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Corporate carbon overhang: Valuing corporate exposure to future carbon costs

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ABSTRACT

This study develops a forward-looking valuation framework to quantify firm-level exposure to future carbon costs. We introduce the Carbon Overhang (COH) metric, defined as the present value of future carbon costs based on firm-level emissions projections and jurisdiction-specific carbon prices. Applying this framework to U.S.-listed firms, we estimate a market-level COH of $2.4 to $4.1 trillion—equivalent to 5 % to 9 % of total market cap. The distribution of COH is highly concentrated, with the top 25 firms—mainly utilities and energy companies—accounting for over half of the total. Still, we find substantial variation within sectors, driven by differences in operational structure and emissions geography. Accounting for carbon cost pass-through reallocates a material share of COH from regulated utilities to downstream customers, with 55 % absorbed by public firms and 45 % by the broader economy. Importantly, even under the most ambitious policy scenario, existing and expected carbon pricing mechanisms would internalize less than one third of the societal damages from corporate emissions. Overall, our framework underscores the importance of forward-looking and location-specific emissions and carbon price forecasts as essential inputs for integrating carbon risk into corporate financial analysis and valuation.

1. Introduction

Carbon pricing—through emissions trading schemes, carbon taxes, and fossil fuel taxes—has emerged as a central policy tool in the global response to climate change. By attaching a financial cost to greenhouse gas (GHG) emissions, these mechanisms convert environmental externalities into direct cash flow obligations for firms. The scale of these liabilities depends on the interaction between firm-level emissions and jurisdiction-specific carbon prices, which vary substantially across geographies, sectors, and regulatory systems. As more jurisdictions adopt or strengthen carbon pricing regimes, the financial exposure of firms to climate policy is becoming an increasingly salient driver of long-term firm value.

Yet despite its growing importance, the financial liability associated with future carbon pricing remains underexplored in capital markets research. Existing approaches often rely on backward-looking emissions disclosures or model-based estimates, which fail to account for the forward-looking and geographically specific nature of regulatory carbon pricing. A firm's carbon liability depends not only on how much it emits, but also where and when it emits, and how carbon prices evolve under future policy scenarios.

This paper addresses that gap by introducing a forward-looking valuation framework to quantify the present value of firm-level carbon liabilities under plausible carbon pricing scenarios. Our objective is to estimate a company's Carbon Overhang (COH), which captures the present value of its expected future carbon costs under current and anticipated carbon pricing mechanisms. Our approach integrates firm-specific projections of emissions and jurisdiction-specific carbon prices with estimates of each firm's cost of equity capital to compute a discounted stream of future carbon costs. The resulting COH metric offers a new perspective on assessing climate transition risk at the firm level.

We ask three main questions: (1) How large is the aggregate carbon liability facing publicly listed U.S. firms under plausible carbon price scenarios? (2) How is this liability distributed across and within sectors? (3) How much of the total societal cost of corporate emissions is currently expected to be internalized by firms through regulatory carbon pricing, and how much is expected to remain an unpriced externality?

We apply our valuation framework to a representative sample of the U.S. stock market, covering approximately $48.23 trillion in market capitalization and 2.28 gigatons of projected 2024 emissions, including

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Scope 1 (direct emissions from company operations) and Scope 2 (indirect emissions from purchased energy). Using firm-level emissions forecasts from MSCI and firm-specific carbon price forecasts from S&P Global Sustainable1, we estimate carbon overhang values under three policy scenarios—low, medium, and high—reflecting different assumptions about the future trajectory of carbon pricing. Our baseline market-level COH estimates range from $2.41 trillion under the low scenario to $3.58 trillion under the medium scenario and $4.14 trillion under the high scenario. These figures represent 5.0 %, 7.4 %, and 8.6 % of the sample's total market capitalization, respectively. Across scenarios, we find that 30 % of the total COH is expected to accrue by 2030, 60 % by 2040, and 75 % by 2050, with the remaining 25 % accruing beyond 2050.

Regulated utilities often pass a substantial share of their carbon costs to downstream customers through higher energy prices. Empirical research in energy economics finds pass-through rates of roughly 80 % (e.g., Fabra and Reguant, 2014), and consistent with the methodology of S&P Global Sustainable1, we adopt this benchmark rate in our analysis of Scope 2 emissions. To capture firms' indirect carbon cost exposure, we construct an adjusted COH metric that (a) reduces regulated utilities' Scope 1 carbon costs by this 80 % pass-through rate and (b) assigns the corresponding Scope 2 costs to other firms.

At an 80 % pass-through rate, regulated utilities' COH falls from $1.22 trillion to $267 billion—a $954 billion decrease, which represents a 78 % reduction in regulated utilities' COH (slightly less than the pass-through rate because of the carbon cost of their limited Scope 2 emissions). At the same time, the COH of other firms rises from $2.36 trillion to $2.88 trillion, an increase of $518 billion. The in-sample net change is a $436 billion decline in market-level COH, from $3.58 trillion to $3.15 trillion. This implies that roughly 55 % of the costs passed through by regulated utilities are absorbed by public firms in our sample—concentrated in Materials and Energy, followed by Consumer Discretionary and Consumer Staples—while the remaining 45 % is borne by the broader economy, including private businesses, households, and the public sector.

Overall, adjusting for the pass-through of carbon costs substantially reallocates COH exposure from regulated utilities to other firms and shifts a significant share of the liability to electricity consumers outside the sample, including private businesses, households, and the public sector. While the macro-level carbon liability is unchanged, sensitivity tests varying the pass-through rate between 0 % and 100 % confirm that this assumption materially affects both the cross-sector distribution and the in-sample aggregate COH.

The COH distribution is highly concentrated. Across price scenarios, emissions-intensive sectors—Utilities, Energy, Materials, and Industrials—account for nearly 90 % of total COH, despite representing only 18 % of total market capitalization. In addition to large cross-sector differences, we observe substantial variation within sectors. While sector fixed effects explain 30 % of the cross-sectional heterogeneity in COH-to-market-cap ratios, the remaining 70 % arises from differences among firms within the same sector. This breakdown highlights the importance of both sector-wide and firm-specific factors—such as emissions geography, decarbonization targets, and operational structure—in shaping the firm-specific valuation of carbon liabilities.

The concentration of COH is particularly stark at the firm level. The top 100 firms ranked by COH account for 86 % of the total, with just the top 25 firms—including utilities such as Southern Company and energy companies like ExxonMobil and Marathon Petroleum—responsible for more than half of the aggregate COH. The COH concentration mirrors the skewed distribution of corporate emissions and underscores that the path to decarbonization runs through carbon-intensive sectors—especially Utilities and Energy, followed by Materials and Industrials.

In a related study, Pástor et al. (2024) quantify the *societal carbon burden*—the present value of future societal damages from corporate emissions—by multiplying projected emissions by the *Social Cost of Carbon* (SCC), an estimate of the economic harm from emitting one additional ton of CO_2. Unlike regulatory carbon prices set through emissions trading systems, carbon taxes, and fossil fuel taxes, the SCC reflects the full social cost of emissions, including impacts on health, agriculture, infrastructure, and ecosystems. While appropriate for measuring societal damages, the SCC substantially exceeds prevailing and projected regulatory carbon prices: the EPA's nominal SCC for 2025 is approximately $236 per ton, nearly 130 % higher than even the most ambitious policy scenarios. As a result, their metric—developed from the perspective of social planners—captures the *gross externality* of corporate emissions but does not indicate how much of these societal damages will be internalized by firms through existing or anticipated carbon pricing mechanisms.

By contrast, our *corporate carbon overhang (COH)* metric is developed from the perspective of investors and capital markets. It quantifies the present value of future carbon costs that firms are expected to incur under current and projected carbon pricing regimes. Put differently, the COH metric therefore represents the internalized portion of the societal carbon burden under plausible market assumptions.

Together, these two metrics allow us to distinguish between the *gross externality* (societal carbon burden) and the *net externality* (the share of societal damages not expected to be internalized into firms' financials). We further define the *internalization rate*—the fraction of societal carbon damages reflected in firms' expected carbon costs—and its complement, the *internalization gap*, which measures the residual societal burden borne by society rather than by firms. To ensure comparability between the societal carbon burden and the COH metric, we re-estimate the corporate carbon overhang using the social discount rate rather than firm-specific costs of equity, so that when projected carbon prices equal the SCC, the internalization rate converges to 100 % and the gap to 0 %.

Our evidence shows that even under the most ambitious policy scenarios, prevailing and anticipated carbon pricing mechanisms are expected to internalize less than one third of the societal damages from corporate emissions. In the high-price scenario, total COH equals roughly 30 % of the societal carbon burden, implying an internalization gap of about 70 % for the U.S. stock market. This gap underscores the need for carbon pricing policies that more effectively align market incentives with societal costs. Although SCC estimates have risen over time (e.g., Tol, 2023), actual and projected regulatory carbon prices remain well below these levels, leaving a substantial share of corporate emissions unpriced.

In sum, our paper develops a valuation framework for incorporating carbon liabilities into corporate valuation. By estimating forward-looking, firm-level carbon liabilities and comparing them to the societal cost of emissions, we quantify the portion of carbon externalities likely to be internalized by firms. The COH metric captures the present value of expected carbon pricing exposure under plausible policy scenarios. Each input to the firm-level COH calculation—emissions forecasts, carbon price projections, and the cost of equity capital—carries inherent uncertainty. We supplement our baseline estimates with sensitivity analyses that bound the COH under reasonable alternative pathways and, where possible, sign the direction of potential estimation errors. Nonetheless, the exact precision of our estimates remains unknown, as the valuation of future carbon costs is not a precise exercise. As carbon pricing regimes continue to expand, the ability to estimate and benchmark future carbon costs will become increasingly important for corporate strategy, capital allocation, and regulatory oversight.

Building on this framework, our study makes several contributions. First, we develop a forward-looking and tractable approach to estimating carbon-related financial risk by integrating emissions forecasts, carbon price trajectories, and firm-specific discount rates. The resulting COH metric provides a new tool for incorporating carbon liabilities into firm valuation, portfolio management, and regulatory oversight. Second, we emphasize the critical role of emissions geography, as carbon pricing varies by jurisdiction. A firm's carbon liability is shaped not just by the volume of its emissions, but also by the timing, location, and future trajectory of regulatory carbon pricing. Third, we document substantial heterogeneity in COH both across and within sectors, reinforcing the importance of firm-level analysis of emissions geography, decarbonization targets, and operational structure.

Our findings have implications for asset pricing, risk management, and climate policy, offering investors, managers, and policymakers a framework for incorporating forward-looking carbon costs into corporate valuation. For investors, the COH metric provides a decision-relevant measure of long-term carbon risk to inform portfolio allocation and shareholder engagement. For corporate managers, a high COH may signal the need for more aggressive decarbonization strategies or operational restructuring. Our framework underscores the importance of accurate, forward-looking, and location-specific emissions and actual carbon price forecasts as essential inputs for integrating carbon risk into financial analysis and valuation.

Policymakers can facilitate this integration by standardizing disclosure methodologies and requiring firms to report the geographic distribution of emissions, which is critical for forecasting when and where companies emit—and thus for estimating corporate carbon liabilities. Making firm-level COH estimates publicly available—and enabling peer comparisons—can further enhance transparency around firms' exposure to future carbon costs and create market-based incentives for emissions reduction. Greater transparency, in turn, can amplify pressure to decarbonize, especially as carbon pricing regimes expand. For such market discipline to be effective, however, emissions data must be credible, verifiable, and subject to independent assurance. Regulators around the globe and standard setters—such as the International Sustainability Standards Board (ISSB) and the International Auditing and Assurance Standards Board (IAASB)—can play a critical role by harmonizing carbon disclosure requirements, advancing assurance standards, and supporting efforts to enhance the quality, consistency, and comparability of emissions data. Applying assurance standards similar to those used for financial statements is essential to build trust in the relevance and reliability of corporate carbon data.

Several studies examine how capital markets price emissions, including Matsumura et al. (2014); Bolton and Kacperczyk (2021, 2023); Baboukardos et al. (2022); Hsu et al. (2023); Atilgan et al. (2024); Aswani et al. (2024); Perdichizzi et al. (2024); and Zhang (2025). Ilhan et al. (2021) analyze downside risk in carbon-intensive firms, while Dutta et al. (2025a, 2025b) focus on carbon-efficient portfolio construction. Pástor et al. (2022) link past green asset outperformance to heightened environmental concerns, implying potential underperformance ahead. Greenstone et al. (2023) estimate the societal cost of current emissions, though unlike Pástor et al. (2024), they do not incorporate future emissions. Related work on investor behavior and ESG performance includes Choi et al. (2020); Krueger et al. (2020); Fahmy (2022); Pedersen et al. (2021); Atta-Darkua et al. (2023); and Ahn et al. (2024).

Relative to this growing body of work, our paper introduces a new valuation framework that quantifies both the priced and unpriced components of carbon exposure under evolving policy scenarios.

2. Valuation framework

We develop and implement a forward-looking carbon valuation metric, the *Carbon Overhang* (COH), to quantify the present value of a firm's expected future carbon costs. A key feature of our framework is the use of forward-looking projections of firm-level carbon emissions and firm-specific carbon prices. These projected carbon prices estimate the actual financial liabilities that firms are likely to face under emerging carbon pricing regimes worldwide. These regimes include emissions trading schemes, carbon taxes, and fossil fuel taxes, and they reflect policy developments as well as firm-level exposure based on sector characteristics and the geographic distribution of a firm's operations and emissions.

Formally, we define firm i's annual carbon cost in year t, denoted as CC_{it}, as the product of its projected GHG emissions (GHG_{it}), measured in metric tons of carbon dioxide equivalent (CO_2e), and the projected carbon price per metric ton of emissions (CP_{it}):

$$CC_{it} = GHG_{it} \times CP_{it}.$$

The carbon overhang for firm i as of the end of year t is defined as the present value of future carbon costs:

$$COH_{it} = \sum_{\tau=1}^{\infty} \frac{CC_{it+\tau}}{(1+r_i)^{\tau}},$$

where r_i is the firm's cost of equity capital, which we use to discount future carbon liabilities. This rate appropriately reflects the required return for shareholders and serves as the relevant discount rate for valuing firm-specific carbon exposures.

To implement this framework empirically, we use annual forecasts of carbon emissions and carbon prices from 2024 through 2050, all available as of the end of 2023.[1] Beyond the terminal forecast year 2050, we assume that emissions grow at a constant rate g and carbon prices grow at a rate ρ, implying that annual carbon costs grow at the compound annual growth rate:

$$(1+\rho)(1+g) - 1 = \rho + g + \rho g.$$

Using the standard constant-growth perpetuity formula, the present value at the end of 2050 of all future carbon costs beyond that year, which we refer to as terminal value, is given by:

$$\textit{Terminal value} = \frac{CC_{i,2050}(1+\rho+g+\rho g)}{r_i - (\rho+g+\rho g)},$$

where $CC_{i,2050}$ is firm i's projected carbon cost in 2050. Accordingly, the carbon overhang for firm i as of the end of 2023 is given by:

$$COH_{i,2023} = \sum_{t=1}^{27} \frac{CC_{i,2023+t}}{(1+r_i)^t} + \frac{1}{(1+r_i)^{27}} \bullet \frac{CC_{i,2050}(1+\rho+g+\rho g)}{r_i - (\rho+g+\rho g)}.$$

The first term represents the discounted value of projected annual carbon costs from 2024 to 2050. The second term captures the discounted terminal value of carbon costs beyond 2050. To obtain a relative measure of carbon liability exposure, we scale the estimated carbon overhang by the firm's market cap.

A key modeling decision involves determining which types of emissions to include when estimating carbon costs. GHG emissions are typically classified into three categories: Scope 1 emissions are direct emissions from sources owned or controlled by the firm (e.g., on-site fuel combustion); Scope 2 emissions are indirect emissions from the generation of purchased electricity, steam, heating, and cooling; and Scope 3 emissions encompass all other indirect emissions that occur in a company's value chain, including upstream suppliers and downstream customers. Carbon pricing systems—whether based on taxes or emissions trading—typically apply only to Scope 1 emissions. As such, rising carbon prices have immediate cash flow implications for firms subject to regulatory pricing of GHG emissions from sources they own or control.

Consequently, our baseline estimates focus on Scope 1 emissions, which are directly targeted by carbon pricing mechanisms. However, we recognize that firms may also face indirect financial exposure due to pass-through carbon cost from upstream energy providers to downstream customers. In particular, regulated utilities may recover their carbon costs by raising energy prices. Empirical research in energy

[1] Section 3 describes our data sources and empirical implementation in detail.

economics finds that regulated utilities often pass through a substantial share of carbon costs to end users, with micro-level estimates indicating pass-through rates of around 80 % (e.g., Fabra and Reguant, 2014).

To capture these indirect effects, we construct an adjusted measure of carbon overhang that incorporates the estimated pass-through costs of Scope 2 emissions. Specifically, we (a) reduce the Scope 1 carbon cost of regulated utilities by the projected pass-through rate, and (b) add the corresponding pass-through cost of Scope 2 emissions to each firm's total carbon cost. These adjustments ensure that our estimates consistently capture both direct and indirect exposure to rising carbon prices without double counting.

In principle, firms may also face financial exposure from upstream Scope 3 emissions—those generated in a company's supply chain prior to its own operations, such as emissions from the production and transportation of purchased goods and services. These emissions could impact cash flows if suppliers attempt to recover their own carbon costs by raising prices charged to downstream firms.

Despite this theoretical exposure, our analysis focuses solely on Scope 1 emissions and the portion of Scope 2 emissions tied to the expected pass-through of carbon costs from regulated utilities. We exclude Scope 3 emissions for several reasons. First, outside of regulated sectors where prices are typically set on a cost-plus basis, it is uncertain whether upstream suppliers can effectively pass carbon costs downstream, and to what extent. The pricing dynamics become even more complex when downstream firms attempt to pass along these costs themselves, making the ultimate financial impact difficult to assess. In addition, empirical evidence suggests that investors do not currently assign significant weight to Scope 3 emissions in equity pricing, largely due to challenges in measurement and a lack of consistent disclosure across firms (e.g., Perdichizzi et al., 2024).

2.1. Sample construction

We construct our sample using data as of December 31, 2023. From S&P Capital IQ, we identify U.S.-incorporated companies with non-missing values for International Securities Identification Number (ISIN), Global Industry Classification Standard (GICS) sector, Trucost primary business activity, market value of equity, book value of equity, and total assets. We merge this dataset with MSCI One to obtain firm-level forecasts of Scope 1 and Scope 2 emissions from 2024 to 2050, and with the S&P Global Sustainable1 database to obtain firm-level forecasts of carbon prices per metric ton of CO_2e emissions over the same horizon. The merged sample includes 2420 U.S.-listed firms—a representative sample of the U.S. stock market—with a total market capitalization of $48.23 trillion as of the end of 2023, equal to 96.6 % of the $49.91 trillion aggregate market cap of the S&P Total Market Index, the broadest S&P index of U.S. stocks.

Panel A of Table 1 reports the empirical distribution of firms across sectors. Among the 2420 firms in our sample, we observe an aggregate market cap of approximately $48.23 trillion and total emissions of around 2.28 gigatons (Gt), comprising 1.91 Gt (84 %) in Scope 1 emissions and 0.37 Gt (16 %) in Scope 2 emissions. We group companies into high carbon intensity (brown) and low carbon intensity (green) sectors. Brown sectors include Utilities, Energy, Materials, and Industrials, while Green sectors include Consumer Discretionary, Consumer Staples, Technology, Telecom, Health Care, Financials, and Real Estate.

Brown sector firms represent 27 % of the sample by count and 18 % of total market capitalization, or about $8.6 trillion. Despite their smaller share of market value, they contribute disproportionately to emissions—producing 91 % of Scope 1 emissions and 53 % of Scope 2. Combining Scope 1 and 2, brown sector firms account for 84 % of total emissions, while green sector firms generate the remaining 16 %. Within brown sectors, Utilities account for 2.2 % of market cap and 34 % of total emissions; Energy accounts for 3.9 % of market cap and 23 % of emissions; Materials account for 2.2 % of market cap and 13.8 % of emissions; and Industrials account for 9.4 % of market cap and 13.4 % of emissions.

Panel B of Table 1 reports the cross-sectional mean (μ) and standard deviation (σ) of the firm-level domestic emissions share, defined as each firm's U.S.-based emissions divided by its global emissions. We compute the share of emissions generated within the U.S. for each firm and summarize the distribution across all 2420 firms in our sample. On average, firms generate 83.5 % of their combined Scope 1 and 2 emissions domestically, with a standard deviation of 25 %, indicating considerable heterogeneity in emissions geography.

This variation is evident both across and within sectors. For example, firms in the Materials sector have an average domestic share of 65 % ($\sigma = 29$ %), reflecting a mix of U.S.-focused and globally-oriented firms. In contrast, utilities have a much higher average of 97.5 % ($\sigma = 9.7$ %), consistent with their primarily domestic operations. These statistics underscore the importance of accounting for both cross-sector differences and within-sector variation in the geographic distribution of emissions when evaluating firm-level exposure to carbon pricing.

3. Empirical implementation

3.1. Carbon overhang inputs

Our corporate carbon overhang metric relies on three key firm-specific inputs: carbon emission forecasts, carbon price forecasts, and the cost of equity capital. Next, we describe each valuation input in detail.

3.1.1. Carbon emission forecasts

We use annual firm-level forecasts of Scope 1 and Scope 2 CO_2e emissions from the MSCI ESG Manager, covering the forecast horizon from 2024 to 2050. All forecasts are as of December 31, 2023. These forward-looking data are essential for estimating firm-level carbon liabilities and assessing exposure to future carbon pricing mechanisms. The MSCI emissions forecasts are widely used by institutional investors, asset managers, and financial analysts to evaluate climate-related financial risks and net-zero alignment. These projections are integrated into climate risk tools and scenario analysis platforms used for portfolio construction, stress testing, and regulatory compliance. The dataset is also used to assess climate value-at-risk and transition readiness in investment strategies focused on decarbonization. Given its methodological rigor and increasing adoption we consider the MSCI emissions forecast dataset to be a best-in-class source for estimating carbon overhang at the firm level. Notably, it was also used by Pástor et al. (2024) in their analysis of the social costs of future corporate carbon emissions.[2]

MSCI projects future emissions based on firms' stated decarbonization targets, adjusted for credibility (MSCI, 2024). Targets are collected from public sources including annual and sustainability reports, CDP submissions, regulatory filings, Science Based Target Initiative (SBTi) disclosures, and investor presentations. MSCI applies a credibility assessment that adjusts projected emissions to reflect the likelihood of achieving them, considering the presence of interim targets, external validation, firms' track records of meeting past commitments, and the alignment of current trajectories with stated goals. Less credible targets lead to higher projected emissions, while more credible targets are modeled closer to the stated pathway. For firms without

[2] We also obtained emissions forecasts from S&P Global Sustainable1, but the dataset only covers 2024 to 2030 and combines Scope 1 and 2 emissions. We therefore rely on MSCI forecasts, which span 2024–2050 and distinguish between direct (Scope 1) and indirect (Scope 2) emissions. In a comparison over the overlapping forecast horizon, we find that projected aggregate emissions differ by just 0.5 % in 2024, widening to about 5 % by 2030. This is consistent with prior research showing high—but imperfect—correlation across emissions data providers (e.g., Busch et al., 2022).

Table 1
Empirical distributions.

Panel A: Sector distribution

	OBS	MV ($TN)	S1 (Mt)	S2 (Mt)	S1 + 2 (Mt)	%OBS	%MV	%S1	%S2	%S1 + 2
Real Estate	153	$1.41	2.98	12.7	15.7	6.3 %	2.9 %	0.2 %	3.4 %	0.7 %
Health Care	382	$5.72	9.07	14.8	23.9	15.8 %	11.9 %	0.5 %	4.0 %	1.0 %
Telecom	106	$4.27	3.66	20.5	24.2	4.4 %	8.9 %	0.2 %	5.5 %	1.1 %
Technology	312	$13.00	9.08	30.0	39.0	12.9 %	27.0 %	0.5 %	8.0 %	1.7 %
Financials	402	$6.62	56.20	13.3	69.5	16.6 %	13.7 %	2.9%	3.6 %	3.1 %
Discretionary	308	$5.62	35.10	42.7	77.8	12.7 %	11.7 %	1.8 %	11.5 %	3.4 %
Staples	101	$3.00	60.89	42.5	103.4	4.2 %	6.2 %	3.2 %	11.4 %	4.5 %
Industrials	374	$4.55	277.56	28.6	306.2	15.5 %	9.4 %	14.6 %	7.7 %	13.4 %
Materials	105	$1.08	233.64	79.7	313.3	4.3 %	2.2 %	12.3 %	21.4 %	13.8 %
Energy	108	$1.87	453.43	70.4	523.8	4.5 %	3.9%	23.8 %	18.9 %	23.0 %
Utilities	69	$1.08	763.71	17.0	780.7	2.9%	2.2 %	40.1 %	4.6 %	34.3 %
Green Sectors	1764	39.64	176.98	176	353	73 %	82 %	9 %	47 %	16 %
Brown Sectors	656	8.59	1728.34	196	1924	27 %	18 %	91 %	53 %	84 %
Market	2420	$48.23	1905.32	372.19	2277.51	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %

Panel B: Geographic distribution

	OBS	% U.S. Scope 1 GHG		% U.S. Scope 2 GHG		% U.S. Scope 1 + 2 GHG	
		μ	σ	μ	σ	μ	σ
Materials	105	65.1 %	29.0 %	64.7 %	29.6 %	65.1 %	28.6 %
Technology	312	72.0 %	30.2 %	67.6 %	33.1 %	69.1 %	31.5 %
Staples	101	79.2 %	27.4 %	78.5 %	27.2 %	78.6 %	27.4 %
Industrials	374	79.0 %	23.6 %	79.1 %	23.4 %	78.9 %	23.1 %
Telecom	106	82.1 %	25.1 %	82.4 %	24.5 %	82.3 %	24.7 %
Discretionary	308	82.8 %	25.6 %	82.3 %	26.6 %	82.4 %	26.3 %
Energy	108	84.7 %	26.6 %	85.0 %	25.9 %	84.8 %	26.4 %
Health Care	382	89.4 %	20.5 %	89.1 %	20.3 %	89.1 %	20.3 %
Financials	402	93.3 %	16.1 %	93.6 %	15.6 %	93.5 %	15.6 %
Real Estate	153	94.6 %	15.9 %	95.5 %	14.4 %	95.3 %	14.4 %
Utilities	69	97.4 %	9.9 %	97.6 %	9.7 %	97.5 %	9.7 %
Green Sectors	1764	85.5 %	24.2 %	84.7 %	25.4 %	85.0 %	24.8 %
Brown Sectors	656	79.7 %	25.4 %	79.7 %	25.4 %	79.6 %	25.1 %
Market	2420	83.9%	24.7 %	83.3 %	25.5 %	83.5 %	25.0 %

Note: TN denotes trillions of U.S. dollars; Mt refers to megatons of emissions. S1 and S2 represent Scope 1 and Scope 2 emissions, respectively.
This table presents the distribution of sample firms across sectors, summarizing market capitalization, Scope 1 and 2 emissions, and the share of domestic versus global emissions. Brown sectors include Utilities, Energy, Materials, and Industrials, while Green sectors include Consumer Discretionary, Consumer Staples, Information Technology, Telecom, Health Care, Financials, and Real Estate. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

targets, MSCI applies sector- and region-specific average pathways based on historical global emissions trends.[3]

Panel A of Fig. 1 shows aggregate emission forecasts from 2024 to 2050 at the market level. Aggregate Scope 1 and 2 emissions, combined, are estimated at 2.28 Gt in 2024 and are projected to decline to 1.65 Gt by 2050. Panel B of Fig. 1 breaks down aggregate total emissions and shows that Scope 1emissions are projected to account for about 84 % of total emissions throughout the forecast horizon from 2024 to 2050, while Scope 2 emissions account for the remaining 16 %.

Panels C and D of Fig. 1 disaggregate total Scope 1 and 2 emissions by sector grouping. They show that firms in brown sectors contribute 84 % of total emissions in 2024, and their share is projected to remain as high as 81 % by 2050. This underscores that the path to decarbonization runs through carbon-intensive sectors—particularly Utilities and Energy, followed by Materials and Industrials. While the projected decline in total emissions is consistent with ongoing decarbonization efforts, the breakdown highlights the outsized role of brown sectors in these efforts, as they are projected to account for nearly 93 % of the total emissions reduction between 2024 and 2050.[4]

To estimate the long-term growth in emissions, we compute the compound annual growth rate of direct emissions over the decade from 2040 to 2050, which is − 0.99%, and use this as our long-run assumption for emissions growth, corresponding to the parameter g in the terminal value component of the carbon overhang metric. We apply the same long-term growth rate to both direct (Scope 1) and indirect (Scope 2) emissions, as their long-term trajectories are shaped by similar underlying drivers, including energy system transitions, regulatory developments, and technological advancements.

3.1.2. Carbon price forecasts

3.1.2.1. Carbon pricing mechanisms. Carbon pricing—through emissions trading schemes, carbon taxes, and fossil fuel taxes—creates direct cash flow exposure for firms subject to these policies. These mechanisms convert carbon emissions into financial costs, with the magnitude determined by both the carbon price and the firm's emissions footprint.

Emissions Trading Systems (ETS), also known as cap-and trade-programs, impose a regulatory limit on total GHG emissions and issue a fixed number of allowances. Firms that emit less than their allowance

[3] In our sample of U.S.-listed firms, 31 % disclose emissions targets. Because these firms tend to be larger, they account for about 80 % of aggregate emissions in 2024, the starting year of the forecast horizon. The remaining 69 % of firms without targets contribute only 20 % of emissions. As a result, MSCI's target-based methodology governs the majority of projected emissions, while the default pathway applies to a relatively small share.

[4] This result is consistent with Cohen et al. (2024), who show that oil, gas, and energy-producing firms—despite having lower ESG scores—are key contributors to green innovation through high-quality, first-mover green patents.

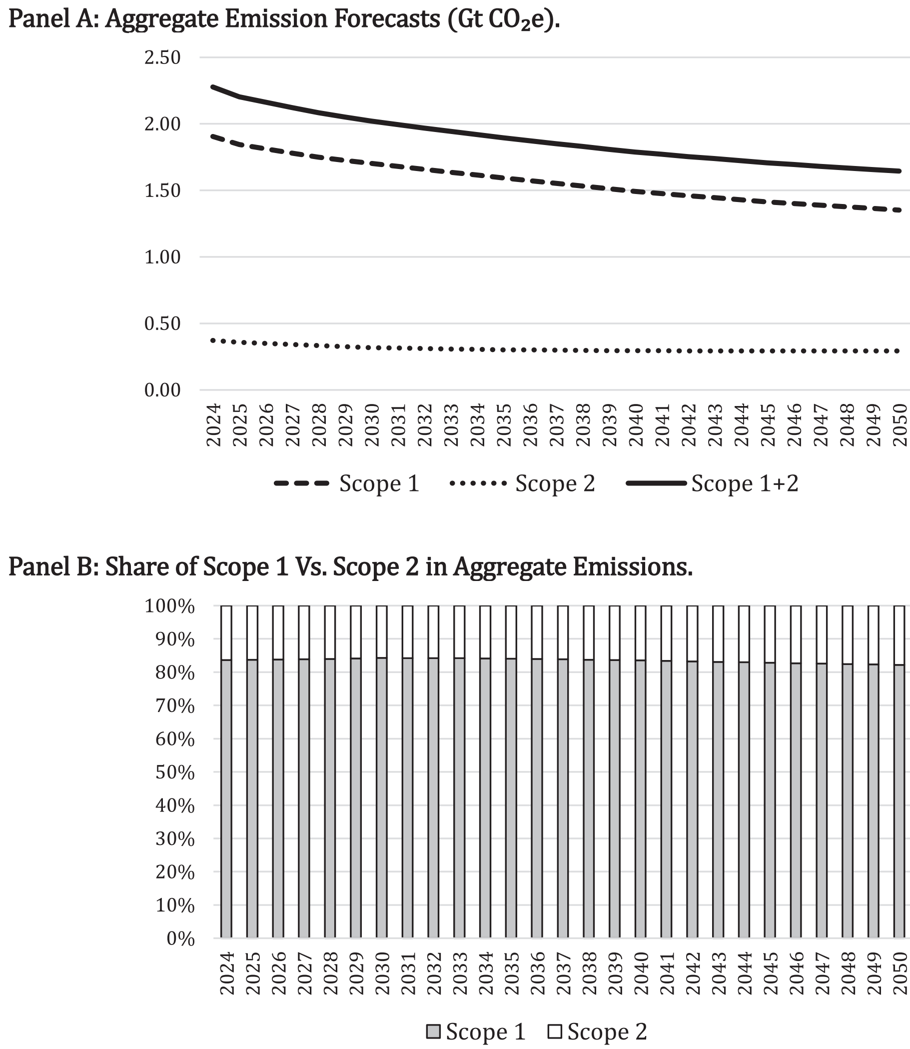


Fig. 1. Carbon emission forecasts.
This figure presents projected aggregate Scope 1 and 2 emissions from 2024 to 2050. Panel A shows aggregate emission forecasts from 2024 to 2050 at the market level. Panel B shows the breakdown of total emissions by scope. Panels C and D disaggregate total emissions by brown and green sector groupings. Brown sectors include Utilities, Energy, Materials, and Industrials, while Green sectors include Consumer Discretionary, Consumer Staples, Information Technology, Telecom, Health Care, Financials, and Real Estate. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

can sell the surplus, while those that exceed their limit must buy additional permits. This creates a market for GHG emissions allowances where prices are driven by supply and demand, and generally rise as emissions caps tighten over time.

Allowance prices vary significantly across ETS regimes. The European Union Emissions Trading System (EU ETS), which covers roughly 1.5 billion metric tons of emissions annually—or about 45 % of total EU emissions—saw average carbon prices around $72 per metric ton in 2024. Prices are projected to double by 2030 as the EU ETS tightens by reducing the number of free emissions allowances (BloombergNEF, 2024). In the U.S., California's cap-and-trade Program covers approximately 350 million metric tons per year, or close to 80 % of the state's total emissions. In 2024, allowance prices in California averaged about $35 per metric ton (California Air Resources Board, 2025).

In contrast to cap-and-trade systems, a carbon tax sets a fixed price per ton of CO_2e emitted, rather than limiting total GHG emissions. Rates vary widely by country. At the high end, Sweden, and Switzerland levy carbon taxes of roughly $125 to $130 per ton, followed by Finland and Norway at approximately $100 and $90, respectively. At the lower end, countries like South Africa and Mexico impose far smaller headline tax rates.

However, the financial impact of a carbon tax depends on more than just the headline rate. Key factors include the scope of the tax—such as which sectors and emission sources are covered—along with the availability of exemptions or rebates, and the extent to which firms can pass through carbon costs to consumers. For instance, South Africa's nominal carbon tax is about $15 per ton, but after accounting for exemptions, the effective rate often falls below $3. In Mexico, while the explicit carbon tax is only $3.50 per ton, additional fuel excise taxes raise the country's average effective carbon rate to around $23.50 per ton.

A third pillar of carbon pricing involves fossil fuel excise taxes, which apply to the production, import, or consumption of fuels such as gasoline, diesel, coal, and natural gas. While both carbon taxes and fuel excise taxes raise the cost of fossil fuel use, they differ in design and

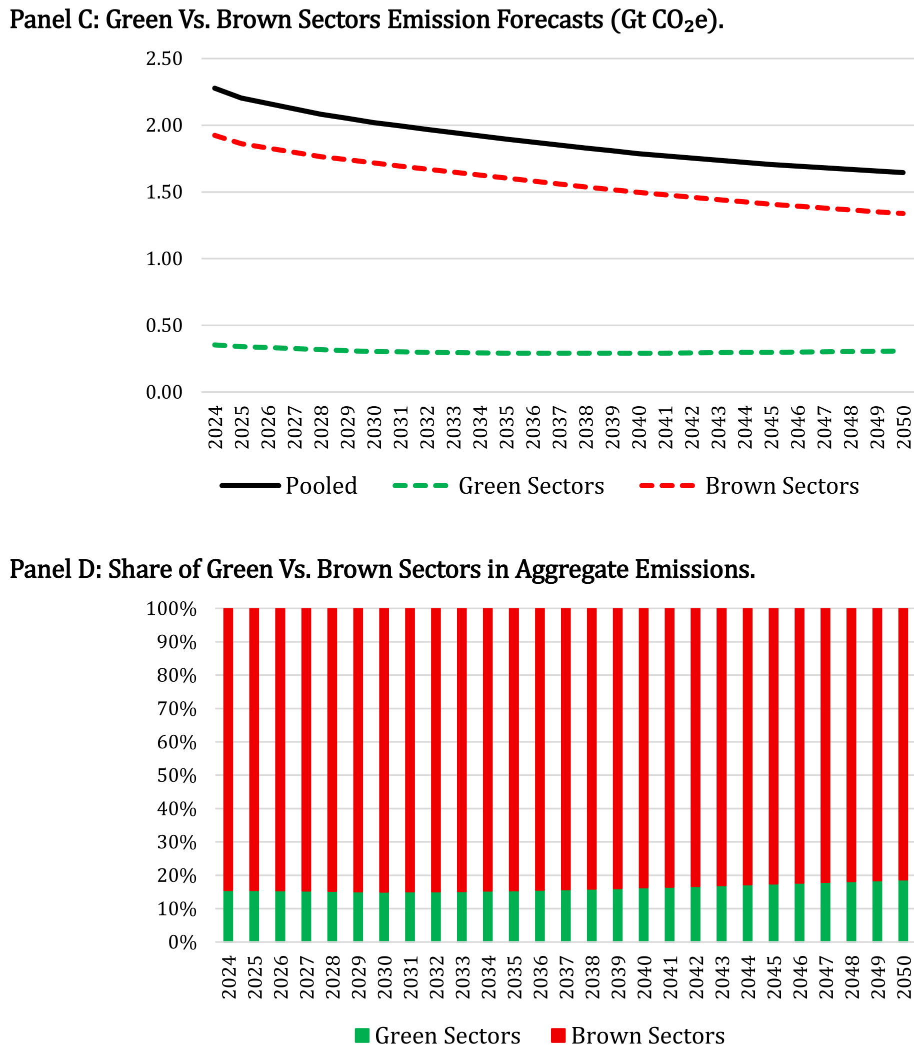


Fig. 1. (*continued*).

intent. Carbon taxes explicitly target the emissions associated with fuel combustion, directly linking the tax to climate policy objectives. Fuel excise taxes, by contrast, are typically levied per unit of fuel without explicit reference to carbon content and were originally introduced for fiscal or energy policy purposes. Yet, by raising the price of carbon-intensive energy in proportion to its use, fuel excise taxes effectively increase the implicit carbon price faced by firms and consumers.

Though differing in design, emissions trading systems, carbon taxes, and fuel excise taxes all operate to internalize the cost of carbon emissions and influence energy consumption and investment decisions. According to the World Bank Carbon Pricing Dashboard (World Bank, 2025), 80 carbon pricing instruments are now in effect worldwide, including 43 carbon taxes and 37 emissions trading systems. Together, carbon taxes and fossil fuel excise taxes account for the majority of global emissions pricing, while emissions trading systems represent a smaller but rapidly expanding share.

These mechanisms continue to broaden across sectors and regions, underscoring the growing importance for managers and investors to assess how carbon pricing may affect future operating costs and firm valuations. New mechanisms are also emerging—most notably the European Union's Carbon Border Adjustment Mechanism (CBAM), scheduled to become chargeable in January 2026, which requires importers to pay the same carbon price as domestic producers to mitigate carbon leakage—that is, the relocation of emissions-intensive production to countries with weaker climate policies. By leveling the playing field, CBAM aims to prevent emissions shifting across borders and could encourage other countries to adopt comparable carbon pricing frameworks.

3.1.2.2. Carbon price forecasts. Estimating firm-specific carbon prices is inherently complex due to substantial variation in carbon pricing mechanisms across jurisdictions and sectors, as well as differences in where firms operate and emit. This complexity is compounded by the evolving nature of climate policies, which adds uncertainty to future carbon price trajectories. Our study relies on carbon price forecasts from S&P Global Sustainable1, which estimate what each firm is expected to pay for emissions based on its sector, geographic footprint, policy scenario, and emissions profile. These estimates, which underpin the S&P Global Sustainable1 Carbon Earnings at Risk dataset, aim to capture firm-level carbon price risk. Because carbon prices vary by geography and sector, firm-specific forecasts like these are essential for integrating carbon costs into financial analysis and valuation.

S&P Global Sustainable1 employs a comprehensive methodology that integrates current carbon price analysis, future price projections, and adjustments tailored to sector- and country-specific factors (S&P Global Sustainable1, 2024). Current country- and sector-specific carbon prices are derived using data from the World Bank, OECD, International Carbon Action Partnership (ICAP), and other sources. The forecasting approach is built on scenario-based carbon price pathways developed by the International Energy Agency (IEA), which are widely adopted by investors and policymakers for climate risk analysis. These carbon price pathways reflect varying levels of policy ambition.

The high carbon price scenario aligns with the IEA Net Zero Emissions by 2050 (NZE 2050) pathway and assumes policies sufficient to limit warming to 1.5 °C by 2100 with a 50 % probability, implying the steepest price trajectory. The medium scenario corresponds to the IEA Announced Pledges Scenario (APS), in which governments meet their pledges in full and on time, consistent with 1.7 °C of warming by 2100 with a 50 % probability. The low scenario reflects the IEA Stated Policies Scenario (STEPS), a business-as-usual pathway based on current policy implementation, associated with 2.4 °C of warming by 2100 with a 50 % probability, and results in the lowest carbon price trajectory.[5]

We obtain carbon price forecasts by sector and country under the three carbon price scenarios from S&P Global Sustainable1 through our access to the Carbon Earnings at Risk dataset. The data is organized into seven emissions sectors: (1) agriculture and fisheries, (2) commercial and residential real estate, (3) electricity, (4) industry, (5) international aviation, (6) off-road transport, and (7) road transport. The data matches each company to an emissions sector by identifying its primary business activity. The raw carbon price data exhibit substantial cross-country variation within each emissions sector, highlighting geographic heterogeneity in projected carbon costs due to differences in national policies and market structures.

To convert the sector- and country-level carbon price forecasts into company-specific forecasts, we obtain the mapping of each firm in our sample to one of the seven emissions sectors based on its primary business activity, as well as the breakdown of its emissions by country. S&P Global Sustainable1 determines the geographic distribution of each firm's emissions using either public disclosures to the CDP or the firm's reported revenue breakdown by region. If this information is unavailable, we assume that the emissions originate in the U.S.[6] Using each firm's emissions sector classification and geographic emissions profile, we compute a weighted average carbon price at each forecast horizon based on S&P Global Sustainable1's sector- and country-specific carbon price projections.

We obtain the sector and country-level carbon price forecasts, as well as company-specific sector classifications and geographic emissions breakdowns, from S&P Global Sustainable1. Although carbon pricing policies primarily target Scope 1 emissions, as discussed in Section 2, firms may also be indirectly affected by carbon costs passed through from electricity providers. To capture this indirect exposure, the S&P data also include Scope 2 carbon prices by emissions sector and country, calculated as 80 % of the Scope 1 carbon prices for the electricity emissions sector in each country.

All carbon price forecasts are expressed in 2023 chained dollars and converted to nominal terms using a 30-year breakeven inflation rate of 2.13 % as of December 31, 2023. This rate, published by the Federal Reserve Bank of St. Louis, is calculated as the difference between the 30-year nominal Treasury yield and the TIPS yield. Our market-based measure of long-term inflation expectations aligns with survey-based estimates, such as the 10-year-ahead CPI forecast from the Livingston Survey by the Federal Reserve Bank of Philadelphia.

Table 2 reports the cross-sectional mean and standard deviation of firm-level carbon prices from 2024 through 2050 under the low, medium, and high carbon pricing scenarios developed by S&P Global Sustainable1. These forecasts, expressed in dollars per metric ton of Scope 1 CO_2e emissions, reflect firm-specific weighted averages based on projected carbon prices by emissions sector and country, as described above. In 2024, the equal-weighted average carbon price in our sample is $64.15 under the low scenario, $89.53 under the medium scenario, and $94.42 under the high scenario. By 2050, these averages rise to $207.40, $336.34, and $425.64, respectively.

Across all forecast horizons and scenarios, firm-level carbon prices exhibit substantial cross-sectional heterogeneity. For example, under the medium scenario, the 2024 mean of $89.53 is associated with a standard deviation of $15.84, while the 2050 mean of $336.34 is associated with a standard deviation of $29.10. By construction, cross-sectional heterogeneity in carbon prices reflects both cross-sector differences, which arise from distinct forecast paths across emissions sectors, and within-sector variation, which is driven by firm-level differences in the geographic distribution of emissions.

Table 3 quantifies the relative contribution of cross-sector versus within-sector variation by reporting adjusted R^2 values from cross-sectional regressions of firm-level carbon prices on sector fixed effects. These regressions are estimated separately for each forecast horizon and carbon price scenario. The adjusted R^2 measures the proportion of variation attributable to systematic differences across sectors, while 1 −

Table 2
Carbon price heterogeneity.

Forecast year	Low carbon price		Medium carbon price		High carbon price	
	μ	σ	μ	σ	μ	σ
2024	$64.15	$12.57	$89.53	$15.84	$94.42	$14.10
2025	$70.03	$13.23	$97.69	$16.76	$103.09	$14.63
2026	$76.13	$13.91	$106.16	$17.71	$112.11	$15.16
2027	$82.46	$14.62	$114.96	$18.68	$121.46	$15.70
2028	$89.03	$15.36	$124.09	$19.68	$131.17	$16.26
2029	$95.85	$16.11	$133.56	$20.71	$141.24	$16.83
2030	$102.93	$16.89	$143.38	$21.78	$151.68	$17.42
2031	$107.19	$17.32	$151.21	$22.18	$162.57	$17.90
2032	$111.59	$17.76	$159.34	$22.56	$173.85	$18.38
2033	$116.13	$18.20	$167.74	$22.93	$185.55	$18.86
2034	$120.82	$18.65	$176.43	$23.32	$197.66	$19.36
2035	$125.66	$19.11	$185.43	$23.71	$210.21	$19.87
2036	$130.65	$19.58	$194.72	$24.10	$223.20	$20.40
2037	$135.79	$20.07	$204.33	$24.51	$236.65	$20.94
2038	$141.10	$20.56	$214.26	$24.93	$250.58	$21.49
2039	$146.57	$21.07	$224.52	$25.36	$264.99	$22.06
2040	$152.21	$21.59	$235.13	$25.80	$279.90	$22.65
2041	$157.06	$22.01	$243.94	$26.12	$292.48	$23.04
2042	$162.05	$22.44	$253.02	$26.44	$305.48	$23.44
2043	$167.18	$22.88	$262.38	$26.76	$318.89	$23.85
2044	$172.46	$23.32	$272.03	$27.09	$332.74	$24.27
2045	$177.89	$23.77	$281.96	$27.42	$347.04	$24.70
2046	$183.47	$24.23	$292.20	$27.75	$361.79	$25.16
2047	$189.20	$24.70	$302.75	$28.08	$377.01	$25.62
2048	$195.10	$25.18	$313.62	$28.42	$392.72	$26.10
2049	$201.16	$25.67	$324.81	$28.76	$408.92	$26.60
2050	$207.40	$26.18	$336.34	$29.10	$425.64	$27.11

This table presents cross-sectional means (μ) and standard deviations (σ) of firm-level carbon price forecasts from 2024 to 2050 under low, medium, and high carbon pricing scenarios. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

[5] Table A1 in the Supplement reports carbon price trajectories for two key geographies in our sample: advanced economies with net-zero pledges (e.g., OECD members, including the U.S. and the E.U.) and emerging market and developing economies with net-zero pledges (e.g., China, India, Indonesia). In the low scenario, prices rise from $97 to $126 per ton in advanced economies and from $29 to $101 in emerging markets between 2030 and 2050. In the medium scenario, prices increase from $135 to $200 and from $40 to $160, respectively. In the high scenario, they rise from $140 to $250 and from $90 to $200. All values are in constant 2023 dollars. These trajectories represent policy-ambition scenarios and are widely used in climate risk analysis.

[6] We note that 19 % of our representative sample of U.S.-listed firms lack geo-allocation data. Assigning missing geography to the U.S. could overstate COH for firms with emissions concentrated in lower-priced jurisdictions and understate it for those with higher-priced exposure. However, our analysis indicates that the impact on aggregate COH estimates is limited: these firms account for only 1.8 % of aggregate revenues and 1.1 % of aggregate emissions. Moreover, using segment information from corporate financial reports, we find that 99.95 % of their income comes from domestic operations and only 0.05 % from foreign operations. This suggests that defaulting missing geography to the U.S. is consistent with the firms' income distribution.

Table 3
Systematic carbon price heterogeneity.

Forecast year	Adjusted R^2 from cross-sectional regressions of carbon prices on sector fixed effects		
	Low carbon price	Medium carbon price	High carbon price
2024	9.7 %	11.0 %	11.0 %
2025	9.6 %	10.9%	10.9%
2026	9.5 %	10.9%	10.8 %
2027	9.3 %	10.8 %	10.7 %
2028	9.2 %	10.7 %	10.6 %
2029	9.1 %	10.6 %	10.5 %
2030	9.0 %	10.5 %	10.4 %
2031	9.0 %	10.4 %	10.3 %
2032	9.1 %	10.4 %	10.2 %
2033	9.1 %	10.3 %	10.1 %
2034	9.1 %	10.3 %	10.1 %
2035	9.1 %	10.2 %	10.0 %
2036	9.2 %	10.2 %	9.9 %
2037	9.2 %	10.1 %	9.8 %
2038	9.2 %	10.0 %	9.7 %
2039	9.2 %	10.0 %	9.7 %
2040	9.3 %	9.9 %	9.6 %
2041	9.3 %	9.8 %	9.6 %
2042	9.3 %	9.8 %	9.5 %
2043	9.4 %	9.8 %	9.5 %
2044	9.4 %	9.7 %	9.5 %
2045	9.4 %	9.7 %	9.4 %
2046	9.4 %	9.6 %	9.4 %
2047	9.5 %	9.6 %	9.3 %
2048	9.5 %	9.5 %	9.3 %
2049	9.5 %	9.5 %	9.2 %
2050	9.6 %	9.4 %	9.1 %
Average	9.3 %	10.1 %	9.9 %

This table presents adjusted R^2 values from regressions of firm-level carbon prices on sector fixed effects, quantifying the proportion of variation explained by cross-sector versus within-sector differences. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

R^2 captures within-sector heterogeneity—primarily driven by differences in emissions geography among firms within the same sector.

Across all horizons and scenarios, adjusted R^2 values average approximately 10 %, with a range of ± 1 percentage point. This implies that about 90 % of the variation in firm-specific carbon prices occurs within sectors, underscoring the critical role of firm-level emissions geography in evaluating carbon price exposure.

3.1.2.3. Long-term growth in carbon prices. To compute the COH metric, we require carbon price estimates beyond 2050, a period for which S&P Global Sustainable1 does not provide firm-level forecasts. To extrapolate carbon prices beyond 2050, we assume that prices continue to grow at the same rate as the emissions-weighted average carbon price during the 2040–2050 period.

To calculate this emissions-weighted average price for each forecast horizon, we first compute each firm's projected annual carbon cost by multiplying its forecasted emissions by its firm-specific forecasted carbon price. We then aggregate these projected carbon costs across all firms and divide by the total projected emissions for that year. This yields an emissions-weighted average carbon price that captures the aggregate carbon price within our sample, placing greater weight on firms with larger projected emissions.

While Table 2 reports simple equal-weighted averages, Panel A of Fig. 2 presents the trajectory of emissions-weighted average carbon prices across scenarios. The two sets of averages are similar, indicating consistency across weighting schemes. Under the medium scenario, the weighted average carbon price increases from $89.38 per metric ton of Scope 1 emissions in 2024—the first year of the forecast horizon—to $337.79 in 2050—the final year of the horizon. This implies a compound annual growth rate of 5.87 % from 2024 to 2040, which slows to 3.67 % between 2040 and 2050. We adopt the 3.67 % rate as our long-run growth assumption for nominal carbon prices beyond 2050. This value is used as the parameter ρ in the terminal value calculation of the COH metric.

Panel B of Fig. 2 presents emissions-weighted average carbon prices after adjusting for the pass-through of indirect emissions from regulated utilities, specifically those classified as electricity utilities by S&P Global Sustainable1 in our sample. The adjusted average carbon prices are calculated by: (a) adding the pass-through cost per metric ton of projected Scope 2 emissions to each firm's total carbon cost; and (b) reducing the carbon cost per metric ton of Scope 1 emissions for regulated utilities by the assumed 80 % pass-through rate.

We find that, across the forecast horizon, these adjustments reduce the emissions-weighted average carbon price by approximately 25 %. The increase in carbon costs for non-utility firms due to Scope 2 pass-through is more than offset by the reduction in Scope 1 costs for regulated utilities. This reflects the fact that a portion of utilities' carbon liabilities is effectively transferred to customers outside our sample of public firms—such as private businesses, households, and public sector entities, thereby lowering the aggregate carbon price borne within our sample.

3.1.2.4. Carbon prices vs. social cost of carbon. It is instructive to compare our estimates of regulatory carbon prices with the social cost of carbon (SCC). The SCC represents a monetary estimate of the economic damages to society—such as impacts on health, agriculture, property, and ecosystems—resulting from the emission of one additional metric ton of carbon dioxide. It serves as a benchmark for public policy by quantifying the societal benefits of reducing emissions. The SCC corresponds to the Pigouvian carbon tax needed to fully internalize the carbon externality and achieve a socially efficient outcome. Because GHG emissions mix uniformly in the atmosphere, they represent a global externality, and the SCC reflects the tax a global social planner would impose to account for the worldwide damages.[7]

To compare carbon prices to the SCC, we use the most recent U.S. Environmental Protection Agency (EPA) estimates (EPA, 2023). Specifically, we use the EPA's headline SCC estimate based on a 2 % social discount rate. In nominal terms, the headline SCC estimate is close to $226 per ton of CO_2e in 2024 and rises to about $580 by 2050.[8] As shown in Fig. 2, the SCC remains consistently and substantially higher than the carbon prices firms are projected to pay between 2024 and 2050. Even under the most ambitious policy scenario, the SCC exceeds projected carbon prices by 140 % in 2024 and by 36 % in 2050. Using the SCC in place of regulatory price forecasts would therefore overstate actual carbon costs and result in significantly larger COH estimates. We return to this point in Section 3.3.

3.1.3. Cost of equity capital

To estimate the carbon overhang metric, we use the cost of equity capital to discount expected future carbon costs, as it reflects the return required by shareholders to bear the risk of holding a company's equity. Using data from Professor Kenneth French's website, we assign firms to size deciles and calculate each firm's cost of equity as of year-end 2023, by adding the Fama-French size factor risk premium to the market-expected return (Fama and French, 1992, 1993, 2015). Our estimated

[7] National governments may disagree on the appropriate level of carbon taxation due to differences in economic priorities, vulnerability to climate impacts, and political constraints. Building on this reality, prior research has developed country-specific SCC estimates. These estimates tend to be higher for low-income countries with large populations—such as China, India, Pakistan, Bangladesh, and Indonesia—reflecting the greater marginal damages experienced in those regions, compared to the E.U. and the U.S. (Tol, 2019).

[8] The SCC values are reported by the EPA in 2020 chained dollars. We convert them to nominal terms using the 2.13 % long term expected inflation rate applied throughout our analysis.

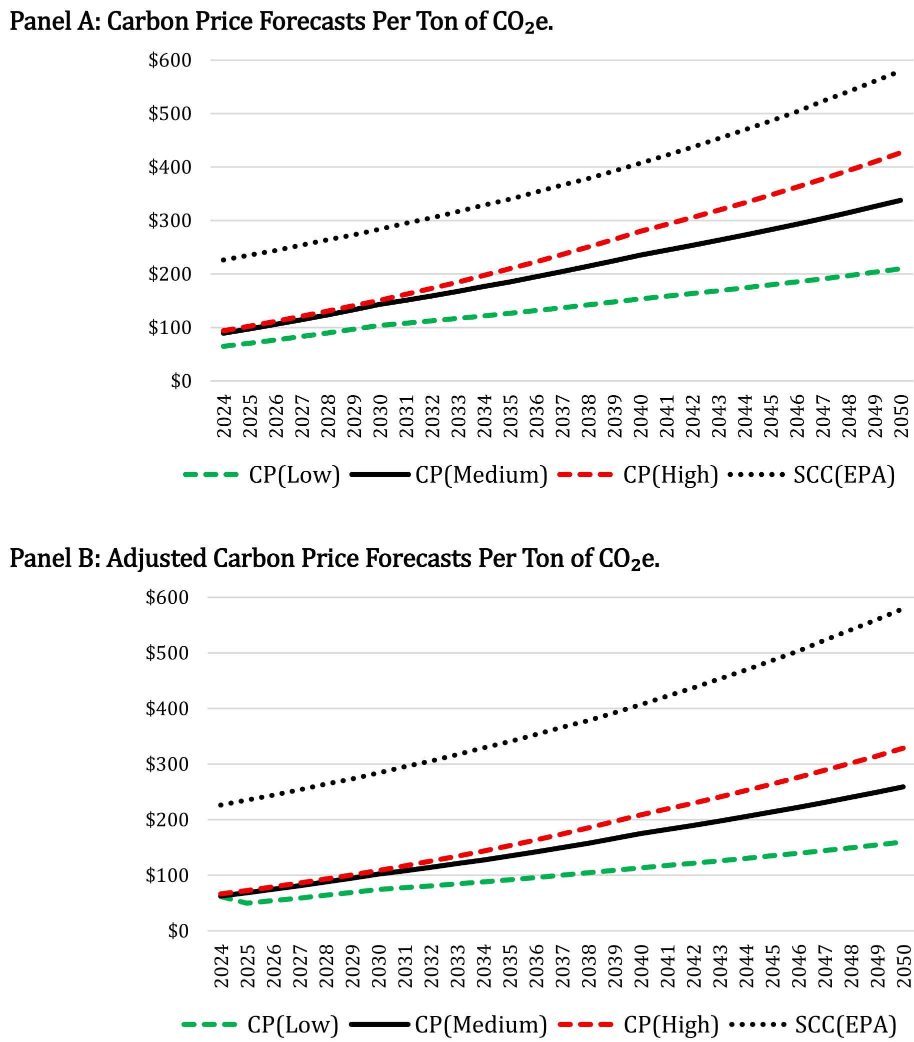


Fig. 2. Emissions-weighted carbon price forecasts.
This figure presents emissions-weighted average carbon prices projected between 2024 and 2050. Panel A shows prices under low, medium, and high carbon price (CP) scenarios. Panel B shows adjusted prices incorporating Scope 2 pass-through costs from regulated utilities. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

cost of equity ranges from 9.97 % for firms in the bottom size decile (market capitalizations below $344.25 million) to 8.31 % for firms in the top decile (market capitalizations above $44.28 billion). The 1.66 % spread between the bottom and top deciles corresponds to the size premium observed through year-end 2023.[9]

3.2. *Carbon overhang estimates*

3.2.1. *Market-level carbon overhang: baseline estimates*

Panel A of Table 4 presents our baseline estimates of carbon overhang at the market level under each carbon price scenario. These figures are computed by estimating COH for each firm in the sample and summing across all firms. The resulting aggregate COH ranges from $2.41 trillion under the low carbon price scenario to $3.58 trillion under the medium scenario and $4.14 trillion under the high scenario. These totals correspond to 5.0 %, 7.4 %, and 8.6 %, respectively, of the aggregate market cap of $48.23 trillion in our sample. At the firm level, 3.0 % of companies have COH estimates that exceed their market cap under the low scenario, increasing to 4.7 % under the high scenario.

We decompose the aggregate carbon overhang into two components: the explicit forecast horizon component, which captures the present value of carbon costs from 2024 to 2050, and the terminal value component, which captures the present value of carbon costs beyond 2050. Panel A of Fig. 3 shows that the terminal component accounts for roughly 25 % of total COH across all scenarios, with the remaining 75 % accruing during the explicit forecast period. Panel B of Fig. 3 provides a year-by-year breakdown of the carbon overhang accrued between 2024 and 2050, offering insight into the timing of these liabilities. Across all scenarios, 30 % of the total COH is accrued by 2030, 60 % by 2040, and 75 % by 2050, with the remaining 25 % accruing beyond 2050.

These breakdowns highlight two key points. First, most of the carbon liability is expected to accrue to stock market investors within the next two decades. Second, aggregate COH estimates are not overly sensitive to assumptions about long-run emissions growth (g) and carbon price growth (ρ). To assess this more directly, Fig. A1 varies g and ρ around their baseline values by ± 1 % and $\pm$ 2 %. The resulting COH estimates remain within a narrow band, with a midpoint sensitivity of about ± 10 % relative to the baseline. These findings indicate that while the terminal value is an important component, its contribution is modest relative to the explicit forecast horizon, and the aggregate results remain

[9] We also estimate the cost of equity capital using alternative specifications that include additional Fama-French factors—book-to-market (HML), profitability (RMW), and investment (CMA)—but these adjustments do not materially affect our COH estimates.

Table 4
Market-level carbon overhang estimates.

Panel A: Baseline estimates

Scenario	COH($BN)	COH components				COH vs. MV	
		2024–2050	2051+	%(2024–2050)	%(2051+)	COH/MV	I(COH/MV > 1)
Low	$2408.4	$1887.2	$521.2	78.4 %	21.6 %	5.0 %	3.0 %
Medium	$3582.9	$2743.6	$839.3	76.6 %	23.4 %	7.4 %	4.3 %
High	$4143.7	$3083.5	$1060.2	74.4 %	25.6 %	8.6 %	4.7 %

Panel B: Adjusted estimates

Scenario	COH($BN)	COH components				COH vs. MV	
		2024–2050	2051+	%(2024–2050)	%(2051+)	COH/MV	I(COH/MV > 1)
Low	$2107.3	$1629.8	$477.5	77.3 %	22.7 %	4.4 %	2.5 %
Medium	$3147.3	$2373.4	$773.9	75.4 %	24.6 %	6.5 %	4.1 %
High	$3671.4	$2689.8	$981.6	73.3 %	26.7 %	7.6 %	4.5 %

Panel C: Adjusted vs. baseline estimates

Scenario	Market COH ($BN)			Regulated utilities COH ($BN)			Rest of companies COH ($BN)		
	Baseline	Adjusted	Change	Baseline	Adjusted	Change	Baseline	Adjusted	Change
Low	$2408.4	$2107.3	-$301.1	$819.60	$179.40	-$640.20	$1588.80	$1928.00	$339.10
Medium	$3582.9	$3147.3	-$435.6	$1220.40	$267.00	-$953.50	$2362.50	$2880.40	$517.90
High	$4143.7	$3671.4	-$472.2	$1387.60	$303.50	-$1084.00	$2756.10	$3367.90	$611.80

Note: BN denotes billions of U.S. dollars.
This reports market-level carbon overhang (COH) estimates under both our baseline and adjusted specifications. Panel A presents baseline estimates under a 0 % pass-through assumption, in which regulated utilities fully absorb their Scope 1 carbon costs. Panel B reports adjusted estimates that reflect an 80 % pass-through of carbon costs to downstream customers: regulated utilities' Scope 1 costs are reduced accordingly, and the corresponding Scope 2 costs are reassigned to the rest of firms in our sample (i.e., non-regulated utilities and non-utilities). We decompose total COH into two components: the explicit forecast horizon (2024–2050) and the terminal value (beyond 2050). Panel C traces the shift from baseline to adjusted estimates, highlighting the reallocation of carbon liabilities from regulated utilities to the rest of firms. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

robust to reasonable alternative assumptions about long-run carbon prices and emissions trajectories.

Our implementation of the COH valuation model extrapolates the current geographic allocation of each firm's emissions and assumes this composition remains constant over time. This is a simplifying assumption necessitated by the lack of long-run forecasts of geographic emission allocations. To gauge the range of estimation uncertainty associated with this assumption, we re-estimate aggregate COH under two extreme "corner" cases: one where 100 % of emissions occur in advanced economies and another where 100 % occur in emerging economies. As shown in Fig. A2, relocating all emissions to advanced economies raises aggregate COH by only about 6 % under the medium carbon price path, since in our baseline implementation most direct Scope 1 emissions of U.S.-listed companies are already generated in advanced economies. By contrast, relocating all emissions to emerging economies reduces aggregate COH by roughly 45 %. Although the likelihood of U.S.-listed firms relocating 100 % of their operations to emerging markets is remote, this sensitivity analysis helps to bound the potential impact of alternative geographic assumptions on aggregate COH estimates.

A limitation of our COH estimates is that MSCI provides only a single set of emissions forecasts rather than scenario-specific forecasts. These forecasts are constructed assuming a baseline carbon price trajectory that most closely corresponds to S&P's medium carbon price scenario. The limitation arises when this single emissions path is applied across different carbon price scenarios. In the high-price scenario, emissions are likely overstated because higher carbon prices would induce stronger abatement, leading us to overstate aggregate COH. In the low-price scenario, emissions are likely understated because weaker policy ambition would slow abatement, leading us to understate aggregate COH. As a result, the estimated range of COH across scenarios is wider than it would be if scenario-specific emissions forecasts were available. Scenario-specific emissions forecasts would compress this range while leaving the baseline COH estimate unchanged. Put differently, given data limitations, our implementation errs on the side of overstating rather than understating the estimation uncertainty of COH.

3.2.2. Market-level carbon overhang: adjusted estimates

Regulated utilities often pass a substantial share of their carbon costs to downstream customers through higher energy prices. Panel B of Table 4 reports aggregate COH estimates after adjusting for the pass-through of indirect Scope 2 emissions. Specifically, we (a) reduce regulated utilities' Scope 1 carbon costs by the projected pass-through rate and (b) add the corresponding pass-through cost of Scope 2 emissions to each firm's total carbon cost. Following the S&P Global Sustainable1 methodology, our baseline assumes an 80 % pass-through of regulated utilities' carbon costs to downstream customers. This assumption is consistent with empirical research in energy economics, which finds that regulated utilities typically pass through a substantial share of carbon costs to end users, with micro-level estimates around 80 % (e.g., Fabra and Reguant, 2014).

Panel B of Table 4 shows that the pass-through adjustment lowers aggregate COH estimates by about 12 % relative to the baseline. This reflects both a reallocation of carbon costs from regulated utilities to other firms in our sample and a partial transfer of costs to entities outside the sample. At the market level, the adjusted COH declines to $2.11 trillion under the low scenario, $3.15 trillion under the medium scenario, and $3.67 trillion under the high scenario—equivalent to 4.4 %, 6.5 %, and 7.6 % of total market capitalization, respectively. The share of firms with COH exceeding their market capitalization also falls slightly, from 2.5 % in the low scenario to 4.5 % in the high scenario.

Panel C of Table 4 attributes the difference between baseline and adjusted market-level COH estimates to the reallocation of carbon liabilities from regulated utilities to other firms in the sample. Under the baseline specification with 0 % pass-through, market-level COH totals

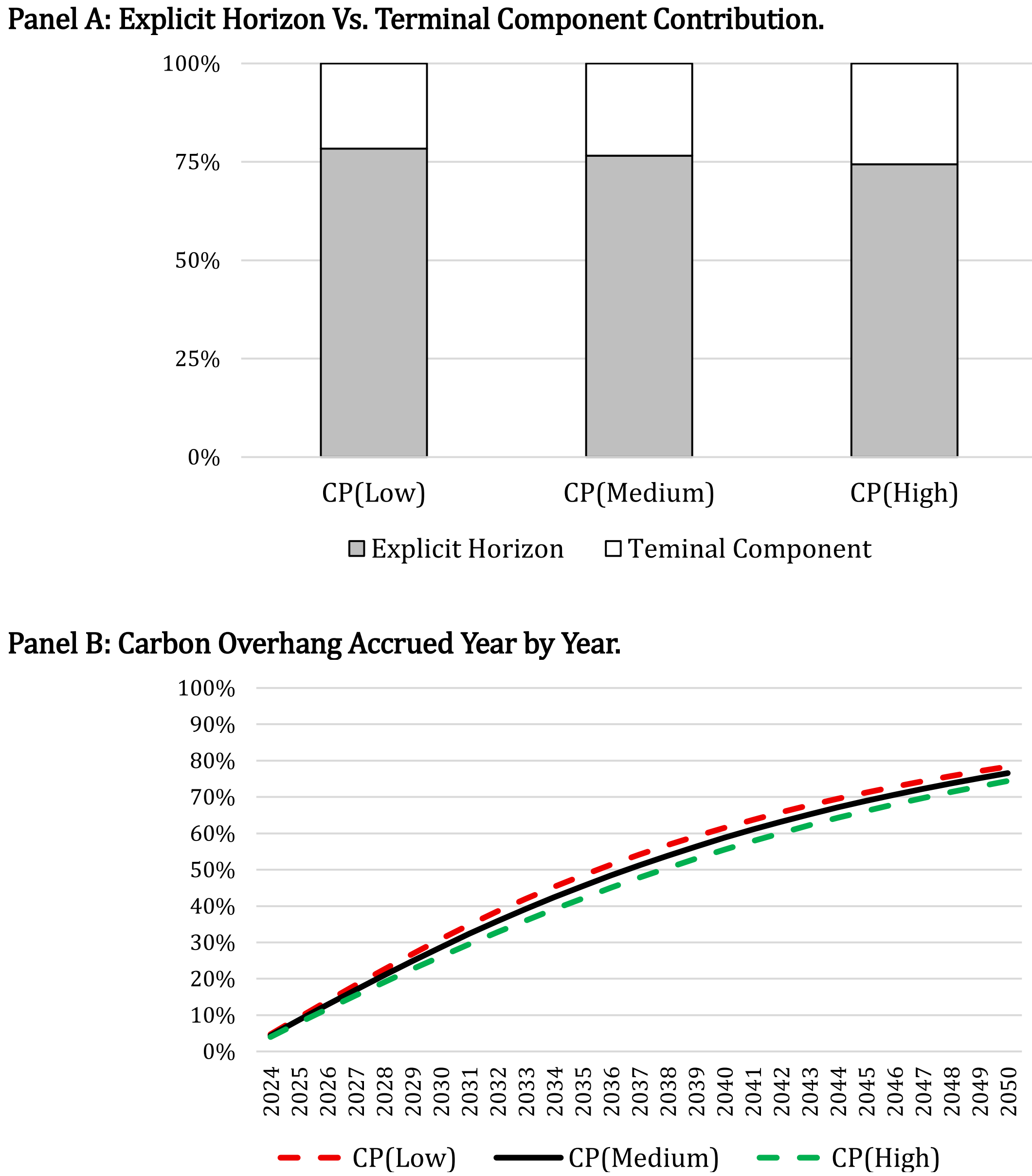


Fig. 3. Aggregate carbon overhang components.
This figure presents the timing and composition of market-level carbon overhang (COH) under the baseline specification. Panel A decomposes total COH into two components: the explicit forecast horizon component, which captures the present value of carbon costs from 2024 to 2050, and the terminal value component, which captures the present value of carbon costs beyond 2050. Estimates are shown under low, medium, and high carbon price (CP) scenarios. Panel B shows the cumulative accrual of market-level COH between 2024 and 2050, under the three carbon price scenarios. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

about $3.58 trillion: $1.22 trillion for regulated utilities and $2.36 trillion for other firms. At an 80 % pass-through rate, regulated utilities' COH falls from $1.22 trillion to $267 billion—a $954 billion decline (78 % reduction, slightly less than the pass-through rate due to the carbon cost of their limited Scope 2 emissions)—while the COH of other firms rises from $2.36 trillion to $2.88 trillion, an increase of $518 billion.

The in-sample net change in market-level COH is a decline of about $435 billion, implying that roughly 55 % of the costs passed through by regulated utilities are absorbed by public firms in our sample (calculated as the ratio of the in-sample decline in COH, $436 billion, to the total reduction in regulated utilities' COH, $954 billion), and about 45 % by entities outside the sample. This 55 % absorption rate corresponds to the ratio of total in-sample Scope 2 emissions to the Scope 1 emissions of regulated utilities. At the macro level, if all entities were included (private firms, households, and the public sector), aggregate COH would be unchanged, since pass-through reallocates carbon costs without altering the total carbon liability.

To gauge sensitivity, we re-estimate COH under alternative pass-through rates ranging from 0 % to 100 % in 20 % increments. As shown in Fig. A3, moving from 0 % to 100 % lowers regulated utilities' COH from $1.22 trillion to just $29 billion—a 98 % decline, with the remaining COH reflecting the carbon cost of their limited Scope 2 emissions. Over the same range, the COH of the rest of firms increases from $2.36 trillion to about $3.0 trillion, a $647 billion (27 %) increase. Across all scenarios, the absorption rate of passed-through costs by public firms in the sample remains constant at 55 %, since the ratio of total in-sample Scope 2 emissions to regulated utilities' Scope 1 emissions does not vary with the pass-through assumption.

Overall, these results highlight that incorporating the pass-through of indirect emissions from regulated utilities leads to a substantial reallocation of carbon cost exposure—from regulated utility firms to non-regulated utilities as well as non-utility firms—and shifts a material share of the burden to electricity consumers outside the sample, including private businesses, households, and public sector entities. While at the macro level total carbon liability is unchanged, the pass-through assumption materially affects both the cross-sector distribution and the in-sample aggregate COH.

3.2.3. Sector-level carbon overhang estimates

While the previous section provides market-level COH estimates, this section disaggregates those results to examine how carbon liabilities are distributed across sectors. The sector-level analysis highlights the uneven exposure to carbon liabilities across the economy and shows how adjustments for pass-through cost of indirect emissions reshape the distribution of carbon overhang values.

Table 5 reports the baseline and adjusted COH estimates aggregated across firms operating in green and brown sectors, both in dollar terms (Panel A) and as a percentage of aggregate market cap (Panel B). Under the baseline specification, green sector COH ranges from $266.8 billion under the low scenario to $473.5 billion under the high scenario, corresponding to 0.7 % to 1.2 % of the total market cap of green sector firms. Brown sectors, by contrast, exhibit far larger carbon liabilities, with COH estimates ranging from $2.14 trillion under the low scenario to $3.67 trillion under the high scenario. These values correspond to 25 %, 37 %, and 43 % of brown sector market capitalization under the low, medium, and high carbon price scenarios, respectively.

The stacked bar chart in Panel A of Fig. 4 shows that firms in brown sectors account for nearly 90 % of the total baseline carbon overhang across carbon price scenarios, while green sectors account for the remaining 10 %. This distribution closely reflects the share of Scope 1 emissions attributable to brown sectors and stands in stark contrast to their share of aggregate market cap, which is only 18 %. Green sectors, by comparison, represent 82 % of total market value. Within the brown sectors, Utilities contribute 39 % of the total carbon overhang, followed by Energy (24 %), Industrials (14 %), and Materials (12 %), for a combined share of roughly 89 %. Among green sectors, Financials account for 4.8 %, Consumer Staples 3.3 %, Consumer Discretionary 2.0 %, and the remaining sectors together make up about 1 %, collectively contributing the remaining 11 %.

Comparing baseline and adjusted COH estimates reveals that accounting for Scope 2 emissions pass-through significantly alters the sectoral distribution of carbon liabilities. Under the high carbon price scenario, Utilities' COH falls sharply—from 147 % of sector market capitalization ($1.6 trillion) to 47 % ($508 billion)—a reduction of nearly $1.1 trillion. In contrast, all other sectors see a combined COH increase of $607.4 billion as they absorb the reallocated costs. The Materials and Energy sectors account for the largest share of this increase, absorbing a combined $274.6 billion (45 % of the total).

Table 5
Sector-level carbon overhang estimates.

Panel A: Dollar estimates

Carbon price scenario	Baseline COH ($BN)			Adjusted COH ($BN)			Change ($BN)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Real Estate	$3.2	$4.8	$5.6	$13.3	$19.9	$23.2	$10.0	$15.1	$17.6
Telecom	$3.6	$5.3	$6.1	$19.0	$28.5	$32.8	$15.4	$23.2	$26.7
Technology	$10.2	$15.9	$18.7	$29.8	$47.8	$58.6	$19.6	$31.9	$40.0
Health Care	$10.8	$16.5	$19.4	$26.5	$40.2	$47.2	$15.6	$23.8	$27.8
Discretionary	$47.5	$72.8	$86.1	$85.0	$130.8	$155.0	$37.5	$58.1	$68.9
Staples	$76.6	$116.5	$137.5	$115.5	$175.6	$207.5	$38.9	$59.1	$70.0
Financials	$114.8	$172.4	$200.1	$132.6	$199.2	$231.2	$17.8	$26.8	$31.1
Materials	$274.4	$415.1	$490.2	$348.1	$527.8	$624.1	$73.7	$112.7	$133.9
Industrials	$367.2	$513.7	$594.2	$394.8	$556.2	$644.9	$27.6	$42.4	$50.7
Energy	$564.6	$854.4	$997.8	$644.9	$975.5	$1138.6	$80.3	$121.1	$140.8
Utilities	$935.4	$1395.5	$1587.9	$297.8	$445.9	$508.3	-$637.7	-$949.6	-$1079.6
Green	$266.8	$404.2	$473.5	$421.7	$642.0	$755.6	$154.9	$237.8	$282.1
Brown	$2141.6	$3178.7	$3670.2	$1685.6	$2505.3	$2915.8	-$456.0	-$673.4	-$754.3
Market	$2408.4	$3582.9	$4143.7	$2107.3	$3147.3	$3671.4	-$301.1	-$435.6	-$472.2

Panel B: Scaled estimates

Carbon price scenario	Baseline COH/MV			Adjusted COH/MV			Change		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Real Estate	0.2 %	0.3 %	0.4 %	0.9%	1.4 %	1.6 %	0.7 %	1.1 %	1.2 %
Telecom	0.1 %	0.1 %	0.1 %	0.4 %	0.7 %	0.8 %	0.4 %	0.5 %	0.6 %
Technology	0.1 %	0.1 %	0.1 %	0.2 %	0.4 %	0.5 %	0.2 %	0.2 %	0.3 %
Health Care	0.2 %	0.3 %	0.3 %	0.5 %	0.7 %	0.8 %	0.3 %	0.4 %	0.5 %
Discretionary	0.8 %	1.3 %	1.5 %	1.5 %	2.3 %	2.8 %	0.7 %	1.0 %	1.2 %
Staples	2.6 %	3.9 %	4.6 %	3.9 %	5.9 %	6.9 %	1.3 %	2.0 %	2.3 %
Financials	1.7 %	2.6 %	3.0 %	2.0 %	3.0 %	3.5 %	0.3 %	0.4 %	0.5 %
Materials	25.3 %	38.3 %	45.2 %	32.1 %	48.6 %	57.5 %	6.8 %	10.4 %	12.3 %
Industrials	8.1 %	11.3 %	13.0 %	8.7 %	12.2 %	14.2 %	0.6 %	0.9 %	1.1 %
Energy	30.1 %	45.6 %	53.3 %	34.4 %	52.1 %	60.8 %	4.3 %	6.5 %	7.5 %
Utilities	86.7 %	129.3 %	147.1 %	27.6 %	41.3 %	47.1 %	−59.1 %	−88.0 %	−100.0 %
Green	0.7 %	1.0 %	1.2 %	1.1 %	1.6 %	1.9 %	0.4 %	0.6 %	0.7 %
Brown	24.9 %	37.0 %	42.7 %	19.6 %	29.2 %	33.9 %	−5.3 %	−7.8 %	−8.8 %
Market	5.0 %	7.4 %	8.6 %	4.4 %	6.5 %	7.6 %	−0.6 %	−0.9 %	−1.0 %

This table presents sector-level carbon overhang estimates under both baseline and adjusted specifications, reported in aggregate dollar terms and as a percentage of sector market capitalization. The adjusted specification reflects an 80 % pass-through of Scope 1 carbon costs from regulated utilities to downstream customers, reallocating carbon liabilities across sectors. Brown sectors include utilities, energy, materials, and industrials, while green sectors include consumer discretionary, consumer staples, technology, telecom, health care, financials, and real estate. The sample includes 2420 U.S.-listed firms with firm-specific carbon emissions and carbon price forecasts as of year-end 2023.

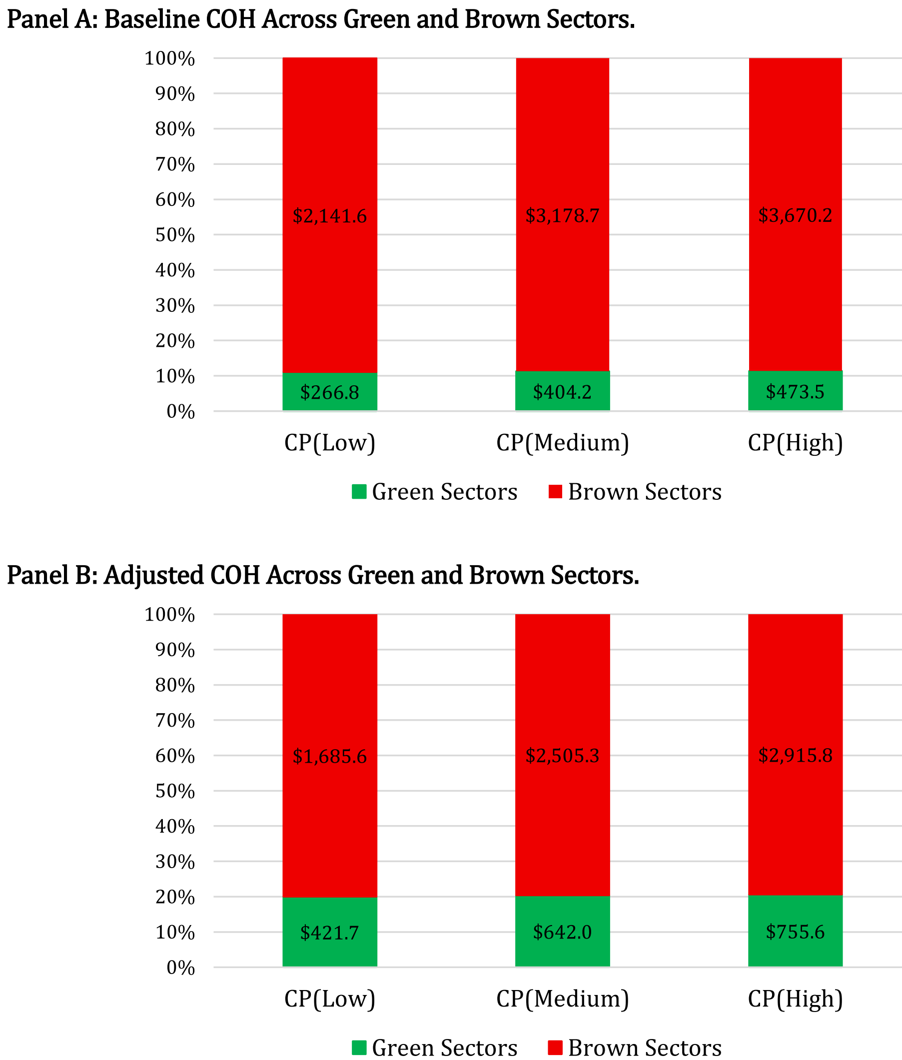


Fig. 4. Carbon overhang across green and brown sectors.
This figure presents the distribution of total carbon overhang (COH) across brown and green sectors for the baseline and adjusted COH metrics under low, medium, and high carbon price (CP) scenarios. Panel A shows the share of total COH attributable to each sector grouping under the baseline specification. Panel B shows the distribution after adjusting for Scope 2 pass-through costs from regulated utilities. Brown sectors include Utilities, Energy, Materials, and Industrials, while Green sectors include Consumer Discretionary, Consumer Staples, Information Technology, Telecom, Health Care, Financials, and Real Estate. The sample includes 2420 U. S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Consumer Discretionary and Consumer Staples absorb $138.9 billion (23 %), followed by Technology and Telecom with $66.7 billion (11 %), Industrials with $50.7 billion (8 %), Financials and Real Estate with $48.7 billion (8 %), and Health Care with $27.8 billion (5 %). Relative to market capitalization, the Materials sector is most affected, with Scope 2 pass-through costs exceeding 12 % of its market cap. This is followed by Energy (7.5 %), Consumer Staples (2.3 %), and Industrials (1.1 %).

Collectively, the adjusted COH for green sectors increases by $155 billion under the low scenario and by $282 billion under the high scenario, representing 0.4 % to 0.7 % of their aggregate market capitalization. In contrast, the COH for brown sectors declines by $456 billion to $754 billion, corresponding to reductions of 5.3 % to 8.8 % of brown sector market value. Reflecting this reallocation, the stacked bar chart in Panel B of Fig. 4 shows the share of green sectors in total carbon overhang rising from 10 % under the baseline specification to 20 % under the adjusted specification, with a corresponding decline in the brown sector share from 90 % to 80 %.

The sector-level analysis underscores the highly uneven distribution of carbon liabilities across sectors. However, while carbon overhang systematically varies across sectors, substantial heterogeneity remains within sectors. To quantify this firm-level variation, we estimate a cross-sectional regression of firm-level log carbon overhang scaled by market value (COH/MV) on sector fixed effects. The adjusted R^2 from this regression captures the share of variation in log COH/MV explained by sector-level differences, while the residual reflects intra-sector variation. As shown in the stacked bar charts in Fig. 5, sector fixed effects explain

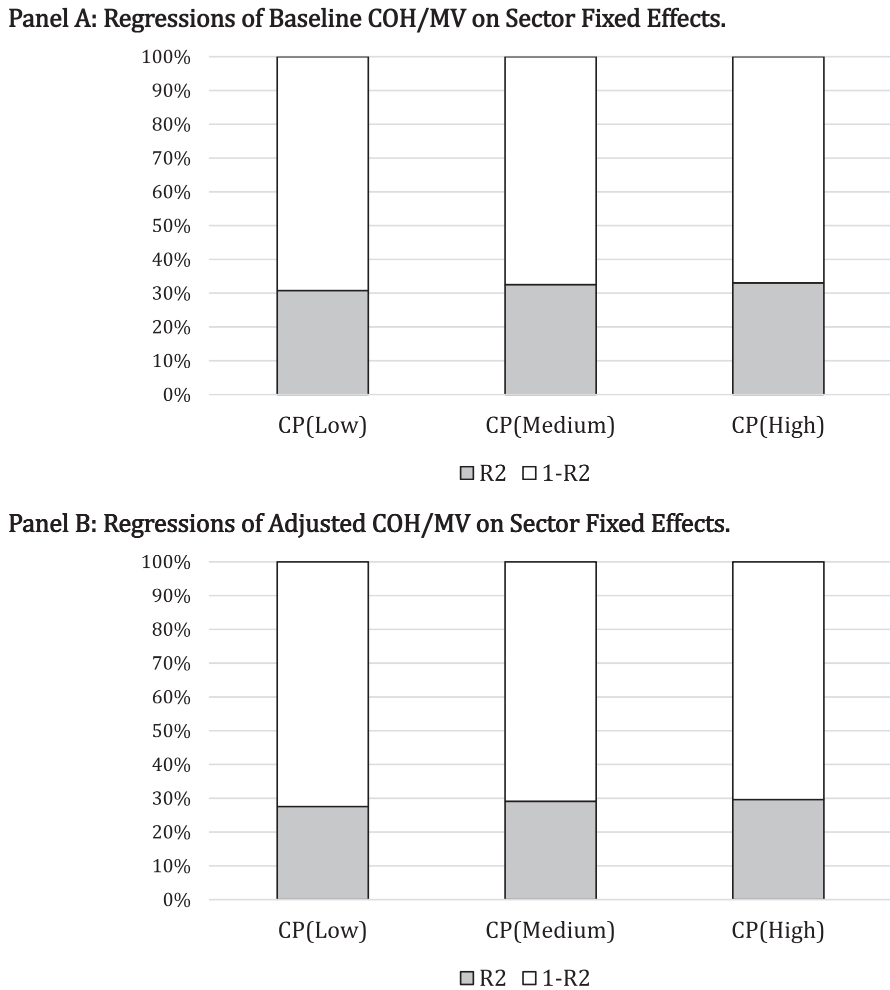


Fig. 5. Decomposing carbon overhang heterogeneity.
This figure presents adjusted R^2 values from regressions of the log ratio of carbon overhang to market value (log COH/MV) on sector fixed effects under low, medium, and high carbon price (CP) scenarios. Panel A uses baseline COH estimates based on Scope 1 emissions. Panel B uses adjusted COH estimates that account for the pass-through of Scope 2 costs from regulated utilities. Within-sector heterogeneity is captured by 1 minus the adjusted R^2. The sample includes 2420 U.S.-listed firms with carbon emissions and carbon price forecasts as of year-end 2023.

approximately 35 % of the cross-sectional variation in COH/MV under the baseline estimates (Panel A) and 30 % under the adjusted estimates (Panel B). These results imply that 65 % to 70 % of the variation in firm-level carbon overhang arises from differences among firms within the same sector. This breakdown highlights the importance of both sector-wide and firm-specific factors—such as emissions geography, decarbonization targets, and operational structure—in shaping the firm-specific valuation of carbon liabilities.

Together, the evidence shows that while sector-level averages are useful for understanding broad cross-sector patterns, they obscure significant firm-level differences in carbon liability. The COH/MV ratio provides a firm-specific measure of carbon exposure, enabling investors to compare firms within the same sector and better assess relative carbon risk among peers.[10]

3.2.4. Carbon overhang concentration

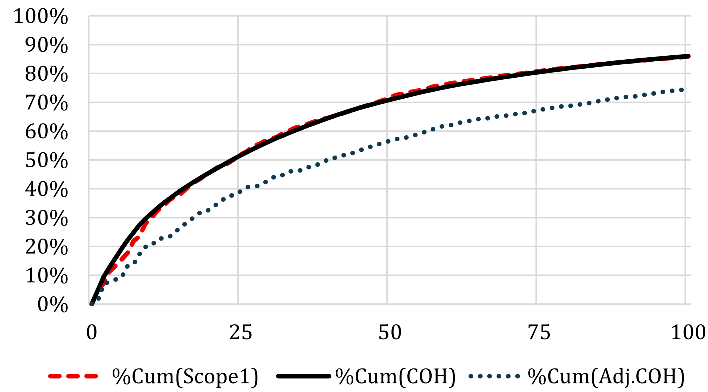
We next examine the concentration of aggregate carbon overhang among large corporate emitters. Panel A of Fig. 6 reports the cumulative share of total COH accounted for by the top 100 firms in our sample of 2420 companies, sorted by firm-specific COH values from highest to lowest. Among these top 100 firms, 95 operate in brown sectors, including 33 in Utilities, 26 in energy, 19 in Materials, and 17 in Industrials. The remaining five firms include Berkshire Hathaway Inc., Amazon.com, Inc., Archer-Daniels-Midland Company, Walmart Inc., and Tyson Foods, Inc. While these companies fall outside the brown sector grouping, they are nonetheless significant Scope 1 emitters.[11]

The distribution of carbon overhang is highly concentrated. The top 25 firms account for approximately 52 % of aggregate COH, the top 50

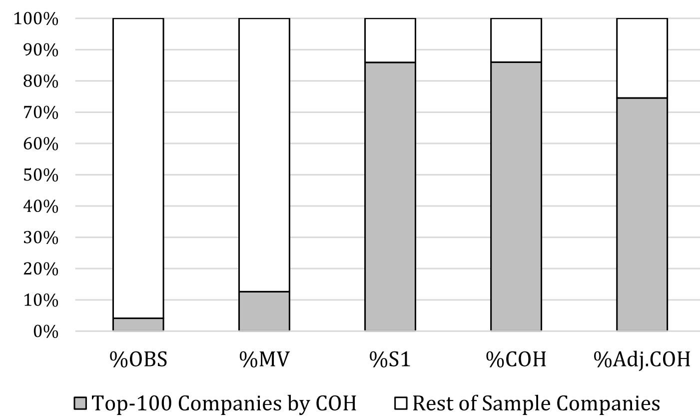
[10] The COH/MV ratio should not be viewed as a literal measure of downside risk, since some portion of the carbon overhang may already be priced in. Translating it into a risk estimate requires an assumption about the fraction λ of COH that is already incorporated into market value: *Downside Risk* $= (1 - \lambda) \times (COH/MV)$. If $\lambda = 0$, the full overhang is unpriced; if $\lambda = 1$, it is fully priced. Estimating the value of λ is nontrivial and beyond this paper's scope.

[11] Berkshire Hathaway's Scope 1 emissions are driven by carbon-intensive subsidiaries such as BNSF Railway and Berkshire Hathaway Energy, which operate freight rail systems, power generation assets, and natural gas infrastructure. Amazon's direct emissions primarily arise from its expansive logistics and delivery operations, including trucking fleets, fulfillment centers, and air freight. Archer-Daniels-Midland runs large, energy-intensive agricultural processing facilities. Walmart's emissions stem from the energy use of its vast network of retail stores, warehouses, and vehicle fleets. Tyson Foods contributes direct emissions through meat processing activities involving combustion, refrigeration, and on-site energy use.

Panel A: Carbon Overhang Concentration.



Panel B: Top-100 Concentration.



	%OBS	%MV	%S1	%COH	%Adj. COH
Top-100 Companies by COH	4%	13%	86%	86%	75%
Rest of Companies	96%	87%	14%	14%	25%

Fig. 6. Carbon overhang concentration.
This figure presents the degree of COH concentration among the top 100 firms ranked by COH under the medium carbon price scenario. The degree of COH concentration is consistent across all three price scenarios (low, medium, and high). Panel A shows the cumulative share of total COH accounted for by the top 100 firms. Panel B compares the COH, market cap, and sample representation of these top 100 firms to the full sample of 2420 U.S.-listed firms as of year-end 2023. COH values reflect baseline estimates based on Scope 1 emissions.

for 71 %, the top 75 for 80 %, and the top 100 for 86 %. This pattern closely mirrors the distribution of emissions: the top 100 firms by COH also account for 86 % of total Scope 1 emissions in our sample. In contrast, as the stacked bar chart in Panel B of Fig. 6 shows, these firms represent just 13 % of total market cap and 4 % of sample observations. This concentration reflects the fact that carbon overhang is largely driven by a small set of firms with large and persistent direct emissions profiles, and is consistent with the right-skewed cross-sectional distribution of corporate emissions documented by Hartzmark and Shue (2022).

Accounting for the pass-through cost of Scope 2 emissions has a material effect on the distribution of COH. Under the adjusted specification, the share of aggregate COH attributed to the top 100 firms declines from 86 % to 75 %, reflecting a shift in cost liability from regulated utilities to other firms. While adjusted COH remains highly concentrated, it is less so than under the baseline specification because some of the Scope 1 emissions cost—originally borne by regulated utilities—is now passed through to other firms across sectors.

For additional context, Table 6 lists the top 25 firms ranked by estimated carbon overhang. The top 10 are dominated by utilities and energy companies. The Southern Company ranks first, with a carbon overhang between $115.2 billion and $192.1 billion across carbon price scenarios. Berkshire Hathaway Inc. follows, driven by its ownership of high-emitting subsidiaries. Other major utilities in the top 10 include Duke Energy, Xcel Energy, NextEra Energy, Vistra Corp., and Entergy Corporation, each operating large fossil-fuel-based power generation fleets. Marathon Petroleum, Phillips 66, and ExxonMobil round out the top 10, reflecting substantial emissions from refining and upstream production activities, including fuel combustion, gas flaring, and hydrocarbon processing.

Beyond the top 10, the list includes additional utilities such as PPL Corporation, American Electric Power, DTE Energy, and Dominion Energy, along with Chevron and Valero Energy from the oil and gas sector. Several firms outside the utilities and energy sectors also appear, including FedEx, American Airlines, Delta Air Lines, United Airlines, CF Industries, Dow Inc., and U.S. Steel. These companies operate in carbon-intensive industries such as transportation, chemicals, and steel production, and report high levels of Scope 1 emissions from combustion processes, jet fuel use, and industrial operations.

The impact of adjusting for Scope 2 emissions is especially pronounced for utilities, which experience COH reductions of approximately 80 % across carbon price scenarios. For example, The Southern Company sees its COH decline from $192 billion to $39 billion under the high scenario. Similarly, Duke Energy, Xcel Energy, and NextEra Energy

Table 6
Top-25 firms by carbon overhang value.

Company name	Sector	MV	Baseline COH across scenarios			Adjusted COH across scenarios		
			Low	Medium	High	Low	Medium	High
The Southern Company	Utilities	$76.5	$115.2	$169.8	$192.1	$23.4	$34.5	$39.0
Berkshire Hathaway Inc.	Financials	$776.9	$112.4	$168.7	$195.8	$122.9	$184.6	$214.2
Duke Energy Corporation	Utilities	$74.8	$83.2	$121.2	$134.7	$17.1	$25.0	$27.8
Xcel Energy Inc.	Utilities	$34.2	$76.8	$115.1	$133.3	$16.6	$24.8	$28.7
NextEra Energy, Inc.	Utilities	$124.6	$75.1	$112.6	$130.4	$15.0	$22.6	$26.1
Marathon Petroleum Corporation	Energy	$56.3	$70.3	$105.2	$121.3	$82.4	$123.2	$142.1
Vistra Corp.	Utilities	$13.8	$66.6	$97.3	$108.6	$13.5	$19.7	$22.0
Phillips 66	Energy	$58.6	$62.2	$94.4	$110.5	$73.0	$111.1	$130.3
Exxon Mobil Corporation	Energy	$399.6	$51.2	$74.9	$87.2	$54.2	$79.3	$92.3
Entergy Corporation	Utilities	$21.4	$45.5	$67.1	$75.8	$9.1	$13.4	$15.2
Chevron Corporation	Energy	$280.7	$42.8	$66.6	$80.5	$45.3	$70.6	$85.3
PPL Corporation	Utilities	$20.0	$41.2	$61.2	$70.0	$8.3	$12.3	$14.0
American Electric Power Company, Inc.	Utilities	$42.7	$38.1	$55.4	$61.4	$8.7	$12.7	$14.2
DTE Energy Company	Utilities	$22.7	$36.8	$54.3	$61.5	$37.0	$54.6	$61.9
FedEx Corporation	Industrials	$63.2	$40.0	$52.9	$61.6	$41.5	$55.1	$64.1
American Airlines Group Inc.	Industrials	$9.0	$39.5	$48.8	$54.1	$39.7	$49.0	$54.4
Delta Air Lines, Inc.	Industrials	$25.8	$37.1	$48.0	$55.1	$37.3	$48.2	$55.3
Valero Energy Corporation	Energy	$44.3	$30.4	$45.6	$52.9	$35.0	$52.6	$61.1
Evergy, Inc.	Utilities	$12.0	$29.9	$44.0	$49.8	$6.0	$8.8	$10.0
Dow Inc.	Materials	$38.5	$28.6	$42.8	$49.5	$30.4	$45.8	$53.2
United Airlines Holdings, Inc.	Industrials	$13.5	$32.4	$42.5	$49.1	$32.6	$42.7	$49.4
Kinder Morgan, Inc.	Energy	$39.2	$27.1	$42.1	$49.3	$32.1	$49.7	$58.0
CF Industries Holdings, Inc.	Materials	$15.2	$27.2	$40.7	$47.8	$28.0	$42.0	$49.3
Dominion Energy, Inc.	Utilities	$39.3	$27.1	$40.3	$46.1	$5.9	$8.8	$10.0
United States Steel Corporation	Materials	$10.9	$26.9	$38.8	$43.4	$29.5	$42.6	$47.7

This table presents the top 25 firms ranked by estimated carbon overhang (COH) across low, medium, and high carbon price scenarios. Adjusted carbon overhang (ACOH) reflects the pass-through of Scope 2 carbon costs. Estimates are based on firm-specific emissions and carbon price forecasts from 2024 to 2050. Firms are listed with sector and market capitalization. The sample includes 2420 U.S.-listed firms as of year-end 2023.

each experience reductions exceeding $100 billion. Among non-utility companies in the top 25, FedEx and Dow Inc. see COH increases of roughly 4 % to 7 %, while ExxonMobil and Chevron experience increases of about 6 %. In absolute terms, the largest increases are observed for Berkshire Hathaway, whose COH rises by more than $18 billion, and Marathon Petroleum, which sees an increase of over $20 billion under the high scenario. These changes reflect the reallocation of electricity-related carbon liabilities to major industrial and commercial electricity consumers.

Together, the top 25 firms by COH represent a concentrated source of carbon-related financial exposure. Their prominence underscores the importance of integrating emissions data and carbon pricing risk into corporate valuation frameworks, particularly in sectors with large and persistent emissions. Our estimates further show that accounting for Scope 2 pass-through costs broadens the distribution of carbon liabilities but still leaves a majority of financial exposure concentrated in a small set of high-emitting firms.

3.3. Corporate carbon overhang vs. societal carbon burden

In a related study, Pástor et al. (2024) quantify the societal externality of corporate emissions—what they term the *societal carbon burden*. This metric captures the present value of future societal damages from a firm's emissions, calculated as the product of projected emissions and the Social Cost of Carbon (SCC). Unlike regulatory carbon prices, the SCC reflects the estimated economic harm from emitting one additional ton of greenhouse gases, including effects on public health, agriculture, infrastructure, and ecosystems. Pástor et al. (2024) discount these costs using a social discount rate rather than firm-specific costs of equity capital. Their metric, developed from the perspective of social planners, measures the *gross externality* of corporate emissions.

By contrast, our *corporate carbon overhang (COH)* metric is developed from the perspective of investors and capital markets. It estimates the present value of future carbon costs that firms are expected to incur under current and anticipated carbon pricing regimes, including emissions trading schemes, carbon taxes, and fossil fuel taxes.

Our approach differs from that of Pástor et al. (2024) in two key respects. First, we calculate carbon costs as the product of firm-specific emissions forecasts and jurisdiction-specific carbon price projections, whereas they compute societal carbon damages using the SCC. Second, we discount these costs using each firm's cost of equity capital—consistent with standard corporate valuation methods—whereas they rely on a social discount rate.

Together, these two metrics allow us to estimate the *net externality* of corporate emissions as the difference between the societal carbon burden and the corporate carbon overhang:

$$\textit{Net Externality} = \textit{Societal Carbon Burden} - \textit{Corporate Carbon Overhang}.$$

The net externality reflects the share of societal damages that are not expected to be internalized into corporate financials through current and anticipated carbon pricing regimes. The ratio of corporate carbon overhang to societal carbon burden measures the *internalization rate*—that is, the fraction of societal damages expected to be internalized into corporate financials:

$$\textit{Internalization Rate} = \frac{\textit{Corporate Carbon Overhang}}{\textit{Societal Carbon Burden}}.$$

The complement of the internalization rate—one minus the internalized share—defines the internalization gap, or the portion of societal carbon damages borne by society rather than firms. This gap also signals potential future regulatory exposure, reputational risk, and strategic misalignment.

$$\textit{Internalization Gap} = 1 - \textit{Internalization Rate}.$$

Replicating Pástor et al. (2024), we compute the societal carbon burden for each firm by substituting firm-specific carbon prices and discount rates with the EPA's headline SCC estimates and a baseline 2 % social discount rate (both in real terms). These firm-level estimates are then aggregated to produce a market-level societal carbon burden. Panel A of Table 7 reports the estimated market-level societal carbon burden for our representative sample of the U.S. stock market. The societal carbon burden from projected corporate emissions in our sample is

Table 7
Carbon burden internalization rates.

Panel A: Carbon overhang vs. carbon burden

	Carbon overhang at social discount rate ($BN)			Societal carbon burden ($BN)
	Low carbon price scenario	Medium carbon price scenario	High carbon price scenario	
Green Sectors	$1144.01	$1813.47	$2241.29	$7995.24
Brown Sectors	$8312.47	$13,001.22	$15,934.22	$55,284.06
Market	$9456.47	$14,814.68	$18,175.51	$63,279.30

Panel B: Internalization rates

	Internalization rates		
	Low carbon price scenario	Medium carbon price scenario	High carbon price scenario
Green Sectors	14.3 %	22.7 %	28.0 %
Brown Sectors	15.0 %	23.5 %	28.8 %
Market	14.9%	23.4 %	28.7 %

This table reports the estimated societal carbon burden, the corporate carbon overhang (COH) computed using a 2 % social discount rate, and resulting internalization rates across low, medium, and high carbon price scenarios. The societal carbon burden is defined as the present value of projected future societal damages from firm emissions, calculated using the EPA's headline Social Cost of Carbon (SCC) and discounted at the 2 % social discount rate. Internalization rates represent the share of these societal damages expected to be borne by firms through existing and anticipated carbon pricing. The sample includes 2420 U.S.-listed firms with firm-specific carbon emissions and carbon price forecasts as of year-end 2023.

estimated at $63.28 trillion, corresponding to 1.3 times the aggregate market capitalization of $48.23 trillion.

To enable a consistent comparison between the societal carbon burden and the COH metric, we re-estimate the corporate carbon overhang using the social discount rate in place of firm-specific costs of equity. This ensures conceptual alignment: when projected carbon prices equal the SCC, the internalization rate converges to 100 % and the internalization gap converges to 0 %. Accordingly, we express annual carbon cost forecasts in real terms and apply the 2 % social discount rate. Using the social discount rate, the adjusted market-level carbon overhang estimates across carbon price scenarios are $9.5 trillion (low), $14.8 trillion (medium), and $18.2 trillion (high). These figures are approximately four times higher than our baseline estimates of $2.41 trillion, $3.58 trillion, and $4.14 trillion, respectively, reported in Panel A of Table 4. The difference reflects the shift from the cost of equity capital to the lower social discount rate applied in this analysis.

Panel B of Table 7 reports the corresponding internalization rates, computed as the ratio of corporate carbon overhang to the societal carbon burden (both under the 2 % social discount rate)—measuring the share of societal damages expected to be internalized into firms' financials through current and projected carbon pricing mechanisms. These rates range from 15 % in the low scenario to 23 % in the medium scenario and 29 % in the high scenario. These figures suggest that, even under the most ambitious pricing assumptions, prevailing and expected carbon pricing regimes are projected to internalize less than one third of the societal damages from corporate emissions.

We also disaggregate these results by sector grouping. Brown sectors account for 87 % of the estimated societal carbon damages, and green sectors for 13 %—consistent with sectoral differences in emissions intensity. Notably, the estimated internalization rates are relatively similar across brown and green sectors, indicating that current carbon pricing regimes are not expected to disproportionately internalize costs for the most emissions-intensive industries. This highlights the broad-based nature of the internalization gap and the potential for policy shifts to affect firms across the emissions spectrum.

The distinction between gross externality (societal carbon burden) and net externality (societal carbon burden minus the corporate carbon overhang) is critical for multiple stakeholders: for investors, it speaks to the materiality of carbon pricing risk; for regulators, it informs the effectiveness and reach of carbon pricing mechanisms; and for policymakers, it quantifies the gap between private incentives and societal climate goals.

Overall, our findings underscore the need for carbon pricing policies that more fully align market incentives with societal costs. Although SCC estimates have risen in recent years (e.g., Tol, 2023), actual and expected carbon prices remain well below these levels. As a result, a substantial share of corporate emissions is likely to remain unpriced in the foreseeable future.

4. Conclusion

This study introduces the corporate carbon overhang (COH) as a forward-looking measure of firm-level carbon liability, providing a valuation framework to quantify the financial consequences of prevailing and anticipated carbon pricing mechanisms. A firm's carbon liability depends not only on how much it emits, but also on when and where those emissions occur, and how regulatory carbon prices evolve over time.

By integrating firm-specific emissions projections, jurisdiction-adjusted carbon price forecasts, and appropriate discounting, COH captures the present value of expected carbon costs that firms are likely to internalize under future regulatory regimes. Our empirical analysis shows that carbon overhang is economically significant—ranging from 5 % to nearly 9 % of total market capitalization across scenarios—and highly concentrated, both across and within sectors. Accounting for the pass-through of indirect emissions from regulated utilities leads to a substantial reallocation of carbon cost exposure—from regulated utilities to non-regulated utilities and non-utility firms—and shifts a material share of the burden to electricity consumers outside the sample, with 55 % absorbed by public firms (primarily in Materials and Energy, followed by Consumer Discretionary and Consumer Staples) and 45 % by the broader economy, including private businesses, households, and the public sector.

Overall, our COH valuation framework underscores the importance of accurate, forward-looking, and location-specific emissions and carbon price forecasts as essential inputs for incorporating carbon risk into financial analysis and valuation. Importantly, our analysis also quantifies a substantial internalization gap: even under the most ambitious policy scenario, current and anticipated carbon pricing mechanisms—including emissions trading schemes, carbon taxes, and fossil fuel taxes—are expected to recover less than one third of the total societal costs of corporate emissions. This suggests that market-based incentives alone may be insufficient to fully align private behavior with societal climate goals. In this context, the COH framework offers investors a practical tool for incorporating carbon risk into valuation and provides policymakers with a foundation for advancing disclosure reform, refining carbon pricing, and strengthening transition risk oversight.

As climate risks become more financially material, integrating robust emissions forecasts, emissions location data, and transparent carbon cost projections into financial analysis will be critical for efficient capital allocation and long-term value preservation. Our study further highlights the need for improved emissions forecasting, enhanced geographic disclosure, and third-party verification of climate-related data. Looking ahead, publicizing firm-level COH estimates—and enabling peer comparisons—could incentivize emissions reductions by increasing transparency around firms' relative exposure to future carbon costs. Ultimately, incorporating carbon liabilities into corporate valuation will be essential for aligning financial markets with global climate transition objectives.

CRediT authorship contribution statement

Byung Hyun Ahn: Software, Formal analysis. **Sunil Dutta:** Writing – original draft, Conceptualization. **Panos N. Patatoukas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.109022.

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