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The Carbon Footprint of Final Demand: Evolving Methods and Insights from Environmentally Extended Input–Output Analysis

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Executive Summary

Environmentally Extended Input–Output (EEIO) analysis has become a cornerstone of climate research and policy design. Rooted in national accounting traditions and originally developed to quantify intersectoral dependencies, input–output analysis was paired with environmental data as early as the late 1960s. EEIO gained momentum with the adoption of greenhouse gas reporting obligations under the United Nations Framework Convention on Climate Change (UNFCCC). While this framework represented a major advance in climate governance, its territorial nature neglects emissions embedded in trade. This raised concerns about fairness between countries that "*export*" and "*import*" emissions, and about the risk of offshoring undermining global mitigation efforts. EEIO provides insights into producer value chains while also allowing upstream emissions to be collapsed into final demand. This consumption-based perspective, which EEIO uniquely enables, complements the production-based view of territorial accounting and supports more balanced debates on fairness and mitigation in a globalised economy.

This note reviews the intellectual and methodological evolution of EEIO models, with particular attention to their application to final demand.

The first part introduces territorial, production-based, and consumption-based emissions accounting and their respective responsibility frames. It situates EEIO in the national accounting tradition and explains how it operationalises consumption-based accounting while enriching production-based perspectives. Early applications extended single-country input–output tables with environmental data, followed by the emergence of domestic EEIO databases and, later, multi-regional and global tables built by harmonising national accounts. Over time, scholars, private initiatives, and national and international statistical bodies refined these databases to cover more countries, sectors, and products, expanding the scope of analysis.

Against this methodological background, the note also reviews global territorial inventories, which show that greenhouse gas emissions in 2019 arose primarily from energy supply (34%), industry (24%), Agriculture, Forestry and Other Land Use (22%), transport (15%), and buildings (c. 6%). While emissions from developed countries have markedly declined since 1990, these reductions have been more than offset by rising emissions in developing countries, most notably China.

The second part focuses on the emissions footprint of final demand under standard consumption-based accounting, identifying the relative importance of household consumption, capital formation, and government consumption. It highlights how empirical insights have depended on advances in EEIO datasets, with the demand for more precise policy-relevant evidence in turn spurring refinements in database coverage, granularity, and consistency. This co-evolution of research and data has been central to the field. Although considerable progress has been made, the review notes that database development remains an area for continued investment to support robust research and policy applications, and also acknowledges the methodological limits of mainstream EEIO models. Nevertheless, the section explains that consumption-based accounting has allowed fairness and equity to be reframed in climate negotiations by showing that most developed countries are net importers of emissions, so their consumption-based footprints exceed the emissions generated within their borders. The section also reviews research on the three main components of final demand in detail, highlighting disparities across contexts and the mitigation potential of each, as well as the opportunities that arise when these levers are considered together.

Household Consumption

Household consumption typically accounts for around two-thirds of greenhouse gas emissions in high- and upper-middle-income countries, and an even greater share in many lower-income economies. The composition of these footprints shifts with income: food and shelter dominate in poorer countries, while mobility and manufactured products grow in importance as incomes rise. In 2010, disparities were already stark: the carbon footprint of the global top decile by expenditure was more than ten times larger than that of the bottom half of humanity, and household footprints varied more than twentyfold between high- and low-income countries. Within countries, inequalities were sharper in developing economies, but even in the EU the top decile accounted for as much as the bottom half, with the top centile alone having an outsized footprint driven by air transport.

Decarbonising household demand will therefore require targeting high-emission categories, particularly mobility and diet, while challenging cultural norms that underpin aspirational, high-carbon lifestyles. In high- and middle-income countries, most household emissions are embedded upstream in supply chains, underscoring the need to pair demand-side measures with production-side decarbonisation. In low-income countries, direct household emissions from cooking, heating, and cooling are more significant, pointing to electrification and grid decarbonisation as priority levers. Evidence also shows that universal access to health, longevity, and education is achievable within the limits set by global climate targets, under different assumptions about income distribution, and with different consumption choices, which could be facilitated by appropriate infrastructure investments and government services.

Capital Formation

Capital formation, especially in long-lived assets such as buildings, infrastructure, and heavy machinery, has historically represented the bulk of material resource use in industrial economies. Investment represents about a quarter of global final demand and close to a third of related emissions.

Patterns nevertheless vary strongly across countries. In industrialised economies, capital formation accounts for around a quarter of final-demand emissions. In industrialising and urbanising economies, its share is typically higher and may even become the dominant component of territorial emissions, as is the case in China. Indeed, the relative share and carbon intensity of capital formation both decline with GDP, as economies shift away from construction and heavy industry toward less emission-intensive forms of investment, such as computer equipment and intellectual property products. This notwithstanding, the built environment remains the dominant contributor to capital-related emissions, including residential housing, public infrastructure, and commercial buildings.

Mitigation options for capital formation include avoiding unnecessary or excessively scaled projects, redirecting investment to lower-carbon sectors where feasible, and improving efficiency in construction and materials use. While these direct mitigation measures are necessary, it is also important to stress that the state and evolution of the capital stock condition long-term consumption and production patterns. The built environment, notably, will shape demand and output for decades, influencing energy, transport, and material use through maintenance, repair, and replacement. New investment may lock in high-emission systems or lock off decarbonisation possibilities.

Government Consumption

Government consumption accounts for about one-ninth of GDP in low- and lower-middle-income countries, and about one-sixth in upper-middle- and high-income countries. Its carbon intensity is lower than that of household consumption, and markedly lower than capital investment, reflecting its service-based nature. Most government consumption emissions arise indirectly through supply chains, which makes procurement a key prima facie lever for reducing the footprint of government services. Government consumption plays an outsized role in reducing in-country disparities in footprints by redistributing resources through the provision of public services such as health, education, housing, and transport, which disproportionately benefit lower-income households. Irrespective of political orientations relative to redistribution, public administration can structure procurement strategically to avoid supporting or locking-in high emissions and instead stimulate innovation and help create or scale markets for low-carbon alternatives and climate solutions. In addition, public service redesign, including dematerialisation, can reduce household and production emissions, while public service innovation can support economy-wide emissions mitigation, including through the development of low-emission lifestyles that do not compromise welfare.

The final part of the note examines methodological advances incorporating capital-related emissions into the consumption they enable. It begins with adjustments developed within standard one-period EEIO models, reallocating observed capital formation emissions or attaching emissions to capital depreciation. Empirical applications show that such reallocations increase emissions embodied in trade by more than 10% and reshape sectoral profiles, with implications for exporter–importer responsibility debates.

It then turns to more advanced approaches that capture the evolution of productive assets over time, either through stylised dynamic modelling or by integrating physical stock tracking. For illustration, dynamic endogenisation of capital increases China's 2015 consumption-based emissions by over a quarter and underlines the importance of lowering the carbon intensity of Chinese construction and extending the durability of its built infrastructure.

The conclusion highlights that recent methodological innovations have expanded EEIO's scope. Improvements in spatial, temporal, and sectoral resolution, together with hybridisation with tools from industrial ecology, are enabling more granular and physically grounded estimates. In parallel, researchers are extending EEIO frameworks to simulate future technological change and policy interventions, thereby increasing their utility for scenario-based planning.

Even with these advances, EEIO retains structural limitations: it typically assumes fixed production technologies, sector homogeneity, and static interdependencies. These features suit historical analysis but constrain its value as a standalone tool for forward-looking modelling. To capture feedbacks, lock-ins, path dependencies, and behavioural change, EEIO should be complemented by system dynamics, macroeconomic scenario tools, or agent-based approaches. Only by integrating such complementary methods can EEIO fully support transition-oriented climate policy analysis.

Introduction

The Great Depression challenged economists working within market-based systems to develop new theoretical and empirical tools to diagnose macroeconomic ills and target government action aimed at initiating economic recoveries. In the United States (US), the first comprehensive estimate of national income was produced in 1934, prefiguring the system of national accounts that would be formalised through transatlantic efforts during the 1940s. Input–output analysis, which was put forward in this context by Wassily Leontief in 1936, enabled the modelling of structural interdependencies between productive sectors. Together, the emergence of detailed sectoral data at the national scale, and the development of a powerful analytical tool to exploit them, enabled more precise and coordinated policy efforts to stimulate recovery, in line with the emerging consensus on aggregate demand management. The need to plan and coordinate industrial production during World War II, and later to support the reconstruction of post-war Europe and Japan, cemented the place of input–output analysis in applied economics and policy design.[1]

Concerns over pollution in the high-growth postwar period surged during the 1960s, prompting parallel efforts to regulate industrial pollution[2] and to incorporate environmental data into economic analysis. Input–output tables were first paired with pollution data toward the end of the decade, marking the birth of environmentally extended input–output (EEIO) analysis. This approach was fully formalised in 1970, the same year the US strengthened its environmental legislation and established the Environmental Protection Agency. The 1970s saw the emergence of environmental accounts that would gradually be developed and aligned with national accounts frameworks in the following decades.[3] During the same decade, mounting concerns about resource depletion and biospheric limits led a small group of heterodox thinkers to argue that economic modelling should be re-embedded in biophysical reality. This intellectual current helped shape the emergence of industrial ecology, an engineering-led field that sought to trace material and energy flows through production and consumption systems and developed tools such as material flow analysis (MFA) and life-cycle assessment (LCA), which would later be hybridised with EEIO to enhance its physical realism and granularity.

A turning point came in the 1990s with the international recognition of climate change as a systemic threat. The United Nations Framework Convention on Climate Change (UNFCCC), signed in 1992 and ratified in 1994, established a global architecture for monitoring and reducing greenhouse gas (GHG) emissions. Under the subsequent Kyoto Protocol (1997), industrialised countries committed to tracking

1 - Economists in the Soviet Union had long relied on material balance methods to support the central planning of production and resource allocation. This approach involved calculating and reconciling the physical supply of key goods with the quantities required across the economy, commodity by commodity. After World War II, several socialist countries adopted input–output analysis to complement these methods and improve planning coherence and coordination across sectors.

2 - The Clean Air Act of 1963 and the Water Quality Act of 1965 marked the first US major federal interventions to control industrial pollution. In a special message to Congress in February 1965, President Lyndon B. Johnson became the first US president to formally acknowledge the climate threat posed by greenhouse gas emissions.

3 - Norway and France began developing environmental accounts in the 1970s and 1980s, focusing on natural resource use, emissions, and sectoral interactions. The Netherlands advanced the field in the early 1990s by formally integrating environmental variables into national accounting structures, producing a key blueprint for European harmonisation. At the global level, these efforts converged in the United Nations' System of Environmental-Economic Accounting, whose first handbook was released in 1993.

and reducing the emissions generated within their own borders. The rapid industrialisation of emerging economies prompted calls from advanced countries to extend mitigation responsibilities globally. In parallel, developing countries underscored the inequity of accounting systems that made them fully responsible for the emissions generated by the production of goods consumed in high-income countries. This tension spurred interest in analytical tools capable of tracing emissions across production and consumption networks. EEIO was applied to this task, and consumption-based analyses attributing emissions to final demand yielded new insights in the 1990s and early 2000s. The development of environmentally extended multi-regional input–output (EE-MRIO) databases over the following decade enabled more accurate estimation of the emissions embodied in trade by accounting for cross-country differences in production systems, i.e., divergences in technologies, sectoral structures, and supply chains that underpin the production and distribution of goods and services. These advances helped inform more nuanced debates on mitigation and equity, and also contributed to the emergence of the comprehensive yet flexible framework of the Paris Agreement (2015).

This note provides a structured review of the evolution of EEIO analysis, with particular attention to its application in attributing emissions to final demand. The consumption-based perspective has become a cornerstone of research into carbon footprints and embodied emissions in trade, and the note reflects this focus.

The review is structured in three parts.

- The first part introduces territorial, production-, and consumption-based emissions accounting and their respective responsibility focuses. It explains how EEIO builds on national accounts and their environmental extensions to operationalise consumption-based accounting and enrich production-based perspectives, and provides high-level figures to illustrate current global emission patterns and drivers.
- The second part focuses on the emissions footprint of final demand under standard consumption-based accounting, identifying the relative importance of household consumption, capital formation, and government spending across national contexts. It then reviews research addressing each component in turn, highlighting disparities, estimation challenges, and the mitigation potential of different demand categories. The section concludes with a discussion of the normative implications of the consumption-based framework in the context of international climate negotiations and equity debates, and points to the limits of mainstream EEIO models.
- The third part examines approaches to incorporating capital-related emissions into the consumption they enable. It begins with adjustments developed within static, single-period EEIO models, reallocating observed capital formation emissions or attaching emissions to capital depreciation. It then turns to more advanced methods that capture the evolution of productive assets over time, either through stylised dynamic modelling or by integrating physical stock tracking in the spirit of material flow analysis. The section concludes that these emerging frontiers enhance the precision of carbon footprinting, offer valuable insights for equity-orientated analysis, and should be further developed to support forward-looking transition planning.

While this note focuses primarily on the evolution of EEIO models and their application to final demand footprinting, it is worth noting that EEIO frameworks are also widely used by data providers to estimate sector-based emissions for corporates, or as sources of average emissions factors for a variety of downstream applications, from product-level life-cycle assessments and corporate-wide footprinting to financial carbon accounting and trade-related policy instruments. A better understanding of the structure, assumptions, and limitations of EEIO models can help inform the appropriate use, interpretation, and development of these derivative tools and datasets.[4]

4 -These derivative uses typically do not inherit the internal consistency of EEIO modelling frameworks. When upstream coefficients or sectoral emissions factors are extracted and reused without appropriate adjustments, they can introduce inconsistencies or result in multiple counting of the same emissions across datasets or tools, potentially inflating aggregate estimates and leading to misinterpretation or misattribution.

From Territorial to Consumption-Based Emissions Accounting

Accounting for GHG emissions is central to climate governance, informing both domestic policies and international commitments. Yet emissions can be allocated in different ways, and these choices shape how responsibility is understood and where mitigation efforts are targeted. This section reviews the main accounting frameworks, and explains, in broad terms, how EEIO operationalises the transition from territorial to consumption-based perspectives.

In climate accounting, emissions are typically allocated using one of two frameworks, both of which are applied on an annual (calendar year) basis:

- **Territorial or production-based accounting.**[5] Territorial accounting, used for national greenhouse gas inventories and target-setting under the Paris Agreement, allocates emissions to the country where they physically occur and classifies them by emitting source (e.g. energy, industry, transport). A related variant, production-based accounting aligned with the System of National Accounts (SNA), assigns emissions to resident economic sectors based on their role in producing goods and services. Both approaches focus on emissions at their source and do not consider who ultimately consumes the output, where such output exists.
- **Consumption-based accounting (demand approach).** This framework reallocates emissions to the final consumers of goods and services. At the country level, it involves adjusting territorial emissions to account for those embodied in imports and exports, resulting in carbon footprints of domestic final demand (as opposed to domestic production). This perspective emerged in part to address concerns about carbon leakage, that is, the risk that emissions reductions in one country may be offset by increases elsewhere due to shifts in production and trade. Consumption-based footprints can inform policy at the intersection of climate mitigation, trade, and development.[6] The same footprinting logic can also be applied at mezzo- and micro-levels – for instance, by combining EEIO results with household expenditure to assess the emissions associated with different consumption patterns and to support the design of context-appropriate mitigation strategies.

Box 1: The System of National Accounts – Foundations for Input–Output and Environmental Accounting

The System of National Accounts (SNA, 2008) is the global standard for macroeconomic accounting. It involves the construction of three types of data tables:

- **Supply Tables** show the total supply of goods and services within the economy, including both domestic production and imports, broken down by product type. Products from broad categories, such as food or machinery, are further subdivided into more specific items, following the Classification of Products by Activity (CPA). This classification is aligned with the International Standard Industrial Classification (ISIC), ensuring consistency with global economic reporting standards. These tables are typically presented in monetary terms at basic prices (i.e., the value of goods and services at the point of production, excluding taxes and subsidies), expressed in the domestic currency of the country compiling the data.
- **Use Tables** display how the goods and services are consumed across different sectors of the economy. They show intermediate consumption (by industries), final consumption (by households or government), gross capital formation (investments), and exports. These tables are typically presented

5 -The territorial approach is used for national GHG inventories under the UNFCCC and is based on the location and physical characteristics of emitting sources. Production-based accounting aligned with the System of National Accounts, the global standard for macroeconomic accounting, attributes emissions to resident economic units and classifies them by economic output. Anchoring to national accounts enables consistency with indicators such as GDP and allows emissions to be fully allocated to countries, including those from international transport (Gravgård Pedersen and de Haan, 2006).
6 - While the reallocation is most robust for fossil fuel- and industry-related emissions, emissions from land-use change and other agriculture, forestry and other land use (AFOLU) sectors are often excluded or only partially included in standard consumption-based models. However, complementary approaches, particularly those linking commodity-driven deforestation (e.g. soy, beef, palm oil) to trade flows, are increasingly used to attribute these emissions to final demand. For a foundational methodological discussion, see Davis et al. (2014).

in purchase prices, which include additional costs such as taxes, subsidies, and margins, but may be harmonised with the supply tables to ensure consistency.

- **Input-Output Tables** (IOTs) integrate supply and use tables to provide a detailed picture of how industries depend on each other, showing both the flow of intermediate goods and services between industries, and the flows of finished goods to final demand – both domestic and imported. IOTs complement the flows of intermediate goods and final outputs with primary inputs so that each industry's total inputs equal its total outputs.[7]

The SNA framework can be extended with satellite accounts, which provide additional data on topics like environmental or social impacts in a manner that is fully consistent with its core tables.[8] Environmental satellite accounts record flows of natural resources and emissions associated with production and consumption activities, enabling integrated analysis of economic and environmental performance.

Each framework carries normative implications, embedding assumptions about responsibility and the levers for climate action. Production-based approaches locate responsibility with those who emit, regardless of who, if anyone, ultimately uses or benefits from the associated outputs. Consumption-based approaches, by contrast, reassign responsibility to end users. In practice, production and consumption are shaped by technology, physical infrastructure, economic systems, markets, institutions, and their dynamic interactions. But each framework foregrounds a different locus of accountability and intervention. A production-based lens tends to emphasise supply-side reforms such as industrial or energy system decarbonisation; a consumption-based lens draws attention to demand shifts, behavioural change, and the carbon intensity of consumption patterns.

In territorial inventories, emissions are reported by the sectors in which they physically occur. Following this logic, global greenhouse gas emissions in 2019 arose from the following sectors: 34% from energy supply, 24% from industry, 22% from Agriculture, Forestry, and Other Land Use (AFOLU), 15% from transport, and 5.6% from buildings (IPCC, 2022).[9] Territorial accounting shows that while the emissions of developed countries have markedly declined since 1990, these reductions have been more than offset by rising emissions from developing countries, driven by rapid economic growth from initially low per capita baselines.[10] The pace of acceleration has been striking: approximately 42% of total CO_2 emissions since 1850 occurred after 1990. The Asia and Pacific region alone accounted for 77% of the global emissions increase over that period, with Eastern Asia, primarily China, more than doubling its share of global emissions to 27% by 2019, despite representing only 19% of the world's population. Over the same period, the share of Europe halves and that of North America falls by a third (IPCC, 2022).

7 - These primary inputs include the contribution of the primary factors of production, i.e., labour and capital (through depreciation, or 'consumption of fixed capital'), together with accounting balancing items such as 'gross operating surplus' and 'taxes less subsidies on production'. The sum of these primary inputs, in the sense of the SNA, is the value added that balances intermediate inputs with outputs.

8 - Such extensions are explicitly encouraged in the SNA 2008 guidelines (United Nations et al., 2009). The best-known example is the System of Environmental-Economic Accounting (SEEA), developed as an international statistical standard. The SEEA Central Framework (United Nations et al., 2014) and the SEEA Ecosystem Accounting (United Nations et al., 2021) provide physical and hybrid accounts for natural resources, energy, materials, emissions, and ecosystem assets.

9 - If the emissions from electricity and heat, which represent about 70% of the emissions of the energy supply sector, are reallocated to the sector of final use, the relative shares of industry and buildings emissions, including these indirect emissions, rise to 34% and 16%, respectively, with the rest of the energy systems rising to 12% of emissions (more than half of which being accounted by fugitive emissions from fossil fuels); the shares of transport and AFOLU remain stable at 15% and 22%, respectively (IPCC, 2022, see Figure 2.12). Direct emissions result from on-site combustion of fossil fuels or are produced by industrial processes while indirect emissions are associated with the use of purchased electricity, steam, heating, or cooling. Note that the emissions from the production of construction materials, e.g., cement, steel, are attributed to the industry sector under production-based accounting.

10 - If we decompose the growth of emissions in the fashion of Kaya (1990), four definitional drivers are distinguished: population, GDP per capita, energy intensity of GDP, and the carbon intensity of energy. Over the past decade, population growth (+1.2% per year) and economic growth per capita (+2.3% per year) have contributed to increasing emissions, more than offsetting the reductions achieved through improvements in energy intensity (–1.9% per year) and a modest decline in the carbon intensity of energy (–0.2% per year). The net outcome has been a continued rise in emissions, underscoring the insufficiency of marginal gains in efficiency and fuel switching in the face of persistent structural growth pressures (IPCC, 2022).

Production-based inventories, particularly those aligned with national accounts, can disaggregate emissions by industry sector and link them to the economic activities that generate output, offering insights into the emissions embedded in goods and services and providing a clearer view of supply chain dependencies within the production system, a perspective valuable for industrial policy and corporate accountability.[11]

In standard consumption-based analyses, by contrast, emissions are attributed to the category of final demand they serve; primarily household consumption, but also productive investment (gross fixed capital formation)[12] and government spending.[13]

Both production-based and consumption-based accounting (PBA and CBA, respectively) emissions can be calculated in practice using EEIO models.[14] The mechanics of how IO and EEIO models work, and how they underpin PBA and CBA, are outlined in Box 2. The intellectual development, applications, and data challenges of EEIO models are presented in Box 3.[15]

Box 2. Structure of Environmentally Extended Input–Output (EEIO) Models

At the core of **canonical input–output analysis** lies the **Leontief identity**, which expresses total output as the sum of intermediate and final uses:

$$x = Z\,1_K + y$$

where:

- x is a $K\times1$ vector of industry outputs,
- Z is a $K\times K$ matrix of intermediate flows between industries, and
- y is a $K\times1$ vector of final demand.
- 1_K is a $K\times1$ column vector of ones.

K denotes the number of industries (or sectors) in the system. Multiplying Z by 1_K sums the columns of Z, giving the total intermediate inputs required by each industry; adding y gives the total output vector x.

From this identity, **technical coefficients** are defined as:

$$a_{ij} = \frac{z_{ij}}{x_j}$$

with z_{ij}, the flow from industry i to j, and x_j the total output of industry j. Each a_{ij} therefore represents the amount of input from i needed per unit of output in j. Collecting these coefficients gives the **technical coefficients matrix A**, which encodes the technological structure of the economy, a representation of how industries combine inputs to generate output, as inferred from observed flows. Using A, the **Leontief model** relates output and final demand:

$$x = (I - A)^{-1}\,y$$

11 - For illustration, production-based inventories are commonly used to estimate upstream Scope 3 emissions from the top-down (Ducoulombier, 2021).

12 - In national accounts, 'fixed' refers to produced assets used repeatedly or continuously in production for more than one year – including for the production of non-market services, such as those provided by owner-occupied real estate. GDP includes imputed rents for owner-occupied housing to reflect the value of the services it provides; by contrast, no comparable adjustments are typically made for real estate assets owned and occupied by other institutional sectors.

13 - The remaining categories are typically changes in inventories, which most footprint studies treat as marginal, and exports, which are not part of domestic consumption-based accounts but are fully represented in multi-regional analyses.

14 - PBA emissions are calculated by directly assigning sectoral emissions to producing industries, i.e. multiplying industry outputs by their emission factors, while CBA reallocates these emissions to final demand categories by tracing them through inter-industry linkages. See Box 2 for a technical outline.

15 - Note that the final-demand perspective of CBA is silent on the direct or total emissions of individual industries: the emissions embodied in an industry's output used as intermediate consumption are reallocated downstream to the final goods that use them. PBA gives us the direct emissions of an industry. EEIO models also allow us to treat industries as nodes within value chains and to compute their indirect emissions: demand-driven formulations can be used to derive upstream emissions, and supply-driven formulations to derive downstream emissions. These extensions, however, must be handled carefully to avoid multiple counting of the same emissions.

where I is the $K \times K$ identity matrix (ones on the diagonal, zeros elsewhere) and $(I\text{-}A)^{-1}$, the **Leontief inverse**, which propagates both direct and indirect requirements through supply chains. Intuitively, this can be expanded as a series

$$x = y + Ay + A^2y + \cdots$$

showing successive "tiers" of upstream inputs needed to satisfy final demand. This backward, demand-driven logic underpins most environmentally extended applications, where emissions or resource intensities are attached to industries and then traced upstream to final demand (consumption-based accounting logic). The Leontief inverse captures not only direct inputs but also all indirect input requirements across supply chains, elegantly resolving the recursive structure of inter-industry dependencies into a closed-form solution.

An **environmental extension** adds a vector q of intensities (e.g. emissions per unit of output). These intensities are typically derived by dividing observed emissions from satellite accounts by sectoral output values recorded in the input–output tables and therefore reflect the average emission per unit of output for each sector.

This allows calculation of:

- **Production-Based Accounts (PBA):** direct emissions allocated to producing industries, typically represented as a $K \times 1$ vector in a single-region model.

$$pba = \hat{q}\,x$$

where $\hat{q}$ denotes the diagonalised matrix built from the vector of intensities q for multiplication with the output vector x. When we extend to a **multi-regional input–output (MRIO) model**, we replicate the industry structure for each of the N countries, resulting in KN country–industry pairs. In that case, the PBA becomes a KN x 1 vector of one element per industry per country.

- **Consumption-Based Accounts (CBA):** total direct and upstream emissions reallocated to final demand, using the Leontief inverse to propagate emissions through supply chains. In a single-region model, collapsing over final demand categories yields a $K \times 1$ vector. In an MRIO with N countries and K industries, summing over the category dimension yields a $KN \times N$ matrix giving CBA by producing industry and consuming country. In a full MRIO with N countries and D demand categories, the result is a $KN \times DN$ matrix.

Alongside the demand driven Leontief model, there exists a conceptually symmetric supply driven model, which was put forward by Ghosh (1958). Instead of technical coefficients based on inputs received, it uses **allocation coefficients**:

$$b_{ij} = \frac{z_{ij}}{x_i}$$

describing the proportion of the output of supplying industry i that is shared with industry j. The allocation coefficients matrix B, also known as the output coefficients matrix, thus encodes the allocation structure of the economy. The Ghosh inverse $(I\text{-}B)^{-1}$ traces how primary inputs, and any associated environmental pressures, propagate downstream through the successive allocation of outputs, in contrast to the Leontief framework which traces requirements upstream from final demand.

Readers interested in the detailed mathematical formulation of production- and consumption-based accounts in single- and multi-regional input-output settings are referred to O'Kane (2025).

Box 3: Environmentally Extended Input–Output Models: Origins, Applications, and Uncertainties

The input–output framework, pioneered by Leontief in the 1930s, describes the flow of goods and services between sectors of an economy by showing how the output of each sector is used as an input by others. Closely tied to the development of national accounts, input–output tables provide a structured snapshot of economic activity over a given period, typically one year, and remain a core component of the System of National Accounts today. Although static by construction, this framework can be used to quantify how changes in final demand affect production across sectors, under the assumption that the observed relationships between industries remain fixed – i.e. that the proportion of inputs required from other industries to produce one unit of output does not change. This demand-driven formulation is known as the Leontief model. A related but less commonly used variant, the supply-driven Ghosh (1958) model examines how changes in primary inputs propagate downstream through the economy's sectoral output. EEIO models build on this framework by attaching environmental data, such as energy use, material extraction, or GHG emissions, to each sector. This allows the environmental impacts associated with producing goods and services to be calculated, not only directly (at the point of emission) but also indirectly, across supply chains.

To estimate the emissions associated with final demand, emissions are propagated through the input-output matrix.[16] The emissions leaving each node (i.e., sector) are the sum of its direct emissions and the indirect emissions embodied in the inputs it receives from other sectors.[17] EEIO frameworks trace their origins to Isard, Schooler and Vietorisz (1968) and Leontief (1970). Early applications focused on estimating pollution generation and abatement costs, primarily to support environmental regulation and policy evaluation. Subsequent studies extended the approach to tracking energy use and material flows through economic systems. By the early 1990s, growing scientific consensus around anthropogenic climate change, crystallised in the first assessment report of the Intergovernmental Panel on Climate Change (IPCC) and the adoption of the UNFCCC brought greenhouse gas emissions to the forefront of environmental policy and research. EEIO was first used to trace GHG emissions within domestic production systems. This research strand was methodologically advanced by Lenzen et al. (2007) and brought to broader policy attention through large-scale empirical applications such as Hertwich and Peters (2009). From the 1990s onward, studies such as Wyckoff and Roop (1994) began to highlight the significance of emissions embodied in international trade, laying the groundwork for the development of consumption-based emissions accounting. This strand of research was methodologically advanced by Lenzen et al. (2007) and brought to policy attention through large-scale empirical applications such as Hertwich and Peters (2009).

To support these developments, researchers extended domestic, or single-region input–output (SRIO) frameworks into EE-MRIO[18] models. These models trace emissions through global supply chains, recognising differences in production technologies[19] across countries in order to capture the full carbon footprint of goods and services consumed in one country but produced in others.

16 -Formally, emissions are estimated by multiplying sector-specific emission intensities (q) by a transformed version of the technical coefficient matrix (*A*), the matrix that describes how much input from each sector is required to produce one unit of output in every other sector. These intensities are typically derived by dividing observed emissions from satellite accounts by sectoral output values recorded in the input–output tables, and therefore reflect the average emission per monetary unit of output for each sector. This transformation, expressed as $(I - A)^{-1}$, where I is the identity matrix, is known as the Leontief inverse. It captures not only direct inputs but also all indirect input requirements across supply chains, elegantly resolving the recursive structure of inter-industry dependencies into a closed-form solution. This enables the calculation of total emissions embodied in final demand. The analogous supply-driven approach based on the Ghosh inverse $(I - B)^{-1}$, may be used to trace the propagation of environmental pressures from primary inputs through the economy. Here, B is the output coefficient matrix, whose entries indicate the proportion of a sector's output that is delivered to each other sector.

17 - Although EEIO models are typically described as attributing upstream emissions to final demand, downstream emissions, such as those arising from product use by the final consumer or from end-of-life treatment, can also be incorporated into the emissions coefficients, where relevant. This expands the model boundary and introduces elements of life-cycle thinking. While analytically convenient, it creates temporal inconsistency: emissions attributed to a given year's demand may include impacts that materialise in future periods.

18 - MRIO tables themselves were put forward by Isard (1951).

19 - Lacking data, early studies based on single-region EEIO models approached embedded emissions by assuming that foreign technologies were emitting in line with domestic technologies.

Given that international trade (still) accounts for roughly a quarter of global economic output and CO_2 emissions (Hubacek et al., 2021), EE-MRIO models are indispensable for robust consumption-based accounting and trade-adjusted emission analyses. They continue to underpin both production- and consumption-based studies, supporting a wide range of climate policy, trade, and sustainability analyses.[20]

To support these analyses, several EE-MRIO databases have been developed, each reflecting different priorities in terms of sectoral granularity, country coverage, temporal consistency, and methodological transparency. For an overview of the main databases, including the OECD ICIO, GTAP, WIOD, Eora, and EXIOBASE, see Appendix A. [21]

The choice of input–output database and environmental satellite accounts can significantly influence computed environmental footprints. These differences arise from how underlying data are sourced and processed – including the reconciliation of differing accounting structures,[22] estimation techniques, and allocation rules – as well as from choices around sector classification and aggregation (Peters, Davis and Andrew, 2012).

Divergences originate both in the economic input-output tables and in the environmental extensions. Moran and Wood (2014), for instance, conduct simulations that produce substantial differences in consumption-based carbon footprints, even when using harmonised emissions data. Giljum et al. (2019) decompose the differences in consumption-based material footprint estimates generated using three major MRIO databases, and show that a significant share of the discrepancies arises from the early stages of supply chains, particularly from how raw material extraction and transformation sectors are represented in the underlying input–output tables.[23]

Sensitivity to MRIO selection is typically greater for consumption-based than for production-based indicators, due to variability in the treatment of trade flows.

Recent country-level studies confirm that materially different footprint estimates persist. For example, Bourgeois, Gervois, and Lafrogne-Joussier (2023) find discrepancies of up to 20% in France's national carbon footprint depending on the MRIO database used, differences they trace primarily to the

20 - EEIO is also used in the context of corporate emissions accounting to estimate upstream value chain emissions and conduct cradle-to-gate analyses when supplier-specific data are unavailable.
LCA is also employed for such accounting, but it involves detailed process-based modelling of a product's entire life cycle, from raw material extraction to end-of-life. It was formalised in the 1990s through the work of the Society of Environmental Toxicology and Chemistry and the United Nations Environment Programme. LCA enables high-resolution cradle-to-grave emissions estimates at the product level and is particularly valuable for product design and supply chain optimisation. However, it is resource-intensive, less suited to large-scale, multi-product assessments, and inherently partial. Because LCA focuses on specific products or production processes, it must define a system boundary – that is, a limit to how far upstream or downstream impacts are traced. Without such a boundary, the analysis could continue indefinitely. This practical constraint results in the omission of indirect contributions across the value chain, a limitation known as truncation error.
Hybrid models that combine the comprehensive, top-down coverage of EEIO, achieved under simplifying assumptions of sector-level homogeneity in prices, outputs, and environmental impacts (Wiedmann, 2009), with the fine-grained, bottom-up, process-based specificity of LCA can improve accuracy while preserving systemic completeness. In such models, LCA is typically applied to key processes or products where detailed data are available, while EEIO fills gaps across the broader production system. These approaches, systematised by Suh et al. (2004), help manage boundary inconsistencies (truncation in LCA and sectoral aggregation in EEIO) and are now widely used in both corporate footprinting (Ducoulombier, 2021) and high-resolution household consumption studies. Hybridisation remains viable and tractable only insofar as the integration of product- or process-level data can be represented as adjustments to technical coefficients within the EEIO framework. This preserves the model's linear structure and solvability. Suh and Huppes (2005) discuss methodological variants – tiered, input–output-based, and integrated – that maintain coherence with the underlying Leontief system. Building on this foundation, recent work has focused on data integration challenges and on formalising frameworks capable of capturing temporal dynamics in sustainability assessments, such as changes in capital stock, associated production technologies, and consumption patterns.
21 - For a higher granularity review of the different characteristics of MRIO databases, refer to Tukker and Dietzenbacher (2013), for an update and a discussion of database suitability in relation to environmental footprint analysis, refer to Tukker et al. (2016).
22 - The sector classifications used in national input-output tables are typically designed to reflect domestic economic structures and the classification choices of statistical offices. Sectors of limited economic weight may be aggregated into broad categories. This aggregation can limit the analytical precision of environmental assessments, particularly when the aggregated sectors differ significantly in their environmental intensities (e.g., energy use, material footprint, or GHG emissions). When integrating such national tables into EE-MRIO frameworks, disparities in sectoral detail and accounting standards across countries pose further challenges to harmonisation and comparability.
23 - Giljum et al. (2019) find that per capita deviations of footprints are within 15% across EXIOBASE, Eora, and ICIO "for a large number of economically important countries" (although very stark differences are observed for some countries, e.g., Taiwan, the Netherlands, and Russia). Raw material extraction and basic processing explain 60% of the total deviations. They thus call on database designers to pay higher attention to "agriculture and forestry and the sectors receiving renewable raw materials for further processing, as well as the mining and quarrying sector and their interlinkages with the basic metal, petroleum, and chemical sectors".

treatment of imports. They also show that sectoral aggregation can shift the estimated footprint by up to 15%.

While such divergences may not undermine internal consistency – such as temporal trends or the identification of high-impact sectors – they highlight the importance of choosing methods that are fit for purpose, and of recognising (if not quantifying) the uncertainty embedded in footprint assessments.

Final Demand Footprints: Insights from Static EEIO Models

Building on the conceptual foundations laid out in the previous part, this part reviews the application of static EEIO models to the analysis of final demand. It begins by highlighting the relative contribution of household consumption, capital investment, and government expenditure to national and global emissions footprints. It then surveys empirical studies that examine each demand category in turn, exploring their estimation challenges, mitigation potential, and distributional implications. This part concludes with a reflection on the normative and policy debates that have shaped, and been shaped by, consumption-based accounting.

High-Level Results

With data from the early 2000s, Hertwich and Peters (2009) used EEIO analysis to trace greenhouse gas emissions across final demand categories in 73 countries and 14 aggregate world regions. National per capita carbon footprints varied by a factor of 30, from the lowest values observed in African countries to the highest in Luxembourg and the US. Carbon-dioxide (CO_2) emissions were found to increase strongly with expenditure (elasticity of 0.81, meaning that a 1% rise in spending is associated with a 0.81% rise in emissions)[24] and other greenhouse gases less so (0.32).[25] 72% of global GHG emissions were linked to household consumption, 18% to investment, and 10% to government spending. The most emission-intensive consumption categories globally were shelter (the operation and maintenance of residences accounted for 19% of emissions while construction, including construction of residences and infrastructure, accounted for 10%), food (20%), and mobility of households (17%). While food and public services dominated emissions in lower-income countries, wealthier nations saw higher shares from mobility and manufactured goods, which were both highly income-elastic.[26]

Using a (then) more recent and higher-granularity database with expanded consumption categories,[27] Tukker et al. (2016) confirm both the wide dispersion of country-level per capita carbon footprints and the global dominance of food, buildings, and transport as key sources of emissions. The authors observe

24 - Since the elasticity of emissions with respect to final expenditure is less than one, the carbon intensity of consumption declines as (national) expenditure increases. This pattern may reflect more efficient production technologies and lower-carbon electricity systems in higher-expenditure economies, as well as compositional shifts in consumption toward lower-emission categories such as services. Price effects may also contribute, as monetary expenditure can partially decouple from physical throughput: consumers in higher-income economies often pay higher unit prices for goods and services due to factors such as quality, customisation, or branding, i.e., attributes that do not scale proportionally with embodied emissions. The use of finer-grain data, whether native to the MRIO or linked externally, could help correct for biases associated with differences in perceived or actual quality. Complementarily, framing consumption in physical or functional units, rather than in market-valued expenditure, can mitigate distortions arising from international price level differences, enabling more accurate comparisons of carbon intensities that reflect material throughput rather than nominal cost.

25 - This is consistent with the fact that these gases are closely linked to food production, and that food, being a basic necessity, exhibits the lowest expenditure elasticity among consumption categories (0.64). The authors indeed find that emissions associated with methane (CH4) and nitrous oxide (N2O) from food production dominate over CO_2 emissions at lower expenditure levels, up to around USD1,000 of final demand.

26 - Manufactured products had an expenditure elasticity of 1.09, mobility of 1.07, and services of 1.16.

27 - Version 2.1 of EXIOBASE (December 2013), a detailed EE-MRIO database described in Wood et al. (2015), which covers the global economy in 2007 across 43 countries (27 EU member states and 16 major economies), five rest-of-the-world regions, 163 economic sectors, 6 final demand categories and 200 product groups per country. The environmental data links economic sectors per country to over 30 energy related and non-energy emissions to air and water, including a full set of greenhouse gases, 80 types of resource extractions, as well as water extraction by agricultural and non-agricultural sectors, and land use (Tukker et al., 2016).

that China and the US each accounted for nearly one-fifth of global emissions in 2007.[28] They also report that Europe's consumption-based carbon footprint is approximately 25% larger than its territorial emissions, underscoring the importance of accounting for emissions embodied in trade when gauging regional responsibility. Finally, the study highlights that countries with high quality-of-life indicators can nevertheless exhibit markedly different carbon footprints,[29] suggesting that certain structural socio-economic choices[30] can generate lower emissions without compromising well-being.[31]

Household Consumption

Hubacek et al. (2017) use an EE-MRIO framework and the World Bank's Global Consumption Database to compare household consumption across and within countries in 2010, providing the first systematic empirical treatment of 'carbon inequality', understood as the unequal distribution of carbon footprints within populations. They find that the consumption carbon footprint of the top decile of the world population by expenditure[32] is an order of magnitude larger than that of the bottom half of humanity (17.9 tCO_2e vs. 1.6 tCO_2e). The top 10% of the global population by consumption—which at the time included nearly all but the lowest decile of people in developed countries (OECD, 2011)—accounted for more than one-third (34%) of global household emissions, while the bottom 50% were responsible for less than one-sixth (15%).[33] Within-country disparities generally decreased with GDP were less pronounced in developed than in developing countries.[34] The authors also observe that the middle and upper expenditure categories in developing economies display carbon footprints similar to their counterparts in rich countries.[35]

While Hubacek et al. (2017) highlight disparities in emissions across global income groups, Ivanova et al. (2016) delve into the structure of household consumption itself. Using the same database as Tukker et al. (2016)[36], they find that household emissions account for 65% of total country emissions on average (standard deviation 7%).[37] Per capita household emissions vary more than twentyfold between India and high-income countries such as the US and Luxembourg, mirroring the wide cross-country differences in total emissions observed in earlier studies. They confirm that household carbon footprints exhibit a

28 - Since investment-related emissions are not reallocated to the final-use sectors they ultimately support, China's consumption-based footprint may be overstated, a modelling limitation explored in later studies. This potential overstatement could be substantial, given the dominance of gross fixed capital formation in China's gross domestic product and its strong export orientation in the years leading up to the Global Financial Crisis (with export promotion and investment remaining central in the immediate aftermath, before a gradual shift from 2012 onward toward reducing reliance on exports and investment-led growth). At the same time, the EEIO assumption of sectoral homogeneity is particularly ill-suited to China and has been shown to understate China's consumption-based footprint by overstating the emissions embodied in exports. Using an augmented Chinese input–output table that explicitly incorporates information on firm ownership and the type of traded goods, Liu et al. (2016) find that "ignoring firm heterogeneity causes embodied CO_2 emissions in Chinese exports to be overestimated by 20% at the national level, with huge differences at the sector level, for 2007.

29 - This dispersion recalls earlier work showing that while energy and/or emissions strongly correlate with living standards at low consumption levels, the relationship weakens at high levels. Steinberger and Roberts (2010) confirm this over 1975–2005 using the UN Human Development Index (HDI, combining life expectancy, literacy and income), and note that achieving well-being has become steadily more efficient in terms of energy and emissions, especially for life expectancy. Whereas development was constrained by resources at the beginning of the period, there is resource sufficiency thirty years later in the sense that high quality of life for all would be achievable at the level of global energy consumption observed in 2005, under different distributional assumptions. This means that high-HDI countries could drastically reduce their energy use and emissions "without any measurable loss" in human development".

30 - Tukker et al. (2016) do not attempt to identify the socio-economic choices that explain these divergent outcomes. Differences in lifestyles and consumption norms, including diets, are likely to contribute to this dispersion. Holding demand-side factors constant, key structural drivers are technical in nature and necessarily include energy systems (electrification, carbon intensity of power), transport systems, and the energy performance of buildings, consistent with the main emissions categories identified above. Technical infrastructure in turn interrelates with the structuration of habitat, and both are shaped by sociogeographic and institutional factors.

31 - However, the authors also caution that all high-performing countries in terms of quality of life still have carbon footprints above the global average, which itself exceeds sustainable levels. This implies that incremental improvements will be insufficient, and that more profound economic and social transformations are indispensable for long-term sustainability.

32 -The authors use purchasing power parity (PPP)–adjusted expenditure, which equalises price levels so that USD1 PPP buys a similar basket everywhere. Without this adjustment, cross-country income differences would appear larger, because nominal dollars in lower income economies typically buy more owing to lower price levels. PPP provides a fairer basis for comparing expenditures and associated footprints.

33 - Hubacek et al. report that the remaining 15% of the top quartile by expenditure accounts for 28% of household emissions, while the second quartile is responsible for 23%. Per-capita footprints range from 1.6 tCO_2e for the lowest income group (half of humanity), to 4.9 tCO_2e for the second quartile, 9.8 tCO_2e for the next 15%, and 17.9 tCO_2e for the top decile.

34 - In 2010, average household footprints were 4.8 t in China and 1.7 t in India. In these populous countries, the bottom half of the population emitted only 1.5 t and 1.2 t, while the top decile reached 29.5 t and 39.9 t. Since then, the output of both economies has more than doubled, necessarily reshaping average footprints and disparities.

35 - Part of this is due to the lower efficiency of developing countries; consistent with this, the authors find that the responsiveness of emissions to income, i.e., carbon elasticity, decreases with GDP, meaning that as countries become richer, each additional unit of income generates proportionally smaller increases in carbon footprints.

36 - The results are based on an update of the second version of EXIOBASE (version 2.2).

37 - Meanwhile gross capital formation accounted for 24% of emissions (s.d.: 7%), government spending 7% (s.d.: 3%), non-profit institutions serving households (NPISHs) 1% (s.d.: 1%), and changes in inventories 3% (s.d.: 2%).

strong positive correlation (of 87%) with gross domestic product (GDP) per capita, although countries with low-carbon electricity grids are notable exceptions. They stress that four-fifths of household emissions are embedded in supply chains[38] rather than generated directly through the combustion of fossil fuels in the home or by personal vehicles. By pairing EEIO data with national household budget surveys, the authors attribute environmental impacts to detailed product categories within household expenditure baskets and estimate expenditure elasticities at the country level for each category and impact.[39] Their analysis confirms that, as income rises, total consumption grows more slowly, but the composition of consumption shifts markedly toward higher-impact goods and services, particularly in the areas of mobility, market-based services, and manufactured products. Dietary patterns evolve as well: higher-income households consume more red meat, dairy, and processed foods, significantly increasing food-related environmental footprints. The study further confirms that a substantial share of household emissions in high-income economies is embedded in imports from lower-income producer countries.In follow-up work, Ivanova and Wood (2020) focus on the European Union, examining the unequal distribution of carbon footprints within the population. The authors combine household surveys from 2010 covering over 50 consumption categories with product level carbon intensities derived from EE-MRIO analysis[40] to measure the carbon footprints of household expenditures.[41] They establish that the top 10% of the population by carbon footprint emits about as much as the bottom half, with each contributing to slightly over a quarter of the region's emissions (27% and 26%, respectively). The top 1% of households by emissions consumes about 6% of the region's emissions, almost as much as the bottom two deciles. Its enormous footprint of 55 tons of CO_2 equivalent (CO_2e)[42] per head, which is almost 12 times that of the bottom half (and 22 times the sustainability target), is driven by mobility, with 41% and 21% of emissions accounted for by air and land transport, respectively. Air transport is identified as the most unequal,[43] most carbon-intensive, most elastic consumption category in the study (the elasticity coefficient is 1.5 on average but increases with expenditure).[44] Land travel, which represents almost a third (32%) of the footprint of the top decile, also comes across as a category requiring urgent attention.[45] The authors find that household income and footprints are strongly positively correlated in aggregate (65%), but that this not as marked in countries with the highest income levels and the lowest carbon intensities such as Denmark or France. The authors also observe wide dispersion in income, education, nutrition, employment, and poverty for comparable carbon footprints, consistent with the lower-resolution results of Tukker et al. (2016), which suggests that it is possible to mitigate emissions while maintaining high levels of well-being. The authors note that such decoupling could be supported by policies targeting "changes in higher-order need satisfiers, such as social structures and practices" and by reimagining how needs are met within environmental constraints. Such changes, however, are unlikely to occur without collective intervention.[46]

38 - Key categories for purchases are services (27% of emissions), shelter (25%), manufactured products (17%), mobility (15%), and food (13%).
39 - The authors measure the percentage change in the quantity of environmental impacts with respect to a 1% rise in the total household demand.
40 - Product-level carbon intensities are derived from the EXIOBASE 3.6 database (1995-2016 period, 44 countries).
41 - The authors estimate consumption based on monetary units. Observing that the price per functional unit increases with income for many consumption categories, Girod and De Haan (2010) show that the use of monetary rather than functional units, leads to overestimating the impact of marginal consumption and to neglecting the potential of "decoupling income and environmental impact by consuming better instead of more." The authors reference Girod and De Haan (2010) and admit that they probably overestimate/underestimate the environmental impact of expensive/cheap products (and wealthier/less well-off individuals).
42 - Emissions of various greenhouse gases are typically expressed in terms of CO_2e based on the global warming potential of these gases over a given period, typically set to one hundred years, relative to that of CO_2.
43 - The authors document that the air travel carbon footprint of the top decile is 3t CO_2e per capita, but below 0.1t CO_2e per capita for the rest of the EU population.
44 - The authors underline that, these categories receive extremely low policy attention, which raises obvious and substantial "ethical and equity concerns." The authors cite in support the study by Dubois et al. (2019) which counts policies aimed at altering private consumption in Sweden, Norway, Germany and France, and finds that the high-emitting consumption categories receive the least policy attention, with air traffic and diet changes being covered by a mere 1.2% of the policies each (three out of 250); with these policies being almost exclusively market-based (e.g., relying on price signals such as taxes or charges to influence consumption rather than imposing regulatory limits or outright bans).
45 - Since that category is also very significant for low-income groups in terms of both expenditure and footprint, policy making must consider equity (and the centrality of the car in rural areas underserved by public transportation).
46 - Dubois et al. (2019), who tested household willingness to adopt mitigation actions, found that the most impactful measures, i.e., those requiring substantial lifestyle adjustments, were also the least likely to be undertaken voluntarily. They concluded that short-term voluntary efforts would be insufficient to deliver the deep emissions reductions expected from households in a 1.5°C warming scenario, and that a supportive regulatory framework would be necessary to enable more transformative behavioural change.

Investment

A comprehensive view of emissions, however, requires close attention to investment. Fixed capital formation is not only the other material final demand category in national accounts, but also a significant and often underappreciated source of emissions. First, capital investment, especially in long-lived, static assets such as buildings, infrastructure, and heavy machinery, has historically constituted the bulk of material throughput[47] – the total flow of physical resources into, through, and out of the economic system – in industrial economies. Crucially, the state and evolution of this capital stock also condition patterns of production and consumption in the short, medium, and long term.[48]

Using the same MRIO database as Tukker et al. (2016) and Ivanova et al. (2016), Södersten, Wood and Hertwich (2018a) find that gross capital formation accounted for approximately one-quarter (24%) of global final demand and nearly one-third (30%) of GHG emissions in 2007 (Södersten, Wood and Hertwich, 2018b). The authors identify a positive relationship between the share of investment in final demand and carbon intensity, and a negative relationship between GDP per capita and the carbon intensity of capital formation. To investigate the sources of this pattern, they pair the MRIO database with a dataset[49] that disaggregates investment by asset type and industry in accordance with national accounts.[50] This enables them to show that the carbon intensity of capital tends to decline with development, in part because wealthier countries invest more in lower-emission assets such as computing equipment and software. At the global level, however, construction-related assets dominate: residential structures alone account for around 25% of the carbon footprint of capital, and the broader construction sector – including public infrastructure and commercial buildings – contributes over 50%. When emissions are examined by using industry, the largest capital-related footprints are found in logistics ("transport and storage"), public administration and defence, equipment leasing ("renting of machinery and equipment"), telecommunications, and resource extraction ("mining and quarrying").

Government Spending

The final major component of final demand and emissions is government spending, which encompasses the ongoing provision of public services, from healthcare and education to general administration and defence. Government spending tends to rise with GDP per capita and accounts for about one-ninth of GDP in low- and lower-middle-income countries, and about one-sixth in upper-middle- and high-income countries.[51] The overall emissions intensity of government final consumption is substantially lower than

47 - The pioneers of industrial ecology were among the first to emphasise the importance of adopting a systemic and life-cycle perspective to reduce resource use and associated emissions, and aim for long-term sustainability. Building on the biophysical critique of neoclassical economics developed by Georgescu-Roegen (1971), who reinterpreted economic processes as thermodynamically bound systems subject to entropy, Ayres (1978) described the economy as embedded in nature, mapping the flows of materials and energy into, through, and out of the economic system. This early work laid the foundation for his later characterisation of the economy as a "self-organizing dissipative system in which intelligent activity", negative entropic accumulation, primarily through technology, "of information-storing structures is more and more consciously controlled and managed" (Ayres, 1988). Drawing a parallel with the use of matter and energy by biological organisms and ecosystems, he then coined the term "industrial metabolism" (Ayres, 1989). Frosch and Gallopoulos (1989) introduced the concept of the industrial ecosystem, envisioning a system in which "the consumption of energy and materials is optimised, waste generation is minimised, and the effluents of one process (…) serve as the raw material for another process". Their closed-loop production ideal constitutes the industrial substrate of what is now known as the circular economy. Interestingly, neither Georgescu Roegen nor Ayres appears to have explicitly drawn on Marx (1867), who had introduced the idea of a "metabolic rift" in the first volume of Capital to describe the disruption of long-term nutrient cycles and the resulting degradation of soil fertility caused by the short-term logic of capitalist agriculture, a striking early articulation of the tension between economic activity and ecological sustainability. Indeed, the ecological dimension of Marx's analysis remained largely overlooked until the work of Foster (2000).

48 -Property and institutional arrangements do not merely determine access to existing resources; they condition the very existence and trajectories of human activities. In capitalist systems, for instance, intellectual property rights structure innovation pathways and market formation, often well before any physical capital is deployed. By defining what can be enclosed and who can extract returns, such arrangements exert a deep structuring influence on the material evolution of the economy. The emphasis here, however, is on the inertia of material capital goods, such as buildings, roads, and blast furnaces, which continue to shape production and consumption patterns if, as, or when political or economic systems change. Pauliuk and Müller (2014) look at the blind spots of impact assessment models in terms of in-use stocks and extend dynamic stock models to incorporate direct and indirect energy demand and greenhouse gas emissions so assess various strategies "to decouple energy and material throughput from service provision", including energy efficiency, material efficiency, and moderate lifestyle changes.

49 - The European Union KLEMS (K for Capital, L for Labour, E for Energy, M for Materials, and S for Services inputs) 'Growth and Productivity Accounts' provides measures of economic growth, productivity, employment creation, capital formation, and technological change at the industry level for European Union Member States as well as several other countries. The 2025 release of the database includes up to 40 industries and 23 industry aggregates, covering the period 1995–2021, and disaggregates capital into multiple tangible and intangible asset types. Refer to https://euklems-intanprod-llee.luiss.it/documentation/ for more information.

50 - National accounts are flow-based instruments: they are not designed to track the composition or evolution of capital stocks over time. Moreover, as Södersten, Wood and Hertwich (2018b) note, capital formation is recorded from a product perspective and is not attributed to the sectors where capital goods are ultimately used.

51 - As of 2023, the respective averages were 11.3%, 11.0%, 15.8%, and 17.4% (World Bank, n.d.).

that of other major components of final demand, reflecting the service-based nature of its output. However, the production of public services may still involve the procurement of carbon-intensive inputs, such as pharmaceuticals for health services.[52]

Despite the importance of government spending as a category of final demand, few studies have undertaken a comprehensive quantification and analysis of its environmental impact. In addition, research on household carbon footprints, whether national or cross-country, typically fails to comprehensively and finely allocate emissions from government spending to households. Yet public services are produced for their benefit, vary substantially across countries, and may accrue unequally across income groups. Each of these limitations obscures the true role of the public sector in shaping both overall carbon footprints and carbon inequality.[53]

Wiedmann and Barrett (2011) offer a rare, comprehensive analysis of the environmental impact of government spending, using a consumption-based approach that assigns emissions by function and source.[54] Commissioned by the UK government to inform procurement strategy, the study found that central government's ongoing expenditure accounted for approximately 6–7% of the UK's total carbon footprint between 1990 and 2008. Including local government, the combined public sector footprint fell from 13.3% of the national total in 1990 to 11.2% in 2008, although in absolute terms it remained stable over the period. This footprint compares favourably to the share of government final consumption in GDP, which ranged from just under one-fifth to somewhat more than one-sixth over the same period (World Bank, n.d.).[55] While direct and energy-related emissions declined by 26% over the period, indirect emissions from the upstream supply chain rose by 36%, driven by increased health expenditures and a shift toward imported pharmaceuticals.[56] The study underscores the importance of tracing supply chain emissions, which accounted for over 80% of the total footprint, to capture the full environmental impact of government services, highlight the role of international trade, and inform effective mitigation priorities, starting with procurement.[57]

Ottelin et al. (2018) conduct a similar analysis for Finland and, using the public welfare service module of the country's household budget survey, examine how differences in the consumption of government services across households affect their emissions. The authors confirm the large economic footprint of government consumption and capital formation in this high-income country, which together amount to half the level of household consumption and capital formation. They also confirm that government

52 - Government investment, such as infrastructure spending, is not included here, as it is recorded under capital formation. Transfers, such as pensions or subsidies, do not count as government final consumption; instead, their effects surface in household consumption or corporate value added, depending on the recipient.

53 - Ivanova et al. (2016) estimate the carbon footprint of ongoing government expenditure at approximately one-fifteenth of consumption-based emissions in high- and upper-middle-income countries (where such expenditures represent about one-sixth of GDP). This footprint is likely understated due to limitations in the resolution of government activities in the underlying global MRIO database, and the loss of detail and partial reclassification of publicly provided services under household consumption. Limited resolution results from the inherent trade-offs between global consistency and national specificity in MRIO construction, while the loss of detail and reclassification stem from the authors' mapping of final demand to the United Nations Classification of Individual Consumption According to Purpose (COICOP), which is necessary for alignment with the household expenditure surveys they use to analyse household consumption footprints.

54 - In contrast to Ivanova et al. (2016), Wiedmann and Barrett (2011) apply a government-focused input–output approach that assigns emissions directly to the institutional actors responsible for public expenditure. Their analysis draws on finer-grained, country-specific data, including detailed government accounts and sectoral emissions, and classifies spending by government function using categories broadly consistent with the United Nations Classification of the Functions of Government.

55 - Central government emissions were dominated by the Department of Health (accounting for 51% of central government's footprint), followed by Public Administration (25%) and Defence (22%). Schools, which fall under local authority control, were addressed in a separate report (Global Action Plan, Stockholm Environment Institute, and Eco-Logica Ltd., 2006) that estimated their emissions at around 2% of the national total, and approximately 15% of combined central and local government emissions, making education, after health, the largest contributor among government functions.

56 - The authors note that the carbon intensity of imports fell by less than 10% over the period, compared to a reduction of more than one-third for domestically produced goods.

57 - A comparable study estimates the carbon footprint of Norwegian public sector activity at 15.8% of the national total in 2017 (Asplan Viak, 2019), roughly half the public sector's economic weight (Statistics Norway, n.d.). While this footprint remained relatively stable in both absolute and relative terms following the global financial crisis, this masks a decline in emissions from operational spending, primarily driven by a sharp reduction in the carbon intensity of the electricity grid, and a corresponding rise in emissions from public investment, attributed to expanded infrastructure outlays. By the end of the period, investments accounted for around 40% of the footprint. Value chain emissions (other than those linked to electricity, heating, cooling, or steam) made up 81% of the total, with approximately 58% of these occurring abroad, underscoring the importance of addressing embedded emissions in procurement strategies.

consumption is less carbon intensive than household consumption (and markedly less so than capital formation): the carbon footprint of individual and collective services is only about half as large as their monetary share would suggest. The study further documents that the use of public welfare services declines with income across household groups, contributing to more equitable distributions of both welfare and carbon footprints.[58] This effect complements the redistributive role of income transfers, which are particularly significant in Nordic countries, in mitigating the high income-related disparities in household consumption and associated emissions.[59]

Final Demand Footprints: Emission Patterns, Climate Policy Levers, and Equity Implications

By offering a different picture of national carbon footprints, consumption-based analyses contribute fresh insights to debates on emissions mitigation and climate equity. While the consumption-based view does not invalidate the decoupling narrative, whereby the GDP of some developed countries continues to grow while territorial emissions stall or fall,[60] it nuances it by showing that these countries are typically net importers of emissions.[61] This reframes discussions around common but differentiated responsibilities – a core principle of the UNFCCC and reaffirmed in the Paris Agreement – by affirming the vast gap in emissions per capita between developed and developing countries and highlighting the need to support low-carbon transitions in exporting economies to mitigate the risk of carbon leakage.[62]

Because final demand is the anchor of consumption-based accounting, analysing its main components, i.e., household consumption, gross fixed capital formation, and government consumption, offers crucial insight into the activities to which supply chain emissions are ultimately allocated, and into how changes in and across these demand categories may contribute to system-wide emissions mitigation.

Most consumption-based studies have focused on household consumption, and understandably so, as it accounts for close to two-thirds of greenhouse gas emissions in high- and upper-middle-income countries,[63] and an even greater share in many lower-middle- and low-income countries.[64] Consumption-based analyses show that as incomes rise, household consumption grows at a lower rate but shifts toward more emission-intensive goods and services. This is reliably, and most strikingly, observed across and within countries in the domains of mobility and manufactured products. Within countries, consumption of meat and dairy products also increases with household income. These insights strengthen the case for demand-side mitigation strategies[65] that address the economic, infrastructural, cultural, and behavioural conditions shaping high-impact consumption patterns, including the aspirational norms associated with high-income households, as part of a more equitable and effective climate response.

58 - This effect is particularly pronounced among adults under 30, due to substantial differences in the use of public education: the bottom income quartile consumes more than three times as much as the top quartile, and more than twice as much as other young people.

59 - The authors note that the carbon footprint of the top income quartile is less than twice that of the bottom quartile – a contrast with the US, where it is about four times as high, according to the study by Shammin and Bullard (2009).

60 - This is the definition of absolute decoupling; relative decoupling refers to the rate of GDP growth exceeding that of emissions, as seen including in China in India after 2015 (on decoupling and how it has been achieved, refer to Hubacek et al., 2021). For readers interested in finer-grained distinctions, see Tapio (2005) for a typology of decoupling states that builds on ideas presented in Vehmas et al. (2003); for forward-looking scenario-based analysis of decoupling at the global scale, refer to Schandl et al. (2016).

61 - Wood et al. (2020) find that we are now beyond peak emission transfers between developing and developed countries.

62 - This notwithstanding, the Asia Pacific region exceeds Developed Countries as the largest emissions source since 2015, using consumption-based accounting.

63 - For the EU-28, He et al. (2025) estimate that, over the period 2010–2020, household consumption accounted for 63.6% of the carbon footprint, gross fixed capital formation for 25.9%, government consumption for 9.3%, and NPISHs for 1.2%.

64 - Shershunovich and Mirzabaev (2024) study household greenhouse gas emissions across twelve low- and middle-income economies using the Eora database. They show that the share of household consumption in national CO_2 emissions increases as income levels decrease, reaching over 80% in some low-income countries. The authors also highlight the shifting composition of household emissions across development levels. In several low- and lower-middle-income countries, per capita household emissions of CH4 and N2O are found to be higher than in high-income countries. In some cases – particularly Myanmar, Pakistan, and Kenya – CH4 dominates the household GHG profile, exceeding CO_2 in its contribution. These findings underscore the importance of moving beyond CO_2 -centric mitigation strategies, especially in economies where agriculture and waste management are the primary sources of household emissions. While these results should not be misinterpreted as assigning disproportionate responsibility to lower-income countries, they do highlight the need for comprehensive emissions accounting frameworks. It should also be observed that the climate significance of CH4 is underestimated in frameworks that express emissions in CO_2-equivalents using the 100-year Global Warming Potential (GWP100) metric. This approach dilutes the short-term warming impact of CH4, potentially obscuring its relevance in the critical near-term window for effective climate mitigation. Attention to CH4 emissions should not be limited to agriculture but must also extend to those arising from fossil fuel extraction, transportation, and processing – including venting, flaring, and leakage.

65 - By contrast, supply-side approaches target changes in energy systems and production technologies, and by extension include carbon removal options.

Capital investment is another critical but often underexamined source of final-demand emissions. While not consumed in the conventional sense, capital investment accounts for around one-quarter of final-demand emissions in industrialised countries. In economies that are industrialising, urbanising, or undergoing rapid infrastructure expansion, its share is typically higher (Södersten, Wood & Hertwich, 2018a, 2018b),[66] and may even become the dominant component of territorial emissions, as is the case in China (Minx et al., 2011; Chen et al., 2018). Empirical evidence shows that capital formation declines and becomes less carbon intensive as economies develop, as its share in final demand declines and the proportion of investment allocated to construction and heavy industry decreases. Yet the built environment, including residential housing, public infrastructure, and commercial buildings, remains the dominant contributor to capital-related emissions.

At any stage of development, the emissions associated with investment can be reduced by avoiding unnecessary projects or excessive scale, redirecting capital to less carbon-intensive sectors where feasible, and, in all cases, adopting more efficient construction and manufacturing practices and procuring more carbon-efficient materials.

Allocating investment-related emissions to the products and services they enable can also lead to a fairer appreciation of embedded emissions, whether in studies of household and government consumption, or in macro-level analyses of trade and carbon leakage.

More importantly, analysing capital investment through a transition lens, particularly long-lived and costly infrastructure, is key to understanding how choices in public infrastructure and production systems create path dependencies that may either enable low-carbon transitions or lock in[67] carbon-intensive practices.[68]

Government consumption, though typically lower in both total emissions and carbon intensity, plays an outsized role in shaping equity outcomes by redistributing resources through public services such as health, education, housing, and transport, and can be leveraged strategically to mitigate economy-wide emissions. In the case of government consumption, emissions from value chains dominate, and a material share of upstream emissions are imported (Wiedmann and Barrett, 2011, inter alia). This suggests that governments can reduce the footprint of their own consumption without altering core processes, not only through energy efficiency improvements and low-carbon energy procurement, but above all by sourcing goods and services with lower embedded emissions. Where appropriate and feasible, shifting the composition of government services toward lower-emission activities can further support mitigation. More broadly, public services should be intentionally redesigned to avoid unnecessary production and consumption and to minimise downstream emissions associated with their use. Finally, given their large economic footprint and the long-term horizons over which they operate, public authorities can also leverage procurement strategically to support both early-stage market formation and the scaling of climate solutions.[69]

66 - Södersten, Wood and Hertwich (2018b) report that, globally, gross fixed capital formation accounted for 25% of the total final demand of goods and services and 31% of the carbon footprint.

67 -The concept of 'carbon lock-in' was introduced by Unruh and popularised in a 2000 article, in which he argues that "industrial economies have been locked into fossil fuel-based energy systems through a process of technological and institutional co-evolution." For typological extensions and reviews of lock-in mechanisms, see Seto et al. (2016) and Klitkou et al. (2015).

68 - Investments in fossil-fuel versus low-carbon power generation; roads and airports versus land-based public transport infrastructure; and spatial planning that promotes segregated versus compact, mixed-use development are traditional examples of technological and infrastructural lock-ins that constrain future options and can shape user behaviour over decades.

69 - While the European Commission's 2008 Communication on *Public Procurement for a Better Environment* (COM(2008) 400 final) defined Green Public Procurement (GPP) as "a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function," it also underlined GPP's potential to stimulate demand for environmentally friendly products and services and to drive market innovation. The 2014 Public Procurement Directive (Directive 2014/24/EU) provides the main legal framework for integrating environmental considerations into public procurement. It also introduces the Innovation Partnership procedure, enabling public authorities to engage suppliers in the development of innovative solutions with the prospect of subsequent purchase. Certain sector-specific directives impose mandatory GPP requirements, such as the Clean Vehicles Directive ((EU) 2019/1161), the Energy Performance of Buildings Directive ((EU) 2010/31), and the Energy Efficiency Directive ((EU) 2012/27), but in most areas, GPP remains voluntary, unevenly implemented, and its strategic potential underused. The Commission's 2020 Circular Economy Action Plan (*A new Circular Economy Action Plan: For a cleaner and more competitive Europe*, COM (2020) 98 final) proposed introducing minimum mandatory GPP criteria and targets in sectoral legislation, along with compulsory reporting to monitor uptake. In December 2024, the Commission launched an evaluation and public consultation on the EU procurement rules, with current discussions focused on strengthening minimum standards, making GPP more robust and potentially mandatory, and aligning procurement practices more closely with the bloc's climate and competitiveness objectives.

The bulk of government consumption supports the provision of public services, some of which – such as health and education – directly benefit identifiable households. These services can significantly affect household welfare and should be properly accounted for in studies of household consumption. In particular, access to public welfare services is often deliberately unequal, e.g., needs-based and means-tested, for reasons of equity. This leads to a differentiated consumption of public services which tends to reduce disparities in household carbon footprints relative to those computed from market-based consumption alone. This notwithstanding, the low carbon intensity of many public services, relative to market-based goods and services, makes carbon footprints particularly poor proxies for material inequality within welfare states. Indeed, carbon footprints are shaped not only by income, but also by needs, availability, and the relative affordability of consumption options with different carbon intensities.[70] Evidently, purpose-designed economic metrics provide a more direct and far more reliable means of capturing such inequalities.[71]

This gap in carbon intensities, which would appear even larger if public services were valued at market rates or in terms of perceived utility, suggests a direction for decoupling household welfare – and, more fundamentally, well-being – from environmental impact: namely, by increasing the share of comparable low-carbon activities in total consumption, whether publicly or privately provided.

More proactively, public service innovation can support the emergence and scaling of sustainable lifestyles that maintain or enhance well-being, by promoting the supply of, and demand for, options that enable households and businesses to avoid unnecessary consumption or investment; shift toward less carbon-intensive categories of goods and services to meet functional needs; or improve choices within categories by selecting products and services with lower carbon footprints. For example, in mobility, governments can encourage telecommuting and digital access to services to reduce travel demand; expand and improve public and active transport to shift demand toward low-carbon modes; and legislate to reduce the carbon footprints of all transport options, starting with the most emission-intensive, for instance, by facilitating the provision and adoption of lower-emission alternatives such as lighter, slower vehicles or electric rather than internal combustion engine vehicles.

Endogenising Capital in EEIO: From Static Reallocation to Dynamic and Stock-Based Modelling

While EEIO models offer valuable insights into the carbon footprints of final demand, their static, single-year structure limits their ability to reflect the temporal dynamics of investment. Yet capital formation, particularly in long-lived assets such as buildings, infrastructure, and heavy machinery, has important and enduring implications for emissions. Examining the nature and composition of capital investment is critical to understanding how emissions may evolve over time and across different development pathways. The types of capital goods produced and deployed shape not only current emissions but also the future carbon intensity of production and consumption systems. As countries develop, the composition of capital formation tends to shift: lower-income economies often invest heavily in emissions-intensive construction and industrial assets, while high-income countries allocate a greater share to lower-emission capital such as information technology, software, and intellectual property. This evolution affects both the immediate footprint of investment and the long-term emissions trajectory embedded in economic activity.

70 - For example, a rural household may have greater mobility needs than an urban one, while also facing limited access to public transportation or safe cycling infrastructure. Differences in affluence may further constrain access to viable alternatives – for instance, if electric vehicles remain significantly more expensive than internal combustion engine vehicles.

71 - In the context of welfare states, a key limitation of monetary-based indicators of household consumption arises from the accounting convention that values government-provided services at production cost rather than at their market-equivalent value or perceived utility. This understates the consumption and welfare of households that rely more heavily on public services relative to households that purchase similar services at market prices.

Capturing these structural and temporal effects, however, requires moving beyond conventional static models. Standard EEIO models are built on single-year input–output tables and are, by construction, static representations of economic structure and environmental flows.[72] While they allow emissions to be traced through economic flows, those flows are themselves shaped by the underlying capital stock and reflect backward-looking production and consumption relationships. Moreover, because national accounts treat gross fixed capital formation as final demand, the full emissions associated with capital goods are typically allocated to the year of investment in standard EEIO applications, offering a limited view of how investment contributes to long-term emissions trajectories. Stated differently, conventional EEIO analysis is not designed to capture dynamic processes such as capital accumulation, technological change, or structural transitions.

If capital formation primarily serves to maintain existing capital stocks without materially altering production technologies or system structures, excluding investment-related emissions may not significantly distort policy insights. However, when investment drives capital accumulation or enables structural transformation, such as shifts in energy systems, infrastructure, or industrial processes, omitting these emissions can obscure critical dynamics and mitigation opportunities.[73]
This part reviews methods that have been put forward to better integrate capital-related emissions into EEIO models. It first examines approaches that reallocate capital emissions within static, single-period EEIO frameworks. It then turns to dynamic and stock-based models that more explicitly capture the temporal and structural dimensions of capital formation and accumulation.

Adjustments within Static EEIO Frameworks

Because EEIO models typically mirror the treatment of capital in national accounts, they assign emissions from capital goods to the year of investment. But they can be restructured to "close" the system for capital, allowing associated emissions to be allocated to intermediate demand.[74]

Two approaches have emerged:

- A forward-looking approach redistributes emissions from new investment (gross fixed capital formation, or GFCF) to the production of goods and services that the new capital assets enable.
- A backward-looking approach attributes emissions to the consumption of fixed capital (CFC), defined as the expected decline in the value of the capital stock over the period, which is recorded as part of value added in national accounts.[75,76]

72 - While Leontief argued that the technical coefficients matrix might remain relatively stable over short periods, coefficients vary in practice with technological change, substitution, and scale or structural effects (see, inter alia, Rose and Casler, 1996).
73 - As a flow-based analysis, EEIO offers limited insight into the history of capital accumulation and the emissions embedded in existing infrastructure and durable assets. Nor is it well-suited to the forward design of alternative production systems, since it does not model structural change, technological evolution, or system-level reconfiguration over time. Moreover, because it is focused on tangible economic and physical flows, EEIO cannot directly account for the intangible enablers and disablers of systemic change, such as institutions and norms.
74 - Two traditional approaches exist for endogenising capital in input–output models. The augmentation method introduces a notional capital-producing sector that supplies a homogeneous capital good, with capital inputs allocated proportionally across industries based on aggregate investment. This approach fails to distinguish between different types of capital goods. Since industries typically use distinct combinations of capital with substantially different emissions intensities, the augmentation method introduces systematic biases that increase with the variance in those intensities (as highlighted by Lenzen and Treloar, 2004). The flow matrix method, by contrast, constructs a capital use matrix (that is merged with the standard intermediate input matrix) that maps specific capital goods to the industries that use them, enabling a more differentiated and accurate attribution of emissions (albeit at the cost of significantly greater data requirements).
75 - According to the SNA definition (European Commission et al., 2009), this may be "as a result of physical deterioration, normal obsolescence or normal accidental damage."
76 - One could similarly argue that the emissions associated with the availability or reproduction of labour should be endogenised. By reproduction, we refer to the consumption and support systems necessary to sustain human capacity to participate in the production process; availability refers more minimally to the presence of a usable labour force, which may be maintained even in the absence of just or sufficient conditions for reproduction. In standard EEIO models, these emissions are attributed to final demand categories such as household and government consumption, without regard to their functional role in sustaining the labour force. Yet much of this consumption, whether private (e.g. food, housing) or public (e.g. education, healthcare), underpins the continued availability of labour for production. Labour is also compensated at vastly different rates across and within countries, including when serving equivalent functional roles in global production systems. In other words, there are significant gaps between actual compensation and the level of consumption required to reproduce labour capacity, gaps that depend on access to the global social surplus but also on how societies value different kinds of outputs at a given time. Reallocating labour reproduction emissions toward production could offer a fairer representation of the social metabolism underpinning consumption-based emissions.

Both the forward- and backward-looking approaches enable more accurate environmental footprinting of household and government consumption and enhance understanding of global supply chains and emissions embedded in trade.[77]

Reallocating investment emissions is particularly relevant for China, where they account for an outsized share of territorial emissions. Given China's status as both the world's largest emitter of greenhouse gases and its largest exporter,[78] such reallocations have the potential to reshape sectoral footprints and trade-adjusted balances globally. Using the forward-looking approach, Minx et al. (2011) reallocate Chinese emissions associated with capital formation to functional end uses between 1992 and 2007. They identify 2002–2007 as the period of fastest emissions growth and find that the large majority of emissions embodied in investment ultimately supported domestic household and government consumption, while between one-fifth and one-third are linked to exports.[79] These results are striking because they apply to the pre-2012 period, when China was pursuing an export-led development model[80] and its production relied heavily on high-emission-intensity, low value-added products.[81] The production of many of these products has progressively relocated to lower-wage economies; a trend that accelerated in the aftermath of the Global Financial Crisis and after 2012 and that has contributed to the marked reduction in the carbon intensity of China's economy (Meng et al., 2018).

Using the backward-looking approach, Södersten, Wood and Hertwich (2018b) provide the first attempt to endogenise capital in a global MRIO.[82] by ayttributing emissions to the consumption of capital[83] and allocating these to asset types and sectors. They find that reallocating CFC-related emissions increases global emissions embodied in trade by 11% and significantly alters national carbon balances, typically widening the gap between production- and consumption-based emissions. At the sectoral level, the reallocation leads to substantial changes in carbon footprints: in OECD countries, telecommunications services see the largest relative increase, while in non-OECD countries, real estate services are most affected. These results underline that accounting for capital consumption can substantially alter both national carbon balances and the sectoral profiles that may guide policy priorities.

77 - Intuitively, the backward-looking approach may be better suited for footprinting current output, as it reflects the consumption of capital goods supporting present production and attributes emissions representative of the technologies in use at the time those goods were produced. By contrast, the forward-looking approach is more appropriate for assessing the implications of a changing productive system, as it considers emissions from new capital investments that will support future production. However, since both the SNA and standard EEIO frameworks are flow-based tools, they do little to track the stock of capital assets with precision. In practice, data availability and fitness for purpose often determine the choice of method. As noted by Södersten, Wood and Hertwich (2018b): "The GFCF is partitioned by product type, but not destination sector; likewise, official statistics do not keep track of which sectors are using which capital stock (…) In order to fully understand the dynamics of capital, information on the distribution of capital expenditures by industry as well as a detailed asset composition of the CFC would be necessary."

78 - China has been the world's largest emitter of CO_2 since the mid-2000s and now accounts for over a third of global emissions. This represents a more than eightfold increase since 1978, i.e., the year that ended with the official launch of Deng Xiaoping's economic reform agenda (2023 figures, excluding land use, land-use change, and forestry, World Bank, n.d.). The most rapid growth occurred from 2001 through 2011, following China's accession to the World Trade Organisation, which spurred industrial expansion and export-led growth (Zheng et al., 2020). China recorded double-digit GDP growth between 2003 and 2007, and average annual growth close to 10% through 2011. After 2012, China implemented policy reforms to rebalance its economy, shifting focus from high investment and exports toward domestic consumption and the service sector (Mi et al., 2018).

79 - Fast growth in capital formation continued from 2007 to 2012 with related CO_2 emissions more than doubling; subsequently, capital formation emissions rose only modestly to 2017 (Gao et al., 2020). Traditional EEIO analyses of final demand find that, over 2007–2012, emissions embodied in China's exports declined, peaking in 2008 (Su and Thomson, 2016; Mi et al., 2018). This was primarily driven by changes in sectoral mix, notably the reduction in exported emissions from highly carbon-intensive but low value-added sectors such as metallurgy and textiles, and by efficiency gains. (Gao et al., 2020).

80 - Following the Global Financial crisis (2007-2009), developing countries became the major destination of China's export emissions (Mi et al., 2017).

81 - This complements Guan et al. (2009), who analysed the 2002–2005 period using a conventional input–output framework and attributed approximately half of the surge in emissions (production-related emissions grew 46% over the period) to export production, and about one-third (36%) to investment (56% of it in manufacturing, notably machinery and transport equipment, and the rest in construction).

82 - Parallel work has adapted similar approaches to single-region models. Berrill et al. (2020) and Miller et al. (2019) refine the flow matrix method within the USEEIO framework by improving asset-level disaggregation and reallocating capital-related emissions to industries via depreciation. These efforts extend the methodological basis for more temporally consistent footprinting in national contexts.

83 - The authors argue that using CFC is "more sensible for footprint-type calculations, since it implies that footprints would include emissions associated with the production of the capital currently used by industries, and that emissions associated with the production of new capital would be assigned to goods and services produced in the future using that capital." One drawback of the backward-looking approach, however, is that in standard EEIO models the environmental extension is applied only to intermediate and final demand flows. CFC is not treated as an intermediate input, as it does not involve transactions between industries but reflects the internal consumption of owned capital assets. Instead, it is recorded among primary inputs, alongside labour compensation, capital services, and taxes or subsidies on production, and contributes to gross output indirectly via the value-added vector, which is used to balance the input–output table. As a result, the emissions embodied in capital goods as they are depreciated are typically excluded from consumption-based accounting. To address this omission, the authors estimate these embodied emissions using current emission intensities of the capital-producing sectors, a simplification they acknowledge as temporally inconsistent, particularly problematic for long-lived assets such as infrastructure or buildings.

Dynamic EEIO Modelling and Intertemporal Capital Accounting

Traditional approaches to incorporating capital into input-output models rely on static representations of capital flows and apply a «current technology» assumption, that is, capital consumed in a given year is produced using that year's technologies.[84] Neither Minx et al. (2011) nor Södersten, Wood and Hertwich (2018b) endogenise capital in a dynamic or iterative sense, nor do they construct models that explicitly track the stock and turnover of capital assets over time.

Theoretical frameworks exist that explicitly endogenise capital within EEIO models. The dynamic input–output model developed in the mid-1980s by Leontief, Duchin, and Szyld (Leontief and Duchin, 1986; Szyld, 1985; Duchin and Szyld, 1985) links sectoral output targets to capital requirements and incorporates depreciation to model the evolution of capital stock over time, thereby determining gross capital formation as final demand.[85] More recently, Pauliuk et al. (2015) treat capital formation as an intermediate input and fully integrate environmental accounts to track the physical capital stock and its characteristics over time. This enables the model to recognise the distinct technologies and operational emissions associated with different investment vintages and to distribute their embodied emissions across their service lives. Drawing on Pauliuk et al. (2015), Chen et al. (2018) integrate the augmentation method into a dynamic stock–flow framework, enabling emissions from capital to be amortised over its useful life. Subsequent extensions by Ye et al. (2021) and Wu, Wang and Ye (2021) introduce capital vintaging and immediate-use dynamics, respectively, while Xu et al. (2023) extend this logic spatially, tracing how emissions from capital formation in one country reappear across time and borders in the consumption footprints of others. Xu et al. (2023) provide an empirical validation of the relevance of this line of work by endogenising capital dynamically in a global MRIO framework. The authors trace the vintages of capital assets present in the year's capital consumption (CFC), quantify their related historical CO_2 emissions (based on the years of formation and the corresponding technologies and intensities), and apportion these, adding capital consumption emissions to those from other inputs to compute sector totals in the year's final consumption. They focus on China and the year 2015, availing of capital data and an EE MRIO[86] framework for the years 2000 to 2015. They observe that China's capital-related emissions accounted for more than 40% of the global total despite representing only 14% of capital consumption (CFC), suggesting both rapid capital accumulation and high embodied emissions. Endogenising capital using their dynamic CBA approach increases China's 2015 footprint to 4.65 Gt CO_2, about 28% higher than conventional CBA.[87] The increase is concentrated in service sectors consuming building structures, such as real estate and public administration, underscoring the role of past investment in residential and commercial real estate and public infrastructure;[88] and highlighting the built environment as a priority for mitigation, through measures to lower construction carbon intensity and extend the relatively short lifespans of

84 -Static input–output models do not capture the dynamics of in-use capital stocks. Gross fixed capital formation appears in final demand, but its material composition and service life are not explicitly modelled. Input–output coefficients reflect the average use of capital services in sectoral production, based on historical input patterns. This backward-looking approach cannot account for the dynamics, ageing, or technological vintages of capital stocks.

85 -Leontief introduced the concept of a dynamic input-output model as early as 1953, highlighting the need to incorporate capital accumulation into economic forecasting (Leontief, 1953). However, this early formulation did not address the risk of economically meaningless outcomes. Leontief and Duchin (1986) advanced the dynamic framework by specifying sectoral capital requirements, introducing vintage capital accumulation, and embedding these within a more concrete, economically grounded structure. It was Szyld (1985), however, who derived formal mathematical conditions to ensure the existence of economically meaningful (i.e., non-negative) solutions in dynamic IO models with time-dependent capital structures. Duchin and Szyld (1985) operationalised the model under these constraints and developed a practical structure for tracking capital maintenance and expansion, enabling the endogenous modelling of capital services and structural change. For this reason, the dynamic IO model is often referred to in the literature as the Leontief–Duchin–Szyld model. Compared to the static IO model, which tracks only intermediate inputs consumed in current production via matrix A, the dynamic approach introduces a capital requirements matrix B, which captures both the replacement needs of existing stock and the investment required to support expanded output. Since the dynamic model was originally developed to study industrial development scenarios, it requires specifying desired future sectoral outputs. These targets determine the required capital stock for each sector through capital coefficients that link output levels to capital needs. The difference between this required stock and the projected capital stock (accounting for depreciation) defines the demand for gross capital formation. This demand is then allocated to the sectors that produce capital goods and enters the model as final demand for investment – closing the capital loop and endogenising structural change over time.

86 -The authors use EXIOBASE 3.8 (Stadler et al., 2018), which covers 44 countries and 5 rest-of-the-world regions, with 200-product granularity 200 (which they merged into 55 products). The capital formation data is from EU KLEMS, WORLD KLEMS (https://www.worldklems.net/), and the Penn World Table 10.1 (Feenstra et al., 2015).

87 - Relative to the emissions embodied in final demand, the footprint decreased by 46%, indicating that a large share of the emissions embodied in net new capital stock would be allocated to output in subsequent years.

88 - Relative to GDP, real estate and infrastructure investment peaked around 2018 (Rogoff and Yang, 2024).

Chinese assets. Capital vintaging analysis revealed that 87% of the emissions embodied in China's 2015 capital consumption stemmed from assets formed before 2015.[89]

The added granularity and intertemporal consistency provided by integrating material flow analysis[90] into the EEIO framework allows for assessing how legacy, current, and future investments shape both current and future production and environmental outcomes. Combined with better representation of the spatial dimensions of emissions in global value chains, the improved temporal attribution of resource use and emissions[91] may support more equitable allocation of environmental responsibility in consumption-based accounting. However, the integrated MFA–EEIO framework does not fully capture the dynamics of socioeconomic transitions. Without complementary modelling, it remains limited in its ability to represent behavioural feedbacks, structural transformations, and technological discontinuities.

Further progress in forward-looking applications may require hybridisation with other traditions, such as system dynamics, agent-based modelling, or macroeconomic scenario analysis, that are better equipped to represent lock-ins, endogenous feedbacks, and exogenous shocks.

Conclusion

Rooted in national accounting traditions and designed to quantify intersectoral dependencies, input–output analysis, paired with environmental accounts, has become a powerful tool for tracing emissions across supply chains and informing environmental and climate policy.

This note has reviewed the intellectual and methodological evolution of EEIO models, with a focus on their application to final demand footprinting. It has shown how EEIO-enabled consumption-based emissions accounting complements the territorial perspective of UNFCCC reporting by capturing emissions embodied in international trade and in the global value chains required to satisfy final demand.[92] Reviewing empirical results, the note has also highlighted how the CBA perspective brings nuance to discussions about territorial emissions: many developed countries that have achieved marked reductions in their territorial totals are net importers of emissions through trade, while a significant share of the dynamic emissions growth in developing countries supports production for export. The note has also surveyed insights into emissions associated with household consumption, capital formation, and government spending across countries – highlighting mitigation levers, equity implications, and the structural co-dependence between consumption and production systems.

From the literature, several substantive insights emerge:

Household consumption

Household consumption typically accounts for around two-thirds of greenhouse gas emissions in high- and upper-middle-income countries, and an even greater share in many lower-middle- and low-income ones.

89 - Xu et al. also note that China's exports embodied an order of magnitude more capital-related CO_2 than its imports, reflecting both the scale of its capital goods exports and the high carbon intensity of its production.

90 - MFA is a biophysically grounded accounting framework that traces the inputs, accumulation, transformation, and outputs of materials within a defined system over time. Rooted in the principle of mass conservation first articulated by Lavoisier, MFA applies mass-balance equations to track physical flows across complex economic and industrial systems, often complementing or extending monetary economic accounts. These equations require that the inputs to a system equal the sum of its outputs and net accumulation, ensuring internal consistency in the accounting of stocks and flows. The conceptual foundations of MFA were laid by Ayres (1978). While Ayres was also influenced by Georgescu-Roegen's thermodynamic and evolutionary reinterpretation of economics, canonical MFA does not incorporate entropy in its full sense – including the irreversible degradation of both material and informational structure – nor the historical contingency and fundamental uncertainty central to Georgescu-Roegen's view of economic processes. As a result, it can lend itself to overly optimistic interpretations of circularity that overlook thermodynamic constraints on material and functional recovery (i.e., reversing entropy requires energy expenditure; hence, in any closed system, including the universe, total entropy must increase over time). Furthermore, MFA does not intrinsically capture historical inertia and path dependency, or the uncertainty generated by endogenous feedback effects and external perturbations.

91 -However, the integrated MFA–EEIO framework does not fully capture the dynamics of socioeconomic transitions. Without complementary modelling, it remains limited in its ability to represent behavioural feedbacks, structural transformations, and technological discontinuities. Further progress in forward-looking applications may require hybridisation with other traditions, such as system dynamics, agent-based modelling, or macroeconomic scenario analysis, that are better equipped to represent lock-ins, endogenous feedbacks, and exogenous shocks.

92 -While CBA traces the direct and upstream emissions embodied in final demand, EEIOs can be repurposed and extended to allow emissions to be attributed to industries and their value chains; see O'Kane (2025) for a primer.

The composition of these footprints shifts with income: food and shelter dominate in poorer economies, while mobility and manufactured products become more important in wealthier ones. In 2010, cross-country disparities were stark: the carbon footprint of the global top decile by expenditure was an order of magnitude larger than that of the bottom half of humanity, and household footprints varied more than twentyfold between high- and low-income countries. Even among developed economies with similar levels of human development, footprints diverged, though all remained well above both the global average and the carbon budget consistent with the Paris Agreement. Within countries, disparities were sharper in developing economies, and already by 2010 the middle and upper expenditure groups there displayed footprints comparable to their counterparts in rich countries. Mobility plays a leading role in these differences: in the EU, the top decile accounts for over a quarter of household emissions, as much as the bottom half, while the top centile alone has an outsized footprint driven by air transport consumption. Decarbonising household demand will therefore require measures that address high-emission consumption categories, particularly mobility and diet, and more broadly challenge the cultural norms underpinning aspirational high-emission lifestyles. In high- and middle-income countries, the vast majority of household emissions are embedded upstream in supply chains, underscoring the need to pair demand-side measures with production-side decarbonisation. In low-income countries direct household emissions, notably from shelter (cooking, heating, and cooling), are relatively more important, pointing to electrification – and grid decarbonisation – as priority levers for decarbonisation.

The evidence reviewed also shows that the core dimensions of human development, i.e., health, longevity, and education, are achievable for all within the global carbon budget under different distributional assumptions and consumption choices. Realising this potential depends on the evolution of the capital stock, which can lock in carbon-intensive pathways or enable low-carbon ones, and on government services that can provide welfare with comparatively low footprints and facilitate low-emission lifestyles

Investment

Capital investment, especially in long-lived, static assets such as buildings, infrastructure, and heavy machinery, has historically constituted the bulk of material throughput in industrial economies. The state and evolution of this capital stock also condition patterns of production and consumption in the short, medium, and long term.

Capital investment accounts for around one-quarter of final-demand emissions in industrialised countries. In economies that are industrialising, urbanising, or undergoing rapid infrastructure expansion, its share is typically higher, and may even become the dominant component of territorial emissions, as is the case in China. The relative share and carbon intensity of capital formation decline with GDP, as economies shift away from construction and heavy industry toward less emission-intensive forms of investment such as computing equipment and software. However, the built environment, including residential housing, public infrastructure, and commercial buildings, remains the dominant contributor to capital-related emissions. Emissions associated with investment can be reduced by avoiding unnecessary projects or excessive scale, redirecting capital to less carbon-intensive sectors where feasible, and, in all cases, adopting more efficient construction and manufacturing practices and procuring more carbon-efficient materials.

Government Consumption

The final major component of final demand and emissions is government consumption, which encompasses the ongoing provision of public services, from healthcare and education to general administration and defence. Government consumption tends to rise with GDP per capita and accounts for about one-ninth of GDP in low- and lower-middle-income countries, and about one-sixth in upper-middle- and high-income

countries. Its carbon intensity is lower than that of household consumption, and markedly lower than that of investment, reflecting the service-based nature of the output. As emissions from value chains dominate, procurement is a key lever for decarbonising government services, but it can also be leveraged strategically to support both early-stage market formation and the scaling of climate solutions. The bulk of government consumption supports the provision of public services, whose differentiated consumption reduces disparities in welfare and household carbon footprints. Public service innovation can further support the emergence of sustainable lifestyles that maintain or enhance well-being.

Finally, the note examined efforts to improve the treatment of capital goods, from redistributing investment emissions in static models to implementing dynamic models that explicitly track capital stock accumulation and depreciation over time to model changing operational emissions and allocate embedded emissions across asset lifetimes. These advances strengthen the spatial and temporal resolution of carbon footprinting and expand EEIO's capacity to support forward-looking transition planning.

Empirical applications show that redistributing capital emissions increases emissions embodied in trade by more than 10% and reshapes sectoral profiles. Such reallocations also bring new perspectives to debates over exporter and importer responsibilities. In this respect, no country is more central than China: fixed capital formation accounts for an outsized share of its territorial emissions, and as the world's largest emitter since the mid 2000s and largest exporter since 2009, reallocation of its investment-related emissions has the potential to alter assessments of emissions embodied in trade globally. Such reallocations reveal that even at the height of its role as 'factory of the world' in the 2000s, China's capital emissions primarily supported domestic household and government consumption. Dynamic endogenisation of capital increases China's 2015 consumption-based emissions by over a quarter and underlines the central importance of reducing the carbon intensity of construction and extending the durability of built infrastructure to mitigate the country's emissions. This illustrates the added value of dynamic EEIO in improving temporal attribution of emissions and highlighting priority mitigation levers.

Recent methodological and data innovations have further strengthened EEIO's relevance. Improvements in spatial, temporal, and sectoral resolution, together with hybridisation with tools from industrial ecology such as MFA, are enabling more granular and physically grounded emissions estimates. In parallel, researchers are extending EEIO frameworks to simulate future technological change and policy interventions, increasing their utility for scenario-based planning.

Nonetheless, EEIO retains structural limitations: it typically assumes fixed production technologies, sector homogeneity, and static interdependencies, features that suit historical analysis but limit its effectiveness as a standalone tool for dynamic and forward-looking modelling. To capture feedbacks, lock-ins, path dependencies, and institutional or behavioural change, EEIO should be complemented by system dynamics, macroeconomic scenario tools, or agent-based approaches. Integrating these approaches will be key to ensuring that EEIO remains fit for purpose in transition-orientated applications.

Appendix A: Overview of Key EE-MRIO Databases: Origins, Coverage, and Structure

The OECD first released Inter-Country Input-Output tables in 1995. It was extended with estimated CO_2 emissions to support a first-of-its-kind global assessment of emissions embodied in trade (Ahmad and Wyckoff, 2003). The database is aligned with the System of National Accounts (2008 version) and the International Standard Industrial Classification (ISIC Revision 4). The OECD started making time series data

available in 2015. The 2023 release of the OECD input-output and greenhouse gas emissions database provides annual time series data from 1995 to 2020, covering 76 countries plus a «rest of the world» aggregate, with a sectoral resolution of 45 industries (Yamano, Lioussis and Cimper, 2024).

The Global Trade Analysis Project network, coordinated by Purdue University, started developing a database in 1992, which was used in early efforts to extend the global input–output framework to environmental applications (Peters & Hertwich, 2008). With its 2001 (GTAP 5) release, it began incorporating energy data. It now covers a wide range of regions but a rather narrow range of sectors - 141 countries (and 19 aggregate regions) and 65 sectors in the 2023 (GTAP 11) release (Aguiar et al, 2023). GTAP offers reference-year representation of the economy, rather than continuous time series (GTAP 11 offers five reference years, from 2004 to 2017).

WIOD, developed under an EU-funded project was the first EE-MRIO to offer consistent, SNA compliant, annual data from 1995 to 2009 in both current and constant prices (Dietzenbacher et al., 2013). Its 2016 tables cover 28 EU countries and 15 other major countries for the period 2000-2014, plus a model for the rest of the world. It has been expanded from 35 to 56 sectors (classified according to ISIC Rev. 4). The Joint Research Centre of the European Commission provides data on energy use and CO_2 emissions by industry and country for 2000-2016 that are consistent with the 2016-release of WIOD. Since 2022, a long-run WIOD is available for the period 1965-2000.

Eora, created at the University of Sydney, employs an automated procedure to generate highly disaggregated MRIO tables and environmental satellite accounts (Lenzen et al., 2012, 2013). It initially achieved coverage of 187 countries with sector classifications ranging from 25 to 500 sectors for each year from 1990 until 2011 in current prices (Geske et al., 2014). Its current release covers "15,909 sectors across 190 countries" for 1990-2022 (https://worldmrio.com accessed on 9 June 2025); for cross-country comparisons, its simplified version has 26 harmonised sectors.

EXIOBASE, developed within EU projects, aims for high suitability in environmental analysis. The initial release (Tukker et al., 2009; 2013) covered the year 2000; annual data (for 1995-2011) were made available starting with the third release (Stadler et al., 2018) and are frequently updated. The next update will cover the period 1995–2020 for 28 EU member countries, 16 major economies, and five rest of the world regions, with 163 industries and 200 product categories, offering high consistency and granularity across sectors with solid environmental extensions (417 emission categories, 662 material and resources categories).

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