

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

Anushka Mukherjee  
Matriculation No: 50075072

University of Bonn

Master's Thesis Presentation  
August 19, 2025

# Overview

---

- ➊ Introduction
- ➋ Research Questions & Methodology
- ➌ Literature Review
- ➍ Methods & Applications
- ➎ Responsibility & Policy Implications

# Motivation

Households are increasingly recognized as key actors in climate mitigation. However, the methods used to estimate their carbon footprints differ widely.

- Existing tools:
  - Apply divergent system boundaries (e.g., direct vs. full life-cycle emissions)
  - Often double-count emissions
  - Fail to account for market feedback or investment-related emissions
- **Analytical Problem:** The attribution logic embedded in each method fundamentally shapes how household responsibility is quantified.
- **Research Gap:** No unified framework currently compares GHG Protocol, LCA, EEIO, and general equilibrium models from a responsibility perspective.
- **Contribution:** This thesis systematically compares four models 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?

## Methodology (I): Analytical Framework

---

- A comparative framework is used to analyze how different carbon accounting methods attribute household emissions.
- The analysis covers four dominant models:
  - **GHG Protocol (Production-based)**: Focuses on direct household emissions (Scopes 1–2)
  - **Life Cycle Assessment (Product-based)**: Attributes emissions across a product's lifecycle
  - **EEIO Model (Consumption-based)**: Traces emissions through upstream production based on household expenditure
  - **Hakenes–Schliephake Model (Consequentialist)**: Assigns responsibility based on marginal impact in general equilibrium framework
- For each method, the attribution logic, model assumptions, and policy outcomes are compared.

# Methodology (II): Addressing the Research Questions

---

## Research Questions Addressed

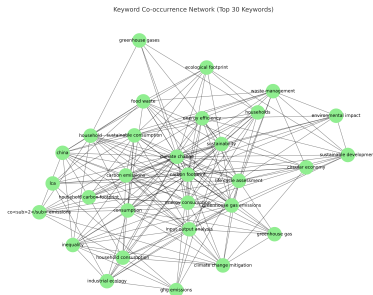
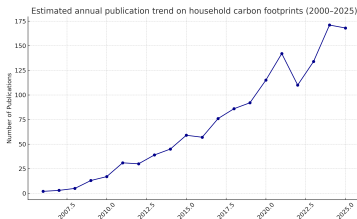
- ⇒ **RQ1:** How do footprint estimates vary across methods?
  - Empirical illustrations are derived using official household expenditure data (Eurostat, USDA) and publicly available emission factors (EXIOBASE, ClimaTiq, IPCC).
- ⇒ **RQ2:** How does each method attribute household responsibility?
  - Theoretical derivations and decomposition techniques illustrate attribution logic and scope.
  - Attribution is classified as operational, consumption-based, or consequentialist.
- ⇒ **RQ3:** What are the equity and policy implications?
  - Each attribution model is linked to relevant policy instruments and their distributional impacts.

# 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:** Inequality, global supply chains, and lifestyle effects (Ivanova et al., 2015; Moran et al., 2018)
- Dominant methods in current literature:
  - **GHG Protocol:** Activity-based, scope-defined inventories (IPCC Guidelines, 2019)
  - **LCA:** Process-based alternative, tracing cradle-to-grave emissions (Steubing et al., 2022)
  - **EEIO:** Economy-wide linkages via input–output matrices (Baiocchi & Minx, 2010, Wiedmann, 2009)
  - **GE Models:** Endogenizes household decisions and emissions via market-clearing and investment feedback. (Hakenes & Schliephake, 2024)

# 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*.

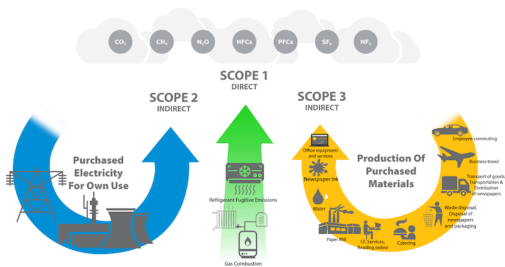


- Top Journals: *Journal of Cleaner Production*, *Science of the Total Environment*, and *Environmental Science & Technology*
- Top institutions: University of Tokyo, Sun Yat-sen University, University of Maryland.



# GHG Protocol: Emission Inventory Framework

**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:

$$CF_{\text{household}} = E_{\text{Scope 1}} + E_{\text{Scope 2}} + E_{\text{Scope 3}}, \quad E_i = \sum_j Q_{ij} \cdot EF_{ij}$$

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.

**Data:** Spanish household expenditure and energy use (INE 2022), mapped to COICOP categories. Emission factors sourced from DEFRA (2022) and IPCC (2019).

**Method:**

- **Scope 1:** Direct emissions from household fuel combustion (e.g., petrol in vehicles, natural gas for heating).
- **Scope 2:** Indirect emissions from electricity and district heating generation due to household demand.
- **Scope 3:** Indirect emissions from purchased goods and services via € expenditure × emission factor

**Avg. annual spending:** = €31,568

**Major spending:** Housing (32.4%), Food (16%), Transport (12%)

# GHG Protocol – Empirical Results (Spain, 2022)

## Total Household Carbon Footprint:

Total Emissions = 11,828.08 kg CO<sub>2</sub>e/year

## Emissions by Scope

Scope	Definition	Emissions (kg CO <sub>2</sub> e)	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): Conceptual Basis

**Definition:** 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.

**Analytical Scope:** This method captures both direct and embodied emissions by integrating three complementary approaches:

- *Process-based LCA*, which quantifies emissions from discrete production activities such as fuel combustion, agriculture, and food processing
- *Input–Output LCA*, which links household consumption to indirect upstream emissions using environmentally extended input–output (EEIO) tables
- *Hybrid LCA*, which combines the process-level specificity of traditional LCA with macroeconomic linkages from IO models to reduce system boundary truncation

**Carbon Footprint Estimation:**

$$fp_h = q_h \cdot LCA_j$$

where  $q_h$  is household consumption and  $LCA_j$  is the unit emission factor for product  $j$

# Life Cycle Assessment (LCA): Integrated Estimation

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

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

## Functional Components:

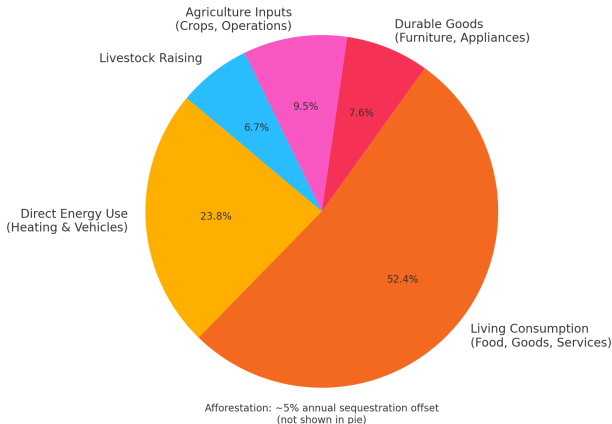
- **Direct Energy Use:**  $E_{id} = \sum_d (F_{id} \cdot EF_d)$
- **Consumption:** Short-lived:  $E_{if} = \sum_f (EF_f \cdot C_{if})$  Durable:  $E_{ij} = \sum_j \frac{EF_j \cdot C_{ij}}{L_j}$
- **Agriculture:**  $CF_{ia} = \sum_a EF_a M_{ia} + \sum_t EF_t FS_{ia} + \sum_v B_v \cdot 0.475$
- **Afforestation (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.

## LCA Illustration

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

Illustrative Breakdown of Household Carbon Footprint  
(adapted from Peng et al. 2021 & Notarnicola et al. 2017)



# Environmentally Extended Input–Output (EEIO) Framework

**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<sub>2</sub>e / € 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:

$$E_1 = C_d \cdot F_d \quad (\text{e.g., direct fuel use})$$

## Tier 2 – Indirect Energy:

$$E_2 = C_e \cdot (I - A)^{-1} \cdot F_e \quad (\text{e.g., electricity, heating})$$

## Tier 3 – Indirect Supply Chain:

$$E_3 = C \cdot [(I - M)(I - A)]^{-1} \cdot [(I - M) \cdot F + EX]$$

## Total Household Footprint:

$$E_{\text{total}} = E_1 + E_2 + E_3$$

**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 Household Carbon Footprints (2021):

Country	Expenditure (bn €)	Emissions (Mt CO <sub>2</sub> e)
France	1322.0	420.0
Spain	747.9	227.0
Germany	1794.8	545.9

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:

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

## 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<sub>2</sub>e per bushel.
- Simulated a 15.6% production shock (2016–2017).
- **Carbon Footprint Calculation:** Emissions =  $Q_{\text{eq}} \times 10.88$  kg CO<sub>2</sub>e/bushel

## Empirical Supply Curve:

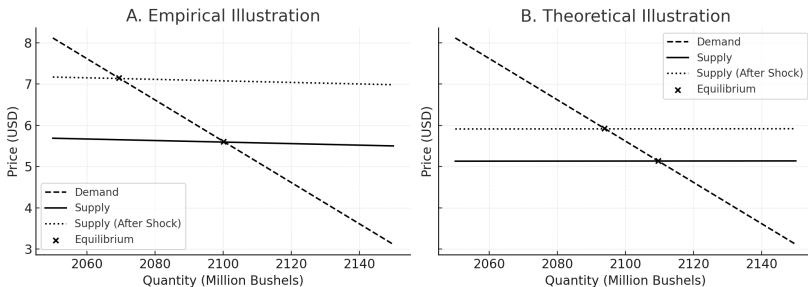
- Estimated by OLS:  $P = \beta_0 + \beta_1 Q$ .
- Demand curve: calibrated linear slope from dataset averages.

## 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 <sub>2</sub> e)	Qty (M bu)	CF (M kg CO <sub>2</sub> e)
	Empirical Model		Theoretical Model	
Before	2100.71	22859.68	2112.45	22983.46
After	2068.38	22500.32	2096.36	22808.40
Δ	—	<b>-359.36</b>	—	<b>-175.06</b>

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<sub>2</sub>e) than the theoretical model ( $-175$  M kg CO<sub>2</sub>e).
- 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.)

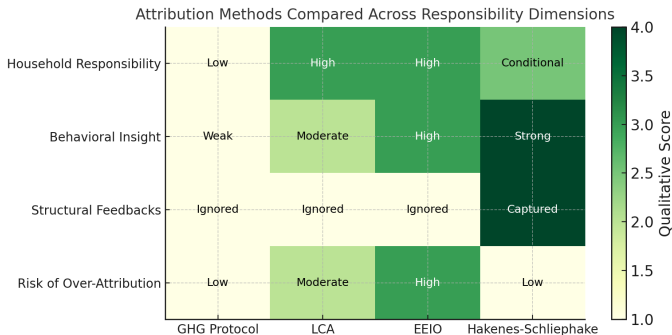
### ③ Consequentialist (Hakenes–Schliephake):

- 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  $\alpha$  (risk aversion) or  $\sigma^2$  (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.

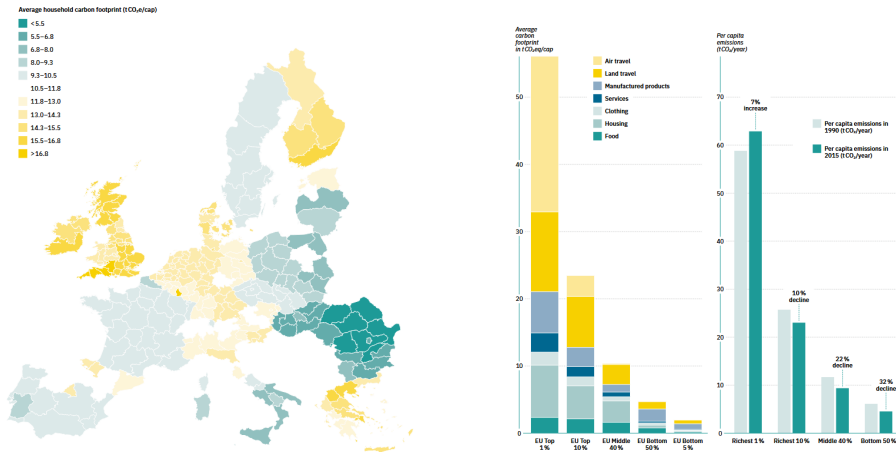
# Comparative Analysis of Attribution Principles



*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.*

# Household Carbon Policy Instruments: Comparative Overview

Instrument	Methodological Basis	Strengths	Limitations
Carbon Taxes	GHG Protocol (Scopes 1–2); extended by EEIO for consumption-based pricing	Price-based efficiency; scalable; fiscal integration	Regressive without redistribution; omits embedded emissions if Scope 3 excluded
Product & Appliance Standards	LCA with embedded carbon and durability criteria	Tech-driven efficiency gains; aligns with trade rules	Enforcement gaps; risk of excluding low-income users
Investment-Based Tools	General equilibrium (Hakennes–Schliephake) with EEIO sectoral intensities	Targets capital-linked emissions; addresses top-income externalities	Data-intensive; politically sensitive in asset-heavy economies
Behavioural Interventions	Behavioural economics; weakly embedded in static models	Low-cost, adaptive, socially contextual	Under-captured in conventional carbon metrics
AI-Enabled Platforms	Hybrid EEIO–LCA with transaction-level data	Real-time tracking; personalised policy feedback	Digital divide; privacy and governance risks

# 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.

# Household Carbon Policy Instruments: Methods, Examples, and Economic Notes

Instrument	Methodological Basis	Example Implementations	Features
Carbon Taxes	GHG Protocol (Scopes 1–2); EEIO for consumption-based pricing	Sweden: 130+ USD/tCO <sub>2</sub> ; 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 inte-	Moneythor tracker; Svalna app; Klima app	Real-time, marginal behaviour targeting; adaptive



# Synthesis: Economic Logic and Strategic Trade-Offs

- **Attribution methods determine instrument choice:**
  - GHG Protocol → direct price signals (carbon taxes, fuel levies).
  - LCA → product-level regulation (standards, eco-design).
  - EEIO → consumption-based taxes, trade adjustments.
  - General equilibrium → capital market instruments.
  - Behavioural/AI → 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.