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

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Overview

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

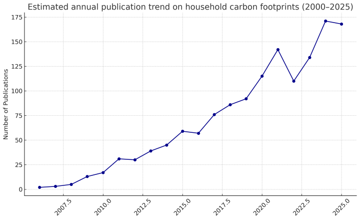
- **RQ1:** How do footprint estimates vary across methods?
  - Empirical illustrations are derived using official household expenditure data (Eurostat, USDA) and publicly available emission factors (EXIOBASE, Climatiq, IPCC).
- **RQ2:** How does each method attribute household responsibility?
  - Theoretical 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.

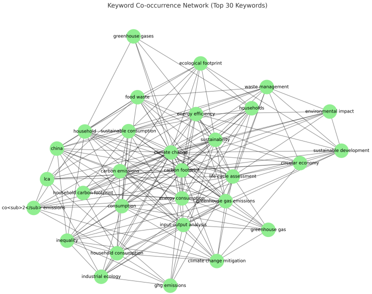
Literature Review: Evolution of HCF Estimation

- 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*.

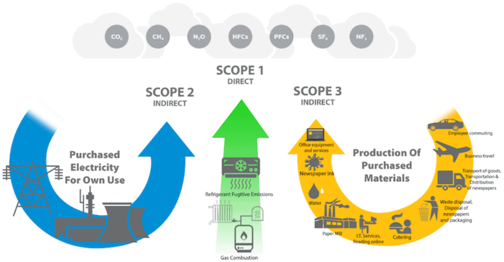




- Top Journals: *Journal of Cleaner Production*, *Science of the Total Environment*, and *Environmental Science & Technology*
- Top institutions: University of Tokyo, Sun Yat-sen University, University of Maryland.

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:

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

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.

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 $\times$ 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:

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

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): 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:

$$fp_h = q_h \cdot \mathrm{LCA}_j$$

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:

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

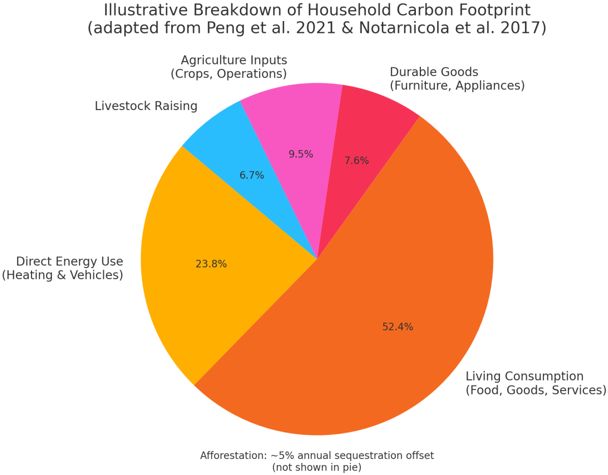
Functional Components:

- **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.



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_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 Household Carbon Footprints (2021):

Country	Expenditure (bn €)	Emissions (Mt CO_2e)
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.