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

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Overview

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- **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.

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2. How is household responsibility estimated and attributed under each carbon accounting method?
3. How do attribution methods shape policy and equity outcomes?

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  - **Input–Output Analysis:** Economy-wide linkages via input–output matrices (Baiocchi & Minx; 2010, Wiedmann, 2009)

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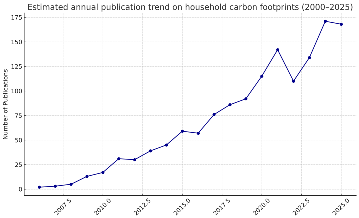

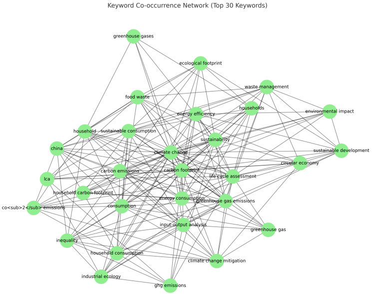

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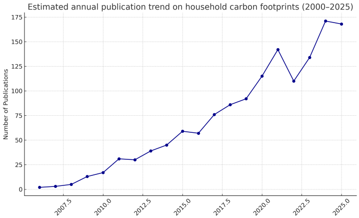

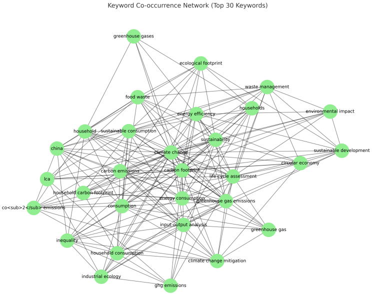

- Top Journals: *Journal of Cleaner Production*, *Science of the Total Environment*, and *Environmental Science & Technology*
- Top institutions: University of Tokyo, Sun Yat-sen University, University of Maryland.

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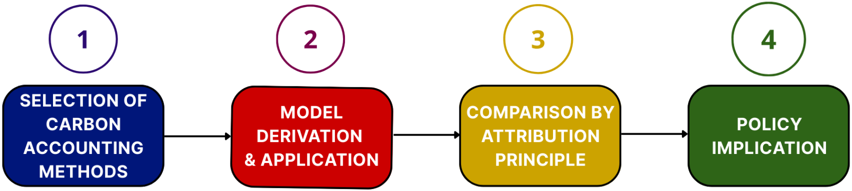

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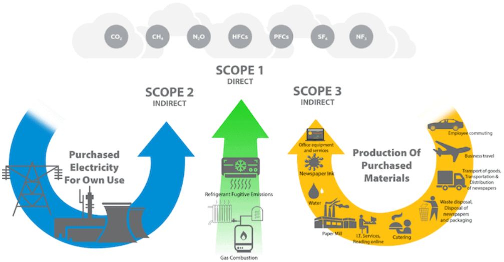

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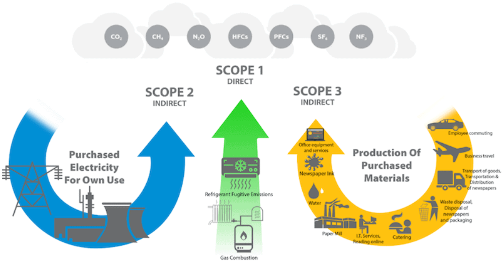

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Formulation:

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

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

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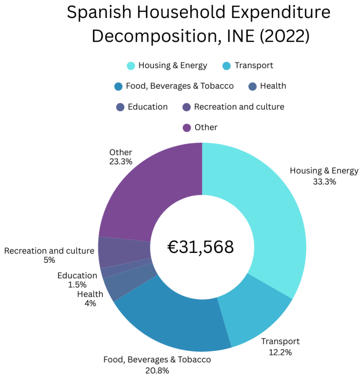

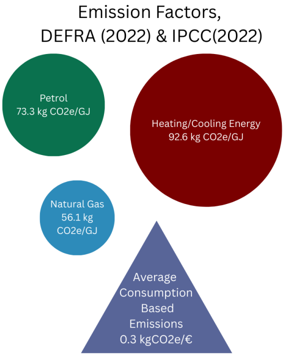

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Scope	**Definition**	**Emissions (kg CO_2e)**	**Share (%)**
Scope 1	Direct fuel use (transport + heating)	1,114.83	9.4%
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Conclusion: The GHG Protocol effectively captures direct emissions but underestimates total responsibility unless Scope 3 is comprehensively integrated.

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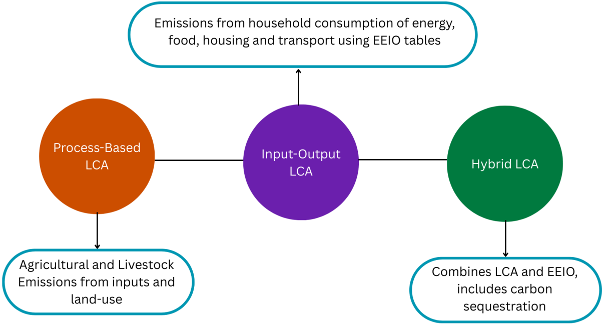
- This method captures both direct and embodied emissions by integrating three complementary approaches:



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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.

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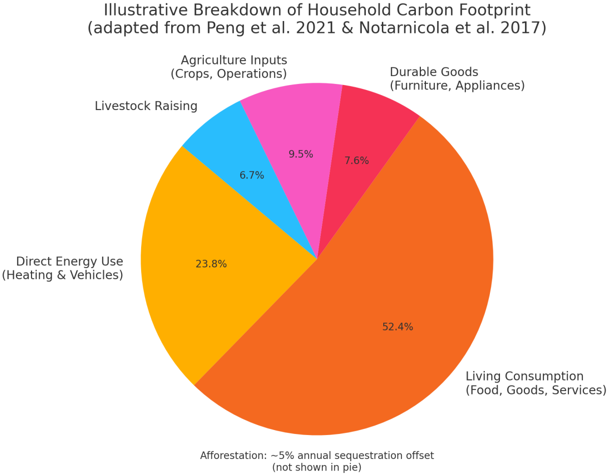

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Components:

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- **F**: Final demand vector captures household expenditure
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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

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Note: Import-adjusted tiers ensure that emissions are attributed to domestic demand.

Enables national-scale footprint analysis with high coverage.

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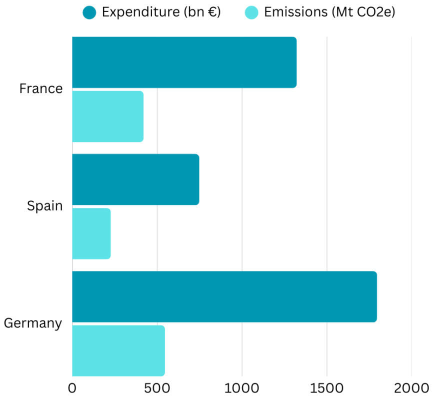
Total Estimated Household Carbon Footprints (2021)



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

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EEIO Illustration: Interpretation of Results

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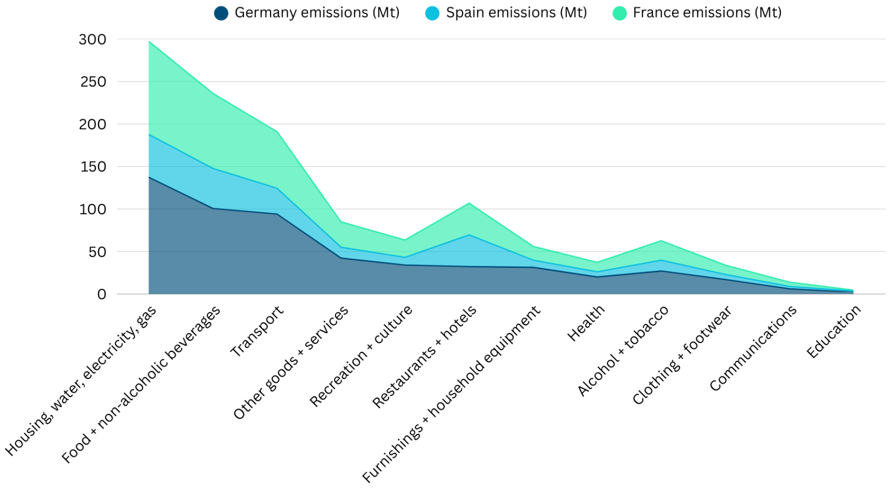

The Hakenes & Schliephake Model

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Model Assumptions under One-Industry Economy:

- One homogeneous good produced with capital only, constant returns to scale.
- Linear technology: $I = cQ$
- Firms raise I from households, repay with $r = \frac{P}{c} + \lambda + \varepsilon$, with $\varepsilon \sim \mathcal{N}(0, \sigma^2)$.
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Households:

- Wealth w allocated to consumption q_h and investment i_h, residual in risk-free asset (r_f): $m_h = ri_h + r_f(w - i_h) - Pq_h$.
- Expected Utility:

$$\mathbb{E}[U_h] = -\exp\left\{-\alpha\left[(a-P)q_h - \frac{b}{2}q_h^2 + r_f w + \left(\frac{P}{c} + \lambda - r_f\right)i_h - \frac{\alpha}{2}\sigma^2 i_h^2 - xQ\right]\right\}$$

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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:

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

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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:

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

Total Household Carbon Footprint:

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

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.

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- FAO/USDA: emission factor of 10.88 kg CO_2e per bushel.
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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.

Carbon Footprint under Empirical & Theoretical Model

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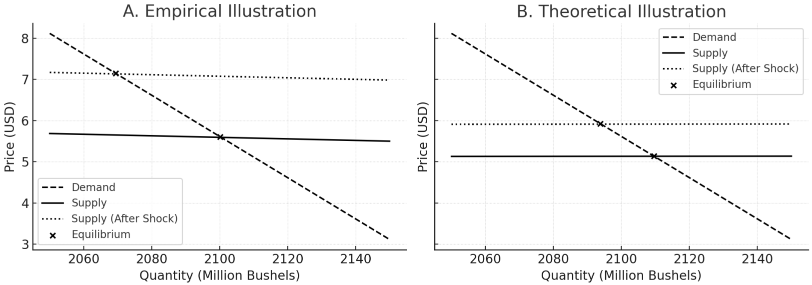

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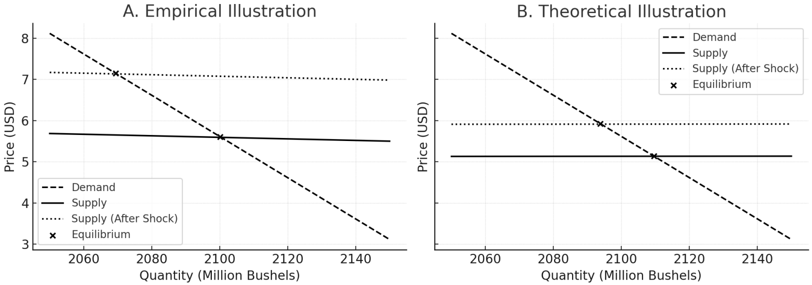


Scenario	Qty (M bu)	CF (M kg CO_2e)	Qty (M bu)	CF (M kg CO_2e)
	Empirical Model		Theoretical Model	
Before	2100.71	22859.68	2112.45	22983.46
After	2068.38	22500.32	2096.36	22808.40
Δ	—	**-359.36**	—	**-175.06**

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

Responsibility for Household Carbon Emissions

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

Attribution Logics

OPERATIONAL CONTROL (GHG PROTOCOL)

- Emissions assigned based on operational responsibility.
- Typically attributes emissions to households from direct fuel use and purchased heat/electricity (Scopes 1 and 2).
- Households not held accountable for upstream emissions embodied in consumption of purchased goods and services (Scope 3).
- Production-based attribution, leads to underestimation of household responsibility.
- Only 10-20% of national emissions assigned to households

CONSUMPTION-BASED (LCA & EEIO)

- Assigns responsibility of emissions to end users.
- LCA quantifies emissions over a product's life-cycle.
- EEIO links household expenditure data with environmental accounts using input-output tables, assigning emissions in proportion to spending categories.
- Results in high attribution to households, typically between 60-70% in high-income countries.

CONSEQUENTIALIST (HAKENES & SCHLIEPAKE)

- Aggregate emissions of an economy depend on the marginal decisions of a household.
- Weighting parameter determines the relative attribution of emission between consumption and investment.
- Includes both product and financial market and accounts for spillovers through capital reallocation, risk preference and price mechanism.
- Avoids double counting and over-attribution.

Policy Implications of Attribution Logics

OPERATIONAL CONTROL (GHG PROTOCOL)

- Suitable for direct emission reduction policies like emission caps, carbon pricing, and corporate responsibility interventions for supply-side decarbonization.
- May incentivize offshoring emissions rather than reducing them.

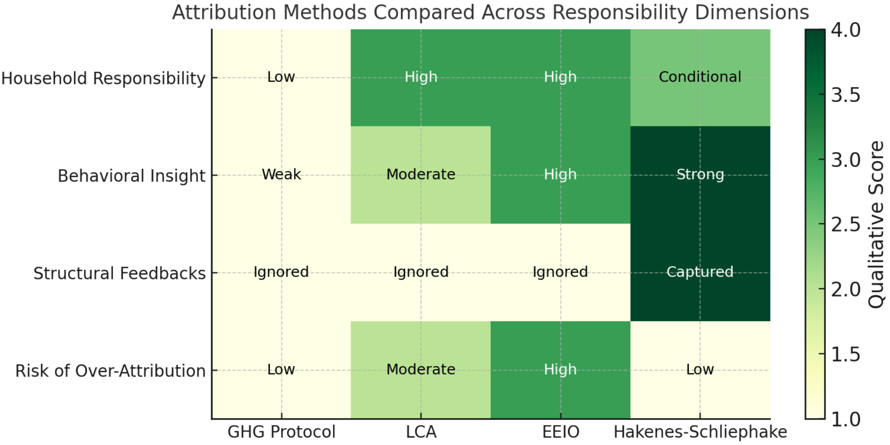
CONSUMPTION-BASED (LCA & EEIO)

- 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.

CONSEQUENTIALIST (HAKENES & SCHLIEPAKE)

- 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



Household Carbon Footprint Disparities

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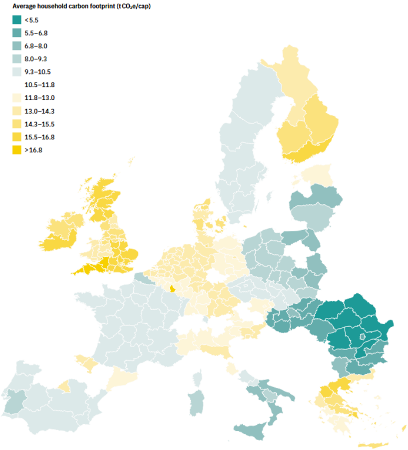

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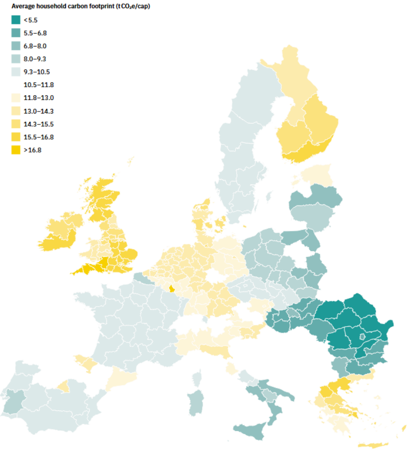

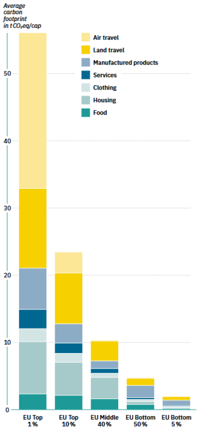

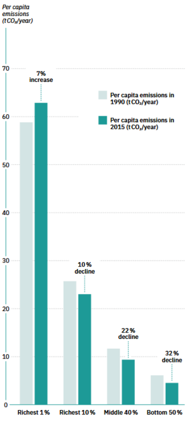

Comparative Overview of Mitigation Instruments

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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

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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

Optimal Mitigation Portfolio

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.

Policy Recommendations

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- **Expand carbon pricing coverage:** Combine GHG Protocol–based taxes on direct fuel and electricity use with EEIO-informed upstream pricing (e.g. border carbon adjustments) to capture embedded emissions in imports.
- **Integrate investment-linked accounting:** Attribute portfolio emissions to households via mandatory financial institution reporting, carbon-intensity metrics in retail products, and differentiated capital gains tax rates, linking investment to market wide externalities.
- **Deploy AI-enabled carbon tracking:** Develop open-source, transaction-linked digital tools integrating banking, utility, and purchasing data to deliver real-time household carbon feedback and tie results to incentive programs.
- **Strengthen product standards:** Ecodesign and efficiency labels extended to cover embodied carbon and lifetime emissions, with mandatory inclusion in public procurement and consumer labeling.
- **Advance hybrid modelling:** Combine dis-aggregated EEIO, dynamic general equilibrium modelling, and behavioral segmentation to simulate differentiated policy impacts across income, asset ownership, and urban-rural contexts.

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- Overall, the study concludes that household decarbonization strategies must be methodologically consistent, equity sensitive and operationally scalable.
- **Limitations and future work:** This analysis uses stylized data, a static equilibrium model, and omits behavioral heterogeneity; future research should integrate microdata, dynamic modelling, and machine learning for digital tracking tools.

Thank you!