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

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Abstract

Environmentally extended input–output analysis shows that carbon responsibility depends on the accounting boundary, but the economic consequences of that choice for voluntary carbon markets have not been quantified. This study compares three responsibility rules (direct emissions, domestic supply-chain responsibility and imports-inclusive total-requirements responsibility), normalized to the same national carbon quantity, for Korea, France, Italy, the Netherlands and Canada over 2005–2022. Annual harmonized input–output tables, industry emissions, capital and investment data and observed voluntary carbon-market prices are combined with a coverage bound calibrated to registry retirements. The rules reallocate 18.6–37.5 percentage points of national responsibility across sectors in every year, systematically shifting responsibility from electricity, primary and fuel-using sectors toward construction and food processing. Applying a single-year input–output table to other years misstates Korean incidence by 21–23 points, so annual tables matter for historical responsibility accounting. By contrast, predicted five-year investment reallocation is at most 0.016 percentage points in any country-year at market-consistent coverage, about 0.011 points in 2022 if energy firms retire all credits, and 0.014 points with an investment elasticity of 1.0. A 0.1-point shift would require prices of 11–15 US dollars per tonne of carbon dioxide equivalent at full coverage. Responsibility accounting therefore changes who bears the cost far more than where capital flows.

Keywords

voluntary carbon markets, environmentally extended input–output analysis, carbon responsibility, carbon accounting, capital allocation, industrial ecology

JEL classification

C67, D57, G11, Q54, Q58

Word count

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1. Introduction

Environmentally extended input–output (EEIO) analysis has long shown that production-based emissions and consumption or supply-chain footprints answer different responsibility questions. Multi-regional input–output (MRIO) systems trace emissions embodied in intermediate inputs, final demand and trade, making the accounting boundary an economically consequential choice rather than a bookkeeping detail (Wiedmann, 2009; Tukker & Dietzenbacher, 2013; Andrew & Peters, 2013). Recent work continues to demonstrate that production, consumption and throughflow-based perspectives identify different actors and sectors as environmentally important (Beaufils et al., 2023; Wilting & in 't Veld, 2025).

A parallel literature on voluntary carbon markets (VCMs) focuses on credit integrity, project quality, corporate climate claims, buyer motivations and market prices. Corporate use of credits is heterogeneous and often difficult to interpret because claims, project quality and retirement practices differ across firms and projects (Trouwloon et al., 2023; André & Valenciano-Salazar, 2022). Recent evidence also shows that large buyers predominantly retire low-quality, low-priced credits, which weakens the environmental meaning of observed VCM activity (Trencher et al., 2024). These concerns are important, but they are conceptually distinct from a prior allocation question: if a benchmark quantity of carbon responsibility is to be priced through a

VCM, which industries should bear that responsibility when supply-chain emissions overlap across production stages?

The research gap lies at the intersection of these two literatures. EEIO and footprint studies are well equipped to trace direct and embodied emissions but generally stop at environmental accounting or policy incidence. VCM studies analyze credit quality, transactions, claims and firm participation but rarely derive buyer responsibility from an interindustry production network. As a result, the literature does not establish how alternative carbon-accounting boundaries translate into VCM monetary incidence, nor whether the resulting sectoral cost redistribution is large enough to alter productive-capital allocation. This paper links carbon accounting to VCM responsibility, monetary exposure and capital reallocation in one internally consistent framework. Three hypotheses organize the analysis. H1 asks whether supply-chain-aware responsibility materially changes sectoral VCM incidence relative to direct emissions when the aggregate carbon quantity is held fixed. H2 asks how observed VCM prices and alternative credit-coverage assumptions translate those responsibility rules into sector-level monetary burdens. H3 asks whether VCM-adjusted relative returns imply economically meaningful capital reallocation when passed through an independently estimated historical productivity-investment relationship.

For industrial ecology, the study makes three contributions. First, it shows how the choice of environmentally extended input–output responsibility rule redistributes national carbon responsibility across sectors, and that the common shortcut of applying single-year multiplier ratios to other years can misstate incidence materially, as in Korea; annual tables avoid this instability. Second, it bounds the domestic-technology assumption of national total-requirements tables and shows that the Network rule coincides with the supply-driven (Ghosh) allocation, which clarifies how demand-pull, supply-push and shared-responsibility readings relate. Third, it

links responsibility accounting to an economic outcome by asking whether the redistribution changes where capital flows when a market price is attached, using a coverage bound calibrated to voluntary-registry retirements, observed energy-sector buying shares and baseline, conservative, bias-corrected and externally calibrated investment responses.

The main result is asymmetric: accounting incidence is large, but predicted real reallocation is small at historical VCM prices. This distinction matters for both input–output analysis and VCM policy. A responsibility rule can substantially change which industries appear carbon-exposed without generating a comparably large change in investment. Conversely, the threshold analysis shows how much stronger the price or coverage signal must become before alternative supply-chain responsibility rules materially affect productive-capital allocation.

A companion study by the author, currently under review elsewhere, examines differentiated carbon taxation on the same harmonized five-economy panel. It asks which carbon-information base a sectoral tax should use and how a mean–variance allocation of capital transmits the resulting tax signal; it concerns a tax rather than voluntary credits. The present study differs in its object (voluntary credit incidence), its price series and market-calibrated coverage, and its estimand (the reallocation of investment shares implied by a historical productivity–investment relationship). The two studies share the underlying data and the definitions of Direct, Network and Total information but no text, tables or results.

The analyses differ in their evidential status. The responsibility calculations (Sections 4.1, 4.6 and 4.7) apply accounting identities to observed tables and emissions, so their results are exact given the data. The investment response (Section 4.4) is an estimated association between relative returns and subsequent investment shares, not a causal effect, and is therefore reported as a range across baseline, conservative, bias-corrected and externally calibrated coefficients. The

reallocation and threshold results (Sections 4.2, 4.3 and 4.5) are counterfactual simulations that combine the two; they quantify scale and break-even conditions under stated assumptions rather than forecasting market outcomes.

2. Literature and hypotheses

2.1. EEIO, footprints and responsibility boundaries

The modern carbon-footprint literature uses EEIO and MRIO models to connect direct environmental extensions to complete production chains. Minx et al. (2009) review applications ranging from national inventories and trade to sectors, organizations and households. Tukker and Dietzenbacher (2013) and Andrew and Peters (2013) document the development of global MRIO systems and their use in environmental applications. This literature establishes that emissions embodied in imports and intermediate production can materially alter responsibility measures. It also highlights approximation and aggregation problems when global supply chains are represented incompletely. Because interindustry linkages propagate sector-specific changes through production networks (Carvalho & Tahbaz-Salehi, 2019), the allocation of responsibility along those linkages is not a neutral convention.

More recent contributions sharpen the responsibility question. Beaufils et al. (2023) show that production- and consumption-based accounts can miss the role of intermediates and propose throughflow-based accounting to capture supply-chain positions. Wilting and in ’t Veld (2025) compare production and consumption footprints across EU member states and show that the accounting approach changes the sectors and imported emissions identified as important. Capital itself can also be incorporated into input–output systems: Södersten and Lenzen (2020) endogenize capital through supply-use tables, illustrating the close conceptual link between

footprint accounting and investment. On the incidence side, ten Raa and Stahlie (2024) show that the incidence of emission taxes across consumer income classes is proportional to the footprints of their consumption bundles; the present paper instead examines incidence across industries and its transmission to investment. Together, these studies motivate treating the accounting boundary as an incidence choice, but they do not translate that choice into voluntary credit responsibility and then into a capital-allocation response.

Responsibility along a production chain need not be assigned to a single party. Shared producer and consumer responsibility divides the emissions of each link between the agents that cause and benefit from them (Gallego & Lenzen, 2005; Lenzen et al., 2007), and supply-driven models allocate the output of a sector to its users rather than tracing demand backwards (Ghosh, 1958; Dietzenbacher, 1997); Section 3.1 relates the three rules compared here to these formulations.

2.2. VCMs, credit integrity and corporate use

VCM research has developed along a different axis. Studies examine why firms adopt voluntary carbon-neutral programs, how credits support corporate climate claims, and whether project attributes and co-benefits affect demand (André & Valenciano-Salazar, 2022; Trouwloon et al., 2023). The market is heterogeneous: project type, location, vintage, co-benefits and perceived quality influence prices and buyer preferences, while over-the-counter (OTC) trading limits price transparency. Recent work further shows that large buyers can retire credits with substantial quality risks, reinforcing the distinction between the quantity of credits and their environmental integrity (Trencher et al., 2024).

Additionality, permanence and credit-quality verification are outside the scope of this paper, which addresses a complementary demand-side accounting problem. Even if every credit were high quality, a firm or industry still requires a rule defining the emissions quantity for which it

takes benchmark responsibility. Direct emissions, domestic upstream emissions and imports-inclusive footprints are plausible but non-equivalent bases. The missing analytical link is therefore responsibility allocation before credit quality: how an input–output boundary changes the sectoral distribution of a fixed aggregate benchmark and how that distribution propagates through returns and investment.

2.3. Hypotheses

H1 (supply-chain responsibility). Holding the aggregate carbon quantity fixed, Network and Total responsibility reallocate VCM incidence across industries relative to Direct responsibility, with larger changes where direct emissions understate upstream dependence.

H2 (monetary incidence and scale). Observed VCM prices convert alternative responsibility rules into different sectoral monetary burdens, but the economic magnitude depends jointly on the credit price and the share of benchmark responsibility covered by credits.

H3 (capital-reallocation channel). VCM costs that reduce an industry's relative capital productivity lower its predicted future investment share; however, at historical VCM prices the real-allocation effect is expected to be substantially smaller than the accounting-incidence effect.

3. Methodology and data

3.1. Input–output responsibility measures

Let Z_{ct} denote the industry transaction matrix, x_{ct} gross output and e_{ct} direct greenhouse-gas emissions. The technical-coefficient and Leontief matrices (Leontief, 1970; Miller & Blair, 2009) are:

$$A_{ct} = Z_{ct}\hat{x}_{ct}^{-1}, \quad L_{ct} = (I - A_{ct})^{-1} \tag{1}$$

Direct responsibility equals observed industry emissions. Domestic Network and imports-inclusive Total responsibility use the DOM and TTL Leontief systems, respectively. Network responsibility is conceptually related to the production footprint of Wilting and in 't Veld (2025), which includes all direct and upstream emissions of a country's production activities, but it is allocated here to industries. The 2022 structure is the benchmark of Sections 4.1–4.5; for each year from 2005 to 2022 the tables of that year are used (Section 3.4).

$$\begin{aligned} Q_{ict}^{\mathrm{D}} &= e_{ict}, \\ Q_{ict}^{\mathrm{N}} &\propto \left[(e_{ct}/x_{ct})' L_{ct}^{\mathrm{DOM}}\right]_i x_{ict}, \\ Q_{ict}^{\mathrm{F}} &\propto \left[(e_{ct}/x_{ct})' L_{ct}^{\mathrm{TTL}}\right]_i x_{ict} \end{aligned} \tag{2}$$

To identify incidence rather than aggregate stringency, Network and Total quantities are rescaled to the Direct country-year total:

$$\tilde{Q}_{ict}^{k} = Q_{ict}^{k} \cdot \frac{\sum_i Q_{ict}^{\mathrm{D}}}{\sum_i Q_{ict}^{k}}, \quad k \in \{\mathrm{N}, \mathrm{F}\} \tag{3}$$

The reallocated burden is one half of the absolute difference between sectoral responsibility shares:

$$\begin{aligned} \mathrm{RB}_{ct}^{k} &= 50 \cdot \textstyle\sum_i \left| s_{ict}^{k} - s_{ict}^{\mathrm{D}} \right|, \\ s_{ict}^{k} &= \frac{\tilde{Q}_{ict}^{k}}{\sum_j \tilde{Q}_{jct}^{k}} \end{aligned} \tag{4}$$

Three clarifications position these rules. First, Total responsibility is computed from national total-requirements tables, in which imported inputs are assumed to be produced with the emission intensity of the same domestic sector, so it is not a consumption-based footprint with traced origins. To bound this assumption, Table S7 scales the emission intensity of imported inputs by a factor κ, where κ = 0 reproduces Network and κ = 1 reproduces Total. The reallocated burden rises monotonically with κ, from 18.6–26.4 points at κ = 0 to 24.7–35.9 at κ = 1 and 32.8–43.6 at κ = 2, so for any import intensity between zero and twice the domestic level

the incidence is at least that of Network. Second, Network responsibility, the emissions embodied in the upstream chain of each sector's output, is numerically identical to the supply-driven (Ghosh) allocation of direct emissions to the sector's output (to machine precision), so the choice between demand-driven and supply-driven models changes the interpretation and not the numbers. Third, both rules overlap across sectors: before rescaling, Network responsibility is 1.8–2.4 times the Direct total, which is why Eq. (3) rescales it. A shared-responsibility rule would split this overlap between suppliers and users; the simplest compromise, a 50:50 mix of Direct and Network responsibility, reallocates 9.3–13.2 points, exactly half of the Network figure because the statistic is linear in the shares (Table S8).

3.2. VCM price, coverage and monetary incidence

Annual VCM prices are taken from Ecosystem Marketplace reports (Ecosystem Marketplace, 2007, 2015, 2021, 2022, 2024, 2025). Explicit market-wide annual prices are classified A-grade; where an explicit price is unavailable, the B-grade price equals reported market value divided by transaction volume. The overlapping empirical period is 2005–2022. Annual exchange rates (Federal Reserve Board, n.d.) convert USD credit costs into local currency, and sector-specific value-added ratios map nominal costs into the real units used for capital productivity.

$$C_{ict}^{k}(\rho) = \rho P_t^{\mathrm{VCM}} \tilde{Q}_{ict}^{k} \tag{5}$$

The coverage parameter ρ is the fraction of benchmark responsibility priced through credits. Because actual sector-level retirements are unavailable, ρ is a scenario parameter rather than an estimated participation rate, but it is not unrestricted. In year t the voluntary registries retire a volume V_t of credits, whereas the five economies jointly emit E_t. If the five economies retired every voluntary credit, coverage would equal $\rho_{\max} = V_t/E_t$; any realistic participation rate is below this bound. We measure V_t with credits retired or cancelled on the six registries in the

Berkeley Voluntary Registry Offsets Database (VROD; Quartson et al., 2026), excluding compliance-offset projects. Scenarios with $\rho \leq \rho_{\max}$ are called market-consistent, and larger values are treated as carbon-tax-like counterfactuals. Sensitivity cases are 0.01, 0.025, 0.05, 0.10, 0.25, 0.50 and 1.00.

$$C_{ict}^{k,\mathrm{LCU}}(\rho) = \mathrm{FX}_{ct} C_{ict}^{k}(\rho) \tag{6}$$

$$C_{ict}^{k,\mathrm{real}}(\rho) = C_{ict}^{k,\mathrm{LCU}}(\rho) \cdot \frac{\mathrm{VA}_{ict}^{\mathrm{real}}}{\mathrm{VA}_{ict}^{\mathrm{nom}}} \tag{7}$$

Credit demand is concentrated rather than proportional to responsibility. Among retirements by identified buyers, energy and utility firms account for close to 40% (Sylvera, 2025b), 50% (Sylvera, 2025c) or 56% (Sylvera, 2025a), depending on the sample, and fossil-fuel companies make up 42% of the ten largest retirees (MSCI, 2026); anonymous retirements are excluded from these figures. As a stylized concentrated-buyer scenario, a share s_E of all credits is retired by the energy sectors (mining and quarrying, refined petroleum, and electricity, gas and steam) and the remainder by all other sectors; within each group credits are split in proportion to the responsibility rule, so that the three designs still differ and national totals are unchanged. We set s_E at 40%, 50% and 56%, the reported range, and at 70% and 100% as stress cases.

3.3. VCM-adjusted returns and capital allocation

The historical investment-response function is estimated independently of the VCM counterfactual. Relative capital productivity is the sector log return deviation from its country-year mean, and the dependent variable is the h-year change in the log share of gross fixed capital formation (GFCF).

$$\mathrm{RRP}_{ict} = \ln(\mathrm{VA}_{ict}/K_{ict}) - \mathrm{mean}_{ct}[\ln(\mathrm{VA}/K)] \tag{8}$$

$$\Delta_h \ln(\mathrm{GFCF\ share}_{ict}) = \beta_h \mathrm{RRP}_{ict} + \alpha_{ic} + \lambda_{ct} + \varepsilon_{ict}^{h} \tag{9}$$

Eq. (9) is the baseline specification. Because country-sector fixed effects and a lagged-level regressor interact in short panels (Nickell, 1981), we also estimate a conservative specification that adds the initial log GFCF share, $\ln s_{ict}$, to Eq. (9). As a bias-corrected check, we estimate an annual dynamic model in which the log share depends on its own lag and on lagged relative productivity, with sector and country-year fixed effects, and remove the Nickell bias with the half-panel jackknife (Dhaene & Jochmans, 2015); the five-year cumulative effect is $\beta\,(1-\alpha^5)/(1-\alpha)$, where α is the persistence of the share, and intervals come from a cluster bootstrap. The baseline, conservative and bias-corrected estimates are treated as a range for the response rather than as competing point estimates.

The preferred counterfactual uses net value added (NLVA) because the VCM cost is interpreted as a charge against the sectoral return available after intermediate production.

$$\mathrm{RP}_{ict}^{k,\mathrm{VCM}}(\rho) = \frac{\mathrm{NLVA}_{ict}^{\mathrm{real}} - C_{ict}^{k,\mathrm{real}}(\rho)}{K_{ict}} \tag{10}$$

$$\Delta\mathrm{RRP}_{ict}^{k}(\rho) = \mathrm{RP}_{ict}^{k,\mathrm{VCM}}(\rho) - \mathrm{RRP}_{ict}^{0} \tag{11}$$

$$\widehat{\Delta}_h \ln(\text{GFCF share})_{ict}^{k}(\rho) = \hat{\beta}_h \Delta\mathrm{RRP}_{ict}^{k}(\rho) \tag{12}$$

Predicted sector weights are renormalized to sum to one. Portfolio carbon intensity (PCI) then summarizes the carbon composition of the predicted investment portfolio.

$$w_{ict}^{k,1} = \frac{w_{ict}^{0}\exp\left(\widehat{\Delta}_h \ln \text{GFCF share}_{ict}^{k}\right)}{\sum_j\left[w_{jct}^{0}\exp\left(\widehat{\Delta}_h \ln \text{GFCF share}_{jct}^{k}\right)\right]} \tag{13}$$

$$\mathrm{PCI}_{ct}^{k} = \sum_i w_{ict}^{k}\mathrm{CI}_{ict} \tag{14}$$

3.4. Thresholds and time-varying input–output structure

Two threshold exercises distinguish statistical transmission from economically material reallocation. The first solves for the price or equivalent coverage required to reallocate 0.1

percentage points of the investment portfolio over five years; it is solved exactly by bisection on the cross-country median, for the baseline and the conservative response coefficient and for each concentrated-buyer scenario. The second reports the approximate price required for a 1% decline in portfolio carbon intensity, obtained by linear extrapolation from the observed-price response. Because price and coverage enter the cost multiplicatively, a price multiplier at full coverage is economically equivalent to the same multiplier applied to coverage at the observed price, subject to the nonlinear log-return transformation. The response coefficient is also calibrated externally. It is the elasticity of a sector's investment share to its relative log return, which is comparable, as an approximation, to the user-cost elasticity of investment; a survey of the tax-policy literature places the latter between −0.5 and −1.0 (Hassett & Hubbard, 2002). We therefore evaluate the response for coefficients from 0.18 to 5 and solve for the coefficient at which the median five-year reallocation reaches 0.1 percentage points at the 2022 market-consistent bound (Table S10).

$$P^* = \inf\{P: 0.5 \sum_i |w_i(P) - w_i(0)| \geq \tau\} \quad (15)$$

Annual harmonized DOM and TTL transaction matrices and gross output are available for all five countries from 1995. For every year t from 2005 to 2022 (2007–2022 for Canada, whose emissions series starts in 2007), Network and Total responsibility are therefore recomputed from the year-t matrices and year-t emissions using Eqs. (1)–(3), instead of applying the 2022 structure to every year. To measure what a fixed-structure approximation would have implied, we also compute that variant, in which year-t direct emissions are multiplied by the 2022 Network-to-Direct and Total-to-Direct ratios and rescaled to the Direct total, and we report its error, defined as the reallocated burden (Eq. 4) between the annual and the fixed-structure share vectors. The real-allocation exercise is repeated in every year with that year's price, exchange rate, value added, capital stock, investment weights and emissions, under two coverage rules: ρ =

10% and the year-specific market-consistent bound. The baseline response coefficient is used throughout. As a complementary check of local sensitivity to the 2022 benchmark, 2022 Network and Total sector responsibility weights are independently perturbed by lognormal shocks with standard deviations of 10% and 20%, renormalized to the same national total, and the reallocated-burden statistic is recomputed over 1,000 draws.

3.5. Data sources and sample

The analysis uses harmonized OECD input–output tables (2025 edition; annual domestic and total transaction matrices and gross output, 1995–2022), OECD greenhouse-gas emissions by industry (ICIO-GHG) and OECD National Accounts statistics (Tables 6 and 8) for Korea, France, Italy, the Netherlands and Canada (OECD, 2025a, 2025b, 2026), supplemented for Korea by Bank of Korea productive-capital, value-added and investment series (Bank of Korea, n.d.). Sectors are harmonized to 30 industries, or 29 for Canada, for which no water and waste emissions series is available. Productive capital is observed for Korea; for France, Italy, the Netherlands and Canada it is constructed by the perpetual-inventory method from OECD GFCF, with Netherlands depreciation and capital-investment ratios set to the medians of the other countries. Korean GFCF is published directly for ten sectors and is allocated to the remaining twenty using same-year productive-capital shares. The VCM panel covers 2005–2022. The investment-response panel starts in 2000 for Korea, France, Italy and the Netherlands and in 2007 for Canada, and the five-country regressions use 2007–2022. Annual gross output and value added in the tables match the industry panel in every year from 2005 to 2022.

All numbers in Tables 1–5, Figs. 1–3 and Tables S1–S11 of Online Resource 1 are produced by the vcm module of the replication code from the deposited workbook (Jin, 2026); random draws use a fixed seed. Generative AI tools were used to assist with the development and debugging of

the analysis code and robustness workflows and with language editing; all code, inputs and outputs were reviewed and verified by the author, who takes full responsibility for the work.

4. Results

4.1. Large responsibility incidence (H1)

Table 1 reports the 2022 incidence comparison. The accounting boundary materially changes sectoral responsibility even though aggregate carbon quantity is identical across designs.

Table 1 Incidence of alternative responsibility rules, 2022.

Country	Design	Rank corr. with Direct	Reallocated burden (pp)
KOR	Network	0.628	26.4
KOR	Footprint	0.542	35.9
FRA	Network	0.913	22.9
FRA	Footprint	0.885	28.9
ITA	Network	0.891	25.5
ITA	Footprint	0.845	30.4
NLD	Network	0.914	21.5
NLD	Footprint	0.847	28.7
CAN	Network	0.924	18.6
CAN	Footprint	0.854	24.7

Notes: Rank correlation is the Spearman correlation between sectoral responsibility under Direct and under the indicated design. Reallocated burden is defined in Eq. (4): half the sum of absolute differences between sectoral responsibility shares, in percentage points (pp). Network and Total quantities are rescaled to the Direct country-year total (Eq. 3). KOR = Korea; FRA = France; ITA = Italy; NLD = Netherlands; CAN = Canada.

Network responsibility reallocates 18.6–26.4 percentage points of the national burden and Total reallocates 24.7–35.9 points. Korea shows the largest change and the weakest rank preservation. H1 is therefore strongly supported as an incidence proposition: supply-chain accounting changes who bears benchmark responsibility, not merely the level of national responsibility. Section 4.6 shows that the same holds in every year from 2005 to 2022.

Table 2 shows where the redistribution occurs. Under Total responsibility the largest losers are electricity in Korea (−23.3 points of the national share), Italy (−11.4) and the Netherlands

(−10.6), agriculture in France (−12.0) and mining in Canada (−6.8). Construction gains 3.7–5.4 points in every country and food, beverages and tobacco 4.2–7.4 points in France, Italy, the Netherlands and Canada. Only 2 to 4 of the five largest sectors under Direct remain among the five largest under Total, and 10 to 15 of the 30 sectors (29 in Canada) move by five or more rank positions. The redistribution is therefore systematic, from fuel-using, energy and primary sectors toward downstream construction and food-processing sectors, and not noise around Direct.

Table 2 Sector-level redistribution of responsibility relative to Direct, 2022.

Country	Largest gains under Total (change in share, pp)	Largest losses under Total (change in share, pp)	Top-5 overlap with Direct (Network / Total)	Sectors moving ≥ 5 ranks (Network / Total)
Korea	Refined petroleum (+7.0); Transport equipment (+5.4); Construction (+4.0)	Electricity (−23.3); Metals (−3.0); Agriculture (−2.7)	4 / 2	13 / 15
France	Food (+5.2); Construction (+4.4); Transport equipment (+2.9)	Agriculture (−12.0); Transport and storage (−7.8); Water and waste (−3.4)	3 / 3	6 / 10
Italy	Food (+4.2); Construction (+3.7); Trade (+2.9)	Electricity (−11.4); Agriculture (−7.3); Transport and storage (−4.2)	3 / 2	7 / 11
Netherlands	Food (+7.4); Construction (+4.0); Trade (+2.9)	Electricity (−10.6); Agriculture (−7.9); Transport and storage (−5.9)	4 / 4	5 / 11
Canada	Construction (+5.4); Food (+4.7); Transport equipment (+1.7)	Mining (−6.8); Electricity (−6.1); Agriculture (−5.4)	5 / 4	4 / 12

Notes: Entries are changes in a sector's share of national responsibility, in percentage points, under Total relative to Direct. Top-5 overlap is the number of the five largest sectors under Direct that remain among the five largest under the rule. Sectors moving ≥ 5 ranks counts the sectors, out of 30 (29 for Canada), whose rank changes by at least five positions.

4.2. Monetary incidence and coverage sensitivity (H2)

Observed VCM prices range from USD 2.52/tCO_2e in 2020 to USD 7.37/tCO_2e in 2022 over the common sample. Because the three responsibility designs are normalized to the same national quantity, aggregate expenditure is identical within a country-year; the responsibility rule determines its sectoral distribution. Table S1 first calibrates the coverage parameter to the size of the market. In 2022 the voluntary registries retired 154 MtCO_2e, equal to 8.0% of the 1,914 MtCO_2e emitted by the five economies; this is the upper bound $\rho_{\max}$. Across 2007–2022 the bound has a median of 1.5% and never exceeds 8.3%. Transacted rather than retired volumes (Ecosystem Marketplace) would raise the 2022 bound to 13.3%. At ρ = 10%, which already exceeds the retirement bound, the five economies would spend USD 1.41 billion, 74% of the value transacted in the entire voluntary market in 2022, and at ρ = 100% they would spend 7.4 times that value. Coverage above $\rho_{\max}$ therefore describes carbon-tax-like counterfactuals rather than VCM exposure.

Table S2 reports the five-year portfolio response based on net value added in 2022 for the full coverage grid. The response scales approximately with coverage but remains small. At the market-consistent bound (8.0%) the median five-year reallocation is 0.0054 points under Direct, 0.0040 under Network and 0.0038 under Total, and portfolio carbon intensity falls by at most 0.03%. At 10% coverage the Direct median is 0.0067 points, and even at 100% coverage less than 0.07 points of investment share are reallocated and PCI falls by less than 0.35% (Fig. 1). H2 is therefore supported for monetary incidence, but monetary exposure at observed prices does not generate a proportionately large real response. The transaction-based bound of 13.3% would raise the median Direct response to 0.0088 points without changing this conclusion.

Medians conceal heterogeneity (Table S3). Korea is the most exposed economy: its Direct response is 0.020 points at ρ = 10% and 0.208 points at ρ = 100%, with a PCI decline of 2.84%, and Canada reaches 0.129 points at ρ = 100%. Only these carbon-tax-like cases exceed the 0.1-point benchmark; within the market-consistent range every country and design stays at or below 0.016 points, and the most exposed sector bears 1.2% of value added at ρ = 10% against 0.004% for the median sector.

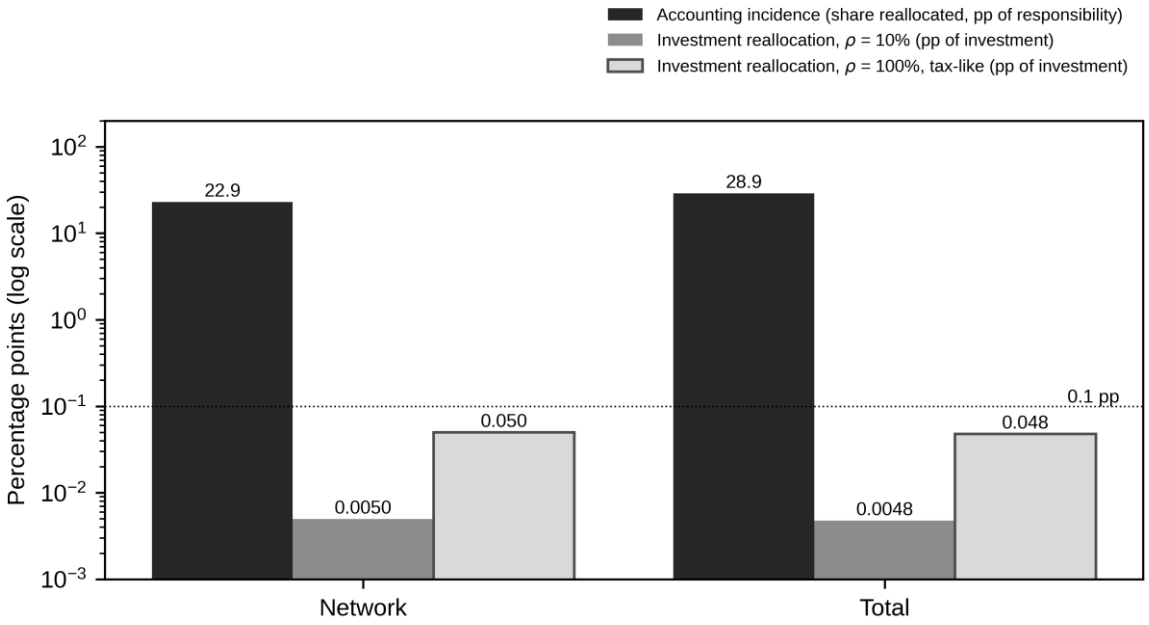


Fig. 1 Accounting incidence versus predicted investment reallocation, medians across countries, 2022. Black bars: median share of national responsibility reallocated relative to Direct (Table 1). Grey bars: median predicted five-year investment reallocation at the observed 2022 price of USD 7.37/tCO_2e and 10% or 100% coverage (Table S2). The vertical axis is logarithmic; the dotted line marks the 0.1-percentage-point benchmark

4.3. Concentrated buyers

Table 3 reports the 2022 response at the market-consistent bound when buyers are concentrated. With the energy share s_E set to the reported range of 40–56%, the median Direct reallocation rises from 0.0054 points under proportional demand to 0.0060–0.0071, and to 0.0082 and 0.0114 in the 70% and 100% stress cases; across designs the response rises by 11–83% at the observed

shares, and the largest sector cost reaches 1.4% of value added at 56% and 2.5% at 100%. Buyer concentration, not the responsibility rule, then determines the cost distribution, so the three designs converge. Even at 100% the response is about 9 times smaller than the 0.1-point benchmark. The full-coverage price for that benchmark falls from USD 11.0–15.4 with proportional demand to 8.0–8.3 at 56% and 4.7–5.1 at 100%, but at the 2022 price of USD 7.37 the benchmark would need coverage of 109–113% of national emissions at 56%, which is unattainable, and 64–70% bought by energy sectors alone at 100%, far above the market-consistent bound of 8.0%. Concentration matters, but it does not make the channel material at market-consistent coverage.

Table 3 Concentrated-buyer scenarios at the market-consistent coverage bound, 2022.

Energy share of credits	Realloc., Direct (pp)	Realloc., Network (pp)	Realloc., Total (pp)	Max. sector cost / VA	Price, Direct (USD)	Price, Network (USD)	Price, Total (USD)
Proportional	0.0054	0.0040	0.0038	0.96%	11.0	14.7	15.4
40%	0.0060	0.0059	0.0057	1.00%	9.8	10.0	10.3
50%	0.0067	0.0067	0.0065	1.24%	8.8	8.7	9.0
56%	0.0071	0.0073	0.0070	1.39%	8.3	8.0	8.3
70%	0.0082	0.0086	0.0084	1.74%	7.1	6.7	6.9
100%	0.0114	0.0123	0.0120	2.49%	5.1	4.7	4.8

Notes: Energy share is the share of all credits retired by mining and quarrying, refined petroleum, and electricity, gas and steam; the remainder is retired by the other sectors, and within each group credits are split in proportion to the responsibility rule. The 40%, 50% and 56% rows span the energy and utility shares reported for identified buyers (Sylvera, 2025a, 2025b, 2025c); 70% and 100% are stress cases. Proportional is the baseline in which credits follow responsibility in all sectors. Coverage is the 2022 market-consistent bound (8.0%), the price is USD 7.37/tCO_2e, the response coefficient is the baseline of Table 4, Panel A, and entries are medians across countries. Max. sector cost / VA is the largest ratio of the nominal credit cost to value added across sectors and countries under Direct. Realloc. is the median five-year reallocation of investment shares; Price is the price at which the cross-country median reaches 0.1 pp at 100% coverage.

4.4. Historical capital-response function and completed H3

The historical panel provides the behavioral bridge, but its strength depends on the specification. In the baseline specification (Panel A of Table 4), relative capital productivity positively predicts subsequent investment-share growth at all four horizons, with the response increasing over time. Adding the initial log share (Panel B) roughly halves the five-year coefficient, from 0.385 to

0.180, and removes statistical significance (p = 0.18). This is partly mechanical: with country-sector fixed effects, a lagged level regressor is correlated with the error term (Nickell, 1981), and the coefficient on the initial share is large and negative (−0.90 at five years), the signature of strong mean reversion in investment shares. The bias-corrected dynamic model (Panel C) implies a persistence of 0.81 (95% bootstrap interval 0.63–0.93), a one-year coefficient of 0.053 (−0.11 to 0.23) and a five-year cumulative effect of 0.181 (−0.34 to 0.83), almost identical to the conservative coefficient of Panel B but imprecise: its interval contains both zero and the baseline estimate. We therefore interpret Panel A as the upper bound and Panels B and C as conservative estimates of the response, and carry the first two through the counterfactual.

Table 4 Historical capital-response function: five-country panel, 2007–2022.

Horizon	β	SE	p-value (A, B); 95% interval (C)	N
Panel A. Baseline (country-sector and country-year fixed effects)				
1	0.063	0.021	0.0022	2,231
2	0.110	0.043	0.0100	2,082
3	0.267	0.083	0.0012	1,934
5	0.385	0.112	0.0006	1,636
Panel B. Conservative (adds the initial log GFCF share)				
1	0.043	0.057	0.45	2,231
2	0.071	0.092	0.44	2,082
3	0.163	0.145	0.26	1,934
5	0.180	0.135	0.18	1,636
Panel C. Bias-corrected annual dynamic model (half-panel jackknife)				
Persistence α	0.807	0.081	[0.63, 0.93]	2,233
One-year β	0.053	0.098	[−0.11, 0.23]	2,233
Five-year cumulative effect	0.181	0.327	[−0.34, 0.83]	2,233

Notes: The dependent variable is the h-year change in the log GFCF share (Eq. 9). The regressor is relative capital productivity (Eq. 8). Panel A includes country-sector and country-year fixed effects; Panel B adds the initial log GFCF share. Standard errors are clustered by country-sector (149 clusters). Panel C estimates an annual dynamic model, ln s(t) on ln s(t−1) and lagged relative productivity with the same fixed effects, and removes the Nickell bias with the half-panel jackknife (Dhaene & Jochmans, 2015); the five-year cumulative effect is $\beta\,(1-\alpha^5)/(1-\alpha)$, standard errors and 95% percentile intervals come from 200 cluster-bootstrap draws. The sample covers Korea, France, Italy, the Netherlands and Canada, 30 sectors (29 for Canada). N = number of observations. A specification with the initial share and country-year effects but without sector effects gives coefficients of 0.006, 0.012, 0.018 and 0.027 at horizons 1, 2, 3 and 5.

Combining these estimates with currency-consistent VCM-adjusted NLVA/K completes H3 as a counterfactual transmission exercise. The sign is as hypothesized: sectors receiving larger VCM burdens experience lower relative returns and lower predicted future investment shares, and all three estimates are positive. Only the baseline estimate is statistically distinguishable from zero, and the magnitude is economically small at observed VCM prices; it is roughly 2.1 times smaller under the conservative coefficient (Table 5). H3 is therefore supported in direction under the baseline specification and weakly supported under the conservative and bias-corrected ones; because a smaller coefficient implies a smaller real response, the quantitative conclusion that real reallocation is small is strengthened, while the claim that a statistically reliable channel exists is moderated.

4.5. Price and coverage thresholds

Table 5 asks how large the VCM signal would have to become before the capital response is economically visible. The 0.1 percentage-point investment-share threshold is solved directly from the nonlinear return and portfolio mapping, for the baseline and the conservative response coefficient. The 1% PCI threshold is a linear extrapolation from the near-linear response.

Table 5 Price and coverage thresholds for economically material reallocation.

Design	Price for 0.1 pp reallocation at 100% coverage	Equivalent coverage at USD 7.37	Approx. price for 1% PCI reduction	Price for 0.1 pp, conservative response	Elasticity needed at the 2022 market bound
Direct	USD 11.0/tCO_2e	149%	USD 21.3/tCO_2e	USD 23.3/tCO_2e	7.2
Network	USD 14.7/tCO_2e	199%	USD 33.8/tCO_2e	USD 31.1/tCO_2e	9.6
Total	USD 15.4/tCO_2e	209%	USD 42.0/tCO_2e	USD 32.7/tCO_2e	10.1

Notes: The price for 0.1 pp reallocation is the smallest price at 100% coverage at which the cross-country median predicted five-year investment reallocation reaches 0.1 percentage points (Eq. 15 with τ = 0.1 pp), solved by bisection. Equivalent coverage is that price divided by the observed 2022 price of USD 7.37/tCO_2e. The price for a 1%

PCI reduction is a linear extrapolation from the observed-price response (baseline coefficient). The fifth column repeats the 0.1 pp threshold using the conservative coefficient of Table 4, Panel B. The last column is the response coefficient at which the median five-year reallocation reaches 0.1 pp at the 2022 market-consistent bound with proportional demand, to be compared with the baseline of 0.385 and the literature range of 0.5–1.0.

The threshold results sharpen the central interpretation (Fig. 2). At the 2022 observed price of USD 7.37/tCO_2e, even 100% coverage does not reach a 0.1-point five-year reallocation in the median country. Achieving that benchmark requires roughly USD 11–15/tCO_2e at full coverage under the baseline response, and USD 23–33/tCO_2e under the conservative response. Because the equivalent coverage at the observed price is 149–209% under the baseline, the benchmark cannot be reached by any market-consistent coverage at 2022 prices. A 1% decline in portfolio carbon intensity requires still larger price equivalents, approximately USD 21/tCO_2e under Direct and USD 34–42/tCO_2e under Network or Total. Supply-chain responsibility therefore changes incidence well before it becomes a strong capital-allocation instrument.

External calibration points the same way (Table S10). At the market-consistent bound, an elasticity of 1.0, the upper end of the literature range, gives a median reallocation of 0.0139 points under Direct, 0.0104 under Network and 0.0100 under Total. The coefficient needed to reach 0.1 points is 7.2–10.1 with proportional demand, 5.3–5.5 if energy sectors buy 56% of credits and 3.2–3.4 if they buy all credits, that is 8–26 times the baseline estimate and 3.2–10.1 times the largest value in the literature range.

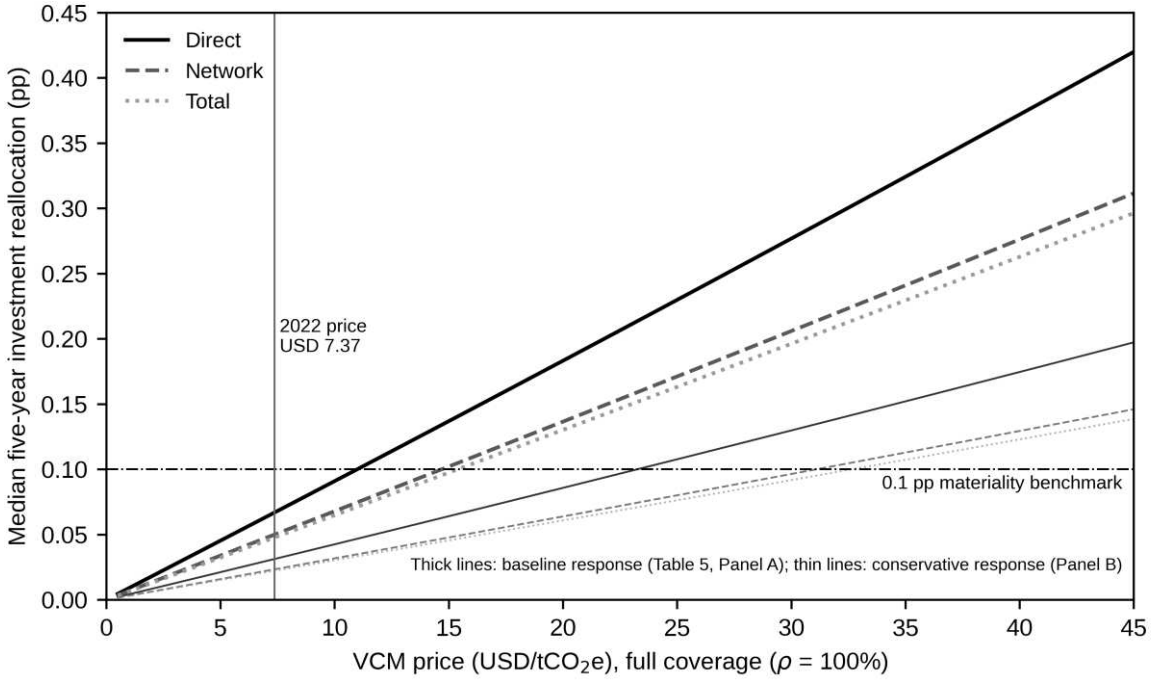


Fig. 2 Median five-year investment reallocation as a function of the voluntary carbon-market price at full coverage. Thick lines use the baseline response coefficient (Table 4, Panel A); thin lines use the conservative coefficient (Panel B). The vertical line marks the observed 2022 price; the dash-dotted line is the 0.1-percentage-point benchmark

4.6. Time-varying input–output structure, 2005–2022

Annual input–output tables allow H1 to be examined in every year rather than only in 2022. Table S4 shows that the reallocated burden under annual structure ranges from 18.6 to 29.9 percentage points under Network and from 24.6 to 37.5 under Total across the 88 country-years; the country medians are 20.2–28.3 and 25.7–35.0 points, and the rank correlation with Direct responsibility stays between 0.54 and 0.93. The large-incidence finding is therefore not an artifact of 2022 (Fig. 3a).

The fixed-structure approximation, which applies 2022 ratios to year-t emissions, performs differently across countries. For France, Italy, the Netherlands and Canada its error has a median of 3.3–6.9 percentage points and never exceeds 8.8. For Korea, however, the error has a median of 20.8 points under Network and 23.4 under Total, and the fixed-structure variant overstates

Korean incidence: its median reallocated burden under Total is 48.2 points against 35.0 with annual structure (Fig. 3a). The cause is a property of the ratio method, which is ill-conditioned for sectors whose direct emissions are very small in the reference year: Korean construction accounts for 0.08% of direct emissions in 2022 but has a Total-to-Direct ratio of 49, and applying that ratio to its larger direct emissions in 2012 (0.6%) assigns it 23% of the Total burden, against 3% with the 2012 tables. Annual tables avoid this instability and are therefore necessary for the historical incidence of the Korean case, although they do not change the qualitative conclusion.

Table S5 repeats the real-allocation exercise year by year. At the market-consistent bound, the largest yearly cross-country median five-year reallocation is 0.0054 percentage points under Direct, 0.0040 under Network and 0.0038 under Total, and portfolio carbon intensity falls by at most 0.22%. The largest country-year response is 0.016 points (Korea, 2022, Direct), and none of the 88 country-years reaches the 0.1-point benchmark; at a fixed $\rho = 10\%$ the largest country-year response is 0.044 points. Using the fixed 2022 structure changes the yearly medians by at most 0.0002 points, so the real-allocation conclusion is insensitive to the structural approximation even where the incidence statistic is not (Fig. 3b). H1 and the quantitative content of H3 therefore hold under time-varying structure, and the asymmetry between large incidence and small real reallocation holds throughout the sample.

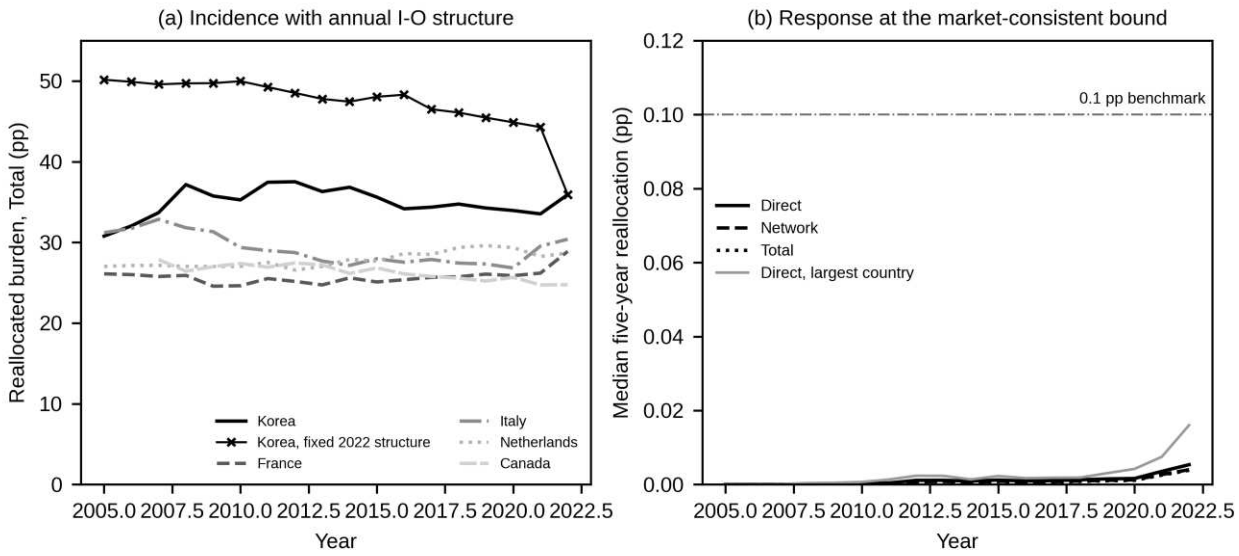


Fig. 3 Incidence and real response with annual input–output structure, 2005–2022. (a) Reallocated burden under Total responsibility by country, annual structure; the crossed line is Korea with the fixed 2022 structure. (b) Cross-country median five-year investment reallocation at the market-consistent coverage bound under annual structure; the grey line is the largest country-year response under Direct; the dash-dotted line is the 0.1-percentage-point benchmark

4.7. Robustness: sector weights, import technology and sharing rules

Tables S6–S9 report four robustness checks. Perturbing the 2022 responsibility weights by 10% or 20% leaves the median reallocated burden near 23 points for Network and 29 points for Total (S6). Scaling the emission intensity of imported inputs by a common factor κ raises the burden monotonically, from the Network level at $\kappa = 0$ to 32.8–43.6 points at $\kappa = 2$ (S7); sector-specific factors with mean one and a log standard deviation of 0.5 give median Total burdens of 24.8–35.5 points across countries, with 95% ranges of 23.0–40.5, and with a standard deviation of 1.0 the median is 24.7–35.0 points (S9). The domestic-technology assumption therefore affects the size but not the existence of the redistribution, and it does not drive the small real response, which depends on the cost per sector and not on the rule. Network responsibility coincides with the Ghosh allocation to machine precision, and a 50:50 shared-responsibility mix reallocates

exactly half of the Network burden (S8), so H1 holds under demand-driven, supply-driven and shared-responsibility readings of the Network rule.

5. Discussion

The main empirical message is a separation between accounting incidence and real-allocation magnitude. Network and Total accounting can reassign roughly one fifth to more than one third of national benchmark responsibility across industries, yet historical VCM prices generate only small changes in relative returns and investment shares. This distinction matters because footprint accounting is often interpreted as if a large change in measured responsibility necessarily implies a large behavioral response. The results show that the two margins are analytically separate.

For corporate carbon accounting, the three rules have sector-level analogues. Direct responsibility corresponds to a sector's own (Scope 1) emissions; Network responsibility adds the emissions embodied in its domestic purchases, in the spirit of cradle-to-gate accounting that includes upstream Scope 2 and Scope 3 categories; and Total responsibility extends that upstream boundary to imported inputs. The analogy is imperfect, because input–output responsibility overlaps across sectors and is rescaled here, but it connects the boundary choices debated in corporate climate claims and credit-use guidance to the results.

The threshold results provide a practical interpretation. At the 2022 market-wide price, full benchmark coverage remains below the 0.1-point investment-reallocation threshold in the median country, and market-consistent coverage is far lower than full coverage: the 2007–2022 median upper bound is 1.5% and the 2022 bound is 8.0%. Prices of roughly USD 11–15/tCO_2e at full coverage are needed to cross the benchmark, about twice as much under the conservative response, and about half as much if energy sectors buy all credits, while a 1% portfolio-carbon-

intensity reduction requires materially higher price equivalents. These figures are break-even calculations that identify when the modeled channel becomes economically visible.

5.1. Limitations

Five limitations remain. First, the responsibility quantities are counterfactual benchmarks rather than observed firm retirements, and coverage is bounded rather than observed, so the paper does not estimate a causal effect of actual VCM purchases on investment. Second, the historical investment response is an association estimated from return differentials and extrapolated to small shocks; the conservative and bias-corrected estimates are positive but imprecise (Table 4), and the external elasticity range is a user-cost elasticity applied by analogy, which is why a range is carried through. Third, although annual tables replace the fixed 2022 structure, they are national tables aggregated to 30 sectors (29 for Canada): imports are treated with the domestic technology, which Tables S7 and S9 bound but multi-regional tables would resolve. Fourth, Ecosystem Marketplace prices are market-wide averages in a heterogeneous OTC market, and the retirement-based coverage bound covers six registries and cannot identify buyers, so the energy-buyer scenario still relies on commercial registry analyses. Fifth, credit integrity, additionality, permanence and leakage are outside the model. The analysis therefore identifies the economic incidence of a responsibility rule conditional on a credit price; it does not certify the environmental quality of the underlying credits.

6. Conclusion

This paper connects environmentally extended input–output accounting to voluntary carbon-market incidence and productive-capital allocation. Holding the national carbon quantity fixed, domestic Network and imports-inclusive Total rules materially redistribute benchmark

responsibility relative to Direct emissions. Across five economies, the 2022 reallocated burden is 18.6–26.4 percentage points under Network and 24.7–35.9 points under Total, and with annual input–output tables it stays between 18.6 and 37.5 points in every year from 2005 to 2022. This large accounting effect is also robust to 10–20% perturbations of the benchmark sector weights.

The real-allocation result is much smaller. Once observed VCM prices are converted into local and real economic units and passed through the historical productivity–investment relationship, predicted investment-share shifts remain tiny at plausible credit coverage. Even if the five economies retired every voluntary credit in 2022 (8% coverage), the median five-year reallocation is 0.005 percentage points under Direct; it is 0.011 points if energy sectors retire every credit and 0.014 points with an elasticity of 1.0, and no country-year in 2005–2022 reaches 0.1 points at the market-consistent bound. The central finding is therefore not that supply-chain accounting is unimportant, but that large changes in carbon responsibility do not translate into large capital movements at historical VCM prices.

Threshold analysis makes this distinction operational. The modeled five-year reallocation reaches 0.1 percentage points only at approximately USD 11/tCO_2e under Direct, USD 14.7 under Network and USD 15.4 under Total at full coverage, at roughly twice these prices under the conservative response estimate, and at about half of them if energy sectors retire all credits, with substantially higher price equivalents required for a 1% decline in portfolio carbon intensity. The economic role of a VCM responsibility rule therefore depends on two separable margins: the input–output structure determines where carbon cost is allocated, while market price, coverage and buyer concentration determine whether that incidence becomes strong enough to affect real investment. This separation provides a tractable bridge between footprint accounting, carbon-market design and capital allocation.

Table S11 in Online Resource 1 translates these results into guidance for standard-setters, policymakers, credit buyers, input–output practitioners and data providers.

Statements and Declarations

Funding No funding was received for conducting this study.

Competing interests The author has no relevant financial or non-financial interests to disclose.

Ethics approval Not applicable. The study uses only aggregated, publicly available statistics and involves no human participants, animals or non-public data.

Consent to participate and consent to publish Not applicable.

Data availability The analysis uses publicly available data: OECD harmonized national input–output tables (annual total and domestic intermediate matrices, value-added components and gross output, 1995–2022), OECD national accounts (real value added and gross fixed capital formation by activity), OECD greenhouse-gas emissions by industry, Bank of Korea national-accounts data (productive capital, value added, gross fixed capital formation and the input–output table), Ecosystem Marketplace State of the Voluntary Carbon Market reports, the energy-sector shares of identified-buyer retirements reported by Sylvera (2025a, 2025b, 2025c) and MSCI (2026), and Federal Reserve G.5A annual exchange rates (FRED series AEXKOUS, AEXCAUS and AEXUSEU). The integrated workbook (analysis_data.xlsx), including the annual input–output matrices and a source manifest, is available in Mendeley Data (Jin, 2026; https://doi.org/10.17632/fwh697spvh.1). Redistribution of OECD and Bank of Korea series remains subject to the providers' terms of use.

Code availability The Python code that reproduces every table and figure (analysis_code.py, module vcm) and the result workbook (vcm_results.xlsx) are deposited with the data (Jin, 2026).

Author contributions Ick Jin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing.

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