

The Network Origins of the Carbon Risk Premium

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Introduction

Who bears carbon transition risk?

- **Standard intuition:** the burden falls on high-emission (“brown”) firms.
- **But carbon risk need not stay where emissions occur.**
 - Firms are linked through **input–output networks**.
 - Carbon-related shocks propagate **among customers and suppliers**.
 - **“Network-brown” firms** Firms with modest emissions can be highly exposed via trading partners.
- **Preview of the headline.** “Network-brown” firms:
 - Produce $< 2\%$ of aggregate Scope 1 emissions,
 - Yet bear $\approx 27\%$ of the aggregate carbon risk premium.
- Emissions identify where carbon is **produced**; networks identify where carbon risk is **borne**.

This Paper

1. **Theory.** A tractable GE asset-pricing framework with input–output linkages, carbon emissions, and aggregate regulatory risk.
 - A model-based coherent measure of indirect carbon risk exposure.
 - Cross-sectional carbon risk premium captured by a **sufficient statistic**:

$$\underbrace{\gamma}_{\text{direct}} + \underbrace{\chi}_{\text{network-propagated indirect}} .$$

2. **Measurement.** Construct industry- and firm-level γ and χ
 - χ is a covariance-based, pricing-relevant exposure — *not* Scope 3 emissions (firm-level correlation ≈ 0.11).
 - χ dominates γ in the cross-section: $\approx 85\%$ of the premium.
3. **Incidence accounting.** Translate pricing estimates into macro objects.
 - Document a systematic **emissions-vs-exposure misalignment**.
 - “Network-brown” firms: $< 2\%$ of emissions, $\approx 27\%$ of the premium, and a comparable share of regulatory-shock wealth losses.

Related Literature

- Carbon risk & the cross-section of returns

Bolton & Kacperczyk (2021, 2023); Pástor, Stambaugh & Taylor (2022); Hsu, Li & Tsou (2023); Aswani et al. (2024); Atilgan et al. (2024); Zhang (2025); Eskildsen et al. (2024).

- This paper: reconcile mixed evidence by indirect network exposure χ .

- Production networks & asset pricing

Ahern (2013); Herskovic et al. (2018); Richmond (2019); Gofman, Segal & Wu (2020); Yang (2020). Foundations: Acemoglu et al. (2012); Carvalho & Tahbaz-Salehi (2019).

- This paper: GE pricing of a specific aggregate risk (carbon transition) transmitted through I–O linkages.

- Climate policy, supply chains & regulatory risk

Croce et al. (2026), Sautner et al. (2023a, b); Pástor et al. (2024); Aghion et al. (2025); Ilhan, Sautner & Vilkov (2021); Hong, Li & Xu (2019); Nordhaus (2019).

- This paper: χ is a covariance-based GE object, distinct from Scope 3

Theoretical Framework

Model in one slide

- Two periods $t = 0, 1$; N industries with a continuum of competitive firms; representative household with log utility.

Production with I–O network

$$Y_{jt} = \xi_j X_{jt}^{\eta_j},$$

$$X_{jt} = \prod_{k=1}^N X_{jkt}^{a_{jk}}.$$

- $\mathbf{A} = [a_{jk}]$: I–O matrix; $a_{jk} \geq 0$, $\sum_k a_{jk} = 1$.
- $\eta_j \in (0, 1)$: intermediate-input share.

Carbon emissions & regulation

- Emission intensity γ_j (units of carbon per \$ of output).
- Effective tax rate $\tau_{jt} = \gamma_j \tau_t$.
- After-tax revenue:
 $(1 - \tau_{jt}) P_{jt} Y_{jt}$.
- τ_t : aggregate **carbon regulatory risk**, $\mathbb{E}\tau_t = \bar{\tau}$, $\text{Var} = \sigma_\tau^2$.

Two channels through which τ_t reaches industry j 's profits:

- **Direct** — through industry j 's own emissions γ_j .
- **Indirect** — through customers' demand contraction, transmitting back along the supply chain.

Domar weight and indirect exposure χ

Domar weight of industry j at time t :

$$S_{jt} = \frac{\Psi_{jt}}{P_t C_t}, \quad \Psi_{jt} = P_{jt} Y_{jt} \text{ (pre-tax revenue).}$$

From firms' and households' optimality + market clearing:

$$S_{jt} = \alpha_j + \sum_{k=1}^N (1 - \gamma_k \tau_t) \eta_k a_{kj} S_{kt} \iff \mathbf{S}_t = \boldsymbol{\alpha} + \mathbf{A}' \mathbf{D}_\eta (\mathbf{I} - \mathbf{D}_\gamma \boldsymbol{\tau}_t) \mathbf{S}_t.$$

Lemma 1 (Network exposure)

Linearizing around $t = 0$, the Domar-weight growth rates satisfy

$$\Delta \log \mathbf{S}_t = -\boldsymbol{\chi} \boldsymbol{\tau}_t, \quad \boldsymbol{\chi} = \mathbf{D}_S^{-1} (\mathbf{I} - \mathbf{A}' \mathbf{D}_\eta)^{-1} \mathbf{A}' \mathbf{D}_\eta \mathbf{D}_S \boldsymbol{\gamma} > \mathbf{0}.$$

- χ_j aggregates all indirect exposures arising from I–O linkages.
- In a recursive expansion, χ_j collects 1st-, 2nd-, 3rd-order ... propagation paths from downstream customers back to j .

Profit, returns, and the sufficient statistic

Proposition 1 (Profit response)

$$\Pi_{jt} = \Pi_{j0} (1 + \phi_{\pi j} \tau_t + \Delta \log C_t),$$

where

$$\phi_{\pi j} = - \underbrace{\gamma_j}_{\text{direct}} - \underbrace{\chi_j}_{\text{network indirect}} < 0.$$

Theorem 2 (Cross-section of expected returns)

$$\mathbb{E} r_{jt} = r_t^f + \phi_{\pi j} \phi_C \sigma_\tau^2 + \text{Var}(\Delta \log C_t), \quad \phi_C < 0.$$

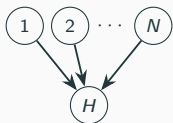
The cross-sectional ranking of $\mathbb{E} r_{jt}$ is determined entirely by

$$\gamma_j + \chi_j.$$

Take-away: A firm's pricing-relevant carbon exposure is **own emissions** + **network exposure** — never γ_j alone.

Three network examples

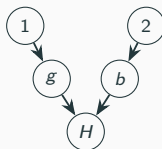
(a) Horizontal



(b) Vertical chain



(c) Centrality



(a) Horizontal.

No I-O linkages.

$$\chi_j = 0 \quad \forall j.$$

Only direct γ matters.

(b) Vertical chain.

$$\eta_j = \eta, \quad \gamma_j = \gamma, \quad S_{j0} = S_0:$$

$$\chi_j = \frac{\eta(1-\eta)^{N-j}}{1-\eta} \gamma.$$

Upstream firms: larger χ .

(c) Centrality.

$$\gamma_1 = \gamma_2 \text{ but } \gamma_b > \gamma_g:$$

$$\chi_1 = \eta \gamma_g < \chi_2 = \eta \gamma_b.$$

$$\Rightarrow \mathbb{E} r_2 > \mathbb{E} r_1.$$

Network exposure depends on *who your customers are*, not just on your own emissions.

Empirical Measurement

Sample. U.S. public firms, annual + monthly data, 2002–2023; 2,698 firms.

Firm-level data

- **Carbon emissions:** Trucost (Scopes 1–3). Construction follows Bolton & Kacperczyk (2021); winsorize at 2.5%.
- **Stock returns:** CRSP.
- **Financials & ICC:** Compustat. ICC follows Hou, van Dijk & Zhang (2012).
- **Business segments:** Compustat Segments, used to allocate firms across industries.

Industry-level data

- **Input-output matrix:** BEA detailed tables. Annual 71-industry tables (1997–2023).
- **Make tables:** BEA, used to compute Domar weights.

Macro / regulatory

- **Carbon Regulatory Index:** constructed from $\approx 50,000$ *Wall Street Journal* articles via GPT-4o-mini (see slide on CRI).

Constructing γ and χ

Step 1. Direct exposure γ (firm and industry).

$$\gamma_{i,t} = \frac{\text{Emissions}_{i,t}}{\text{Revenue}_{i,t}}, \quad \gamma_{j,t} = \sum_{i \in j} w_{ij,t} \gamma_{i,t} \text{ (sales-weighted).}$$

Step 2. Industry indirect exposure χ (from Lemma 1).

$$\chi_t = D_S^{-1} (I - A' D_\eta)^{-1} A' D_\eta D_S \gamma_t.$$

- A : BEA 71-industry I-O matrix. **Input-Output Matrix**
- $D_\eta = \text{diag}(\eta_j)$ with $\eta_j = \text{COGS}_j / \text{Revenue}_j$. **Return-to-scale matrix**
- $D_S = \text{diag}(S_j)$: Domar weights from BEA tables. **Domar weights matrix**

Step 3. Firm-level χ via Compustat business segments.

$$\chi_{i,t} = \sum_j \frac{\text{sale}_{ij,t-1}}{\sum_k \text{sale}_{ik,t-1}} \chi_{j,t}.$$

Multi-segment firms get a weighted average of industry-level χ 's.

Carbon Risk Exposure across Industries

- Top 10 industries by indirect (χ) carbon risk exposure ► Decomposition

BEA Code	Industry Description	χ	γ	$\chi + \gamma$
211	Oil and Gas Extraction	2.373	0.500	2.873
486	Pipeline Transportation	2.194	0.787	2.981
331	Primary Metals	0.868	1.362	2.230
212	Mining, Except Oil and Gas	0.708	0.882	1.591
482	Rail Transportation	0.589	0.517	1.107
324	Petroleum and Coal Products	0.393	0.369	0.762
22	Utilities	0.344	3.514	3.859
212	Support Activities for Mining	0.328	0.116	0.444
327	Nonmetallic Mineral Products	0.233	0.467	0.700
331	Truck Transportation	0.182	0.118	0.300

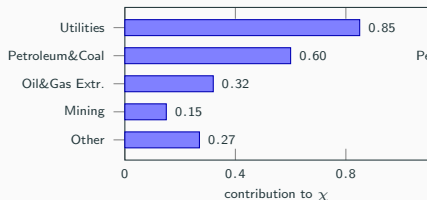
Indirect exposure: (χ); Direct exposure: (γ); Total exposure: ($\gamma + \chi$)

Case Study: Pipeline Transportation vs. Utilities

Decompose indirect exposure: $\chi_j = \sum_k \mathcal{L}_{jk} \gamma_k$ (contribution of industry k to j 's χ).

Pipeline Transportation

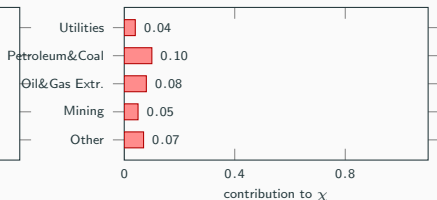
$\gamma = 0.79$, $\chi = 2.19$ (top of χ)



Two carbon-intensive suppliers (Utilities, Petroleum & Coal) drive most of χ .

Utilities

$\gamma = 3.51$ (top of γ), $\chi = 0.34$



Production structure self-contained \Rightarrow small spillovers from carbon-intensive sectors.

High direct $\gamma \neq$ high network χ . Where carbon is *emitted* differs from where it is *borne*.

χ is not Scope 3 emissions

Conceptual distinction

- **Scope 3**: accounting measure of *embodied carbon quantities* through the supply chain. Comparability across firm is limited.
- χ : a *general-equilibrium covariance* object — how firm cash flows co-move with aggregate carbon shocks, transmitted via Domar weights.

Empirically distinct

- Firm-level $\text{corr}(\chi, \text{Scope 3}) \approx 0.11$.
- Industry-level $\text{corr} \approx 0.14$.

χ captures pricing-relevant carbon risk exposure that Scope 3 emissions do not.

Horse race: add Scope 3 to baseline ICC regression

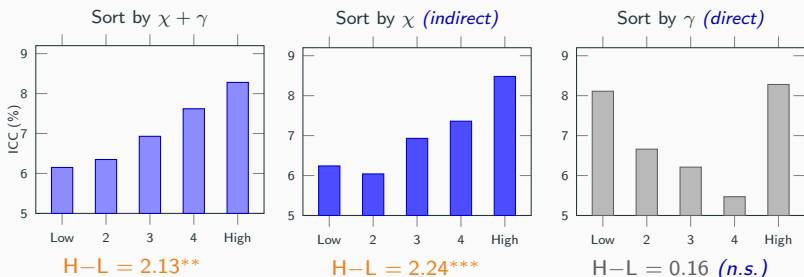
	Baseline	+ Scope 3
χ	1.25*** (5.85)	1.27*** (5.99)
γ	0.19* (1.75)	—
Scope 3	—	0.027 (0.61)
Controls, FE	Y	Y

Coefficient on χ is essentially unchanged. Scope 3 enters with a small, insignificant coefficient.

Cross-sectional Pricing

Portfolio sorts: ICC quintile spreads

Annual sorts into quintiles; ICC reported in annualized percent. Newey–West (12 lags).



Indirect exposure χ generates a large monotone spread; direct γ alone does not.

Cross-sectional pricing of χ and γ

Panel regression: $ICC_{it} = \alpha + \beta_{\chi} \chi_{it} + \beta_{\gamma} \gamma_{it} + \mathbf{X}'_{it} \beta_x + \text{Fixed Effects} + \epsilon_{it}$.

Exposures standardized; ICC in annualized %; SE clustered at industry.

	Total exposure ($\chi + \gamma$)		Separate χ and γ	
	(1)	(2)	(3)	(4)
$\chi + \gamma$	0.51*** (7.77)	0.78** (2.17)		
χ			1.25*** (5.85)	1.27*** (5.99)
γ			0.19* (1.75)	—
Emissions			—	0.027 (0.61)
Controls	Y	Y	Y	Y
Firm + Month FE	N	Y	Y	Y

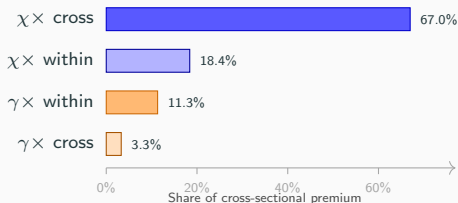
Fama–MacBeth (Newey–West, 12 lags): coefficient on χ is **1.29*****; same story.

One SD higher $\chi \Rightarrow \approx 1.25$ pp higher annualized ICC. γ and emissions: small / fragile.

Within- vs. cross-industry decomposition of the premium

Two-step procedure.

1. Project χ and γ on industry FE \Rightarrow split each into *cross-industry* (industry mean) and *within-industry* (residual) components.
2. Re-estimate ICC regression on all four components. Premium share_c = $\beta_c \times SD(c)$, normalized.



χ total \approx 85% | γ total \approx 15%

Reading the result

- χ delivers \approx 85% of the premium, mostly via the *cross-industry* channel.
- γ delivers \approx 15%, almost entirely *within-industry*.

Implication

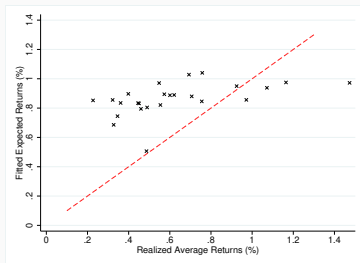
- χ is *not* an industry-FE relabel: within- χ alone is \approx 18%.

Factor-model evaluation: 25 carbon-sorted portfolios

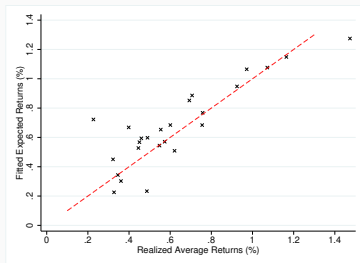
Test assets. 5×5 value-weighted portfolios on γ and χ ; monthly returns, 2002–2023.

Factors. (i) CAPM; (ii) CAPM + γ Factor + χ -Factor.

Panel A: CAPM (rejected)



Panel B: Extended CAPM (not rejected)



Carbon-risk factors absorb the pricing errors that the market factor alone cannot explain.

Carbon Regulatory Risk

The Carbon Regulatory Shock (CRS)

Goal. An aggregate, time-varying measure of *carbon regulatory risk*.

Construction. We filter $\approx 50,360$ *Wall Street Journal* articles (1996–2023) on energy keywords (Acharya et al., 2025), then use *GPT-4o-mini* ($T = 0$) to classify each article as

“going up” / “going down” / “unknown”.

The monthly Carbon Regulatory Index and the Carbon Regulatory Shock are

$$\text{CRI}_t = \frac{\#\text{up}_t - \#\text{down}_t}{\#\text{articles}_t}, \quad \text{CRI}_t = \alpha + \rho \text{CRI}_{t-1} + \text{CRS}_t, \quad \hat{\rho} = 0.30^{***}.$$

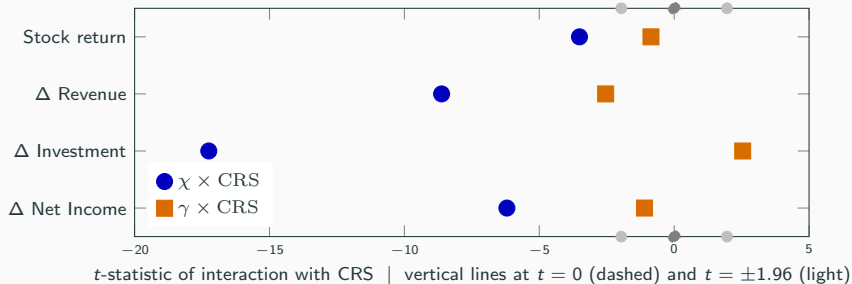
Validation. CRI tracks the firm-based regulatory-risk measure of *Sautner et al.* (2023): annual correlation = 0.753^{***} , quarterly = 0.456^{***} . Spikes also line up with major regulatory episodes (Paris Agreement, IRA, etc.).

CRI is the level of regulatory pressure; CRS is the surprise — what we use in pricing tests.

High- χ firms react more sharply to CRS shocks

Interact CRS with firm-level χ and γ across four outcomes:

$$y_{it} = \alpha + \beta_{\text{CRS}} \text{CRS}_t + \beta_{\text{CRS},\chi} (\chi_{it} \times \text{CRS}_t) + \beta_{\text{CRS},\gamma} (\gamma_{it} \times \text{CRS}_t) + \mathbf{X}'_{it} \beta_x + \text{FE} + \varepsilon_{it}$$



Observations: $\chi \times \text{CRS}$ is large and *negative* on every outcome ($\hat{\beta} \approx -0.17$ pp/mo on returns; -71% on $\Delta \text{Revenue}$; -19% on $\Delta \text{Investment}$). $\gamma \times \text{CRS}$ is small and inconsistently signed (positive for investment).

Network-exposed firms transmit regulatory shocks into real activity — consistent with the model.

Aggregate and Policy Implications

Aggregate incidence: who bears the carbon risk premium?

Setup. Estimate the baseline ICC regression and define each firm's carbon risk premium as

$$\hat{\pi}_i^{\text{carbon}} = \hat{\beta}_\chi \chi_i + \hat{\beta}_\gamma \gamma_i.$$

Sort firms into a 2×2 grid on γ and χ ; aggregate with market-cap weights.

Market-cap share (B)		Share of carbon risk premium (F)			
	$\chi=L$	$\chi=H$		$\chi=L$	$\chi=H$
$\gamma=L$	24.13%	20.04%	$\gamma=L$	3.30%	26.80%
$\gamma=H$	25.22%	30.60%	$\gamma=H$	17.32%	52.60%

Key messages (Low- γ , High- χ = “network-brown”):

- $\approx 20\%$ of aggregate market cap — comparable to high-emission firms.
- Bears **26.80%** of the carbon risk premium — **more** than the 17.32% borne by high- γ /low- χ “classical brown” firms.
- Carbon-policy risk is not confined to high-emission producers.

The emissions–exposure wedge

Do these same firms lose when CRS materializes? Compute average abnormal returns in regulatory-shock months and the group's share of aggregate revaluation losses.

	Policy-shock return (G)	
	$\chi=L$	$\chi=H$
$\gamma=L$	0.16%	-2.62%
$\gamma=H$	-0.84%	-3.33%

	Share of shock losses (H)	
	$\chi=L$	$\chi=H$
$\gamma=L$	1.63%	16.43%
$\gamma=H$	15.91%	66.03%

Compare incidence to emissions:

	Scope 1 emissions share (I)	
	$\chi=L$	$\chi=H$
$\gamma=L$	1.92%	1.76%
$\gamma=H$	36.72%	59.60%

The wedge. The same group that bears

- 26.80% of the carbon risk premium (ex-ante),
- 16.43% of regulatory-shock wealth losses (ex-post),

produces only 1.76% of aggregate Scope 1 emissions.

Emissions are governed by γ . Risk incidence is governed by $\gamma + \chi$.

Real adjustment runs through the network

Does the financial incidence map into real outcomes? Average growth rates during regulatory-shock periods, by group.

Investment growth (K)		Net income growth (L)			
	$\chi=L$	$\chi=H$		$\chi=L$	$\chi=H$
$\gamma=L$	0.21%	-3.25%	$\gamma=L$	0.06%	-1.07%
$\gamma=H$	-0.55%	-1.76%	$\gamma=H$	-0.33%	-0.46%

Key messages:

- **Network-brown firms** contract investment by **-3.25%** during shock periods — the *largest* drop among the four groups.
- Net income declines by **-1.07%**, also the largest contraction.
- Pattern is consistent with $\chi_{it} \times \text{CRS}_t$ effects seen at the firm level.

Aggregate mapping. A reduced-form aggregation, $\frac{\Delta I_{\text{agg}}^{\text{shock}}}{I_{\text{agg}}^{\text{base}}} \approx \hat{\theta}_1 \sum_i w_i \chi_i + \hat{\theta}_2$,

implies a substantial share of the macro investment contraction is driven by firms that are *not* themselves major emitters.

Network exposure shapes the allocation of real adjustment, not just risk premia.

Conclusion

Conclusion

A general-equilibrium asset-pricing framework with input–output linkages, carbon emissions, and aggregate regulatory risk.

- **Theory.** The cross-sectional carbon risk premium is summarized by a sufficient statistic:

$$\mathbb{E} r_{jt} \propto \underbrace{\gamma_j}_{\text{direct}} + \underbrace{\chi_j}_{\text{network-propagated indirect}} .$$

- **Measurement.** Quantify the role of indirect exposure.
- **Incidence accounting.** “Network-brown” firms produce <2% of Scope 1 emissions yet bear $\approx 27\%$ of the carbon risk premium and a comparable share of regulatory-shock losses.

Bottom line. Emissions are governed by γ ; carbon-policy risk is governed by $\gamma + \chi$.

Policy implications. Stress tests, disclosure rules, and transition-policy design built on emissions alone can target the wrong firms.