Modeling Household Carbon Footprints: Methods, Metrics, and Estimation Frameworks

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Overview

1. Introduction
2. Methods & Applications
3. Responsibility & Policy Implications

Motivation

- **Problem:** Households are increasingly recognized as key actors in climate mitigation. However, the methods used to estimate their carbon footprints differ widely.
- **Research Gap**: No unified framework currently compares estimation frameworks for Household Carbon Footprint from a responsibility perspective.

- **Contribution**: This study systematically compares four models, namely the GHG Protocol, Life-Cycle Assessment, Environmentally Extended Input-Output Analysis, and general equilibrium model of Hakenes–Schliephake to assess attribution differences, empirical consequences, and policy alignment.

Research Questions

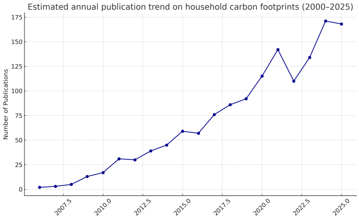
1. How do footprint estimates vary across models?
2. How is household responsibility estimated and attributed under each carbon accounting method?
3. How do attribution methods shape policy and equity outcomes?

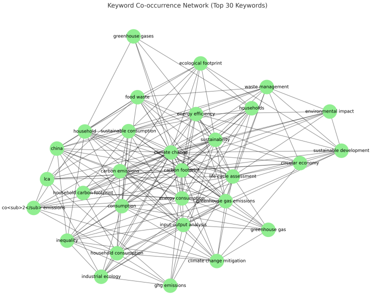
Literature Review: Evolution of HCF Estimation

- Research on household carbon footprints (HCF) has expanded since the early 2000s, evolving across three broad phases:
  - **Early phase:** IO-based estimation of emissions by expenditure category (Pachauri & Spreng, 2002; Lenzen, 2004)
  - **Expansion:**
    - National comparisons and household heterogeneity (Druckman & Jackson, 2009; Baiocchi & Minx, 2010)
    - Integration of inequality, global supply chains, and lifestyle effects (Ivanova et al., 2015; Moran et al., 2018)
- Dominant methods in current literature:
  - **Carbon emission coefficient:** Inventory based emission assignment (GHG Protocol under IPCC Guidelines, 2019)
  - **Life Cycle Assessment:** Process-based alternative, tracing cradle-to-grave emissions (Steubing et al., 2022)
  - **Input–Output Analysis:** Economy-wide linkages via input–output matrices (Baiocchi & Minx; 2010, Wiedmann, 2009)

Literature Review: Publication Trends and Focus Areas

- A bibliometric analysis of **1,311 peer-reviewed articles (2000–2025)** shows a sharp rise post-2015 (Paris Agreement).
- Research is concentrated around *input–output analysis, sustainable consumption*, and *life cycle assessment*.





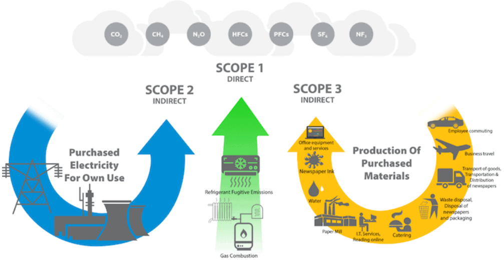
- Top Journals: *Journal of Cleaner Production*, *Science of the Total Environment*, and *Environmental Science & Technology*
- Top institutions: University of Tokyo, Sun Yat-sen University, University of Maryland.

Methodology

- A comparative framework is used to analyze how different carbon accounting methods estimate and attribute household emissions.
- Models are derived and illustrated using official household expenditure data (Eurostat, USDA) and publicly available emission factors (EXIOBASE, Climatiq, IPCC).
- Each model is classified an attribution logic as operational, consumption-based, or consequentialist based on its scope.
- Each attribution model is linked to relevant policy instruments and their distributional impacts.

The GHG Protocol

Definition: The Greenhouse Gas (GHG) Protocol is a standardized framework developed by WRI and WBCSD for tracking emissions across three scopes.



Source: Green Element (2023) — https://greenelement.co.uk

Formulation:

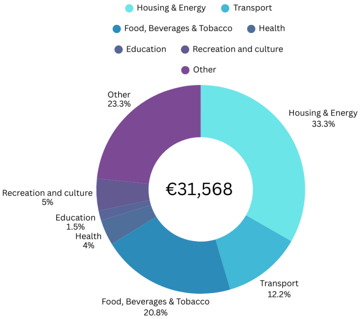
$$\mathrm{CF}_{\text{household}} = E_{\text{Scope 1}} + E_{\text{Scope 2}} + E_{\text{Scope 3}}, \qquad E_i = \sum_j Q_{ij} \cdot EF_{ij}$$

where Q_{ij} is the activity level and EF_{ij} is the emission factor for activity j under scope i.

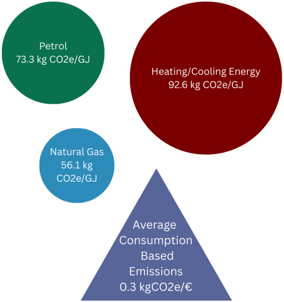
GHG Protocol – Empirical Application (Spain, 2022)

- **Objective:** Estimate average household emissions by scope using GHG Protocol.
- **Method:** Scope 1, 2, and 3 emissions are calculated using the GHG Protocol's framework using data on Spanish household expenditure and energy use (INE 2022) and emission factors sourced from DEFRA (2022) and IPCC (2019).

Spanish Household Expenditure Decomposition, INE (2022)



Emission Factors, DEFRA (2022) & IPCC(2022)



GHG Protocol – Empirical Results (Spain, 2022)

Total Household Carbon Footprint:

$$\text{Total Emissions} = 11{,}828.08 \text{ kg } CO_2\text{e/year}$$

Emissions by Scope

Scope	Definition	Emissions (kg CO_2e)	Share (%)
Scope 1	Direct fuel use (transport + heating)	1,114.83	9.4%
Scope 2	Purchased electricity/heating	829.70	7.0%
Scope 3	Lifecycle emissions from consumption	9,883.55	83.6%
Total		**11,828.08**	**100%**

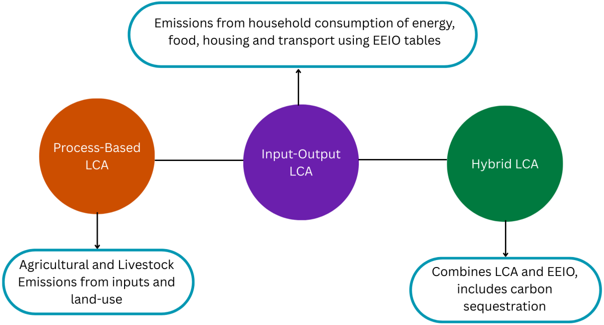
Key Findings

- Over 80% of emissions stem from scope 3 indirect consumption (e.g., food, housing, services).
- Scopes 1 and 2 combined account for less than 20%.

Conclusion: The GHG Protocol effectively captures direct emissions but underestimates total responsibility unless Scope 3 is comprehensively integrated.

Life Cycle Assessment (LCA)

- Life Cycle Assessment (LCA) calculates greenhouse gas emissions across the full life cycle of a product or service, from resource extraction and production to use and end-of-life disposal assigning life cycle emission factors to household consumption in units using the $fp_h = q_h \cdot \mathbf{LCA}_j$ principle.
- This method captures both direct and embodied emissions by integrating three complementary approaches:



Life Cycle Assessment (LCA): Integrated Estimation

Framework: Adapted from Peng et al. (2021), the hybrid LCA model aggregates activity-based emissions and sequestration:

$$CF_i = \sum_n E_{in} + \sum_m S_{im} \quad \text{(emissions + sequestration)}$$

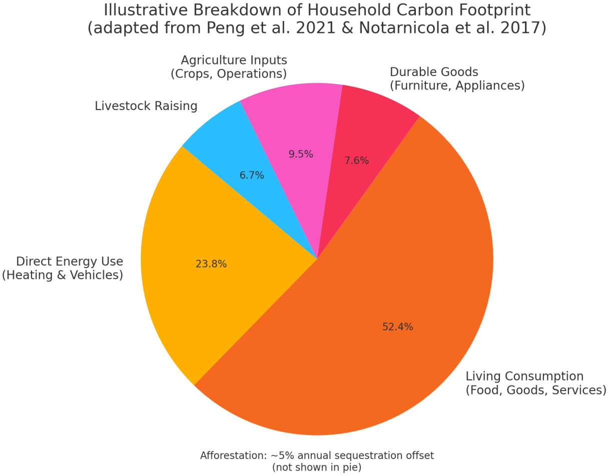
Functional Components:

- **Direct Energy Use:** $E_{id} = \sum_d (F_{id} \cdot EF_d)$
- **Consumption:** Short-lived: $E_{if} = \sum_f (EF_f \cdot C_{if})$ Durable: $E_{ij} = \sum_j \frac{EF_j \cdot C_{ij}}{L_j}$
- **Agriculture:** $CF_{ia} = \sum_a EF_a M_{ia} + \sum_t EF_t FS_{ia} + \sum_v B_v \cdot 0.475$
- **Afforestation (Sequestration):** $S_{iaf} = FS_{iaf} \cdot CS_{\text{citrus}}$
- **Livestock:** $E_{il} = \sum_f EF_{if} F_{if} + \sum_l EF_{il} N_{il}$

Implication: The Hybrid LCA structure reduces truncation error and better reflects household-level carbon responsibility particularly in domains such as food, housing, and land use.

Life Cycle Assessment (LCA): Illustration

- Indirect emissions from food, goods, and services dominate household carbon footprints highlighting the limits of focusing solely on energy behavior.



Environmentally Extended Input–Output (EEIO) Model

Definition: The EEIO model quantifies household carbon footprints by tracing both direct and upstream emissions embedded in goods and services using macroeconomic inter-industry linkages.

Core Identity:

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{F} \quad \Rightarrow \quad \mathbf{E} = \mathbf{C} \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{F}$$

Components:

- **A**: Technical coefficient matrix gives the economic input structure
- **F**: Final demand vector captures household expenditure
- **C**: Emission intensity vector (kg CO_2e / € output)

Model Assumptions and Stability:

- Fixed production coefficients (Leontief structure)
- No substitution across sectors or inputs
- The matrix **A** must satisfy $\rho(\mathbf{A}) < 1$ for stability
- Empirically: $\sum_i A_{ij} < 1$ for all j

EEIO Emissions Decomposition: Tiered Attribution

Following Matthews et al. (2008) and Long et al. (2019), household emissions are decomposed into three analytical tiers:

Tier 1 – Direct Emissions:

$$\mathbf{E}_1 = \mathbf{C}_d \cdot \mathbf{F}_d \quad \text{(e.g., direct fuel use)}$$

Tier 2 – Indirect Energy:

$$\mathbf{E}_2 = \mathbf{C}_e \cdot (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{F}_e \quad \text{(e.g., electricity, heating)}$$

Tier 3 – Indirect Supply Chain:

$$\mathbf{E}_3 = \mathbf{C} \cdot [(\mathbf{I} - \mathbf{M})(\mathbf{I} - \mathbf{A})]^{-1} \cdot [(\mathbf{I} - \mathbf{M}) \cdot \mathbf{F} + \mathbf{EX}]$$

Total Household Footprint:

$$\mathbf{E}_{\text{total}} = \mathbf{E}_1 + \mathbf{E}_2 + \mathbf{E}_3$$

Note: Import-adjusted tiers ensure that emissions are attributed to domestic demand. Enables national-scale footprint analysis with high coverage.

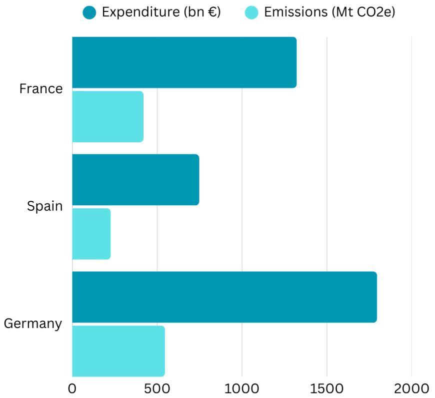
EEIO Illustration: Method and Aggregate Estimates

Methodology:

- Emission intensities EF_i reflect $\mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}$, derived from EXIOBASE (via Climatiq.io).
- National consumption $F_{i,c}$ from Eurostat (2021) is multiplied by category-specific EF_i for each country:

$$E_{i,c} = F_{i,c} \cdot EF_i$$

Total Estimated Household Carbon Footprints (2021)



Source: Eurostat (2021), EXIOBASE (2025); Author's calculations.

EEIO Illustration: Interpretation of Results

Sectoral Composition of Emissions

- Housing, food, and transport consistently emerge as the most emission-intensive categories.
- These three sectors jointly account for over 60% of total household carbon footprints in France, Spain, and Germany.

Cross-Country Differences

- **Germany:** Highest absolute emissions, reflecting both higher household expenditure and carbon-intensive energy use.
- **France:** Lower footprint per euro spent, can be attributed to cleaner energy mix and less carbon-intensive consumption.
- **Spain:** Intermediate values, with emissions closely tied to transport and agri-food supply chains.

The EEIO framework captures upstream emissions embedded in household consumption, providing a robust basis for cross-country comparison.

The Hakenes & Schliephake Model

The model captures the *marginal causal impact* of household behaviour on total emissions, accounting for both **consumption** and **investment** channels in a general equilibrium setting.

Model Assumptions:

- One homogeneous good produced with capital only, constant returns to scale.
- Linear technology: $I = cQ$, where Q is total output and I total investment.
- Emissions proportional to output: $X = xQ$.

Households:

- Wealth w allocated to consumption q_h and investment i_h, residual in risk-free asset (r_f).
- Firms raise I from households, repay with $r = \frac{P}{c} + \lambda + \varepsilon$, with $\varepsilon \sim \mathcal{N}(0, \sigma^2)$.
- Utility:

$$U_h = \mathbb{E}\left[-\exp\left(-\alpha\left(aq_h - \frac{b}{2}q_h^2 + m_h - xQ\right)\right)\right]$$

First-Order Conditions:

$$q_h = \frac{a - x - P}{b}, \quad i_h = \frac{1}{\alpha\sigma^2}\left(\frac{P}{c} + \lambda - r_f\right)$$

Market Equilibrium and Footprint Derivation

Market Clearing:

$$Q = q_h + (n-1)q_{-h}, \quad I = i_h + (n-1)i_{-h}, \quad I = cQ$$

From other households' FOCs:

$$q_{-h} = \frac{a - x - P}{b}, \quad i_{-h} = \frac{1}{\alpha\sigma^2}\left(\frac{P}{c} + \lambda - r_f\right)$$

Total investment:

$$I = \frac{n-1}{\alpha\sigma^2}\left(\frac{P}{c} + \lambda - r_f\right) \quad \Rightarrow \quad Q = \frac{n-1}{c\alpha\sigma^2}\left(\frac{P}{c} + \lambda - r_f\right)$$

Supply Curve:

$$P = c(r_f - \lambda) + \frac{c^2\alpha\sigma^2}{n-1}Q$$

Solving Supply & Demand:

$$Q = (n-1)\frac{a - x - c(r_f - \lambda)}{b + c^2\alpha\sigma^2} + \phi q_h + (1-\phi)\frac{i_h}{c}$$

where:

$$\phi = \frac{b}{b + c^2\alpha\sigma^2}$$

Empirical Illustration: U.S. Wheat Market

Objective: Apply the single-industry Hakenes–Schliephake model to quantify the impact of supply shocks on the carbon footprint.

Data & Market Setup:

- USDA (2010–2017): production volumes (supply), total domestic use (demand), average farm-gate wheat prices.
- FAO/USDA: emission factor of 10.88 kg CO_2e per bushel.
- Simulated a 15.6% production shock (2016–2017).
- **Carbon Footprint Calculation:** Emissions $= Q_{\text{eq}} \times 10.88$ kg CO_2e/bushel

Empirical Supply Curve:

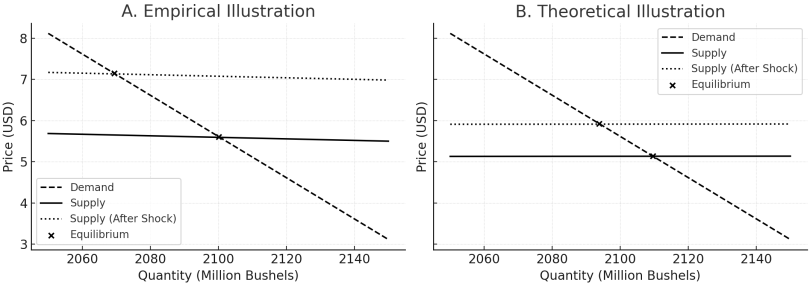
- Estimated by OLS: $P = \beta_0 + \beta_1 Q$.
- Demand curve: calibrated linear slope from dataset averages.

Theoretical Supply Curve:

$$P(Q) = c(r_f - \lambda) + \frac{c^2 \alpha \sigma^2}{n-1} Q$$

- Parameters: $c = 4$, $r_f = 0.05$, $\lambda = 0.01$, $\alpha = 0.5$, $\sigma = 0.4$, $n = 100{,}000$.
- Demand curve identical to empirical case.

Methodology: Empirical vs. Theoretical Supply



Scenario	Qty (M bu)	CF (M kg CO_2e)	Qty (M bu)	CF (M kg CO_2e)
	Empirical Model		Theoretical Model	
Before	2100.71	22859.68	2112.45	22983.46
After	2068.38	22500.32	2096.36	22808.40
Δ	—	**-359.36**	—	**-175.06**

Source: Author's calculations based on USDA (2010–2017) and FAO data.

Results and Interpretation

Key Insights:

- Despite using the same demand curve, the empirical model estimates a larger emissions reduction (-359 M kg CO_2e) than the theoretical model (-175 M kg CO_2e).
- Discrepancy arises from supply modeling:
  - Empirical: OLS estimation on historical data; no explicit modeling of risk or equilibrium feedback.
  - Theoretical: derived from structural parameters, incorporating risk aversion, return volatility, and optimal capital allocation.
- Theoretical framework embeds a consequentialist attribution, internalizing substitution effects and capital reallocation—muting output and emissions responses.
- Highlights the need to integrate behavioral and market feedbacks into footprint assessments for robust policy evaluation.

Responsibility for Household Carbon Emissions

Central Question: How should household responsibility for climate change be defined, measured, and fairly attributed?

Attribution Logics:

1. **Control-based (GHG Protocol)**:
    - Emissions assigned to actors with operational control of sources (Scopes 1–2); producer-focused.
    - Upstream supply-chain emissions (Scope 3) typically excluded.
    - Limited to operational control, often underestimates total responsibility.
    - Under household lens: 10–20% of national emissions assigned
    - **Policy Implication:**
        - Focuses on direct emissions reduction; less effective for upstream supply chains.
        - May incentivize offshoring emissions rather than reducing them.

Responsibility for Household Carbon Emissions (cont.)

2. **Consumption-based (LCA, EEIO)**:
    - **LCA:** Attributes responsibility to households by assigning them all direct and upstream emissions generated across a product's entire life cycle, proportionally to their consumption of that product or service.
    - **EEIO:** Links household final demand vector **F** to sectoral emissions via

$$\mathbf{E} = \mathbf{C}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{F}$$

    - Under household lens: 60–80% of national emissions assigned.
    - **Policy Implication:**
        - Encourages individual climate responsibility through policies that use behavioral nudges to encourage sustainable consumption.
        - Risks overstating household agency by ignoring structural and supply-side constraints.

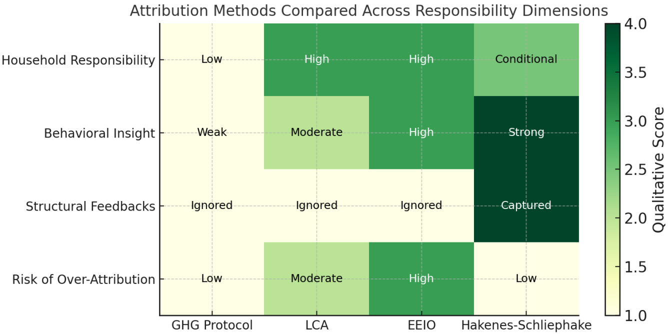
Responsibility for Household Carbon Emissions (cont.)

3. **Consequentialist (Hakenes–Schliephake)**:
   - Attributes household responsibility to the *marginal causal impact* of its consumption and investment decisions on total emissions.
   - Compares general equilibrium with the household present to the counterfactual without it, capturing direct and indirect market spillovers.
   - Defines marginal impact footprint:

$$fp_h = x\left(\phi q_h + (1-\phi)\frac{i_h}{c}\right)$$

   - $\phi = \frac{b}{b+c^2\alpha\sigma^2}$ allocates responsibility between consumption and investment.
   - Higher α (risk aversion) or σ^2 (return variance) shifts responsibility toward consumption; greater substitutability amplifies investment effects.
   - Can yield near-zero responsibility if actions are fully offset by others, avoiding over-attribution in static frameworks.
   - **Policy Implication:**
     - Aligns with structural mechanisms such as green financial regulation or carbon-intensity weighting of investment portfolios.
     - Differentiates between symbolic and substantive household climate action.

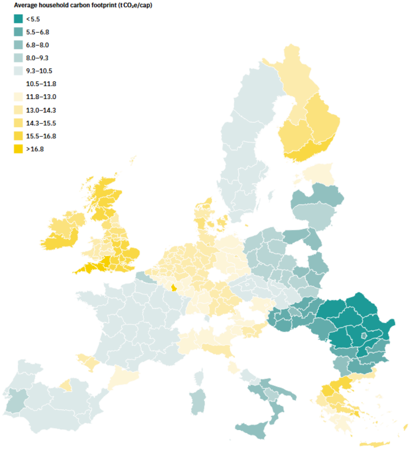
Comparative Analysis of Attribution Principles

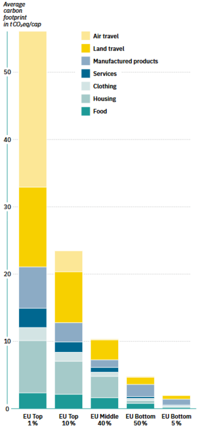


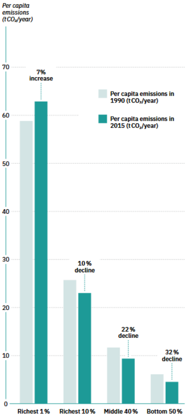
The heatmap compares attribution frameworks across behavioral relevance, structural sensitivity, and over-attribution risk.

Main finding: Consequentialist attribution (H&S) uniquely captures systemic feedbacks, avoiding double-counting while grounding responsibility in causal impact.

Household Carbon Footprint Disparities







The heterogeneity in carbon footprints across regions and income groups determines the efficiency and equity outcomes of policy instruments.

Comparative Overview of Mitigation Instruments

Instrument	Methodological Basis	Example Implementations	Features
Carbon Taxes	GHG Protocol (Scopes 1–2); EEIO for consumption-based pricing	Sweden: 130+ USD/tCO_2; Canada federal backstop; EU Border Carbon Adjustment	Internalises marginal social cost; scalable; regressive without revenue recycling; leakage risk if embedded emissions excluded
Product & Appliance Standards	Life Cycle Assessment (LCA); embedded carbon and durability metrics	EU Ecodesign Directive; Japan Top Runner; US Energy Star	Corrects efficiency market failures; harmonisable in trade policy; effectiveness depends on enforcement and affordability
Investment-Based Tools	General Equilibrium (Hakenes–Schliephake) with EEIO sectoral intensities	EU ETS; California Carbon Allowance; ESG ETFs; Green Bonds	Targets capital allocation to low-carbon sectors; addresses emissions concentration; politically sensitive, data-intensive
Behavioural Interventions	Behavioural economics; typically outside static carbon models	UK smart meter nudges; diet-shift campaigns; cookstove adoption programs	Low-cost demand adjustment; high social adaptability; persistence and measurement challenges
AI-Enabled Platforms	Hybrid EEIO–LCA with transaction-level data integration	Moneythor tracker; Svalna app; Klima app	Real-time, marginal behaviour targeting; adaptive feedback; digital divide and privacy governance concerns

Strategic Insights from Comparative Assessment

Key Takeaways:

- Attribution logic is endogenous to policy design — *what is measured constrains what can be mitigated*.
- Static, control-based approaches (GHG Protocol) facilitate fiscal and regulatory instruments but understate indirect and imported emissions.
- LCA and EEIO expand system boundaries, enabling product regulation and consumption-based taxation, but risk over-attribution absent behavioural or supply-side constraints.
- Equilibrium models capture inter-market spillovers and capital flows, offering distribution-sensitive interventions, particularly for high-wealth cohorts.
- Behavioural and AI tools bridge micro-level heterogeneity with adaptive policy targeting, but remain weakly institutionalised in formal carbon accounting.

Conclusion: Method–Instrument Alignment

Synthesis:

- No single instrument is universally optimal — efficiency, equity, and political feasibility trade-offs are shaped by the underlying attribution framework.
- Integration across methods is essential: *fiscal* (tax), *technological* (standards), *financial* (investment), and *behavioural* levers target distinct channels of household emissions.
- Economically coherent design requires aligning price signals, regulatory standards, and behavioural incentives within the structural constraints revealed by the chosen model.

Implication for policy: Incomplete or mismatched attribution undermines both cost-effectiveness and distributional legitimacy.

Synthesis: Economic Logic and Strategic Trade-Offs

- **Attribution methods determine instrument choice:**
  - GHG Protocol $\rightarrow$ direct price signals (carbon taxes, fuel levies).
  - LCA $\rightarrow$ product-level regulation (standards, eco-design).
  - EEIO $\rightarrow$ consumption-based taxes, trade adjustments.
  - General equilibrium $\rightarrow$ capital market instruments.
  - Behavioural/AI $\rightarrow$ adaptive, personalised demand-side measures.
- **Core trade-offs:** Taxes = allocatively efficient but potentially regressive. Standards = technology-forcing, risk of exclusion. Investment tools = target high-emission wealth segments, politically sensitive. Behavioural = socially embedded, hard to monetise. AI = granular and dynamic, constrained by digital equity.
- **Strategic implication:** No single instrument optimises efficiency, equity, and political feasibility. An optimal portfolio integrates complementary tools, each grounded in the correct attribution logic, to maximise mitigation while maintaining fairness and public acceptance.

Conclusion

Key Takeaways:

- Household carbon footprints are highly sensitive to **attribution framework**:
  - GHG Protocol, LCA → lower footprints, focus on direct use.
  - EEIO, general equilibrium → higher footprints via supply chains, market spillovers, capital allocation.
- Method choice **determines policy alignment**:
  - GHG Protocol → direct fuel/energy pricing.
  - LCA → product and appliance standards.
  - EEIO → upstream interventions, border carbon adjustments.
  - GE model → investment-based and capital-sensitive instruments.
- Ensuring **internal consistency** between accounting method, policy instrument, and financing strategy is critical for efficiency and fairness.

Future Work:

- Integrate micro-level household data, dynamic GE extensions, and behavioural/digital mechanisms.