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MatMat - Hybrid Input-Output framework to estimate country-level carbon and material footprints in future scenarios

Antoine Teixeira (ADEME – CIRED) – August 2024

Abstract

As nations intensify efforts to design and implement low-carbon strategies, aligning these with the broader sustainability objectives of the Sustainable Development Goals (SDGs) becomes essential. These strategies must extend beyond mere territorial decarbonization to include comprehensive assessments using local indicators that accurately reflect the sustainability of global supply chains. However, a significant gap exists in modeling tools capable of assessing economy-wide sustainability for future scenarios at national scale. This paper introduces the MatMat Hybrid Input-Output (HIO) model, a novel framework developed to assess and map country-specific carbon and materials footprints across supply chains and trade, for both current situation and future transition scenarios. Employing methods such as capital endogenization within a national context, and by integrating and reconciling diverse economic, technical, and policy projections, the model enables forward-looking analyses that are technically realistic and macroeconomically consistent.

The MatMat model provides detailed insights into the factors driving the evolution of future carbon and material footprints across various final consumption sectors, differentiating between territorial contributions and those embodied in imported goods and services. Demonstrated through its application to France, the model proves invaluable for policymakers to assess the effectiveness of Net-Zero Emissions (NZE) scenarios and to identify necessary intervention areas to enhance sustainability. The architecture of the MatMat model ensures transparency, reproducibility, replicability, and extensibility, supporting its application to similar case studies in France and other countries, as well as the integration of new functionalities.

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Introduction

Sustainability assessment in national low carbon strategies

As global awareness and commitment to environmental sustainability intensify, nations are increasingly motivated to align their low-carbon strategies with the expansive goals set by the Sustainable Development Goals (SDGs). The European Green Deal (2019) exemplifies this shift by broadening the scope of sustainability to encompass comprehensive targets in waste and water management, biodiversity and ecosystem conservation, soil erosion limitation, and dependency on imported raw materials reduction.

Despite these advancements, current strategies primarily aimed at achieving Net-Zero territorial Greenhouse Gas Emissions (NZE) by mid-century (Allen et al., 2022), tend to overlook broader environmental issues. These strategies need to extend beyond mere territorial decarbonization and consider a more holistic approach. This includes accounting for both local territorial environmental impacts, and global impacts embodied in imported goods and services required to support domestic production and consumption.

However, a significant challenge persists in the landscape of sustainability assessment of future transition scenarios. The existing modeling tools are inadequate for comprehensively evaluating the multifaceted environmental issues of such scenarios at the national level. This gap hinders effective policymaking and strategy development aimed at achieving strong sustainability in line with global SDGs.

Challenges in current modeling approaches

Technology-rich Integrated Assessment Models (IAMs) and Environmentally Extended Input-Output (EEIO) analyses have proven to be complementary tools for forward-looking sustainability analysis. Recent academic efforts have discussed on integrating IAMs with IO models to accurately represent global material supply chains and assess the multifaceted environmental implications of future scenarios (Lefèvre, 2023; Pauliuk et al., 2017). Despite these advancements, applications that merge these models remain scarce, mostly at the worldwide scale, and generally do not encompass whole-scenario analyses. There is a pressing need to extend current modeling tools by bridging these two fields to provide a more holistic perspective of the environmental and socio-economic impacts of low-carbon transitions.

Traditionally, technology-rich Integrated Assessment Models (IAMs) have played a pivotal role in designing and studying low-carbon scenarios at global and regional levels, especially in support of IPCC reports (Shukla et al., 2022). These models, which integrate energy, economic, and land-use systems through partial or general equilibrium modeling, facilitate the exploration of investment needs and energy-economy feedback under various climate policy and technology strategies (Keppo et al., 2021). However, they often fall short in several critical areas (Lefèvre, 2023; Pauliuk et al., 2017). Firstly,

while IAMs focus on sector-specific mitigation technologies, they frequently overlook the lifecycle impacts of the carbon-intensive materials required to build and renew capital stocks across sectors. This oversight can lead to underestimations of material demands and associated emissions, creating significant gaps in scenario planning. Secondly, by omitting a comprehensive life-cycle perspective, IAMs fail to account for broader environmental impacts, thus compromising the overall sustainability of the scenarios they generate. Lastly, these models predominantly focus on technological solutions for emission reduction and often neglect alternative strategies such as demand-side management (Creutzig et al., 2022; Grubler et al., 2018) or circular economy approaches (Aguilar-Hernandez et al., 2018, 2021; McCarthy et al., 2018), which could substantially enhance sustainability.

In the field of Industrial Ecology (IE), Environmentally Extended Input-Output (IO) analysis (Miller & Blair, 2009; Suh, 2009) provides a comprehensive representation of the environmental and economic dimensions of global supply chains. This is largely thanks to the development of detailed sectoral and regional Multi-Regional Input-Output (MRIO) databases (Stadler et al., 2018; Lenzen et al., 2013; Timmer et al., 2016; Aguiar et al., 2019; Remond-Tiedrez & Rueda-Cantuche, 2019; Lenzen et al., 2022), and the advent of flexible open-source tools like the pymrio Python package for MRIO analysis (Stadler, 2021). Despite these advancements, existing applications often rely on static analyses at the global scale, underscoring the unsustainability of current consumption and production patterns. While some researchers have attempted to bridge carbon and material footprint assessments (E. G. Hertwich, 2021; Rasul & Hertwich, 2023), based on past studies on both carbon (E. G. Hertwich & Peters, 2009) and material footprints (Tukker et al., 2016; Wiebe et al., 2012; Wiedmann et al., 2015), these efforts are not tailored to national contexts nor do they adequately explore policy interventions in future country-level scenarios (Lefèvre, 2023). Furthermore, few studies have utilized MRIO models to assess the impacts of policy shocks and changes in demand patterns on carbon footprints (Moran et al., 2020; Wood et al., 2018), but only few studies assess the carbon footprint in full transition scenarios (De Koning et al., 2016; Wiebe et al., 2018). Consequently, a versatile modeling environment capable of conducting comprehensive economy-wide sustainability analyses of future scenarios at a national scale is still lacking. Here, we propose to fill this gap by leveraging the complementarity of IAM and EEIO approaches.

Introduction of the MatMat Hybrid Input-Output model

To address the identified gap, we developed the MatMat Hybrid Input Output (HIO) model. Coded in the python language, this novel modeling platform is designed to assess and map country-specific carbon and materials footprints across supply chains and trade, both in the present situation and for future policy scenarios:

- The model employs a simplified Single country National Accounts Consistent footprints (SNAC) approach (Tukker et al., 2018), combining Single Region Input-Output (SRIO) tables with outcomes from a global Multi-Region Input-Output (MRIO) model. SRIO tables enable faithful description of specific countries or regions.

Integration with MRIO model allows for the estimation of indirect GHG emissions and raw materials extraction embodied in imports.

- The model is designed to study the determinants of current and future carbon footprints by dissecting the link between GHG emissions, capital formation, and materials production along supply chains, from foreign and domestic producers to final consumption sectors. To facilitate this analysis, it incorporates a capital flow matrix that enables the endogenization of capital formation in the computation of the carbon and materials footprints (Södersten et al., 2018).
- For applications in France, the model is meticulously calibrated by aligning the Exiobase v3.8.2 database (Stadler et al., 2018, 2021) with country-specific databases. Exiobase is recognized for its capabilities in environmental assessment and its comprehensive detailing of material and energy fluxes. Integrating national information ensures a high-fidelity representation of the national context.
- It features a parametrization interface that allows the implementation of economy-wide exogenous scenarios derived from various expert projections on future economic, energy, materials, and policy developments. This capability enables forward-looking analyses of climate, energy, and circular economy policies (Donati et al., 2020; Wiebe et al., 2018, 2019). The Hybrid Input-Output framework, combined with the high sectoral detail of Exiobase, facilitates this integration.
- While initially built around the case of France, the model follows and extends best practices in Industrial Ecology (IE) modeling (E. Hertwich et al., 2018; Pauliuk et al., 2015), making it adaptable and replicable for other country contexts.

In the next sections, we delve into these key modeling features outlined above and provide a detailed mathematical background of the model. The concluding part of the chapter will introduce briefly its applications in assessing current and future carbon and materials footprints in France and the ongoing and planned future developments of the model.

Key modeling choices

Single country National Accounts Consistent footprints approach

Our modeling framework employs a simplified Single country National Accounts Consistent footprints (SNAC) approach (Tukker et al., 2018), structured around a bi-regional unilateral Input-Output framework (Miller & Blair, 2009; Suh, 2009). This approach utilizes environmentally extended Single Region Input-Output (SRIO) tables to describe a specific country or region. A global Multi-Region Input-Output (MRIO) model complements this to estimate indirect GHG emissions and raw materials extraction embodied in imports.

To simplify the implementation of the method for future scenarios while keeping track of the structure and composition of foreign value chains beyond imports (including foreign intermediate consumptions and capital formation required to source imports), we combine two SRIO databases: one for the country under study and another representing

the Rest of the World (RoW). National accounts are calibrated by reconciling the MRIO database with national statistics in SRIIO format. The accounts for the RoW are derived by aggregating the MRIO database into a supplementary SRIIO database, which enables the determination of indirect GHG emissions and raw materials embodied in imports of the country studied.

Despite the growing popularity of the global Multi-Region Input-Output (MRIO) approach, facilitated by advancements in detailed MRIO databases (Stadler et al., 2018; Lenzen et al., 2013; Timmer et al., 2016; Aguiar et al., 2019; Remond-Tiedrez & Rueda-Cantuche, 2019; Lenzen et al., 2022) and new software tools such as `pymrio` python package (Stadler, 2021), we opted not to use it directly. While MRIO models offer comprehensive assessments of global supply chains, featuring high sectoral and country detail within a standardized environmental accounting framework (Suh, 2009; Miller & Blair, 2009; Leontief, 1986), their emphasis on global consistency and balance of flows often leads to discrepancies with national statistics, such as issues with re-exports (Edens et al., 2015). These discrepancies can introduce biases that undermine the credibility of national-level analyses for local experts and stakeholders. Our SNAC approach effectively addresses this challenge by integrating MRIO with specific national data.

Furthermore, our framework allows for distinct manipulation of each SRIIO table, France versus Rest of the RoW, with specific features tailored for each. This includes more detailed hybridization of economic and physical data for national accounts compared to the RoW tables (see the section below titled “Model calibration”), and more nuanced national scenario projections compared to global scenarios (see the section below titled “Implementation of policy scenarios”). Additionally, we adopt a unilateral trade representation, assuming the marginal impact of domestic exports on foreign supply chains, especially pertinent for small open economies. For instance, French exports utilized by trade partners to produce imports for France represent less than 1% of the total foreign production required to source French imports, including intermediate consumption and capital formation (own calculations based on Exiobase database and `pymrio` calculation tools). This assumption, although generally valid for smaller economies, may not be applicable to larger ones.

Endogenization of capital formation in environmental footprints

Endogenizing capital in environmental footprints is based on the premise that the use of capital, such as buildings, energy supply infrastructures, machinery, and transport equipment, in producing goods and services should be included in footprint calculations. For GHG emissions, this specifically involves accounting for scope 3 GHG emissions, which encompass emissions from the use and the production of capital goods (E. G. Hertwich & Wood, 2018). Following the service-stock-flow thinking in Industrial Ecology (Pauliuk et al., 2017), this approach includes environmental pressures linked to both the formation of capital and the use of capital. For instance, the housing services category includes for direct and indirect GHG emissions related to both building heating and the production of construction materials. Similarly, the personal mobility category includes direct and indirect GHG emissions associated with the combustion of motor fuels as well

as emissions associated with the entire supply chains of transport equipment and infrastructure.

More concretely, endogenization of capital formation in IO analyses means that, transactions related to capital formation and consumption are treated akin to intermediate consumptions to fully capture the lifecycle impacts of final goods and services (E. G. Hertwich, 2021; Lenzen & Graham, 2004; Södersten et al., 2018; Ye et al., 2021). There are two primary national account measures for endogenizing capital in environmental footprint assessments:

- Gross Fixed Capital Formation (GFCF) represents the net annual acquisitions less disposals of fixed assets. It is a component of final demand. It measures long-term investment flows aimed at maintaining or enhancing production capacities.
- Consumption of Fixed Capital (CFC), part of value added, accounts for the depreciation of fixed capital over an accounting period, reflecting the expected decrease in the current value of fixed assets.

Both metrics are used to endogenized capital for environmental footprints (E. G. Hertwich, 2021; Lenzen & Graham, 2004; Södersten et al., 2018; Ye et al., 2021). Here, we employ the GFCF static approach (Lenzen & Graham, 2004) which accounts for GHG emissions from capital formation during the first year of operation. This approach maintains constant total annual emissions, aligning with official statistics based on the conventional consumption-based approach. It is particularly useful for forward-looking analysis, where sectoral expertise typically estimates investment needs rather than the depreciation of existing capital.

Recent studies advocate for using CFC as a better proxy to account for GHG emissions from capital use over the lifetime of the assets (Södersten et al., 2018). This method is advantageous in contexts with fluctuating investment dynamics, such as periods of rapid economic growth or crises, as it allocates emissions from capital formation more consistently over time. In our modeling, where we assume a steady growth path in future scenarios, both GFCF and CFC approaches yield equivalent results, allowing us to smoothly integrate capital formation into our environmental footprint analysis. Assuming a smooth steady growth path in future scenarios, the capital flow matrix also enables to endogenize investments demand (i.e. GFCF) in the same way as intermediate consumptions.

Model calibration

For the calibration of our bi-regional unilateral Hybrid Input-Output (HIO) framework, we constructed two Single Region Input-Output data systems: one for France and another for the Rest of the World (RoW). Both systems are based on the Environmental Extended IO (EEIO) database, Exiobase v3.8.2 (Stadler et al., 2018, 2021), which is recognized for its comprehensive detailing of material and energy fluxes (Fontaine, Teixeira, Vicard, et al., 2023; Teixeira et al., 2020), and has supported the development of the capital endogenization approach in previous studies (E. G. Hertwich, 2021; Södersten et al., 2018; Ye et al., 2021). We utilized the non-public version of Exiobase, which includes a

detailed calibration of energy and GHG balances by energy sources. This enhancement facilitates the integration of expert energy scenarios into the model.

The RoW system is directly taken from the MRIO database while the French system is calibrated by reconciling data from Exiobase with national statistics, such as for energy balance (European Commission & Eurostat, 2019) (e.g. considering re-exports of natural gas), raw materials (European Commission & Eurostat, 2018), and processed materials (ADEME et al., 2021), including the disaggregation between primary and secondary materials (Donati et al., 2020). Employing a multi-layer approach (Merciai, 2019), energy fluxes are expressed in k.tep, GHG emissions in MtCO₂eq, raw and processed materials in k.tons, while other fluxes are considered in M.€. The resulting mixed unit IO framework facilitates the implementation of economy-wide exogenous scenarios, regarding sectoral expertise expressed in physical units. The framework also accounts for the six main GHGs (CO₂, NH₄, NO₂, SF₆, HFC and PFC) associated with fossil fuel combustion, industrial processes, waste treatment, and emissions from land-use change and agriculture. Additionally, the KLEMS database (Stehrer, 2021) is utilized to build capital flow matrices for France and RoW regions, and to disaggregate Gross Fixed Capital Formation (GFCF) into a square matrix format (Södersten et al., 2018).

The database calibrated for the year 2015 is in the process of being made available in open source (Teixeira & Fontaine, forthcoming), apart from the non-public data previously mentioned.

Implementation of policy scenarios

Our model adopts an advanced and innovative method for integrating national low-carbon transition scenarios into the IO framework, in line with existing global approaches (De Koning et al., 2016; Wiebe et al., 2018). This integration is achieved by reconciling various scales and types of expertise, from bottom-up analyses (such as energy model outcomes) to top-down projections (like macroeconomic outlooks), ensuring a comprehensive meso-level analysis. This method enables the production of consistent, detailed, and forward-looking assessments that align energy, material, and economic data within an IO framework. Furthermore, our parametrization interface allows for the detailed specification of drivers along supply chains, including the material, energy, carbon, and capital content of both domestic production and imports. It also accounts for the evolution of final demand and trade changes.

The parametrization of each scenario is based on existing bottom-up and macroeconomic outlooks from French governmental scenarios (ADEME, 2021; Ministère de la Transition Écologique, 2020), covering key emitting sectors such as transport, buildings (residential and commercial), industry, agriculture and forestry, energy supply, and waste management. The scenario framework includes: (i) macroeconomic drivers from macroeconomic models such as ThreeME (Callonnec et al., 2013) or Imaclim-S France (Le Treut, 2020; Le Treut et al., 2019); (ii) detailed descriptions of energy production and consumption structures across economic sectors from the MedPro energy model developed by Enerdata (Lapillonne & Chateau, 1981); (iii) investment

timelines for low-carbon infrastructures and equipment based on bottom-up data (Ledez & Hainaut, 2022); (iv) assumptions about materials efficiency and sufficiency in each sector of the economy (Donati et al., 2020; Wiebe et al., 2019); (v) projections about the global behavior under various global mitigation scenarios from the World Energy Outlook (IEA, 2022), such as the Stated Policies Scenario (STEPS). IEA scenarios are publicly available only at the global level, restricting the use of a bi-regional approach in our analysis.

Flexible software architecture

The software architecture of the MatMat model, developed in Python using object-oriented programming, adheres to key modeling principles (E. Hertwich et al., 2018; Pauliuk et al., 2015) essential for robust and flexible application. These principles ensure:

- Transparency and reproducibility: The model's operations and results are fully documentable and reproducible, ensuring that case studies can be transparently reviewed and verified by other researchers and stakeholders.
- Replicability: Its design facilitates replication for similar case studies, not only within France but also in other international contexts. This feature is crucial for comparative analyses and scaling the model's applications across different geographic and economic settings.
- Extensibility: The architecture is designed to be modular, making it easier to accommodate the integration of new functionalities. This adaptability ensures that the model can evolve in response to emerging research findings and policy needs, supporting continuous improvement and updates.

Moreover, the model is in the process of being made open source and will be available on the Zenodo platform (Teixeira & Grand, forthcoming). This move will further enhance its accessibility and utility, allowing a broader community of researchers and policymakers to contribute to and benefit from the ongoing development of the model.

Mathematical background

The core Input-Output system

A standard IO model is composed of extensive quantities representing economic fluxes of n goods and services between institutional agents: (i) an interindustry matrix Z , (ii) a final demand matrix Y composed of m columns including the final consumption of households and public administrations, GFCF and exports, (iii) a supply vector x . It includes a market balance between each good and service as:

$$x = Z \cdot \mathbf{1}_n + Y \cdot \mathbf{1}_n \quad (1)$$

where “.” corresponds to the matrix multiplication, and $\mathbf{1}_n$ is a vector of ones enabling to sums over the columns of the preceding matrix. The technical coefficients matrix (or regular requirement matrix) A describes the specific production technologies of each

industry. It is built from the inter-industry matrix Z and the diagonalized ($\hat{\cdot}$ symbol) and inverted supply vector x as:

$$A = Z \cdot \hat{x}^{-1} \quad (2)$$

This matrix enables the calculation of the total requirement matrix (or Leontief matrix), with I_n being the Identity matrix of the size of A , as:

$$L = (I_n - A)^{-1} \quad (3)$$

This matrix is at the core of the Leontief demand-driven model, expressed as:

$$x = L \cdot Y \quad (4)$$

To endogenize capital formation into this standard IO framework (Lenzen & Graham, 2004), we define the capital flow matrix (i.e. GFCF) K and the capital coefficients matrix (or capital requirement matrix) k as:

$$K = k \cdot \hat{x}^{-1} \quad (5)$$

Thus, capital is described as a component of production technologies for each industry, enabling the definition of augmented technical coefficients and interindustry matrices with capital requirements, A^k and Z^k , respectively:

$$A^k = A + k = (Z + k) \cdot \hat{x}^{-1} = Z^k \cdot \hat{x}^{-1} \quad (6)$$

With L^k as the total requirement matrix augmented with capital requirements, and Y^k the final demand matrix excluding GFCF, the standard IO model then translates into:

$$L^k = (I_n - A^k)^{-1} \quad (7)$$

$$x = L^k \cdot Y^k \quad (8)$$

In line with the SRIO framework employed and depicted in Figure 0-1, each variable previously mentioned distinguishes the sourcing origin between domestic supply, noted respectively with indexes **dom** and **imp**. For example, x_{dom} (resp. x_{imp}) corresponds to total production (resp. imports) while Z_{dom} (resp. Z_{imp}) describes intermediate inputs that have been produced domestically (resp. abroad). Table 0-1 describes the variables of the SRIO system.

The calculation of technical coefficients, capital coefficient and the Leontief matrix are based on domestic production as:

$$A_r = Z_r \cdot \hat{x}_{dom}^{-1}, \text{ with } r \text{ in } \{\mathbf{dom}; \mathbf{imp}\} \quad (9)$$

$$k_r = K_r \cdot \hat{x}_{dom}^{-1}, \text{ with } r \text{ in } \{\mathbf{dom}; \mathbf{imp}\} \quad (10)$$

$$L_{dom}^k = (I_n - A_{dom}^k)^{-1} \quad (11)$$

The core of the Leontief demand-driven model expresses as:

$$x_{dom} = L_{dom}^k \cdot Y_{dom}^k \quad (12)$$

The rest of the system is governed by the market balance equation as:

$$x_r = Z_r^k \cdot \mathbf{1}_n + Y_r^k \cdot \mathbf{1}_n \text{ with } r \text{ in } \{\mathbf{dom}; \mathbf{imp}\}. \quad (13)$$

Note that equations (11) to (13) are applicable both with and without the use of the k exponent, depending on whether the analysis incorporates capital endogenization in the system. This flexibility allows for adjustments based on specific analytical needs or preferences.

		Intermediate demand Activities	Final Demand Vectors	Supply
Srio System	Goods and services Produced domestically	Z_{dom}^k	Y_{dom}^k	X_{dom}
	Produced abroad	Z_{imp}^k	Y_{imp}^k	X_{imp}
Extensions	By input	Direct	F_Y^k	
		Indirect		
	By output	Direct	$F_{X_{dom}^k}$	
		Indirect	$F_{X_{imp}^k}$	

Figure 0-1: Structure of Single Region Input-Output (SRIO) database including capital endogenization.

Variable name	Description	Dimensions
n	Number of goods and services, or activities. For the calibration data described above, $n = 200$ based on the sectoral detail of Exiobase.	$(1, 1)$
m	Number of final demand vectors. For the calibration data described above, $m = 6$, including (i) final consumption of households distinguishing the demand of goods and services for housing services and personal mobility from other final consumption, (ii) final consumption of public institutions, (iii) GFCF, and (iv) Exports.	$(1, 1)$
x	Supply vector including domestic production x_{dom} and imports x_{imp} .	$(2n, 1)$
Y	Final demand matrix distinguishing between domestically produced Y_{dom} and imported Y_{imp} uses.	$(2n, m)$
Y^k	Final demand matrix excluding GFCF, distinguishing between domestically produced Y_{dom} and imported Y_{imp} uses.	$(2n, m - 1)$
Z	Interindustry matrix distinguishing between domestically produced Z_{dom} and imported Z_{imp} uses.	$(2n, n)$
K	Capital flow (or GFCF) matrix distinguishing between domestically produced K_{dom} and imported K_{imp} uses.	$(2n, n)$
Z^k	Interindustry matrix augmented with capital flow, distinguishing between domestically produced Z_{dom}^k and imported Z_{imp}^k uses.	$(2n, n)$
A	Technical coefficients (or regular requirement) matrix distinguishing between domestically produced A_{dom} and imported A_{imp} unitary uses.	$(2n, n)$
k	Capital coefficients (or capital requirement) matrix distinguishing between domestically produced k_{dom} and imported k_{imp} unitary uses.	$(2n, n)$
A^k	Technical coefficients matrix augmented with capital requirements, distinguishing between domestically produced A_{dom}^k and imported A_{imp}^k unitary uses.	$(2n, n)$
L	Total requirement matrix (or Leontief matrix) distinguishing between domestically produced L_{dom} and imported L_{imp} unitary uses.	$(2n, n)$
L^k	Total requirement matrix (or Leontief matrix) augmented with capital requirements, distinguishing between domestically produced L_{dom}^k and imported L_{imp}^k unitary uses.	$(2n, n)$

Table 0-1: Description of the Single Region Input-Output (SRIO) system variables.

Main framework for environmental assessment

In this section, we focus on calculations that include the endogenization of capital formation. The equations presented below can be adapted to exclude this feature by omitting the exponent k . Table 0-2 summarizes the variables used with and without capital endogenization.

Variable name	Description	Dimensions
l	Number of dimensions included in the environment extensions.	$(1, 1)$
F_x (F_x^k)	Environmental factors of the supply including direct factors of productions $F_{x_{dom}}$ ($F_{x_{dom}}^k$ if augmented with environmental stressors related to capital flow) and indirect factors of imports $F_{x_{imp}}$ ($F_{x_{imp}}^k$ if it includes capital endogenization abroad).	$(2n, l)$
F_Y (F_Y^k)	Direct environmental factors of final demand (excluding GFCF in the case of F_Y^k) including the direct factors associated with uses produced domestically $F_{Y_{dom}}$ ($F_{Y_{dom}}^k$ if excluding GFCF) and the ones imported $F_{Y_{imp}}$ ($F_{Y_{imp}}^k$ if excluding GFCF).	$(2n, m)$ $(2n, m - 1)$
F_Z (F_Z^k)	Direct environmental factors of intermediate demand including the direct factors associated with uses produced domestically $F_{Z_{dom}}$ ($F_{Z_{dom}}^k$ if augmented with environmental stressors related to capital flow) and the ones imported $F_{Z_{imp}}$ ($F_{Z_{imp}}^k$ if augmented with environmental stressors related to capital flow).	$(2n, n)$
S_x (S_x^k)	Environmental factor coefficients of the supply including direct factor coefficients of productions $S_{x_{dom}}$ ($S_{x_{dom}}^k$ if augmented with environmental stressors related to capital flow) and indirect factor coefficients of imports $S_{x_{imp}}$ ($S_{x_{imp}}^k$ if it includes capital endogenization abroad).	$(2n, l)$
S_Y (S_Y^k)	Direct environmental factor coefficients of final demand (excluding GFCF in the case of S_Y^k) including the direct factors associated with uses produced domestically $F_{Y_{dom}}$ ($F_{Y_{dom}}^k$ if excluding GFCF) and the ones imported $F_{Y_{imp}}$ ($F_{Y_{imp}}^k$ if excluding GFCF).	$(2n, m)$ $(2n, m - 1)$
S_Z (S_Z^k)	Direct environmental factor coefficients of intermediate demand including the direct factors associated with uses produced domestically $F_{Z_{dom}}$ ($F_{Z_{dom}}^k$ if augmented with environmental stressors related to capital flow) and the ones imported $F_{Z_{imp}}$ ($F_{Z_{imp}}^k$ if augmented with environmental stressors related to capital flow).	$(2n, n)$
M (M^k)	Environmental multipliers (including capital endogenization in the case of M^k) distinguishing between domestic requirements factors M_{dom} (M_{dom}^k) and imported requirements factors M_{imp} (M_{imp}^k).	$(2n, l)$
D_{cba} (D_{cba}^k)	Consumption-based accounts (including capital endogenization in the case of D_{cba}^k) accounting for domestic D_{dom} (D_{dom}^k) and imported D_{imp} (D_{imp}^k) environmental stressors embodied in final demand.	$(2l, m, n)$ $(2l, (m - 1), n)$

Table 0-2: Description of the Single Region Input-Output (SRIO) extensions variables.

Our model categorizes domestic environmental stressors into two types:

- Output-based extensions are defined by the direct domestic factors of productions, augmented with environmental stressors related to capital flow $F_{x_{dom}}^k$. This approach

is suitable for extensions like GHG emissions related to industrial processes, land use, and waste, directly linked to the overall production process.

- Input-based extensions are defined by assigning in addition direct domestic factors to each to each intermediate and final demand, F_{Z^k} and F_{Y^k} , respectively. This approach is useful for environmental stressors such as GHG emissions from the combustion of fossil fuels, where an emissions factor can be assigned to each intermediate and final use, following a multi-layer IO framework (Merciai, 2019).

Additionally, the model includes indirect imported environmental factors $F_{x_{imp}}^k$, which represent the indirect environmental impacts embodied in imports, including capital endogenization abroad. These impacts are estimated using either SRIO or a MRIO model, representative of the Rest of the World (RoW) following a simplified SNAC approach.

For each factor previously introduced, we define environmental factor coefficients that normalize the factors relative to their corresponding system variable. Output-based factor coefficients account for environmental stressors per unit of supply, as:

$$S_x^k = F_x^k * x^{-1} \quad (14)$$

where “*” corresponds to the element-wise product. Input-based factor coefficients account for environmental stressors by unit of intermediate and final consumption as:

$$S_v = F_v * v^{-1} \text{ for } v \text{ in } \{Y^k, Z^k\} \quad (15)$$

Using input-based factors leads to the endogenization of direct domestic factors and coefficients of production, which are dependent on the SRIO system. For instance, direct domestic factors that account for the overall direct GHG emissions from the combustion involved in production are calculated as follows:

$$F_{x_{dom}}^k = (F_Z^k)^T \cdot \mathbf{1}_{2n} = S_{x_{dom}}^k * x_{dom} \quad (16)$$

The model employs environmental multipliers, namely total domestic and imported requirements factors M_{dom}^k and M_{imp}^k , to quantify total direct and indirect environmental stressors per unit of final demand from a life cycle perspective:

$$M_{dom}^k = S_{x_{dom}}^k \cdot L_{dom}^k \quad (17)$$

$$M_{imp}^k = S_{x_{imp}}^k \cdot A_{imp}^k \cdot L_{dom}^k \quad (18)$$

Applying both multipliers to the diagonalizing final demand (\widehat{Y} symbol), it enables to build the consumption-based accounts D_{cba}^k accounting for domestic and imported environmental stressors embodied in final demand following a life cycle perspective, D_{dom}^k and D_{imp}^k , respectively, as:

$$D_{dom}^k = M_{dom}^k \cdot \widehat{Y}_{dom}^k (+ \widehat{F}_{Y_{dom}^k} + \widehat{F}_{Y_{imp}^k}) \quad (19)$$

$$D_{imp}^k = M_{imp}^k \cdot \widehat{Y_{dom}^{/k}} + S_{x_{imp}}^k \cdot \widehat{Y_{imp}^{/k}} \quad (20)$$

Drivers and shocks for scenario analysis

The equations described above are verified for a given SRIO system and its extensions, calibrated to depict current economies (noted with the exponent "0"). They also apply to potential future economies (noted without an exponent), which are obtained by introducing exogenous shocks to the calibrated system and its extensions. As previously, we focus on calculations that include the endogenization of capital formation. The equations presented below can be adapted to exclude this feature by omitting the exponent k . Table 0-3 summarizes the shock variables used to build future economy.

Variable name	Description	Dimensions
$\delta_{x_{imp}/x_{dom}}$	Growth rates of average import/production ratio.	$(n, 1)$
$\delta_{Y^{/k}}$	Growth rates of final demand excluding GFCF.	$(n, m - 1)$
δ_A	Growth rates of technical coefficients.	(n, n)
δ_K	Growth rates of the capital flow matrix. This shock variable is applicable in the case of exogenous investment demand and cannot be applied simultaneously with the shock variable δ_k .	(n, n)
δ_k	Growth rates of the capital coefficients matrix. This shock variable is applicable in the case of endogenous investment demand and cannot be applied simultaneously with the shock variable δ_K .	(n, n)
$\delta_{S_x^k}$	Growth rates of the environmental factor coefficients for the supply, including those for domestic factor coefficients $\delta_{S_{x_{dom}}^k}$ and for imported factor coefficients $\delta_{S_{x_{imp}}^k}$.	$(2n, l)$

Table 0-3: Description of shock variables of the Single Region Input-Output (SRIO) system and extensions.

Shocks are applicable to (i) the final demand excluding GFCF ($Y^{/k}$), (ii) the technical coefficients (A), (iii) the capital flow matrix (K) or the capital coefficients matrix (k) depending on if we desire to have exogenous or endogenous capital demand, (iv) the average import rate for each good and service x_{imp}/x_{dom} , (v) and the environmental factor coefficients of the supply (S_x^k) for each extension. For each variable in the system, shock variables δ_v for v in $\{Y^{/k}, A, K, k\}$ introduce relative variations to the total quantities of the associated variables, i.e., independently of the supply origin, and the imported versus domestic share for each use evolves according to the corresponding growth rate shock $\delta_{x_{imp}/x_{dom}}$. Thus, for v in $\{Y^{/k}, A, K, k\}$, we have:

$$(v_{dom} + v_{imp}) = (v_{dom}^0 + v_{imp}^0) * (1 + \delta_v) \quad (21)$$

$$v_{dom} = \frac{v_{dom} + v_{imp}}{1 + (v_{imp}^0/v_{dom}^0) * (1 + \delta_{x_{imp}/x_{dom}})} \quad (22)$$

Furthermore, the model enables to shocks the environmental factor coefficients of the supply (S_x^k) for each extension as:

$$v = v^0 \cdot (1 + \delta_v), \text{ with } v = S_x^k \quad (23)$$

Applying, the Leontief equation, the market equilibrium, and the calculation of the environmental extensions previously defined, we find back a projected SRIO system and its environmental extensions.

Conclusion

Current developments and applications

The development and application of the MatMat Hybrid Input-Output (HIO) model represent significant advancements in environmental and economic modeling. By offering a comprehensive framework that assesses both current and future carbon and materials footprints at the national level, this model fills critical gaps in the sustainability assessment of future national low-carbon scenarios. It incorporates technical changes, investment needs evolution, and key macroeconomic drivers to provide a nuanced view of direct and indirect environmental impacts, thereby enhancing the analysis of national low-carbon strategies.

Applied to France, the MatMat model provides crucial insights that can guide policy decisions towards achieving Net-Zero Emissions (NZE) while considering broader environmental impacts. Utilized to analyze the latest French governmental NZE strategies released in 2018 (Ministère de la Transition Écologique, 2020), the model identifies critical shortcomings, such as the current strategy's inability to effectively address the Carbon Footprint of Materials production (CFM). Including both direct and indirect GHG emissions associated with material needs, it accounts for a substantial portion of the French carbon footprint (Teixeira & Lefèvre, 2023). Moreover, the model's analysis of the contrasted NZE scenarios designed by ADEME (ADEME, 2021) demonstrates that scenarios promoting sufficiency are more effective than technological solutions in reducing France's material and carbon footprints by mid-century (Vicard & Teixeira, 2024). A recent study applied on these scenarios has also isolated the individual impacts of each measure related to sufficiency and efficiency (Fontaine, Teixeira, Lefevre, et al., 2023).

The model is now instrumental in the ongoing revision of the French NZE strategies. Employing an iterative scenario-building process, informed by the insights from these analyses, the goal is to establish precise carbon footprint reduction targets for 2050.

Next steps

To further enhance the MatMat model's capabilities and broaden its application spectrum, several developments are planned:

- Finalizing the structuring of the MatMat model's architecture to enhance its flexibility, ensuring it is open-source, transparent, and extensible. This step is crucial for enabling broader adoption and adaptation by the research community and stakeholders, fostering collaboration and continuous improvement of the model.
- Extending and consolidating the calibration data within the MatMat model to improve the socio-economic and environmental evaluation of low-carbon and circular transition scenarios. This includes:
 - o Expanding coverage to include water, land use, and waste environmental extensions.
 - o Integrating socio-economic extensions such as employment, value added, basic and purchase prices, margins, taxes, etc. in a multi-layer approach.
 - o Disaggregating further key sectors to facilitate the integration of external expertise. This includes a detailed representation of key circular economy sectors like repair and remanufacturing or disaggregating the construction sector by type of work and trades.
- Improving the SNAC approach by coupling MRIO-SRIO more effectively rather than relying on a simplified bi-regional unilateral model. This adjustment will allow for more precise and locally nuanced assessments.
- Connecting the MatMat model with a Computational General Equilibrium (CGE) model to simulate the impacts of public policy economic instruments that promote the circular economy (taxes, subsidies, etc.).
- Breaking down environmental footprints by socio-economic characteristics of households and scaling the analysis to the sub-national level to address local low-carbon transition challenges.

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