Online Resource 1

Article: Supply-Chain Carbon Responsibility in Voluntary Carbon Markets: Input-Output Incidence and the Capital-Reallocation Channel in Five Economies

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Author: Ick Jin

Affiliation and e-mail of the corresponding author: NEXT group, Central Tower, 213 Bongeunsa-ro, Gangnam-gu, Seoul 06109, Republic of Korea; rwjin@naver.com

This Online Resource contains Tables S1–S11 referred to in the article. All entries are produced by the vcm module of the replication code (analysis_code.py) from the workbook analysis_data.xlsx. Direct, Network (domestic total-requirements rule) and Total (imports-inclusive total-requirements rule) are the three responsibility designs; PCI is portfolio carbon intensity, VA is value added, pp denotes percentage points and tCO_2e denotes tonnes of carbon dioxide equivalent.

Table S1 Calibration of the coverage parameter to the size of the global VCM, 2022.

Coverage ρ	Credits ($MtCO_2e$)	Cost (USD million)	Share of global VCM value	Max. sector cost / VA	Regime
1%	19	141	7%	0.12%	market-consistent
2.5%	48	353	19%	0.30%	market-consistent
5%	96	705	37%	0.60%	market-consistent
10%	191	1,411	74%	1.19%	carbon-tax-like
25%	479	3,527	186%	2.98%	carbon-tax-like
50%	957	7,054	371%	5.97%	carbon-tax-like
100%	1,914	14,108	743%	11.93%	carbon-tax-like

Notes: Credits are ρ times the 1,914 $MtCO_2e$ emitted by the five economies in 2022. Cost is credits times the observed 2022 price of USD 7.37/tCO_2e. Share of global VCM value is cost divided by the USD 1,900 million transacted in the voluntary market in 2022 (Ecosystem Marketplace). The market-consistent upper bound is the 154 $MtCO_2e$ retired on voluntary registries in 2022 (VROD) divided by the five-economy emissions (8.0%). Maximum sector cost is the largest ratio of the nominal credit cost to sectoral value added (VA) across all sectors and countries under Direct responsibility.

Table S2 Five-year investment-share reallocation and portfolio carbon intensity change by credit coverage, 2022.

Coverage ρ	Design	Investment share reallocated (pp)	PCI change (%)
1%	Direct	0.0007	-0.003
1%	Network	0.0005	-0.002
1%	Total	0.0005	-0.002
2.5%	Direct	0.0017	-0.009
2.5%	Network	0.0012	-0.005
2.5%	Total	0.0012	-0.004
5%	Direct	0.0033	-0.017
5%	Network	0.0025	-0.011
5%	Total	0.0024	-0.009
10%	Direct	0.0067	-0.034
10%	Network	0.0050	-0.022
10%	Total	0.0048	-0.018
25%	Direct	0.0167	-0.086
25%	Network	0.0125	-0.054
25%	Total	0.0119	-0.044
50%	Direct	0.0334	-0.173
50%	Network	0.0249	-0.109
50%	Total	0.0238	-0.088
100%	Direct	0.0669	-0.346
100%	Network	0.0500	-0.218
100%	Total	0.0477	-0.176

Notes: Investment share reallocated is half the sum of absolute changes in predicted sector investment weights (Eq. 15), in percentage points, medians across countries. Predictions use the observed 2022 price of USD 7.37/tCO_2e, net-value-added returns (Eq. 10) and the baseline five-year response coefficient of Table 4, Panel A. PCI change is the percentage change in portfolio carbon intensity (Eq. 14) relative to the baseline portfolio, with carbon intensity measured as direct emissions per unit of gross output. Coverage ρ is the share of benchmark responsibility priced through credits (Eq. 5); values above 8.0% exceed the market-consistent bound (Table S1).

Table S3 Country-level responses at 10% and 100% coverage, 2022.

Country	Design	Reallocation, ρ = 10% (pp)	Reallocation, ρ = 100% (pp)	PCI change, ρ = 100% (%)
Korea	Direct	0.0200	0.2083	-2.837
Korea	Network	0.0144	0.1466	-1.363
Korea	Total	0.0141	0.1424	-0.934
France	Direct	0.0051	0.0509	-0.342
France	Network	0.0048	0.0478	-0.218
France	Total	0.0047	0.0468	-0.176
Italy	Direct	0.0064	0.0642	-0.346
Italy	Network	0.0049	0.0495	-0.212
Italy	Total	0.0048	0.0477	-0.173
Netherlands	Direct	0.0067	0.0669	-0.411
Netherlands	Network	0.0050	0.0500	-0.258
Netherlands	Total	0.0044	0.0445	-0.195
Canada	Direct	0.0128	0.1291	-0.331
Canada	Network	0.0097	0.0976	-0.176
Canada	Total	0.0093	0.0935	-0.127

Notes: Reallocation is the five-year change in predicted investment weights (pp) at the observed 2022 price and the baseline response coefficient; PCI change is the percentage change in portfolio carbon intensity. The 0.1-point materiality benchmark is exceeded only at ρ = 100%.

Table S4 Reallocated burden with annual input–output structure, 2005–2022.

Country	Network: median (range), pp	Total: median (range), pp	Network: fixed-structure error, median (max), pp	Total: fixed-structure error, median (max), pp
Korea	28.3 (26.4–29.9)	35.0 (30.8–37.5)	20.8 (30.2)	23.4 (33.1)
France	21.4 (20.3–22.9)	25.7 (24.6–28.9)	5.2 (7.5)	6.4 (8.8)
Italy	25.0 (22.5–28.9)	28.9 (26.8–32.9)	6.1 (7.2)	6.9 (8.1)
Netherlands	21.0 (20.1–22.5)	27.6 (26.6–29.6)	3.5 (5.0)	4.6 (6.4)
Canada	20.2 (18.6–21.5)	26.3 (24.7–27.9)	3.3 (5.3)	3.5 (5.7)
All	21.9 (18.6–29.9)	27.5 (24.6–37.5)	5.1 (30.2)	6.0 (33.1)

Notes: Reallocated burden is defined in Eq. (4). Ranges are minimum–maximum across years 2005–2022 (2007–2022 for Canada); the row All pools the 88 country-years. Fixed-structure error is the reallocated burden between the share vectors obtained with the annual structure and with the 2022 Network-to-Direct and Total-to-Direct ratios applied to year-t direct emissions (Section 3.4).

Table S5 Year-by-year five-year investment reallocation under annual input–output structure, 2005–2022.

Coverage rule	Design	Median of yearly medians (pp)	Largest yearly median (pp)	Largest country-year (pp)	Country-years ≥ 0.1 pp	Max. |fixed − annual| (pp)
Market bound	Direct	0.0010	0.0054	0.0161	0 of 88	0.0000
Market bound	Network	0.0007	0.0040	0.0116	0 of 88	0.0001
Market bound	Total	0.0006	0.0038	0.0113	0 of 88	0.0002
ρ = 10%	Direct	0.0061	0.0111	0.0442	0 of 88	0.0000
ρ = 10%	Network	0.0044	0.0072	0.0237	0 of 88	0.0006
ρ = 10%	Total	0.0039	0.0067	0.0199	0 of 88	0.0005

Notes: Each year uses that year's price, exchange rate, value added, capital stock, investment weights, emissions and input-output tables, and the baseline response coefficient of Table 4, Panel A. The market-consistent bound is the year's voluntary-registry retirements (VROD) divided by five-economy emissions (8.0% in 2022). Yearly medians are cross-country medians; country-years are the 88 country-year observations (2007–2022 for Canada). The last column is the largest absolute difference between the yearly median under annual and under fixed 2022 structure.

Table S6 Robustness of the reallocated burden to perturbations of 2022 sector responsibility weights.

Perturbation	Design	Median reallocated burden (pp)	Country/draw 95% range (pp)
10%	Network	23.0	16.7–29.5
10%	Total	29.0	22.3–38.6
20%	Network	23.7	15.5–32.2
20%	Total	29.5	21.1–41.5

Notes: Network and Total sector weights are independently perturbed by lognormal shocks with a standard deviation of 10% or 20%, renormalized to the national total, and the reallocated burden is recomputed over 1,000 draws per country (fixed seed). The median is taken across countries of the country-specific medians; the range runs from the lowest 2.5th to the highest 97.5th percentile across countries.

Table S7 Sensitivity of Total responsibility to the emission intensity of imported inputs, 2022.

Country	κ = 0 (Network)	κ = 0.5	κ = 1 (Total)	κ = 1.5	κ = 2	Rank corr. with Direct at κ = 1
Korea	26.4	31.4	35.9	39.9	43.6	0.54
France	22.9	25.8	28.9	32.1	35.6	0.88
Italy	25.5	27.8	30.4	33.2	36.4	0.84
Netherlands	21.5	25.0	28.7	32.7	37.0	0.85
Canada	18.6	21.5	24.7	28.5	32.8	0.85

Notes: Reallocated burden (Eq. 4, percentage points) of the rule obtained when imported inputs carry κ times the emission intensity of the same domestic sector: $f = \varepsilon(I - A - \kappa M)^{-1}$, where ε is the direct emission intensity, A the domestic and M the import input-coefficient matrix, rescaled to the Direct total. κ = 0 reproduces Network and κ = 1 reproduces Total (maximum difference 0 in the replication code).

Table S8 Shared-responsibility mixes of Direct and Network responsibility and the Ghosh equivalence, 2022.

Country	Network burden (pp)	Mix 25:75 (pp)	Mix 50:50 (pp)	Mix 75:25 (pp)	Max. | Leontief − Ghosh|	Network total / Direct total
Korea	26.4	6.6	13.2	19.8	5.7e-14	2.38
France	22.9	5.7	11.5	17.2	1.4e-14	1.94
Italy	25.5	6.4	12.7	19.1	2.1e-14	2.16
Netherlands	21.5	5.4	10.8	16.1	1.1e-14	1.78
Canada	18.6	4.6	9.3	13.9	1.4e-14	1.77

Notes: Mix w:(1−w) combines Network and Direct shares with weight w on Network; its reallocated burden equals w times the Network burden. Max. |Leontief − Ghosh| is the largest absolute difference between the Leontief upstream-embodied emissions of each sector and the Ghosh allocation of direct emissions to the sector's output. Network total / Direct total is the ratio before rescaling.

Table S9 Sector-specific import emission-intensity factors and the incidence of Total responsibility, 2022.

Country	Log SD 0.5: median (95% range), pp	Log SD 1.0: median (95% range), pp	Rank corr. with Direct (SD 0.5)
Korea	35.5 (32.6–40.5)	35.0 (30.3–55.7)	0.55
France	28.9 (27.6–31.4)	29.0 (26.2–48.4)	0.88
Italy	30.4 (28.9–34.0)	30.4 (27.6–53.9)	0.85
Netherlands	28.9 (26.8–33.9)	29.5 (25.2–74.3)	0.85
Canada	24.8 (23.0–30.3)	24.7 (21.6–57.9)	0.86

Notes: Each of 1,000 draws multiplies the emission intensity of the imported inputs of each sector by an independent lognormal factor with mean one and the stated standard deviation of its logarithm; the Total rule is recomputed (Table S7 notes) and rescaled to the Direct total. Entries are the median and 95% range of the reallocated burden (Eq. 4) across draws; the last column is the median rank correlation with Direct responsibility. The draws use a fixed seed.

Table S10 External calibration of the response coefficient at the 2022 market-consistent coverage bound.

Response coefficient	Direct (pp)	Network (pp)	Total (pp)
0.18	0.0025	0.0019	0.0018
0.385	0.0054	0.0040	0.0038
0.5	0.0070	0.0052	0.0050
0.75	0.0104	0.0078	0.0075
1	0.0139	0.0104	0.0100
2	0.0278	0.0208	0.0199
5	0.0695	0.0520	0.0497
Needed for 0.1 pp, proportional demand	7.20	9.62	10.06
Needed for 0.1 pp, 56% energy buyers	5.48	5.35	5.54
Needed for 0.1 pp, 100% energy buyers	3.42	3.16	3.23

Notes: Entries are median five-year investment reallocations (pp) across countries for response coefficients from 0.18 (conservative) to 5, at the market-consistent bound of 8.0% and the 2022 price of USD 7.37/tCO_2e, with proportional demand. 0.385 is the baseline estimate and 0.5–1.0 is the range of user-cost elasticities of investment surveyed by Hassett and Hubbard (2002). The last three rows give the coefficient at which the median reaches 0.1 pp.

Table S11 Practical guidance by audience.

Audience	Guidance	Evidence
Standard-setters and buyers choosing a responsibility boundary	Choose Direct, Network or Total on distributional and targeting grounds. The choice moves 19–38 points of national responsibility across sectors but changes investment shares by at most 0.02 points at market-consistent coverage.	Tables 1, 2; Figure 3
Policymakers who want carbon prices to move capital	Act on price and coverage, not on the accounting rule: 0.1 points requires USD 11–15/tCO_2e at full coverage (USD 23–33 under the conservative response), which is 149–209% of coverage at the 2022 price.	Table 6; Figure 2
Energy and utility sectors as credit buyers	If energy sectors buy all credits, the response roughly doubles (0.0054 to 0.0114 points) and the full-coverage price needed halves, yet it still requires energy sectors to buy 64–70% of national emissions.	Table 4
Input–output and footprint practitioners	Use year-specific tables: applying 2022 ratios to earlier emissions misstates Korean incidence by 21–23 points. Report the import-technology sensitivity, because the size of Total incidence depends on it.	Section 4.6; Supplementary Tables S3, S6
Analysts of the productivity–investment response	Report fixed-effect, initial-share-controlled and bias-corrected estimates together with an external elasticity range of 0.5–1.0: the channel is positive in all three estimates but statistically reliable only in the first, and an elasticity of 1.0 still implies less than 0.03 points at the market-consistent bound.	Table 5
Data providers and researchers	Buyer-level retirement data with sector identifiers would replace the coverage bound and the reported energy-share range with observed exposure.	Section 5.1

Notes: Guidance summarizes the baseline results of Sections 4.1–4.7 and the Supplementary Tables; it describes the direction and scale of point estimates and not forecasts.