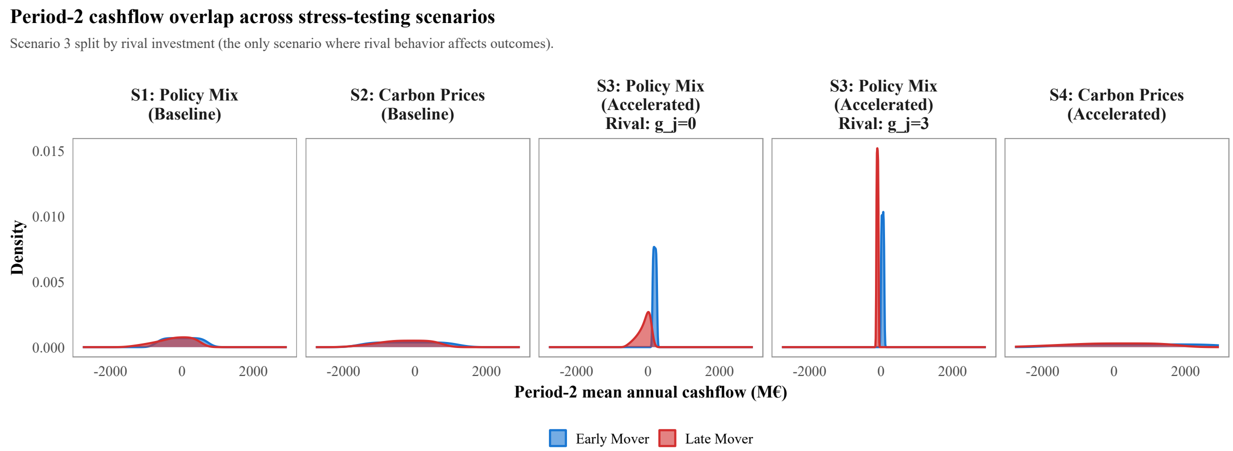

Figure 6: Overlap of period-2 mean annual cash flow distributions across policy scenarios (brownfield case).

3.3 Implications for stress testing under accelerated policy scenarios

To better understand the differences to different stress testing methods, we now look at how the results under different methodological choices vary. Figure 7 illustrates how the choice of stress testing methodology shapes firm-level transition risk assessments. For this we look at the NPV of the firms in period 2 under the accelerated scenarios where the shock realizes under three approaches.

First, Approach 1 uses the following stress testing logic: firms' exposure to transition is modeled along their status quo emission intensities that decline linearly along the "IEA NZE" trajectory as calibrated by the Climate Bonds Initiative Steel Criteria (Climate Bonds, 2024). The transition shock is the carbon price path assumed in scenario 4. We also vary the the degree of carbon cost pass-through and carbon leakage protection. Under this approach, the late mover - which however has slightly lower status quo emission intensity than the early mover - consistently outperforms the early mover across all policy design assumptions. Given the status quo bias - hence not accounting for the actual investment strategy of the firm - the late mover appears less exposed to the carbon price shock precisely because its lower starting emission intensity reduces its direct carbon cost burden. As illustrated earlier, this "risk ranking" is highly sensitive to assumed values of (α, ρ): under full pass-through and no leakage protection ($\rho = 1$, $\alpha = 0$), both firms benefit from higher product prices and appear resilient, while under no pass-through and no leakage protection ($\rho = 0$, $\alpha = 0$), both face severe losses, with the early mover bearing a disproportionately larger burden due to its higher current emission intensity.

Approach 2 integrates actual firm-level investment decisions into the framework while retaining the carbon price shock and assuming a constant emission intensity per technology choice over time. The early mover is assumed to have converted its full capacity to green steel production (6 Mt green in period 2), while the late mover retains a mixed production portfolio (3 Mt green, 3 Mt brown). No further financial support for the green technology is assumed under this approach. This approach reveals the investment-decision dimension of transition risk: the early mover's higher green share insulates it from carbon costs on the production side, but it foregoes the carbon cost revenue channel that benefits brown producers under partial pass-through. The late mover's continued brown production exposes it to carbon costs on 3 Mt of output, generating larger losses under high carbon prices. Importantly, however, the risk ranking between firms remains sensitive to (α, ρ) assumptions and does not yet capture the regulatory and demand-side risks associated with an accelerated policy transition.

Approach 3 applies the full scenario framework developed in this paper: firms face the accelerated policy-mix scenario (S3) with full support for the green technology via CCfDs and shrinking demand for primary steel in period 2. Two configurations for the demand reduction (9 Mt and 8 Mt) are considered. This approach generates a qualitatively different risk picture. For both configurations, the early mover achieves positive period-2 NPV, benefiting from early investment and priority access to the constrained market. The late mover, by contrast, faces negative NPV outcomes driven by stranded asset costs on idle brown capacity and quantity rationing. Hence, the primary driver of transition risk under an accelerated policy-mix scenario is not emission intensity but strategic positioning: early green investment secures market access and avoids stranded costs, while late investment leaves firms fully exposed to both.

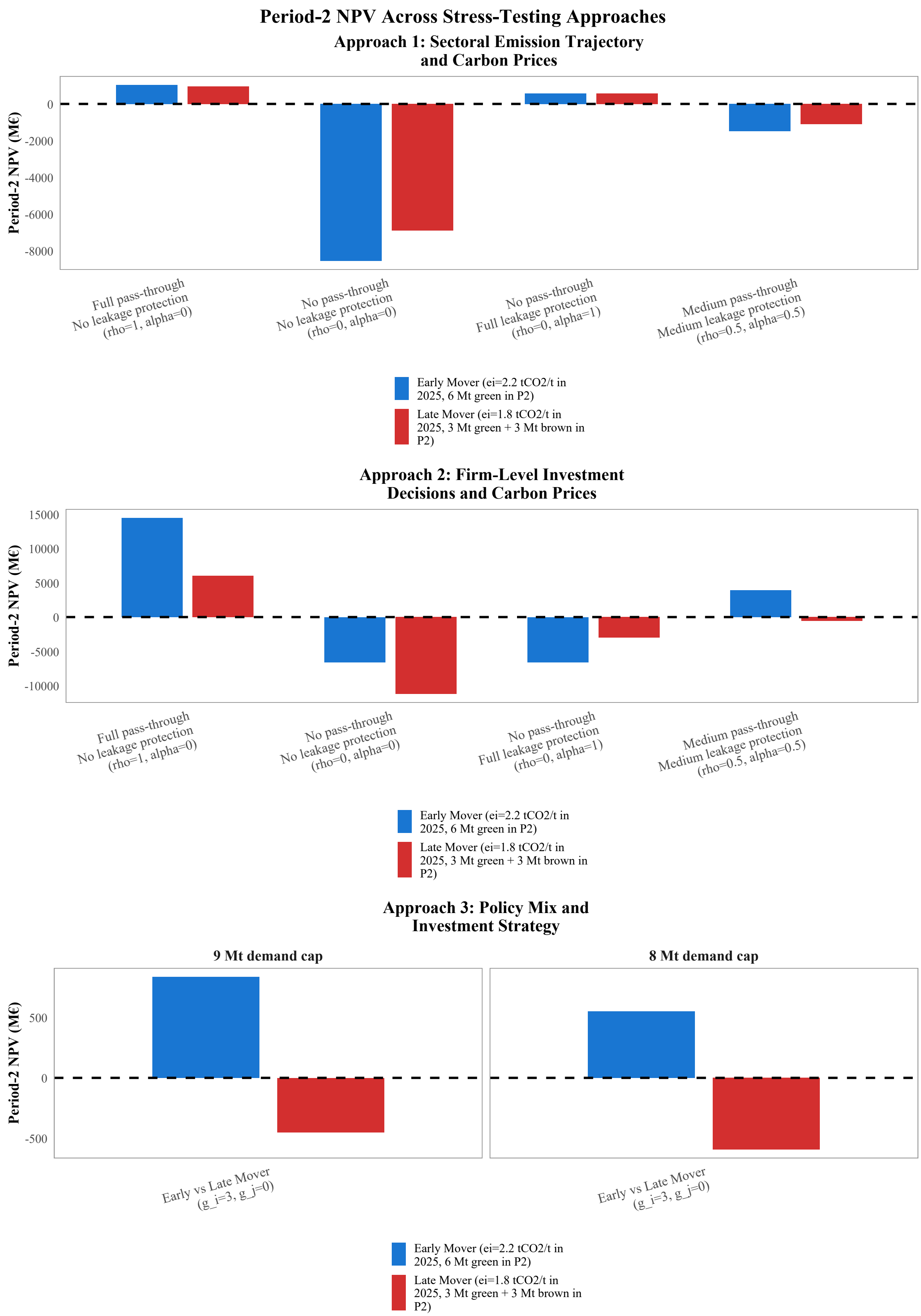

Figure 7: Period-2 NPV across three stress testing approaches.

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 often 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 policy shock that benefits firms aligned and punishes firms non-aligned with the transition.

We use a stylized microeconomic model of green capacity investment under policy uncertainty and apply it to the European steel sector, comparing how different scenario designs affect firms' strategic investment decisions and valuation outcomes. Two otherwise identical steel firms differ in their subjective beliefs about future climate policy: the early mover assigns high probability to accelerated transitions, while the late mover expects policy continuity. Firms choose irreversible green capacity investment in the initial period before uncertainty about future policy is resolved. Investment incentives depend on two main channels: operating cost savings where the green technology is cheaper than brown, and preferential market access when shrinking demand for primary steel creates binding capacity constraints in the accelerated transition scenario. In this scenario, early green investment raises output allocated and reduces stranded asset costs.

Our results show that scenario design fundamentally shapes the informativeness of firm-level analysis. Under carbon-price-only scenarios, investment incentives depend heavily on three parameters: the carbon price level, the carbon cost pass-through rate, and the degree of carbon leakage protection. Over the full grid of those parameters, 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 cashflow distributions for early and late mover that obscure heterogeneity. By contrast, the accelerated policy-mix scenario delivers a "non-contingent" transition shock through two additional elements: reduced demand for primary steel reflecting material efficiency improvements and increased secondary production as well as CCfDs that offer financial support for green steel producers. This mix operates independently of pass-through rates or carbon price levels. Instead, when reduced demand falls below the combined initial capacity of both firms, it triggers rationing that rewards early investment through priority allocation. Under this scenario, early mover firms capture substantially more market share. 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 several 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. Future research could for example through structural credit risk models link changes in firm value to equity and debt losses in the spirit of Merton-type frameworks (Reinders, Schoenmaker, and M. A. Van Dijk, 2023). Furthermore, we illustrate the mechanism using the steel sector, which is a relatively homogeneous sector. Additional assumptions would be required for more complex, hard-to-abate sectors, such as the organic chemicals sector. Nevertheless, the core insight remains: firm-level decarbonization or 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 or risk management frameworks, integrating them into stress testing exercises using accelerated policy-mix benchmarks would substantially strengthen climate risk assessment in the financial sector.

Appendix 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. In our baseline specification brown steel can always be sold, so the relevant distinction is not whether brown is banned but whether the period-2 demand cap binds. A product-ban variant is treated as a robustness check in Section A.6.

A.1 Period-2 Production Quantities

Period-2 production depends on whether the demand cap $\overline{S}_2^s$ binds. Let $\hat{g}_i := g_i + \frac{1}{2}K_0$ denote firm i's green-ready capacity.

Case A: No rationing ($\overline{S}_2^s \geq 2K_0$). When combined desired production does not exceed the cap, each firm produces at full capacity, converting to the technically feasible maximum:

$$q^s_{i2,\text{green}} = g_i + \tfrac{1}{2}K_0, \qquad q^s_{i2,\text{brown}} = \tfrac{1}{2}K_0 - g_i, \qquad q^s_{i2,\text{total}} = K_0. \tag{A.1}$$

Production is a deterministic function of period-0 investment, and no capacity is stranded.

Case B: Rationing binds ($\overline{S}_2^s < 2K_0$). When the cap binds, total output is allocated in proportion to green-ready capacity (derived in Section A.2):

$$q^s_{i2,\text{total}}(g_i, g_j) = \min\left\{ \frac{\overline{S}_2^s\, \hat{g}_i}{\hat{g}_i + \hat{g}_j},\ K_0 \right\}. \tag{A.2}$$

Green capacity is served first, up to the available green capacity. Any remainder is served from brown existing capacity:

$$q^s_{i2,\text{green}} = \min\{\hat{g}_i,\ q^s_{i2,\text{total}}\}, \qquad q^s_{i2,\text{brown}} = q^s_{i2,\text{total}} - q^s_{i2,\text{green}}. \tag{A.3}$$

Two sub-cases arise. When $q^s_{i2,\text{total}} \leq \hat{g}_i$, equivalently $\overline{S}_2^s \leq \hat{g}_i + \hat{g}_j$, the entire allocation is served green. When $q^s_{i2,\text{total}} > \hat{g}_i$, the marginal unit of allocated demand is served brown. The firm strands the residual $K_0 - q^s_{i2,\text{total}}$.

Define the marginal allocation parameter:

$$\theta_i^s(g_i, g_j) := \frac{\partial q^s_{i2,\text{total}}(g_i, g_j)}{\partial g_i} \in [0, 1), \tag{A.4}$$

which measures how an additional unit of period-0 investment translates into period-2 market access under scenario s. Capacity left idle by rationing incurs stranded-asset costs

$$c^s_{\text{stranded}} := c^{\text{ann}}_{x,\text{brown}} + c^{\text{ann}}_{\ell,\text{brown}}, \tag{A.5}$$

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

A.2 Allocation Rule Under Demand Constraint

We now derive the allocation rule that determines period-2 production when the demand cap binds.

Setup. Each firm has green-ready capacity $\hat{g}_i = g_i + \frac{1}{2}K_0$ and $\hat{g}_j = g_j + \frac{1}{2}K_0$. When demand $\overline{S}_2^s$ falls below total capacity of $2K_0$, the market is rationed.

Case 1: No rationing ($\overline{S}_2^s \geq 2K_0$). Both firms produce at full capacity, $q^s_{i2,\text{total}} = K_0$, and

$$\theta_i^s = \frac{\partial q^s_{i2,\text{total}}}{\partial g_i} = 0. \tag{A.6}$$

At the capacity ceiling the marginal benefit operates through the green/brown mix (Case A above): period-0 investment shifts the technology mix one-for-one but leaves total output unchanged. Equivalently, period-0 investment shifts the technology mix one-for-one but leaves total output unchanged.

Case 2: Rationing binds ($\overline{S}_2^s < 2K_0$). Total demand is allocated in proportion to green-ready capacity, capturing green lead markets and low-carbon procurement that channel scarce demand toward firms with more convertible capacity:

$$q^s_{i2,\text{total}}(g_i, g_j) = \frac{\overline{S}_2^s\, \hat{g}_i}{\hat{g}_i + \hat{g}_j}, \qquad \hat{g}_i = g_i + \tfrac{1}{2}K_0. \tag{A.7}$$

Differentiating with respect to g_i, and using $\partial \hat{g}_i / \partial g_i = 1$:

$$\theta_i^s(g_i, g_j) = \frac{\partial q^s_{i2,\text{total}}}{\partial g_i} = \overline{S}_2^s \frac{(\hat{g}_i + \hat{g}_j) - \hat{g}_i}{(\hat{g}_i + \hat{g}_j)^2} = \frac{\overline{S}_2^s\, \hat{g}_j}{(\hat{g}_i + \hat{g}_j)^2} \in (0, 1). \tag{A.8}$$

The marginal return to early investment is strictly positive but *decreasing* in own investment, since

$$\frac{\partial \theta_i^s}{\partial g_i} = -\frac{2\,\overline{S}_2^s\, \hat{g}_j}{(\hat{g}_i + \hat{g}_j)^3} < 0. \tag{A.9}$$

This diminishing marginal access is what makes the firm's problem strictly concave in the rationed scenario and delivers interior optima.

Strategic interaction. The cross-partial governs how the rival's investment shifts firm i's marginal access:

$$\frac{\partial \theta_i^s}{\partial g_j} = \overline{S}_2^s \frac{\hat{g}_i - \hat{g}_j}{(\hat{g}_i + \hat{g}_j)^3}, \qquad \text{sign}\left(\frac{\partial \theta_i^s}{\partial g_j}\right) = \text{sign}(g_i - g_j). \tag{A.10}$$

Early investments are therefore strategic *complements* for a firm that leads ($g_i > g_j$) and strategic *substitutes* for a firm that lags ($g_i < g_j$). Rival investment always reduces a firm's own allocation. What changes the sign is the marginal return to further own investment. That return is highest when the two firms have the same investment level. Hence, a leader whose rival catches up finds additional conversion more productive, whereas a laggard facing a rival that pulls further ahead is discouraged. The sign thus depends on relative position rather than on rationing as such.

A.3 Marginal Benefit of Early Investment

We now derive the marginal benefit $MB_i^s(g_i, g_j) := \partial \Pi_i^s(g_i, g_j)/\partial g_i$.

Period-1 marginal benefit. Using $q_{i1,\text{brown}} = K_0 - g_i$, period-1 profit is

$$\Pi_{i1}^s(g_i) = \sum_{t=2028}^{2034} \frac{1}{(1+r)^{t-2025}} \Big[K_0(\bar{p}_{1t}^s - \bar{c}_{1t,\text{brown}}^s) + g_i(\bar{c}_{1t,\text{brown}}^s - \bar{c}_{1t,\text{green}}^s)\Big], \tag{A.11}$$

so that

$$B_1^s := \frac{\partial \Pi_{i1}^s}{\partial g_i} = \sum_{t=2028}^{2034} \frac{1}{(1+r)^{t-2025}} (\bar{c}_{1t,\text{brown}}^s - \bar{c}_{1t,\text{green}}^s). \tag{A.12}$$

This captures period-1 operating cost savings from substituting brown with green capacity; $B_1^s > 0$ whenever green production is less costly.

Period-2 marginal benefit, Case A (no rationing). Using (A.1), period-2 profit is

$$\Pi_{i2}^s(g_i) = \sum_{t=2035}^{2044} \frac{1}{(1+r)^{t-2025}} \Big[K_0\Big(\bar{p}_{2t}^s - \tfrac{1}{2}\bar{c}_{2t,\text{brown}}^s - \tfrac{1}{2}\bar{c}_{2t,\text{green}}^s\Big) + g_i(\bar{c}_{2t,\text{brown}}^s - \bar{c}_{2t,\text{green}}^s)\Big], \tag{A.13}$$

giving the constant marginal benefit

$$B_2^s = \sum_{t=2035}^{2044} \frac{1}{(1+r)^{t-2025}} (\bar{c}_{2t,\text{brown}}^s - \bar{c}_{2t,\text{green}}^s). \tag{A.14}$$

As in period 1, this is the simple cost differential between technologies and does not depend on the rival's investment.

Period-2 marginal benefit, Case B (rationing binds). Using (A.2) and (A.3), period-2 profit is

$$\Pi_{i2}^s = \sum_{t=2035}^{2044} \frac{1}{(1+r)^{t-2025}} \Big[q_{i2,\text{total}}^s(\bar{p}_{2t}^s + c_{\text{stranded}}^s) - \bar{c}_{2t,\text{green}}^s q_{i2,\text{green}}^s - \bar{c}_{2t,\text{brown}}^s q_{i2,\text{brown}}^s - K_0\, c_{\text{stranded}}^s\Big]. \tag{A.15}$$

The stranding term enters with a positive sign because each additional unit of allocated production reduces idle capacity by one unit. Differentiating gives two sub-cases, according to which technology serves the marginal allocated unit:

$$B_2^s(g_i, g_j) = \begin{cases} \theta_i^s \displaystyle\sum_{t=2035}^{2044} \frac{\bar{p}_{2t}^s - \bar{c}_{2t,\text{green}}^s + c_{\text{stranded}}^s}{(1+r)^{t-2025}}, & q_{i2,\text{total}}^s \le \hat{g}_i, \\ \displaystyle\sum_{t=2035}^{2044} \frac{\theta_i^s \big(\bar{p}_{2t}^s - \bar{c}_{2t,\text{brown}}^s + c_{\text{stranded}}^s\big) + \big(\bar{c}_{2t,\text{brown}}^s - \bar{c}_{2t,\text{green}}^s\big)}{(1+r)^{t-2025}}, & q_{i2,\text{total}}^s > \hat{g}_i. \end{cases} \tag{A.16}$$

In the first first case the marginal allocated unit is produced green, and the bracket is the per-unit value of market access: price net of the green unit cost, plus the avoided stranding cost. As for the second case, one more unit of early investment raises green output by one unit but total output by only θ_i^s as the market does not grow.

Total marginal benefit. Combining both periods,

$$MB_i^s(g_i, g_j) = B_1^s + B_2^s(g_i, g_j). \tag{A.17}$$

In non-rationed scenarios MB_i^s is constant in g_i and independent of g_j, reducing to cost differentials. In rationed scenarios the marginal benefit depends on g_i through the diminishing θ_i^s and on g_j through the allocation, so marginal incentives become state-dependent and strategic interdependence arises. The sign of that interdependence is given by (A.10).

A.4 Optimal Investment

First-order condition. The first-order condition for (1) is

$$\frac{dJ_i}{dg_i} = \sum_{s=1}^{S} \pi_i^s MB_i^s(g_i, g_j) - 2\lambda \sum_{s=1}^{S} \pi_i^s \big(\Pi_i^s(g_i, g_j) - \bar{\Pi}_i(g_i, g_j)\big) MB_i^s(g_i, g_j) = 0, \tag{A.18}$$

with the solution projected onto $[0, \frac{1}{2}K_0]$.

Risk-neutral case ($\lambda = 0$). When no scenario rations ($\theta_i^s = 0$ for all s, equivalently every scenario is in Case A), MB_i^s is constant in g_i and the solution is bang–bang: $g_i^* = \frac{1}{2}K_0$ if $\overline{MB}_i > 0$ and $g_i^* = 0$ otherwise, where $\overline{MB}_i := \sum_s \pi_i^s MB_i^s$. However, when a rationed scenario carries positive belief weight, θ_i^s is strictly decreasing in g_i, so $\overline{MB}_i(g_i)$ declines in own investment and the optimum is interiorwherever $\overline{MB}_i$ crosses zero inside $[0, \frac{1}{2}K_0]$.

Closed form (no rationing, $\lambda > 0$). When the demand does not bind in any scenario, MB_i^s is constant and profits are linear, $\Pi_i^s(g_i, g_j) = A_i^s + MB_i^s g_i$. The first-order condition then yields

$$g_i^* = \frac{\overline{MB}_i - 2\lambda \operatorname{Cov}(A_i^s, MB_i^s)}{2\lambda \operatorname{Var}(MB_i^s)}, \tag{A.19}$$

with bounds $[0, \frac{1}{2}K_0]$ enforced.

Numerical solution (rationing binds). When the demand binds in some scenarios, $\theta_i^s > 0$ makes MB_i^s depend on g_i, and (A.18) is solved numerically by grid search over the feasible set. Because the rival's investment enters through the allocation, the firm's optimum is a best response $g_i^*(g_j)$, and the equilibrium is the fixed point (g_i^*, g_j^*) of mutual best responses with each firm using its own beliefs (see Section 2.1). Best responses are continuous on the compact interval $[0, \frac{1}{2}K_0]$, so an equilibrium exists. Uniqueness is shown numerically.

A.5 Comparative Statics

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

$$\frac{\partial g_i^*}{\partial \lambda} = -\frac{\overline{MB}_i}{2\lambda^2 \operatorname{Var}(MB_i^s)} < 0 \quad \text{if } \overline{MB}_i > 0, \tag{A.20}$$

so risk aversion reduces investment. Lower dispersion of marginal benefits across scenarios raises investment, while higher covariance between the profit intercept and the marginal benefit lowers it. When rationing binds, the diminishing θ_i^s already curbs investment through the level channel, and risk aversion compounds this effect by penalizing the cross-scenario dispersion of profits.

A.6 Robustness: Product-Ban Variant

As a robustness check we consider a variant in which brown steel is banned in the accelerated scenario ($\delta^s = 0$). Brown output then yields no revenue but still incurs operating costs, so firms set $q_{i2,\text{brown}}^s = 0$, the green technology becomes price-setting, and unconverted capacity is stranded directly. Retaining the proportional allocation (A.7) for green output, the period-2 marginal benefit becomes

$$B_2^s(g_i, g_j) = \theta_i^s(g_i, g_j) \sum_{t=2035}^{2044} \frac{1}{(1+r)^{t-2025}} \left(\bar{p}_{2t}^s - \bar{c}_{2t,\text{green}}^s + c_{\text{stranded}}^s\right), \tag{A.21}$$

which differs from the baseline (A.16) only in that the marginal technology is forced to be green ($\bar{c}_{2t,\text{green}}^s$ replaces $\bar{c}_{2t,\min}^s$) and the green technolgoy is price setting. The early-mover advantage operates through the same $\theta_i^s\, c_{\text{stranded}}^s$ channel, now reinforced on the supply side, so the qualitative results are unchanged.

Appendix 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:

$$\bar{c}^s_{pt,\text{brown}} = \bar{ox}^s_{pt,\text{brown}} + \bar{cx}^s_{pt,\text{brown}} + \left(\bar{ei}^s_{pt,\text{brown}} - \underbrace{\bar{ei}^s_{pt,\text{brown}} \cdot (1-\rho)\,\alpha}_{\bar{fab}^s_{pt,\text{brown}}} \right) \bar{cp}^s_{pt}, \tag{A.22}$$

where $\bar{fab}^s_{pt,\text{brown}}$ represents free allowances.[8]

B.2 Green steel.

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

$$\bar{c}^s_{pt,\text{green}} = \bar{ox}^s_{pt,\text{green}} + \bar{cx}^s_{pt,\text{green}} + \left(\bar{ei}^s_{pt,\text{green}} \cdot \bar{cp}^s_{pt} \right) - \beta^s \cdot \bar{ccfd}^s_{pt,\text{green}}. \tag{A.23}$$

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

When the demand in period 2 falls below installed capacity, idle capacity results in stranded asset costs:

$$c^s_{\text{stranded}} = c^{\text{ann}}_{x,\text{brown}} + c^{\text{ann}}_{\ell,\text{brown}}, \tag{A.24}$$

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 $(K_0 - q^s_{i2,\text{total}})$ that cannot produce due to idle capacity-

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

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 5).
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).
$\bar{ei}^s_{pt,\cdot}$	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
$\bar{fab}^s_{pt,\cdot}$	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)

Appendix 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) steel-making. 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 and Nele (n.d.), and does not incorporate potential green premiums that steel producers may receive. The annual per-tonne support is given by:

$$\bar{ccfd}^s_{pt,\text{green}} = \left\{ \underbrace{\frac{(\bar{ox}^s_{pt,\text{green}} - \bar{ox}^s_{pt,\text{brown}}) + (\bar{cx}^s_{pt,\text{green}} - \bar{cx}^s_{pt,\text{brown}})}{\bar{ei}^s_{pt,\text{brown}} - \bar{ei}^s_{pt,\text{green}}}}_{\text{(1) Strike Price}} - \underbrace{\bar{cp}^s_{pt} \cdot \frac{(\bar{ei}^s_{pt,\text{brown}} - \bar{fab}^s_{pt,\text{brown}}) + (\bar{fab}^s_{pt,\text{green}} - \bar{ei}^s_{pt,\text{green}})}{\bar{ei}^s_{pt,\ brown} - \bar{ei}^s_{pt,\text{green}}}}_{\text{(2) Effective CO}_2\text{ Price}} \right\} \cdot \underbrace{(\bar{ei}^s_{pt,\text{brown}} - \bar{ei}^s_{pt,\text{green}})}_{\text{(3) Avoided Emissions}}$$

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

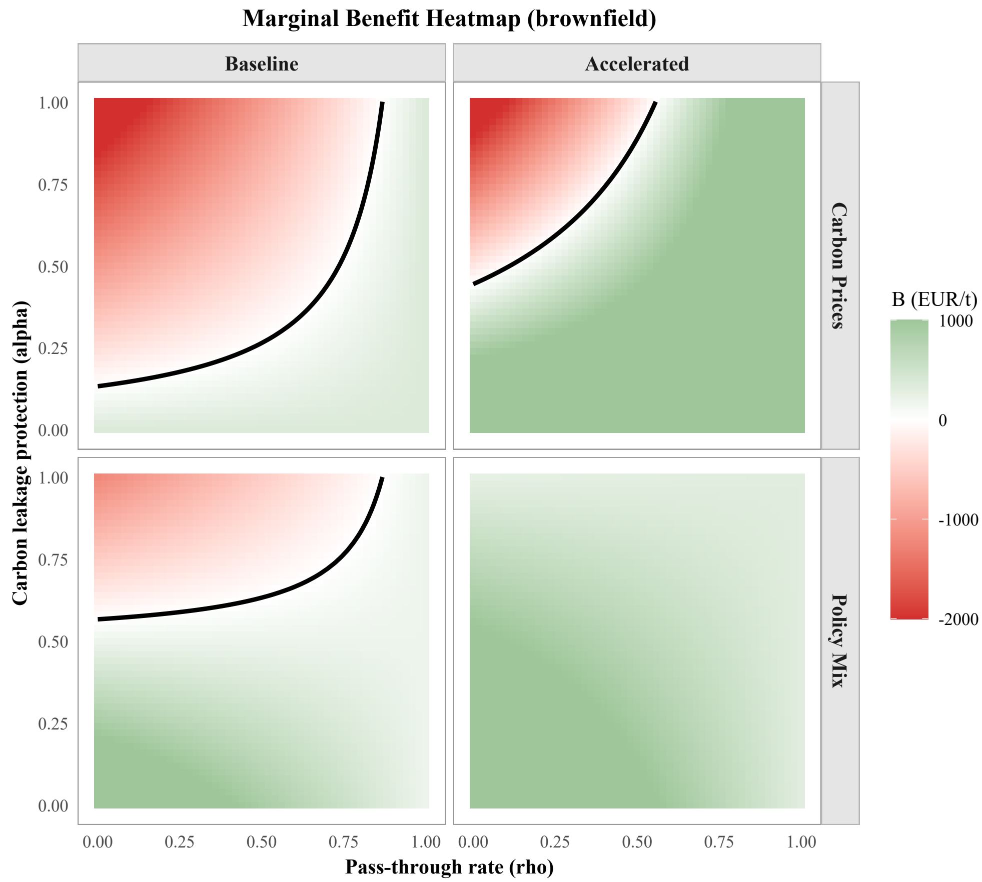

Figure 8: Discounted Marginal benefit (MB) per scenario and period with 8 MT demand

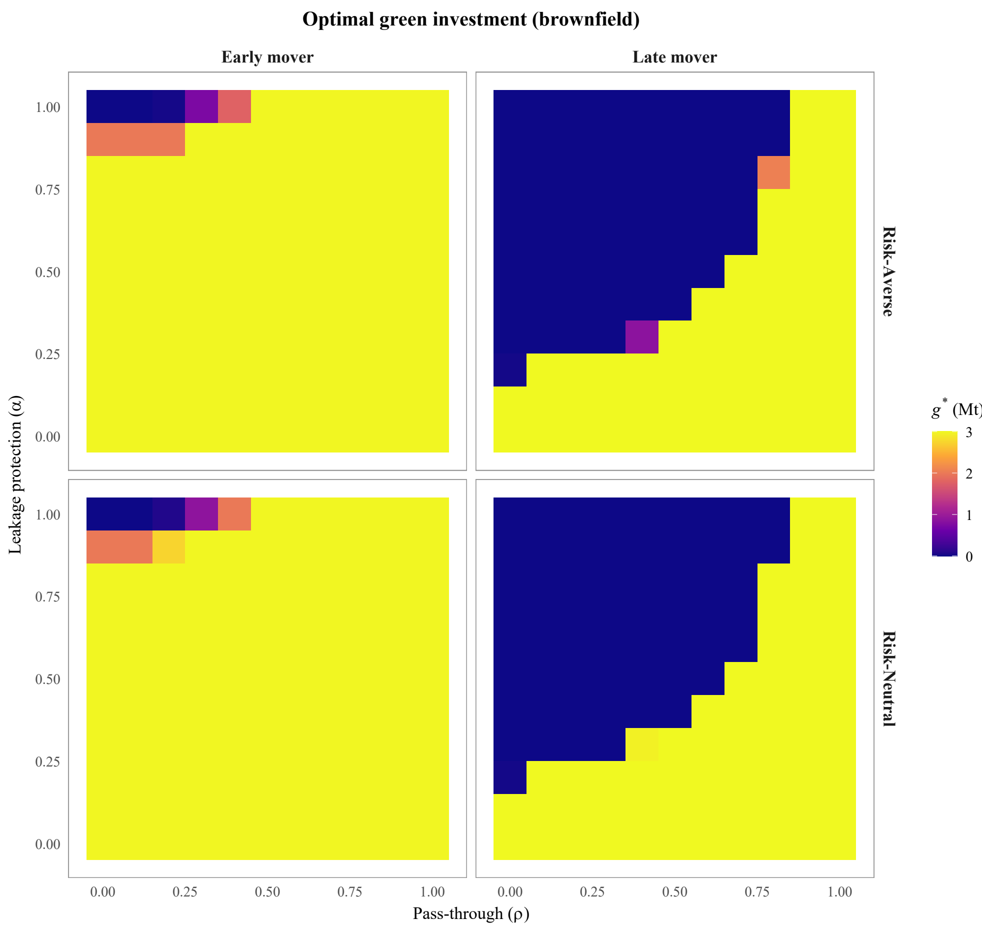

Figure 9: Optimal level of green investment for risk neutral and risk averse case for different belief profiles

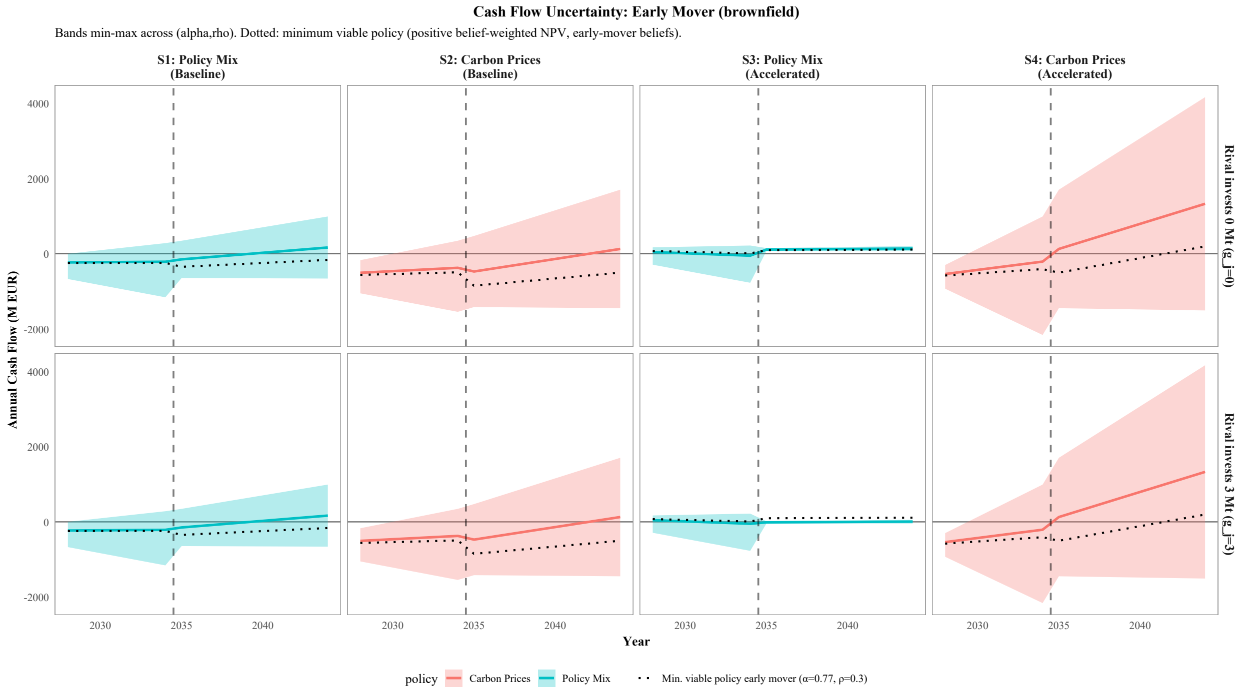

Figure 10: Cash flow over time for early mover

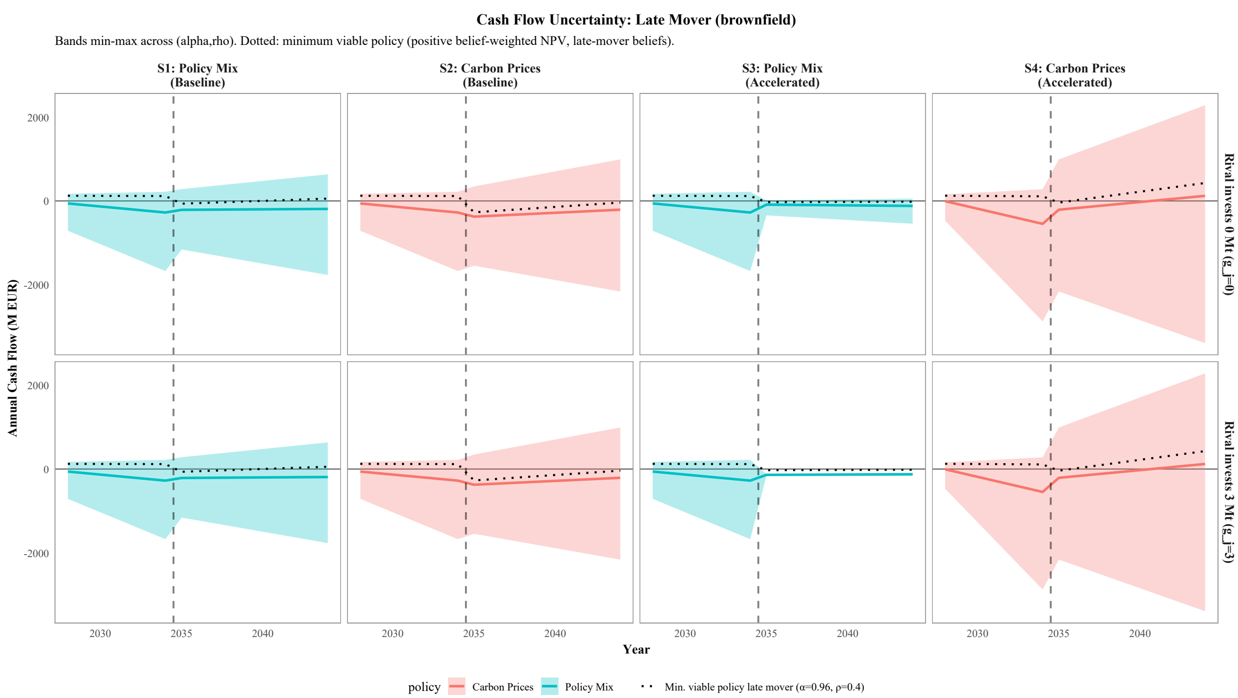

Figure 11: Cash flow over time for late mover

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