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Carbon cost pass-through and access to capital shape firms' carbon strategies

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Regulators globally deploy carbon pricing to drive down emissions through market forces. The effect of carbon pricing on firms' financial profiles is not well understood. However, a financially successful transition of industrial firms is critical for maintaining macroeconomic stability and achieving comprehensive decarbonisation. Here we analyse the costs of carbon pricing compliance and decarbonisation, and their effects on the cashflows and margins of six steel and cement firms across various future cost scenarios. We used a model framework that estimates the impact of carbon pricing and decarbonisation costs on operating margins and capital expenditure on a company level for a range of scenarios. We conclude that the key determinant of how readily energy-intensive companies can adapt to the climate transition is the 'carbon cost pass-through', that is, their ability to effectively pass on carbon-related expenses to consumers. Importantly, even the ability to pass through all costs does not guarantee financially successful decarbonisation, as capital markets can restrict the financing of zero-carbon solutions.

Carbon pricing is recognised as a key policy for decarbonisation and is being introduced rapidly in different areas of the world[1]. It can take the form of a direct carbon tax or of a 'cap-and-trade' emission trading scheme (ETS), which combines a regulatory limit on emissions (the 'cap') with the ability for companies to trade allowances to emit a certain amount (the 'trade'). While the global average carbon price[2] in 2023 was merely US$5.48 per tonne of CO_2 according to Bloomberg data, economists believe that this price must rise to US $75 by 2030[3], and US$250 or higher by 2050[4], to deliver the Paris climate target[5]. However, we still lack any systematic evidence of how these measures are likely to affect firms' financial performance and decarbonisation strategies—let alone their potential wider macroeconomic impacts (for example, inflation or financial stability).

On a small firm sample, this paper investigates (1) how compliance carbon costs impact firms' financial performance, (2) which factors drive such impacts, and (3) whether decarbonisation investment is a reasonable and feasible way to reduce the carbon price liability.

Internalising carbon costs poses major financial challenges to the cement and steel industries, which together account for 16% of global greenhouse gas (GHG) emissions[6,7]. To explore this issue, we provide six detailed case studies of cement and steel firms with substantial operations in the EU, where the carbon pricing pressure is building up the fastest[8]. Until 2030, we focus on firms' pricing of their EU emissions only, building on the detailed data provided by SparkChange, a carbon markets data company. After 2031, we add the impacts of global gradual expansion of carbon pricing with 100% of firms' emissions fully priced by 2040 based on the regional carbon price scenarios provided by the Network for Greening the Financial System (NGFS).

While the sample of only six firms is small, the analysis demonstrates structural challenges facing energy-intensive companies. If firms cannot pass through carbon-related costs, as the carbon price ramps up, such companies face quickly eroding margins while decarbonisation costs remain high. How firms handle the challenge of rising costs of carbon will depend on their financial health and strategy.

In our sample, if carbon costs have to be absorbed partially (or fully) by firms themselves, operating margins decline at various speeds (Fig. 1). In the near term, financial performance is affected by firms' historic free allocations and trading activity. One of the key factors behind the long-term margin loss is firms' carbon efficiency (their ability to convert carbon into revenues). The only way to reduce carbon price liability is to decarbonise, but the financial incentive to do so depends on the relationship between expected carbon pricing and decarbonisation costs, while the scale of capital required in the face of potential capital market limitations may make decarbonisation much costlier if not impossible.

We present three key findings:

(1) Companies must prepare now for a future of high effective carbon prices and align their investment strategies accordingly. Decarbonisation may require capital restructuring, while any unabated fossil fuel facilities may turn into stranded assets well before a net zero target year.

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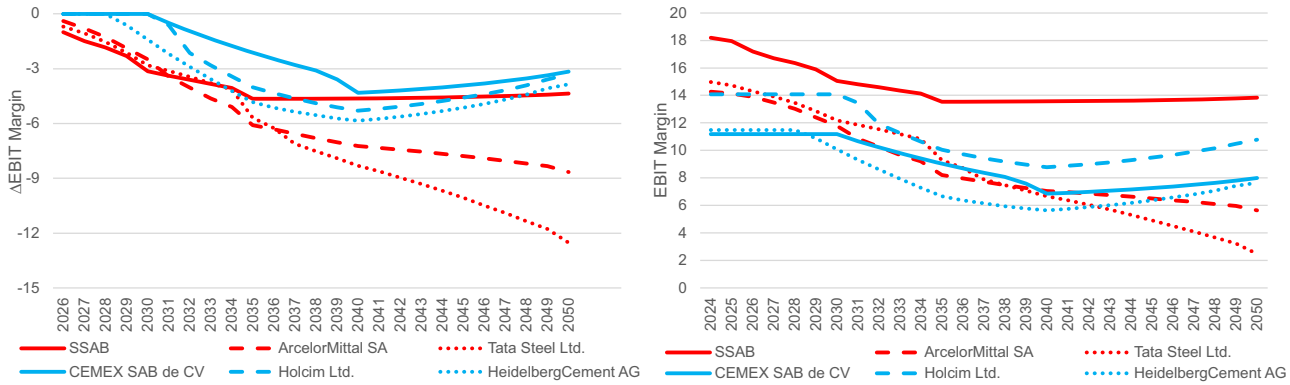


Fig. 1 | Changes in earnings before interest and taxes (EBIT) margin in a reference scenario. NZ emission reductions, low-price NDC carbon price path, medium decarbonisation costs and a 75% cost pass-through rate. Left panel – changes in EBIT margin (ΔEBIT Margin); Right panel – absolute EBIT margin projections.

(2) Investors need data and tools (like this framework) to identify firms that will perform better in the face of these challenges.
(3) Finally, policy makers and regulators must consider the impacts of potential capital market limitations on overall decarbonisation potential, and the impact of carbon pricing and decarbonisation costs on inflation and financial stability.

Historically, many companies in carbon-intensive sectors have not paid the full price of carbon, even in jurisdictions where they are subject to emissions regulation, e.g. the EU Emission Trading Scheme (EU ETS). Due to generous free allowances for carbon, some high-emitting companies paid no carbon price at all (or even received a net carbon subsidy) until the early 2020s, according to SparkChange data. The introduction of Carbon Border Adjustment Mechanism (CBAM) in 2026, which imposes a tax on carbon-intensive imports, is expected to have potentially far-reaching implications for global trade and carbon pricing dynamics[9]. Full CBAM implementation requires phasing out of free allowances in the EU ETS, which will create a substantial cost burden for carbon emitters.

While the carbon market design weighs heavily in the short-term, we find that the ability to shift carbon costs to consumers without diminishing demand, or cost pass-through, is the key determinant of the long-term financial success of firms under carbon pricing. However, sectoral estimates vary widely. In the cement industry, the European Commission[10] reports a potential pass-through rate of 20-100%. But there could be stark regional variations, from 0% in Portugal to nearly 90 + % in Poland[10–13]. In the steel industry, pass-through estimates also show wide variability by both country and technology, some as low as 6%[14], while others reach 120%[15], and many in-between[13,16]. On firm-level, while more research is needed to identify the exact factors, product specialisation and long-standing client relationships would contribute positively towards marginal cost passthrough. Whether these factors would be sufficient to pass through substantial decarbonisation cost if cheaper carbon-intensive alternatives are available is yet to be seen. It is possible that the pass-through rates are going to be product- and firm-specific. As different firms will experience different effective carbon and decarbonisation costs, they will be able to pass through various proportions thereof to the consumers, leading to either under- or over-compensation (windfall profit when the carbon cost surcharge on the product exceeds the actual firm's costs on the same). We recognise that passthrough rates are crucial for assessing the economic resilience and competitiveness of firms under carbon pricing rules.

Ultimately, there is only one way to reduce the carbon price liability: to decarbonise. Decarbonising the cement and steel industries will be capital-intensive[17]. However, capital markets may be able to accommodate the magnitude or timing of upfront capital that full decarbonisation requires. This potential uncertainty may in turn lead to an array of impacts, from changes in capital structures to financial instability, resulting in even higher decarbonisation costs amid higher risk premiums demanded by investors. The relationship between credit risk and carbon prices has received some attention in the literature, especially as high emissions have been shown to correlate with lower credit ratings[18]. Higher perceived carbon risk is also shown to increase the cost of protection against default[19]. Climate policies may have varying impact on operating efficiency[20]. Evidence also suggests that emission costs are priced into asset valuations[20], suggesting that some carbon pricing liabilities and expected decarbonisation costs are implied. Given the limited focus of traditional financial analyses'(1–3 years), an open question remain whether full emissions-related costs are priced in.

This paper highlights long- and short-term factors behind the carbon pricing impact on firms' financials, and sheds light on the realities of financial markets in the context of decarbonisation funding. These factors can pose not only the risk to financial performance of the high polluting firms, but also may have systematic financial impact and present an obstacle to achieving the optimal path to net zero. In this paper we did not explore the endogeneity of the feedback loop between carbon pricing levels, financial stability (at the firm and macro levels) and emissions.

Results

We focus our research on the Materials sector which has a high carbon intensity, is covered by most existing cap and trade markets and is responsible for 23% of global CO2 emissions[21]. Within this sector, we constructed our sample group to represent a regional mix of companies and varying approaches to decarbonisation. We limited our research to public companies due to data availability, and acknowledge that the results for smaller, private companies in the sector might differ. Therefore, we chose Holcim Ltd, Heidelberg Materials AG and CEMEX SAB de CV in the cement sector; and ArcelorMittal SA, Tata Steel Ltd and SSAB SA in the steel sector.

Data availability is the biggest obstacle for a bigger sample size.

To this date, 20 years after the launch of EU ETS, companies do not have to disclose in their annual statements either their liability under EU ETS or the free allocations they receive from the Commission. Often it is a laboursome process to allocate installations to corporates, which sometimes also change hands, and to track free allocation and any EUA trading activities. This data limitation unfortunately limits our ability for large sample analysis. Where data cannot be obtained or inferred, we make assumptions (see Methods).

We analyse the results over three scenarios of decarbonisation costs and two scenarios of carbon price evolution (key scenario metrics are presented in Table 1). Regional carbon prices are consolidated on firm level and follow one of two NGFS-based pathways: a Nationally Determined Contributions (NDC) carbon price path (US$61 global average carbon price(GACP) by 2050) and a Net Zero 2050 (NZ) carbon price path (US$157 GACP by 2050)[22]. Our framework can be applied to evaluating any scenario. The two given carbon pricing scenarios outline

Table 1 | – Key scenario assumptions

A

t	Technology	$LCCA_{low}$	$LCCA_{mid}$	$LCCA_{high}$	Lifetime	*OPEX*%
1	EAF	14	208	600	30	37%
2	Bioenergy	169	177	184	30	20%
3	CCUS_Steel	27	100	115	30	37%
4	H_2-BF	121	280	440	30	20%
5	H_2-EAF	100	379	650	30	20%
6	Fuel Shift	122	122	122	30	20%
7	CCUS_Cement	70	100	155	30	40%

B

	ARCELOR	TATA	SSAB
Electrification	10.26%	10.26%	10.26%
Bioenergy	15.39%	15.38%	15.38%
Hydrogen (BF-BOF)	10.26%	10.26%	10.26%
Hydrogen (EAF)	10.26%	10.26%	10.26%
CCUS	41.03%	41.03%	41.03%
Other Fuel Shifts	12.82%	12.82%	12.82%
	Cemex	Holcim	Heidelberg
CCUS	52%	51%	52%

C

	Low			Middle			High		
	2024-34	2035-50	WACC	2024-34	2035-50	WACC	2024-34	2035-50	WACC
Arcelor	51.92	72.25	7.08%	138.16	186.38	8.74%	218.70	296.42	9.23%
Tata Steel	54.21	76.59	7.41%	127.43	172.57	7.47%	195.44	264.67	7.49%
SSAB	43.89	61.31	5.12%	120.47	162.11	6.85%	192.14	259.61	7.37%
Holcim	55.02		4.20%	81.85		4.84%	131.20		5.36%
Cemex	69.84		7.48%	101.50		7.90%	159.55		8.24%
Heidelberg	58.83		5.22%	90.13		6.33%	147.96		7.24%

D

		Observed	NetZero2050			NDC		
		2023	2030	2040	2050	2030	2040	2050
CEMEX SAB de CV	Nominal EUA price	90	263	569	875	148	154	157
	Effective EUA price	-21	58	569	875	33	154	157
	Nominal Average Carbon price RoW			337	535		84	89
	Effective average Carbon price RoW			337	535		84	89
Holcim Ltd.	Nominal EUA price	90	263	569	875	148	154	157
	Effective EUA price	-12	84	569	875	48	154	157
	Nominal Average Carbon price RoW			347	553		86	91
	Effective average Carbon price RoW			347	553		86	91
HeidelbergCement AG	Nominal EUA price	90	263	569	875	148	154	157
	Effective EUA price	-3	106	569	875	60	154	157
	Nominal Average Carbon price RoW			361	556		86	93
	Effective average Carbon price RoW			361	556		86	93
SSAB	Nominal EUA price	90	263	569	875	148	154	157
	Effective EUA price	27	180	569	875	101	154	157
	Nominal Average Carbon price RoW			395	526		147	150
	Effective average Carbon price RoW			395	526		147	150
ArcelorMittal SA	Nominal EUA price	90	263	569	875	148	154	157
	Effective EUA price	7	117	569	875	66	154	157
	Nominal Average Carbon price RoW			398	637		106	110
	Effective average Carbon price RoW			398	637		106	110
Tata Steel Ltd.	Nominal EUA price	90	263	569	875	148	154	157
	Effective EUA price	-53	67	569	875	38	154	157
	Nominal Average Carbon price RoW			210	527		35	42
	Effective average Carbon price RoW			210	527		35	42

A Technology-Specific Assumptions (Generic Levelised cost of carbon abatement, useful economic lifetime, percentage OPEX, and technology readiness level). B Decarbonisation technology mix (% of total emissions decarbonised. C Company-specific LCCA (split into pre- and post-TRL based on TRL achieving economic feasibility) and WACC. D Carbon pricing scenarios and corporate-level details. Corporate-level carbon pricing in EU and Rest of the World, nominal and effective (inclusing of regulatory allowances) in USD per tonne of CO^2

the range of possible outcomes while allowing for the exploration of the key drivers behind the financial success or failure. As regional carbon prices are considered, even within the same overarching scenario the firm-level average price for emissions are different as they depend on the regional production mix. At the same time, decarbonisation costs differ based on each firm's cost of funding, capital structure and the scale of decarbonisation CAPEX (See Methods).

Overall, we find that when facing a choice between paying for emissions or investing in decarbonisation, the following factors will play a critical role in determining financial success:

1. Carbon pricing market structure and firms' effective carbon cost (actual price paid for emissions, net of all subsidies);
2. Carbon efficiency, pricing power and demand resilience;
3. Corporate strategy, including carbon pricing hedging activities and structuring of decarbonisation investments;
4. The decarbonisation speed and timing (which is also part of corporate strategy);
5. Firms' capital market access capacity and cost of capital to finance decarbonisation, which will generally correlate with credit ratings, but may be affected by unexpected increases in incremental capex;
6. Carbon conversion, meaning firms' ability to transform emissions and emission reduction into revenues and financial value, primarily via a cost pass-through or through new product value creation; and
7. Firms' financial capacity to absorb financial shocks.

To decarbonise or not to decarbonise: a carbon pricing case

A high effective carbon price path (for example, NZ scenario) presents a direct financial incentive to decarbonise (Fig. 2). The combined cost of carbon pricing and decarbonisation is lower than that of paying the carbon price alone. If unable to pass through related costs, without decarbonisation all sample companies' EBIT margins turn negative by 2033. In the long term, the most carbon efficient companies (as measured by emissions relative to their revenues) are slowest to experience margin losses. If carbon prices are relatively low, EBIT margins turn negative for four out of six companies. The two remaining: most carbon efficient company (facing least carbon liability) and least EU exposed company (facing lowest overall carbon price) – manage to maintain positive margins until 2050. The long-term margin comparison however is conditional on survival until 2050 in spite of prolonged periods of negative margins which is highly unlikely without structural changes or other strategic adjustments.

Knock-on inflation

If companies can fully pass on emission costs, margins deteriorate only slightly due to rebalancing between revenues and costs, even if profits stay the same. If companies do not decarbonise, steel and cement prices rise by an average 0.5%–0.7% and 0.7%–1.1% annually respectively in an NDC carbon price scenario. In a NZ carbon price scenario with 100% of emissions costs passed through to consumers, the average annual price increase range is 2.4%–3.5% for steel and 3.1%–4.0% for cement. Cumulatively, by 2050, product prices would increase by 15%–33% in NDC carbon price environments and by 87%–192% in NZ carbon price environments due solely to direct carbon pricing.

Our analysis shows that at sufficiently high carbon prices (e.g. NZ scenario), decarbonisation results in lower production costs. Assuming the NZ carbon price pathway, high-decarbonisation costs and full cost pass-through, the peak cumulative price increases are 41%–85% for steel and 49%–71% for cement by 2050, less than a half of the increases in a scenario without any decarbonisation. However, if the carbon price follows a lower NDC trajectory, the optimal strategy and thus costs depend on the level of decarbonisation costs: in the medium decarbonisation cost scenario, cement companies are still better off decarbonising, while steel companies could be better off paying carbon price as it is more costly to decarbonise a unit of carbon in steel than in cement.

While steel and cement price increases do not constitute inflation in CPI (consumer price index) sense, they raise input costs for housing and infrastructure, and are ultimately paid by consumers directly or via taxes, and add to other climate-related price pressures. The ultimate price increases however depend on the pass-through level and the ability of companies to efficiently raise capital for decarbonisation.

Carbon cost pass-through

Given that firms' ability to pass through carbon costs to consumers is critical for achieving successful decarbonisation, it is crucial to ask what, specifically, is being passed through. One way the pass-through could manifest is via industry-wide product price increases, with every company subject to the same price. If the average industry price increase is passed through in this way, companies with lower cost bases would make windfall profits, while companies with higher cost bases would bleed. Another possibility for pass-through is through markets splitting into green/non-green products, with each having their own price dynamics. Importantly, the scale of price increases required by carbon pricing and decarbonisation may diminish consumers' appetites, while more steel and cement would be needed for mitigation and adaptation solutions. Additionally, price increases would open the door to innovation and research for low cost/carbon alternatives.

For present purposes, we assume that each company passes through a given percentage of its own cost, spread across all its outputs. We analyse the inter-company dynamics under our reference scenario: an NDC carbon price path, medium decarbonisation costs and net zero emission reductions, and a 75% cost pass-through rate. This scenario results in a modest product price increase of 0.3–1.1% annually, while EBIT margins deteriorate but remain positive. Steel companies, having a full scale of decarbonisation solutions costed from the start, observe immediate rapid margin declines regardless of the initial effective carbon price or the bank of EU allowances (EUAs). In the long-term revenue-measured carbon intensities is the defining factor of steel companies' financial performance. Cement companies, in contrast, enjoy delayed (and cheaper) decarbonisation in our

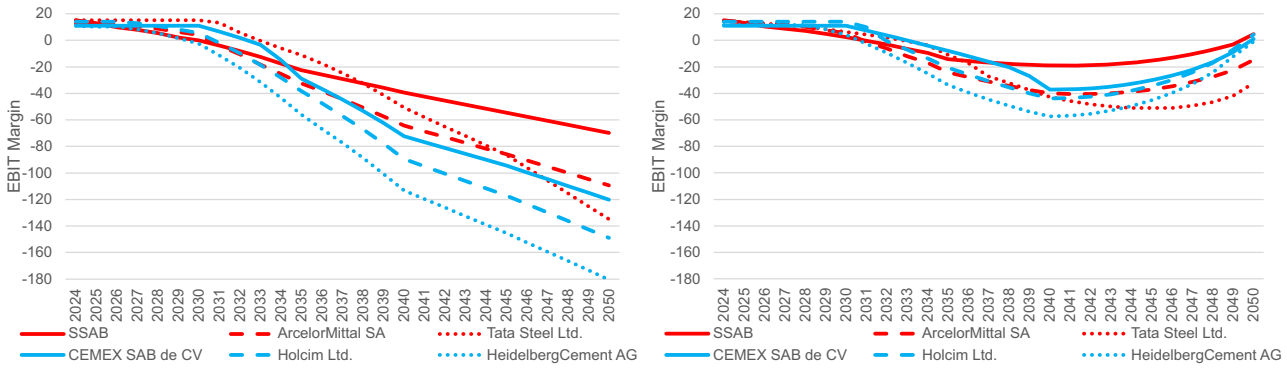


Fig. 2 | EBIT margin amid NZ carbon price path and 0 pass-through. Left panel - no decarbonisation. Right panel - decarbonising to net zero by 2050, medium decarbonisation cost.

Table 2 | Emissions-related metrics of in-sample companies

			% of EU Emissions			2023 Nominal EUA Price US$ 90.3528/tonne CO_2	
Company	Avg REV CO2int	2023 PHYS CO2int	EUA bank, 2023	Max Bank, 2023-30	EU emissions % of Total, 2023	EU Effective Carbon Price (2023)	EU effective carbon price estimate (2030)(NDC/NZ carbon price trajectory)
SSAB	867	1420	4%	4%	91%	26.64	101.5/180
ArcelorMittal SA	1598	1830	0%	0%	34%	7.27	65.8/116.7
Tata Steel Ltd.	2644	2210	114%	329%	8%	−52.67	37.5/66.6
CEMEX SAB de CV	2262	603	386%	483%	14%	−21.42	32.7/58.1
Holcim Ltd.	2601	587	13%	66%	21%	−11.99	47.5/84.3
HeidelbergCement AG	2900	569	3%	13%	32%	−2.81	59.6/105.8
						average	57.4/101.9

model; hence, they enjoy relative stability in the short term and their margin decline is less pronounced compared to steel companies. In the long term, margin decline for cement companies is also correlated with the revenue-measured carbon intensity, although the final outcome depends on the initial margin. Ultimately, all cement companies see increasing margins post-2040 (Fig.1).

The above assumption is a simplification of the market. Most likely there will be bifurcation of the market into green and carbon-intensive commodities. The green premium, or the price increase relative to conventional steel/cement on the back of decarbonisation costs, will increasingly be put against carbon penalty (the carbon price component passed through to the consumers). It is also likely that steel vs cement pass-through dynamics would present differently due to industry and product specialisation. Product immobility (locally produced and hard to transport), premium product specialisation, high capacity utilisation rates and mono-/oligopolistic producers all will enhance the pass-through, likely leading to higher steel pass-through rates than that in cement industry. However, more research and evidence are needed.

Role of ETS design

In the short to medium term, the design of the carbon pricing scheme and companies' management of carbon compliance liabilities (and resulting differences in effective carbon prices and EUA bank) (Table 2) are the most important requirements for financial success.

Data shows that participation in a cap-and-trade market can create additional revenues: all companies in our study received more EUAs than their EU emissions in the second trading period (2008–2012). The excess free allowances constituted a net subsidy of US$21.5 billion by 2020, according to our calculations. By 2023 only two out of six companies received fewer free allocations than their emissions. Moreover, five companies had an inventory of surplus EUAs from previous years, allowing them to avoid purchases in the near term. The accelerated decline of the emissions cap from 2021, combined with the phase-out of free allowances in the EU ETS beginning in 2026 in line with the CBAM implementation, increases the average EU effective price paid by all steel companies, reaching US$101.50/tonne on average by 2030 in the NZ Carbon price scenario.

Short-term performance in the cement sector is directly correlated with the effective carbon price and each firm's bank of EUAs. The impact in the steel sector is more nuanced. The most carbon efficient steel company has the highest share of EU emissions, the highest effective carbon price and near zero allowances in the bank, which results in underperformance relative to the peers until 2030. The steel company with the highest banked allowances (as a share of 2023 emissions) and the highest effective price is not the best performer, as it has the lowest share of EU emissions and the worst carbon intensity, which elevates the decarbonisation cost early on.

Post-2030, the average effective carbon price per company starts to increase sharply, reflecting global carbon price coverage and a rapid phase-out of free allowances across all markets. On a comparative basis, the steel industry experiences losses much earlier and deeper than the cement industry, driven by the assumption that steel manufacturers begin fully costed decarbonisation without delay, while cement companies face costly decarbonisation of only 50% share of their emissions beginning in 2030. In addition, the weighted average decarbonisation costs are lower for cement than steel.

The range of financial impacts of the various scenarios depends on the magnitude of the underlying estimates. Figure 3 demonstrates the changes in EBIT margin (ΔEBIT) of our reference scenarios as a result of four key parameters: carbon price, decarbonisation costs, pass-through rate and cost of capital. The lower the costs and the higher the pass-through, the better the margins for companies, but the range of outcomes can be wide. Decarbonisation costs are particularly sensitive to the cost of capital assumption. While our reference scenario assumes a historic WACC subject to a leverage cap, in practice, substantial additional capital raising would push up the cost of capital. In the panes E and F we demonstrate the sensitivity of levelised cost of carbon abatement to the cost of capital on corporate level and relative to the generic costs cited in decarbonisation literature.

It is important to note that the long-term results and comparative analysis depend on the firms' survival – either by passing though their costs or reorganising/restructuring their businesses. In fact, in a general equilibrium setting there will be a relationship between firms' decarbonisation speed, their financial viability and the carbon price itself. If the carbon price rises high and fast and corporates go out of business, emissions will come down and the carbon price will correct lower, which in turn would increase chances of other firms' survival and strengthen their market position/dominance. The relationship which we do not examine here.

The capital dilemma

Even if companies can survive paying additional average annual costs or are able to pass them through to customers, they may face substantial challenges to raising capital for full decarbonisation. In the medium-decarbonisation cost scenario, cement companies must raise an additional 60–130% of their market capitalisation, or 40–70% their total capitalisation. In comparison, the steel companies in our sample would have to raise up to 600% of their market cap or 200–400% of their total capitalisation (Fig. 4). In the high-decarbonisation cost scenario, these numbers increase to up to 2 times market cap for cement and up to 9 times market cap for steel companies. On an annualised basis, the additional CAPEX spending should be 45–128% higher for steel and around 30% higher for cement companies between 2024–2050 in the low decarbonisation cost scenario, increasing up to four-fold if decarbonisation costs follow a high trajectory (Fig. 5). (It is important to note that the exact decarbonisation CAPEX would depend heavily on the technological choice for decarbonisation. The results here present the global average technology basket, but firms will have a bias towards the cheapest in the regional context or most in demand based on the outcome product type.)

Carbon efficiency dictates the overall costs of both carbon price liability bill and decarbonisation cost. But firms' financial health at the

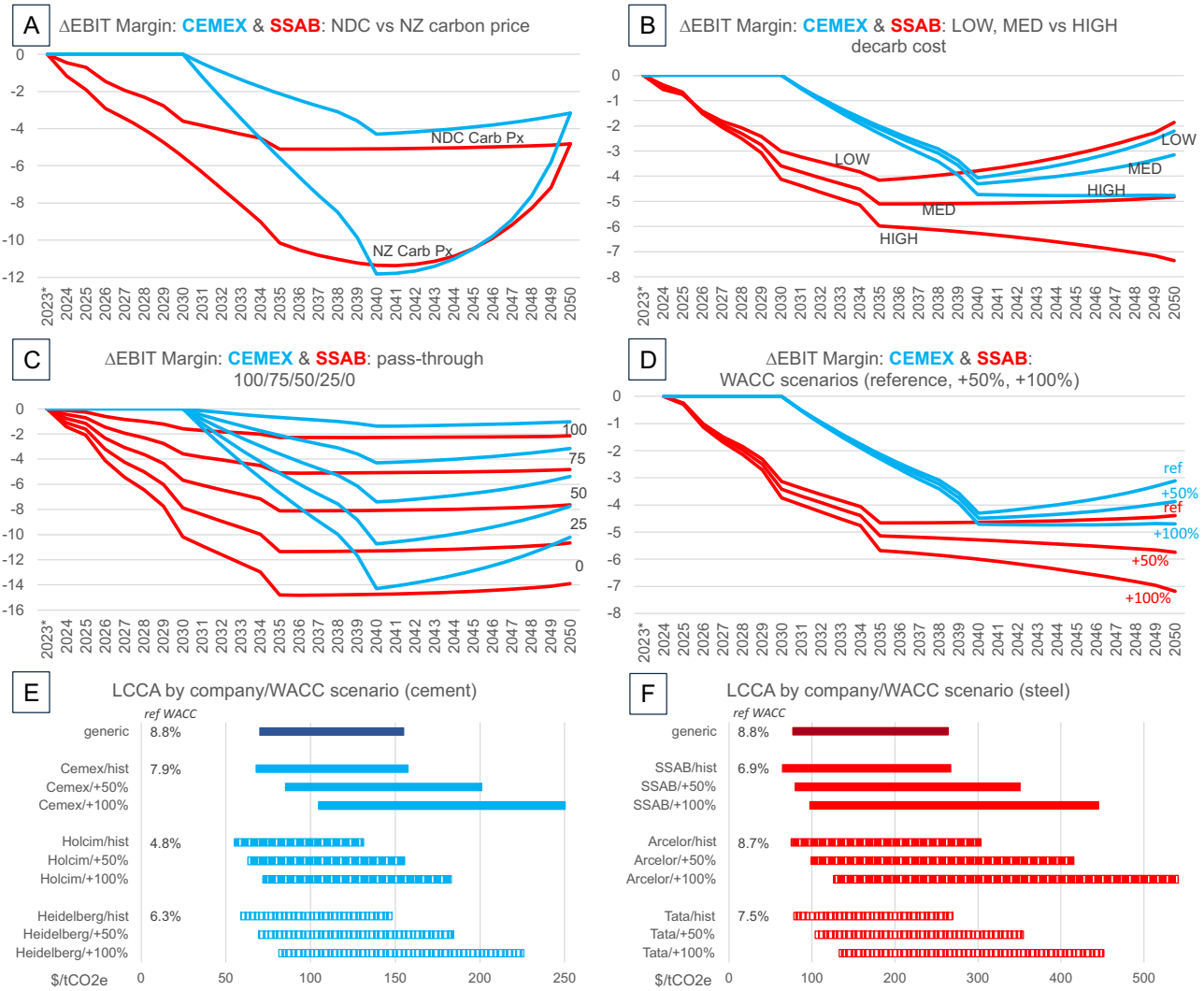


Fig. 3 | Sensitivity analysis, changes in EBIT margins (ΔEBIT Margin) and levelised cost of carbon abatement (LCCA) of a reference scenario to changes in a single variable. Demonstrate sensitivity of change in EBIT Margin in a reference scenario (NDC carbon price path, Net Zero corporate emissions path, medium decarbonisation cost scenario, 75% cost pass-through) to carbon price path (**A**), level of decarbonisation costs (**B**), level of cost pass-through (**C**), level of cost of capital (**D**). Demonstrate the sensitivity of company-level LCCA under different cost of capital (weighted average cost of capital (WACC)) scenarios for cement (**E**) and steel (**F**) relative to the generic LCCA estimate.

beginning of decarbonisation journey is critical: a healthy balance sheet, low leverage and borrowing costs, high margins all give more room to transition without duress. Importantly, one of the major factor differentiating firms' financial success is their capacity to access capital markets. The concept of levelised cost of carbon abatement prevailing in engineering literature is based on limitless and efficient capital market access without liquidity constraints. It is unlikely firms can raise large amounts of funding without materially altering their debt profiles. The deterioration of margins in any scenario may lead to a vicious cycle: the lower firms' margins, the higher the cost of capital, which leads to a higher cost of decarbonisation, resulting in even lower margins. Equity infusions, taxpayer bailouts or subsidies may be required.

Discussion

Steel and cement companies face extraordinary financial challenges in dealing with higher carbon prices and decarbonisation costs. Until recently, these costs were negligible due to the generous subsidies. But as subsidies wind down, new carbon pricing schemes are likely to appear and decarbonisation ambitions will rise (following macroeconomic and geopolitical headwinds.) Firms will have to make important strategic decisions on how to manage these rising costs[23].

Will carbon compliance costs impact firms' financial performance?

Margins deteriorate quickly if companies have to fully absorb carbon-related costs. Depending on carbon price level, most companies show negative margins as early as the first half of the 2030 s. Technically, if firms can pass through the full carbon cost, they can largely maintain their operating margins. If the expected carbon price is sufficiently high (higher than decarbonisation costs), the (levelised) cost of decarbonising and of paying the carbon price on the unabated emissions in the interim is lower, so that companies are financially incentivised to decarbonise.

What factors are driving these potential changes?

Beyond macro or sectoral assessments, new firm-level evidence shows carbon pricing materially re-allocates performance across listed firms: a global triple-difference study covering 52 countries finds profitability and valuations fall for high-emitters after carbon pricing, via both lower expected cash flows and higher required returns, with knock-on cuts to capex and employment[24]. We extend this literature by opening the black box of *how* these effects arise, quantifying the roles of carbon-cost pass-through and financing constraints in shaping cash flows and investment feasibility. In parallel, bank-system stress tests suggest that, on average, even large

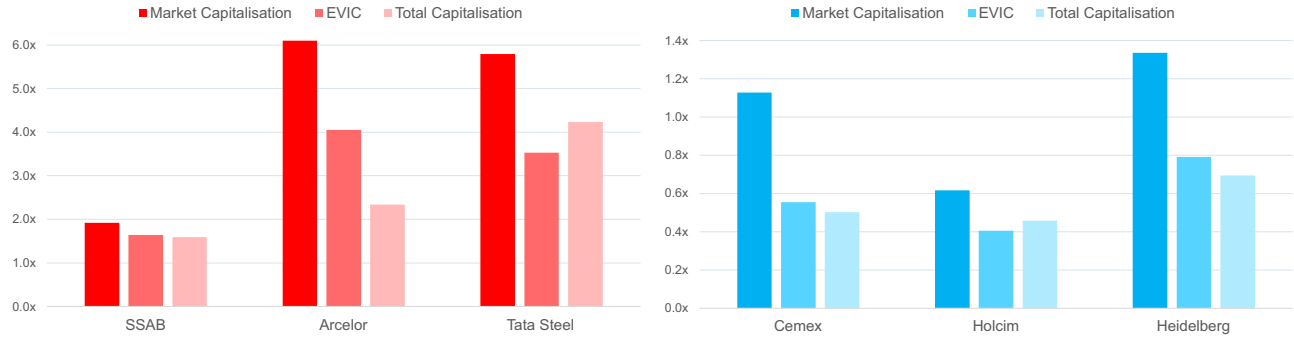
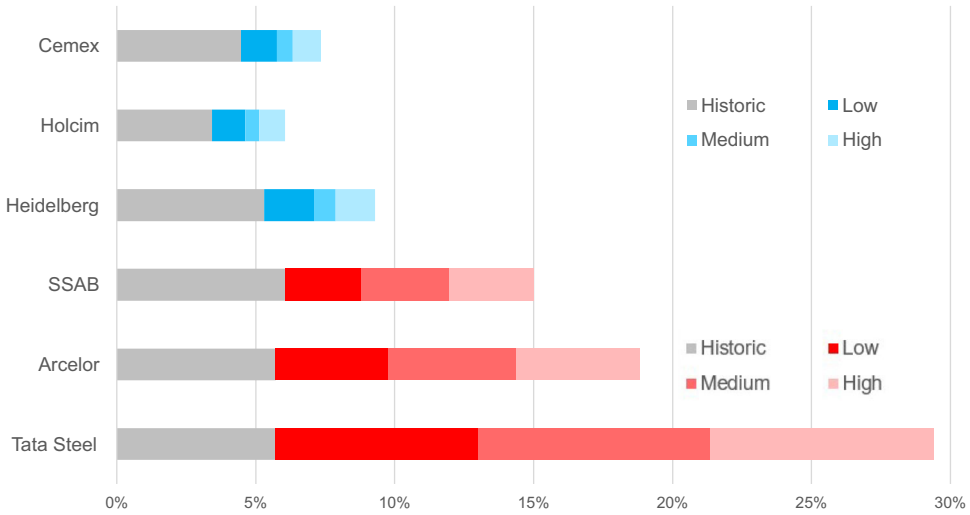


Fig. 4 | Company-specific nominal full decarbonisation CAPEX (up to 2050) expressed as a multiple of the company size/valuation. Company-level CAPEX (medium decarbonisation cost scenario) relative to historic (2021–2023) market capitalisation, enterprise value including cash (evic) and total assets for steel (left panel) and cement (right panel) companies.

Fig. 5 | Annual decarbonisation CAPEX by decarbonisation cost scenarios. Average annual incremental CAPEX to achieve Net Zero based on the modelled decarbonisation technology mix relative to historic annual CAPEX (2021–2023) as a share of firms' total capitalisation.



carbon price shocks translate into limited capital-ratio impacts once partial pass-through is allowed, masking substantial firm-level dispersion[25]. Our firm-financial mechanism helps explain that dispersion and when decarbonisation becomes cash-flow- and balance-sheet-consistent.

If companies *should* decarbonise, the question they then face is whether they can raise sufficient funds to finance decarbonisation CAPEX in the capital markets, and whether this process will impact credit profiles. The resulting impacts could lead to possible lower credit ratings, firm capital restructuring, equity issuance, or the necessity of government subsidies or nationalisation. The magnitude of funds required for full decarbonisation will be challenging for most firms, potentially putting at risk their survival and wider financial stability or putting brakes on decarbonisation efforts.

Is decarbonisation investment a reasonable and feasible way to reduce the carbon price liability?

Our results suggest that decarbonisation measures will be necessary to meet expected carbon reduction demands in the future. To the best of our knowledge, none of the literature addresses the financial pressures of the trade-off between carbon pricing and decarbonisation costs at the corporate level. Many papers on carbon pricing focus on carbon leakage, some on asset pricing implications, but they do not examine the channels of risk transmission and how these affect corporate financial performance. Some literature[26] examines the impact of carbon price volatility in cap-and-trade system on decarbonisation, while we look at the claim that even if corporates want to invest in decarbonisation solutions, limited access to capital markets (when sums required would shift the overall capital structure) can restrict such progress. Importantly, often climate finance literature uses the carbon intensity as the ultimate beacon of transition risk. We demonstrate that while that is indeed important, the key driver is actually the carbon cost pass-through, which to this date unfortunately did not get much attention in either academic or industry literature. The green steel/cement cost increases are discussed across literature (e.g. 10–125% higher price tag for clean steel/cement in the recent industry report[27–29]) but often the green product only compared to unabated fossil fuel one, while we demonstrate that under the carbon pricing regime, the price of carbon-intensive steel and cement will have to change as well. To our knowledge, the capital required for full decarbonisation on corporate level and its impact on financial performance are not discussed in literature. Our study is focussed on 6 carefully selected companies, which risks that the results are case-specific. However, the challenges we discuss are structural challenges affecting all players in the energy-intensive industries. Our company selection offers a glimpse into a range of outcomes and differences in response to common challenges. While more research is needed on industry- and economy-wide conclusions, the transition will be expensive and the cost of it, whether it's successful or not, will have to be covered by investors, consumers or taxpayers. This observation has implications for policy-makers dealing with issues relating to future decarbonisation requirements.

Methods

We create a model framework that estimates the impact of carbon pricing and decarbonisation costs on capital expenditure (CAPEX) and operating expenses (OPEX) (revenues and costs) on a company level for a range of scenarios. The scenarios are defined as emission pathway, *dp*, carbon price

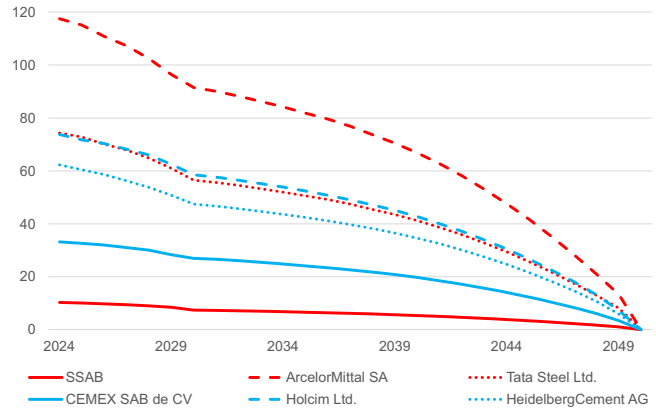


Fig. 6 | Emission trajectories. Absolute (gross) Emission Projections (mtCO2) – NetZero.

pathway, *cpp*, level of decarbonisation cost, *dc* (low, medium, high), and cost pass-through, *cpt*.

Our OPEX model runs on two emissions scenarios. The first scenario is a static emissions pathway anchored at a constant level of the average absolute emissions between 2021 and 2023.The second scenario (Fig. 6) follows a concave trajectory to the net-zero emission target by 2050 anchored at the interim targets published by corporations (the targets expressed in terms of physical carbon intensity, converted into absolute emissions by multiplying by the average of 2021–2023 production volume, which is assumed to be constant. This first scenario is used to inform our CAPEX model.

Model construction

For each company we calculate the aggregate incremental CAPEX in nominal terms required to achieve its net zero target by 2050. Levelised cost of carbon abatement (LCCA) is the average annual cost of reducing one tonne of GHG from an industrial process, based on fixed upfront and variable costs using a discounted cashflows process. LCCA is the common way the decarbonisation costs are commonly expressed in literature, but this concept assumes unrestricted access to limitless capital, which is not the case in the corporate world. We calculate total decarbonisation CAPEX for each firm from generic LCCA estimates found in literature, split over three scenarios—low, medium and high cost—based on total emissions reported by companies and an assumption of full decarbonisation.

Within each industry, for every decarbonisation technology, i, $LCCA_{i,dc}$ is defined as levelised costs of carbon abatement in US$ per unit of carbon dioxide equivalent (CO_2e). DUR_i is a duration term for the technology's modelled expected useful life (in years), for comparability we use duration of 10.45 for all technologies in this study (based on assumptions used in literature and further discussed in the *data and assumptions* section). $OPEX\%_i$ is the share of the LCCA that is attributed to OPEX. TRL_i^y is the binary marker for the technology i readiness level (TRL) in year y (1 if the TRL is level 9 or commercially viable, otherwise 0). $\Delta GHG_{i,dp}^{c,y}$ denotes the incremental emission reduction by company, c, and technology, i, in year, y.

For every firm, c, the cumulative nominal CAPEX is calculated in Eq. 1:

$$CAPEX_{dp,dc}^{c} = \sum_{i,y}^{Y} LCCA_{i,dc} \cdot TRL_i^y \cdot DUR_i \cdot \left(1 - OPEX\%_i\right) \cdot \Delta GHG_{i,dp}^{c,y} \quad (1)$$

The last term of the Eq. 1, $\Delta GHG_{i,dp}^{c,y}$, the yearly change in absolute emissions, is a function (Equation (of the annual percentage change in emissions relative to the 2023 level (Eq. 2a) and the total emission reduction attributed to each technology (Eq. 2b). TLF_i is the technology load factor delivered by the technology, i, to achieve the emission reductions required for dp. It reflects the importance of each technology in reaching net-zero and is based on sectoral decarbonisation pathway data from the IEA[30] (Table 1A, B).

$$\Delta GHG_{i,dp}^{c,y} = GHG_{i,dp}^{c,2023} \cdot \%\Delta GHG_{dp}^{c,y} \quad (2)$$

$$GHG_{i,dp}^{c,2023} = GHG_{dp}^{c,2023} \cdot TLF_i \quad (2a)$$

$$\%\Delta GHG_{dp}^{c,y} = \frac{GHG_{dp}^{c,y-1} - GHG_{dp}^{c,y}}{GHG_{dp}^{c,2023}} \quad (2b)$$

We use incremental capital expenditures, $CAPEX_{dp,dc}^{c}$, historical leverage and capital costs (based on 2021–23 averages) to calculate company-specific levelized cost of carbon abatement, $LCCA_{i,dp,dc}^{c}$ (Equation (. We assume firms raise debt for the incremental capital expenditures until it represents 50% of their capital structure (1 debt-to-equity ratio), any surplus is raised at a 1:1 ratio between debt and equity, which is reflected in WACC term (Eq. 4) using the average tax rate across the industry representative company's between 2021 and 2023. Comparing $CAPEX_{dp,dc}^{c}$ to market-observed capital structures enables the creation of firm-specific weighted cost of capital.

$$\%E_{dp,dc}^{c} = \frac{\left(\frac{CAPEX_{dp,dc}^{c} - \left(E_{Avg}^{c} - D_{Avg}^{c}\right)}{2}\right)}{CAPEX_{dp,dc}^{c}} \quad (3)$$

$$WACC_{dp,dc}^{c} = \%D_{dp,dc}^{c} \cdot r_d \cdot (1 - \tau) + \%E_{dp,dc}^{c} \cdot r_e \quad (4)$$

D_{Avg}^{c} and E_{Avg}^{c} are the 2021–23 average book debt and equity values for company, c. $\%D_{dp,dc}^{c}$ and $\%E_{dp,dc}^{c}$ are the new debt and equity values that need to be raised as a percentage of decarbonisation CAPEX under each cost scenario. r_d and r_e are the costs of debt and equity. The cost of debt is calculated by adding the term risk-free rate to the company's risk premia estimated using company's extrapolated CDS rate. The cost of equity is obtained from Bloomberg. τ is the corporate tax rate. For this analysis, we use the average tax rate for each industry between 2021 and 2023 due to volatility between years and companies.

Company-specific duration, $DUR_{dp,dc}^{c}$, is calculated using WACC from Eq. 4 and the useful life of technology, i, (Equation (. The duration is applied to the pathway-specific LCCA to derive company- and technology-specific levelised costs of capital, $LCCA_{i,dp,dc}^{c}$ (Equation).

$$DUR_{dp,dc}^{c} = \frac{\sum_{y=1}^{Y} \frac{1}{\left(1 + WACC_{dp,dc}^{c}\right)^{y}}}{1 + WACC_{dp,dc}^{c}} \quad (5)$$

$$LCCA_{i,dp,dc}^{c} = \left(LCCA_{i,dp,dc} \cdot \left(1 - OPEX\%_i\right) \cdot \frac{DUR_i}{DUR_{dp,dc}^{c}}\right) + \left(OPEX\%_i + LCCA_{i,dp,dc}\right) \quad (6)$$

It is further aggregated across all technologies to deliver company-specific LCCA in year y (Eq. 7).

$$LCCA_{dp,dc}^{c,y} = \sum_{i} LCCA_{i,dp,dc}^{c} \cdot GHG_{i,dp}^{c,y} \quad (7)$$

We assess the impact of the carbon compliance costs for the unabated GHG emissions and company-specific levelised decarbonisation costs ($LCCA^{c}_{i,dc}$) on corporate cashflows. Revenues and costs are projected annually until 2050 based on historical revenues and costs (averaged over 2021–2023) and adjusted for three factors: each respective year's (1) effective carbon price liability for unabated emissions (costs), (2) levelised decarbonisation costs on cumulative abated

emissions (costs) and (3) pass-through impacts of both types of costs on revenues.

For each company, c, geographic region, r, and year, y, we calculate corporate regional emissions (in tonnes of CO_2e) equivalent to the development of the global emissions:

$$GHG_{r,dp}^{c,y} = GHG_{r}^{c,2023} \cdot \frac{GHG_{dp}^{c,y}}{GHG_{dp}^{c,2023}} \tag{9}$$

$FreeGHG_{r}^{c,y}$ represents the respective region's ETS allowances allocated free of charge. $p_{r,cpp}^{y}$ is the nominal carbon price for region r. $GHGSales_{r}^{c,y}$ represents annual sales of excess allowances for $y < 2024$. Consequently, we can define the accumulated inventory of ETS allowances as:

$$Inventory_{r,dp}^{c,Y} = Max(0, \sum_{y}^{Y}(FreeGHG_{r}^{c,y} - GHG_{r,dp}^{c,y} - GHGSales_{r}^{c,y})) \tag{10}$$

As a result, the costs related to compliance carbon pricing per company are computed as:

$$ETSDue_{dp,cpp}^{c,y} = \sum_{r} Max\left(0, GHG_{r,dp}^{c,y} - FreeGHG_{r}^{c,y} - Inventory_{r,dp}^{c,y-1}\right) \cdot p_{r,cpp}^{y} \tag{11}$$

For each company and year, the total incremental annual costs against the baseline are defined as:

$$\begin{aligned} \Delta Cost_{dp,dc,cpp}^{c,Y} = {} & LCCA_{dp,dc}^{c} \cdot \sum_{y=2024}^{Y} \Delta GHG_{dp}^{c,y} \\ & + \left(ETSDue_{dp,cpp}^{c,y} - ETSDue_{dp,cpp}^{c,2023}\right) \end{aligned} \tag{12}$$

The respective impact on revenues is based on the level of pass-through rate ($PassThrough_{cpt}$ is between 0 (no pass-through) and 1 (all additional costs are passed on) of the effective costs). Since we assume that from 2024 there is no selling of excess allowance or bank thereof and no hedging, the total revenue of a company due to compliance carbon pricing is defined as:

$$\Delta Revenue_{dp,dc,cpp}^{c,y} = PassThrough_{cpt} \cdot \Delta Cost_{dp,dc,cpp}^{c,y} \tag{13}$$

Data and assumptions

Our model framework includes a few major assumptions:

1. We exclude any feedback loops between carbon price levels, technology costs, decarbonisation efforts, production volumes and cost of financing.
2. We assume constant production, market shares and prior financial data based on the 2021–2023 average and even decarbonisation rates across geographies.
3. We do not consider the existing technology mix for any firm, and we assume that the technological decarbonisation mix will be proportionally the same across firms in the same industry.

In addition, we use empirical and best-in-class estimation to populate the model and define a range of scenarios:

Decarbonisation cost-related variables

We include seven technologies to decarbonise, of which six are used in the steel sector and one in the cement sector.

For steel production, we include electrification in the form of electric arc furnaces (EAF), bioenergy, and carbon capture, utilisation and storage (CCUS), all of which are commercially feasible in 2024 ($TR_y = 1$ for $y \geq 2023$). For the three other steel-decarbonising technologies—hydrogen in combination with blast furnaces, hydrogen with EAF and additional fuel shifts to net zero alternatives—we assume commercial viability starting in 2035 ($TR_y = 0$ for $y < 2035$).

In the cement sector, we only cost decarbonisation by CCUS of the last 280 tCO2/t cementitious material of each company's physical intensity, starting in 2030. We were unable to find the cost estimates for other required solutions (for example, clinker substitution or biomass fuels). We assume that the use of non-CCUS solutions is being priced into maintenance and scheduled plant upgrades (an assumption supported by conversation with equity analysts in banking industry). We list details of assumptions by technology and scenario in Table 1. The cost data for technologies 1–6 is taken from a variety of sources[31–33]. Cost for CCUS in Cement is a blend of estimates from IEA[30] and McKinsey[34]. LCCAs are reported as ranges, as the cost remain uncertain, where the ranges are composed of estimates from the difference sources. The expected economic life and the OPEX-share of costs for technologies 1,3,4, and 5, are 30 years and 20%-37%, respectively[35–37]. An OPEX percentage is not found in literature for bioenergy and other fuel shifts, as such, we assume a 20% OPEX and 30 years economic life for consistency in the analysis. For Cement CCUS, technological lifetime is taken as 30 years[38] and the OPEX-share is 40%[39].

The emission reductions per technology are calculated using data from the IEA[40]. The IEA split the cumulative direct emission reduction to the different technologies; their values are scaled to reflect the omission of material efficiency and technology performance as variables from our model. We refer to this as the technology load factor. The product of the relative percentages with the company-specific annual emission reduction yields the technology-specific emission reduction.

For the cement sector, the discount rate is calculated using a weighted average cost of capital, where 40% of capital is debt with 6% interest rate and 60% is equity with a 12% return[24]. This approach gives a discount rate of 8.8% used to derive duration of 10.45. For consistency and comparability, we use the same capital structure and cost, and thus duration, assumptions for the six steel technologies.

The company/technology-specific duration is determined by the firm-specific cost of financing, which is based on the decarbonisation CAPEX relative to the size of debt and equity of the respective company. The overarching assumption is that the companies finance using debt first, and once their debt-to-equity ratio reaches 1, they raise equity and debt in equal amounts. The calculations are based on the averages of cost of debt and cost of equity, tax rate, debt and equity levels of the three years from 2021 to 2023.

The WACC is then used to produce a modified duration that is applied in Eq. (6) to produce a unique LCCA for each company and technology in our sample. Table 1 lists the company-specific LCCA, both pre and post 2035.

Variables related to carbon pricing

We define r for 13 regions: the EU ETS as one standalone region and the 12 NGFS regions. We correct the NGFS region "EU28" to activities out of scope of the separately defined EU ETS region. We treat the EU ETS region differently than other regions, so that we populate all emissions beginning in the year 2008, while variables for the NGFS regions are only applied from 2031. We do this to exhibit the mechanics of a carbon mechanism in compliance with the EU ETS, one of the most mature and well-developed carbon markets.

The EU ETS region. For the EU ETS region, we use data from the EU Transaction Log on an installation basis, aggregating the data up to a firm level. For the aggregation we use SparkChange data and list the installations per company in *Error! Reference source not found*. This enables us to obtain verified emissions data for each company for 2008–2023, and free allowances data for 2008–2025.

In the steel sector, however, such data can be incomplete, as waste gas transfers need to be included; the steel production process creates waste gases as a by-product, which are usually burnt in power plants. The free allowances account for the global warming potential of these waste gases, so

that the allowances have to be transferred to the installation that burns the waste gases and thus emits CO_2. For all three companies in our sample, some of the waste gas is burnt in power plants that are controlled by third parties. We use SparkChange data that track historic carbon allowance transfers between companies, and then add these volumes to the respective emissions per company and year. However, that dataset only covers transfers until the year 2020. We use the average ratio of waste gas transfers and emissions for 2018–2020 to extrapolate waste gas transfers for 2021 to 2050.

Free allowances in the EU ETS for the years 2026 and beyond are not yet published by the EU. However, the cap development in the EU ETS and the free allowance rules allow some approximation of such allocation development until 2030. We use data from SparkChange through 2030, and extrapolate the trend of 2027–2030 in a linear way to reduce free allowances to zero by 2034; this is in line with the EU's ambition to phase out any free allowances by 2034.

The emissions data for 2024 to 2050 depend on the decarbonisation scenario *dp*:

In the 'static emissions' scenario, the EU ETS emissions of a company are the average of its 2021–2023 emissions:

$$GHG_{Y,c,EUETS,flat\ emissions} = \frac{\sum_{y=2021}^{2023} GHG_{y,c,EUETS,flat\ emissions}}{3} for\ Y > 2023$$

In the 'own forecast' scenario, the EU ETS emissions develop in line with companies' GHG reductions globally $\sum_i \Delta GHG_{i,y}$ for $y > 2023$.

For historic surplus sales of carbon allowances, we use data from SparkChange which scans financial reports and EUA account transfers in the EU Transaction log to triangulate EUA sales. We assume no sales of EUAs for 2024 or later.

The price for the EUETS region is the average annual front-year December EUA futures contract on ICE Exchange for $y < 2024$. For the years 2024 and beyond, we assume two different carbon price pathways in US$/tonne as detailed in Table 1D. The data are based on the NGFS scenarios for the EU-28 region in the model REMIND-MAgPIE 3.2–4.6, calibrated to 2020-2024 levels.

All other regions. Until 2031, only carbon pricing in the EU ETS is considered and all variables for other regions are zero. That changes in year 2031, when we start to include all emissions globally of the companies in the carbon pricing model.

For emissions, we break down the reported scope 1 emissions by country using revenue by geography to calculate the emissions priced per region *r*. For the region EU-28, we deduce region EUETS emissions, so that this region now only represents companies' emissions outside of the scope of the EU ETS.

For allocations, we use the EUETS allocation trajectory as defined in Directive 2003/87/EC for all European emissions. For all other regions, we assume 90% free allowances in 2031, with a linear decline to 0% by 2040

We assume no selling of surplus allowances or inventory in these regions (or advance hedging), as companies receive, at best, exactly the amount of allowances needed to comply with the systems.

The price for each region is taken from the NGFS REMIND-MAgPIE model, except for the EU-28 (excl EUETS) and No-EU28 Europe prices, which are set as $p_{EU-28exl\ EUETS} = p_{Non-EU28Europe} = p_{EUETS}$

Linking of EU ETS installations to companies

The underlying data used on the EU ETS is based on verified emissions and allocation data from the European Commission. However, this data is published on installation leve—not on company. SparkChange has mapped the installations to its ultimate parent with a proprietary algorithm. Table 3 presents the mapping of the individual Operator Holding IDs in the EU Transaction Log to the ultimate parent. The details for each installation in the EU Transaction Log can be accessed at https://union-registry-data.ec.europa.eu/report/eu-registry-operator-accounts.

Companies contact

We contacted all companies analysed in the paper with a request for comments. SSAB did not agree with our findings, arguing that our assumption about the decarbonisation technology mix does not reflect the company's decarbonisation strategy (SSAB will not be using CCUS), and as

Table 3 | Mapping of European Union Transaction Log (EUTL) installations to ultimate parent company

Parent Company	Unique registry IDs of EU ETS installations
ArcelorMittal	5626, 9254, 9255, 9256, 9257, 9258, 9259, 9260, 9261, 9262, 9264, 9265, 9266, 9267, 9268, 9289, 10710, 10866, 10935, 10937, 11376, 16113, 16114, 17932, 17933, 17934, 17935, 17936, 19237, 19238, 22113, 22114, 23918, 23932, 48873, 62334, 62335, 62381, 62382, 62383, 62384, 62385, 62386, 62437, 92652, 92656, 92847, 92857, 92877, 92881, 93251, 93257, 93270, 93271, 93404, 93408, 93411, 93436, 93443, 93446, 93451, 93455, 93536, 94048, 94172, 94174, 94175, 94176, 94177, 94178, 94179, 94180, 94181, 94183, 94184, 94185, 94261, 94362, 94399, 94415, 94667, 94803, 94838, 95062, 95066, 95098, 95450, 96452, 98404, 98405, 98603, 98749, 98798, 99135, 99157, 99449, 99664, 99666, 103362, 103363, 103364, 103473, 103480, 104203, 104205, 104393, 104423, 104948, 105259, 105266, 105381, 105429, 105437, 105438, 105456, 105470, 107706, 108102, 108141, 109272, 109273, 109610, 109611, 110087, 110094, 110795, 111112, 111452, 111757, 111782, 111783, 112909, 1547625
CEMEX	4509, 4520, 4524, 7092, 7093, 7094, 7095, 7096, 7097, 7098, 14205, 19224, 19225, 92883, 92914, 96519, 96990, 96992, 96996, 98459, 98483, 98878, 98923, 99238, 99576, 105524, 110700
HeidelbergCement	2418, 2446, 2449, 2819, 2820, 2821, 2822, 2823, 4947, 4948, 4952, 5481, 5665, 5667, 5849, 5850, 5851, 5940, 6147, 6966, 6969, 8360, 9809, 9832, 9833, 9979, 9980, 9981, 10907, 10908, 10910, 14115, 18546, 48886, 48887, 48888, 59095, 59785, 62077, 62078, 83126, 83127, 83128, 83223, 83224, 83225, 83226, 83227, 83228, 83921, 83922, 84005, 91208, 91209, 91210, 92001, 93385, 94077, 94079, 94081, 94104, 94631, 94713, 94941, 95265, 95409, 95412, 95451, 95579, 95603, 95608, 95658, 96488, 96489, 96491, 98272, 98274, 98275, 98493, 99045, 99144, 99678, 99679, 99680, 101925, 101926, 102384, 102392, 102401, 102406, 102414, 102423, 102431, 102437, 102447, 102457, 102463, 102468, 102475, 102483, 102488, 102494, 102495, 103239, 103242, 103412, 103413, 103414, 103415, 103416, 103417, 103418, 103419, 103420, 103444, 103445, 103446, 103618, 103626, 103630, 103634, 103640, 103647, 103653, 103658, 103661, 103671, 103704, 103711, 105836, 106013, 114608, 3130625, 90809
Holcim	5350, 5351, 5352, 5353, 5354, 5787, 5788, 6240, 6242, 7276, 7277, 7278, 7439, 7440, 7441, 7442, 7443, 7444, 8327, 8328, 8329, 8332, 8334, 8335, 8336, 8337, 8338, 8339, 8340, 8616, 11357, 13180, 13181, 17600, 17601, 17603, 19904, 48984, 48985, 59740, 59741, 74723, 91995, 91997, 92339, 92920, 92923, 93735, 93737, 94309, 94372, 94396, 94497, 94545, 94773, 94932, 94938, 95068, 95144, 95231, 95275, 95321, 95426, 95495, 95610, 96410, 96766, 96768, 98559, 98701, 98833, 99044, 99332, 99461, 99473, 99566, 99754, 99755, 101536, 101571, 102239, 102241, 103716, 103724, 103731, 105487, 105490, 105509, 105514, 105791, 105792, 110800, 111475, 111537, 111539, 111540, 111541, 113380, 113381, 113382, 115896
SSAB AB	1778, 1779, 2285, 2393, 2401, 19649, 91075, 91183, 91186, 91447, 100097, 100098, 108122, 111640
Tata Steel	1324, 4215, 4231, 4253, 4306, 4427, 4571, 4572, 4575, 4874, 94264, 96794, 97884, 97890, 97896, 97906, 97912, 97921, 101086, 106325, 106326, 110212, 110371, 110373, 111435, 117406

Source: SparkChange CarbonAlpha database.

a result, our CAPEX estimate for the company is too high. The other companies did not comment.

Data availability

The datasets generated and analysed in this study are available in the Helix repository. https://doi.org/10.82186/cnvn6-f2w85.

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Author contributions

A.O. and J.A. conceived and directed the project. A.O., J.A. and J.S. developed the methodology and performed the modelling and analysis. A.T. conducted the literature review and contributed to the conceptual framing of the study. B.B. provided financial analysis input and contributed to the interpretation of results. All authors contributed to the discussion of the findings and to the writing and revision of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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