Integrated Assessment Models and Input-Output Analysis: bridging fields for advancing sustainability scenarios research

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Abstract

Technology-rich Integrated assessment models (IAMs) and Environmentally-Extended Input-Output Analysis (EEIOA) are widely employed for sustainability analysis, each offering unique strengths. IAMs focus on forward-looking scenarios, exploring technological shifts and climate change mitigation costs. EEIOA provides more comprehensive but static assessments of environmental and socio-economic impacts throughout supply chains, adopting a lifecycle perspective. I conduct a literature review to assess the current state of IAM-IO integration, paving the way for future research opportunities with advanced models. Existing studies have loosely linked IAM and IO models to improve one field or the other. This perspective highlights the potential for more advanced IAM-IO model linking and identifies three domains within sustainability scenarios research where IAM-IO integration could play a crucial role : the energy-industry nexus in decarbonization pathways, multi-dimensional sustainability impact assessment and demand-side solutions and post-growth climate mitigation scenarios. The expected research insights may be pivotal to design effective sustainable policies.

Keywords : Integrated Assessment Models ; Input-Output Analysis ; model linking ; sustainability ; climate mitigation scenarios

1. Introduction

Urgent global sustainability issues, such as climate change and the Sustainable Development Goals (SDGs), require immediate attention and viable solutions. Technology-rich Integrated Assessment Models (IAMs) serve as central tools for exploring available options and understanding the consequences of various strategies to mitigate climate change and address other policy goals (Keppo et al., 2021). IAMs simulate interactions within and between critical systems in future scenarios, including energy, economic, and land use systems. These models rely on narratives about future technological and socio-economic trends, such as the Shared Socio-economic Pathways (SSPs) (Riahi et al., 2017) and quantify transformation pathways and cost-effective technological developments to achieve climate targets. A strong research community has built around IAMs, with formal organization (e.g. with the IAM Consortium - https://www.iamconsortium.org/) and fostering collaborative efforts through Model Intercomparison Projects and collective work across various international projects (e.g. EU ADVANCE and NAVIGATE projects). The IAM community also plays a key role in the assessments conducted by the Intergovernmental Panel on Climate Change (IPCC). The usefulness of IAM analysis is widely recognized in both scientific and policy arenas, as it has greatly influenced the framing of mitigation issues and the formulation of solutions to address climate change and broader sustainable development issues.

The field of Input-Output Analysis (IOA) predates that of IAMs and is more comprehensive in its approach. IOA was pioneered by Leontief (Leontief, 1937), who introduced a multi-sectoral perspective to macroeconomics, effectively capturing inter-industry linkages. IOA focuses on assessing impacts across entire supply chains, considering the perspective of consumption. Environmentally-Extended Input-Output Analysis (EEIOA) (Miller and Blair, 2009), (Ewing et al., 2012; Kitzes, 2013) expands the application of IOA to the environmental and material aspects of supply chains, facilitating the assessment of various environmental issues like climate change, water scarcity, and natural resource depletion. EEIOA has become a crucial tool in Industrial Ecology (IE) research, which aims to analyze the intricate biophysical linkages within society (Pauliuk et al., 2017). More recently, the development of global Multi-Regional Input-Output (MRIO) databases with comprehensive environmental and social accounts (Stadler et al., 2018)(Lenzen et al., 2013)(Timmer et al., 2012), has supported extensive analysis of the environmental and socio-economic footprints of nations (Hertwich and Peters, 2009) (Simas et al., 2015) (Tukker et al., 2016) (Giljum et al., 2016) (Wiedmann and Lenzen, 2018).

These studies have brought attention to the unsustainability of present economies (from both environmental and social viewpoints) (Fanning et al., 2022) (Wiedmann et al., 2020) (Hickel et al., 2022), revealing the profound impact of current consumption and production patterns on the planet and society at large.

IAMs and IOA offer complementary strengths for sustainability analysis. While IAMs provide a forward-looking perspective on transformative technological change, they lack coherence in describing the lifecycle impacts of technologies and usually fail to consider supply chains beyond the energy system (Pauliuk et al., 2017). Conversely, EEIOA comprehensively captures the environmental and economic dimensions of global supply chains, but falls short in providing only static assessments, ignores technical change and lacks technology detail. Apart from a few IAMs that originate from macroeconomic modeling and incorporate an IO economic accounting, IAM and IO fields have mostly developed independently. Nevertheless, recent endeavors to integrate IAM and IO methods hold great promise for future research. In this perspective paper, I conduct a literature review to assess the current state of IAM-IO integration and provide an outlook on the future research opportunities with advanced IAM-IO models. I find that most existing studies rely on loose model linking to improve assessment of one field based on the other. Then I identify opportunities for more advanced IAM-IO model linking and three domains within sustainability scenarios research where IAM-IO integration could play a pivotal role : the energy-industry nexus in decarbonization pathways, multi-dimensional sustainability impact assessment and demand-side solutions and post-growth climate mitigation scenarios.

2. Two complementary fields for sustainability analysis

IAM refers to a variety of models with alternative scope, granularity, and intended purposes (Krey et al., 2019). Process-based IAMs delve into technology and process dynamics and can be distinguished from cost-benefit IAMs that consolidate these processes into simplified relationships between abatement costs and climate change damage (Weyant, 2017). This paper focuses on process-based technology-rich IAMs – hereafter IAMs. IAMs cover the main sources of GHG emissions and model integrated energy, land-use and economic systems with a focus on technology and process dynamics to achieve climate and other policy goals. In doing so IAMs highlight feedbacks and trade-offs between choices about the energy system, economy and the environment. Although having been criticized along different lines, IAM have demonstrated valuable in exploring key topics such as technology dynamics, investment needs

for decarbonization, energy-economy feedbacks and policy scenarios (Keppo et al., 2021). Energy System Modelling (ESM) is the core of most IAMs (Wilson et al., 2021) and in this case the energy system is linked to the broader economy through different ways : partial equilibrium (PE) IAMs include GDP as a main exogenous driver for energy demand but disregard the feedbacks of the energy system on the economy, contrary to general equilibrium (GE) IAMs. IAMs also vary in the way the model is solved over the time horizon : some models optimize intertemporal welfare or minimize costs with perfect knowledge of future conditions whereas others adopt a recursive dynamic approach based on myopic expectations.

In addition, typical IAMs based on ESMs reflect a 'linear' representation of energy flows and energy-economy relationships (see Fig. 1). GDP drives demand for energy services (in industry, transport and buildings sectors), which drive demand for final energy through end-use technologies (industrial processes, transport vehicles, heating systems, etc.). Final energy is supplied by the energy system after conversion of primary sources (fossil fuels, renewable sources, biomass, etc.) into final carriers (electricity, final solid, liquid and gas fuels) based on different technologies (e.g. gas-fired, solar or wind power). GE-IAMs also include aggregated feedbacks between the energy system and the overall economy : energy system costs must be covered by GDP and energy services are input to macroeconomic production.

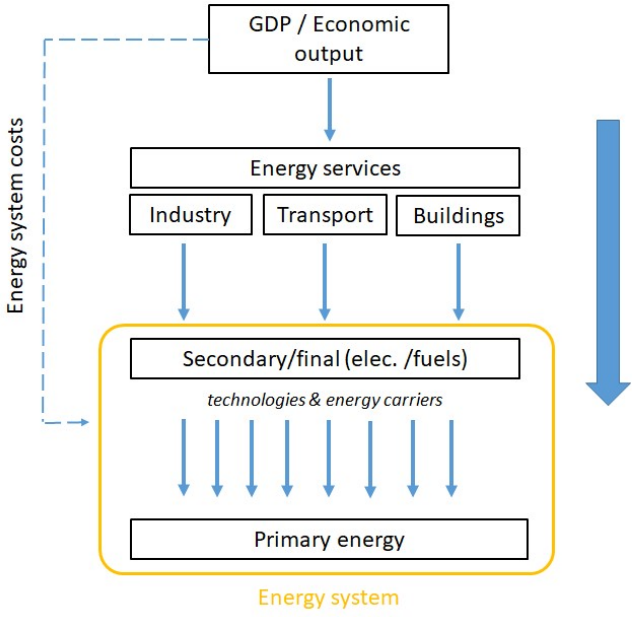

Figure 1 : Linear representation of energy – economic systems in typical IAMs (based on ESMs)

In the context of sustainability analysis, IAMs have been criticized for their weak coverage of the linkages within and between biophysical and economic systems. (Pauliuk et al., 2017)

highlight the main limitations of IAMs from an industrial ecology perspective. First, IAMs incoherently describe the lifecycle impacts of technologies, i.e. the environmental and economic impacts of technologies across their entire lifespan, from their creation and use to their disposal (extraction of resources, manufacturing and production, use phase, end-of-life, etc.). In particular, the linear linkages between energy supply, energy demand and economic production can not properly describe the indirect environmental and economic impacts of energy conversion and end-use assets, especially related to the build-up of these assets (e.g. emissions linked to producing the materials for given asset). At best, in GE-IAMs, the macroeconomic feedback of energy system costs on economic output allows capturing the global supply chains of total capital investment in the energy system in a highly aggregated form (one single macroeconomic production). Second, standard IAMs focus on energy flows and ignore other physical balances (e.g. material cycles). Likewise, IAMs capture the direct GHG impacts of processes but generally ignore broader environmental impacts across supply chains. Eventually, the aggregate production perspective of the economy does not allow for consumption-based analysis of upstream and downstream industrial impacts and exploration of inter-sectoral linkages.

These weaknesses of IAMs are basically the strengths of EEIO analysis. IO and supply-and-use tables (SUTs) capture the detailed interlinkages between economic sectors (intermediary consumption) and final demand (Miller and Blair, 2009). As illustrated in Fig. 2, IO analysis is based on an interlinked representation of economic flows including those associated to the energy system as part of the broader economy, as opposed to the linear IAM approach centered on the energy system. The IO framework enables to estimate direct and indirect economy-wide impacts across supply chains from a consumption-based viewpoint. Environmentally-Extended Input-Output tables include satellite accounts of physical flows (e.g. materials) and environmental stressors attached to main production matrix – describing resource requirement or environmental impacts per unit of output for individual sectors - for environmental analysis across supply chains (e.g. consumption-based assessments of various environmental impacts such as climate change, land use and biodiversity). IO linkages can also be downscaled to technology levels and hybridized with lifecyle inventories (LCI) through so-called hybrid LCA (lifecycle assessment)-IO approach (Suh et al., 2004). In this case, the detailed bottom-up data from LCIs describing the inputs and outputs in physical units for individual processes and technologies are introduced within a broader top-down IO framework in monetary units (outside environmental extensions). This approach allows capturing the lifecycle impacts of

individual technologies. Multi-Regional IO (MRIO) models represent the bilateral trade linkages between countries and give a complete picture of the global production network and supply chains. MRIO models thus generally offer a higher sectoral and regional resolution than IAMs. There has been growing interests in global value chain environmental and socio-economic footprint analysis supported by the recent development of global Environmentally-Extended MRIO database (GTAP (Aguiar et al., 2019), EXIOBASE (Stadler et al., 2018), EORA (Lenzen et al., 2013), WIOD (Timmer et al., 2012), etc.). A range of studies has provided key insights on the environmental footprints of nations including carbon footprints (Hertwich and Peters, 2009) (Wiebe et al., 2012), material and other resource footprints (Wiebe et al., 2012) (Tukker et al., 2016) (Wiedmann et al., 2015) (Giljum et al., 2016) and broader environmental and socio-economic footprints (Simas et al., 2015) (Ivanova et al., 2016) (Malik et al., 2019) (Wiedmann and Lenzen, 2018). It has paved the way for enhanced sustainability assessments, offering complementary perspectives on, for instance, the industrial ecology of linked material and carbon footprints (Hertwich, 2021) (Rasul and Hertwich, 2023) (Lenzen et al., 2022), the quantification of ecological thresholds and overshoot of nations (Hickel et al., 2022) (Fanning et al., 2022), global carbon inequality both between and within countries (Chancel, 2022) (Zheng et al., 2023) and progress towards the SDGs (Gómez-Paredes and Malik, 2018).

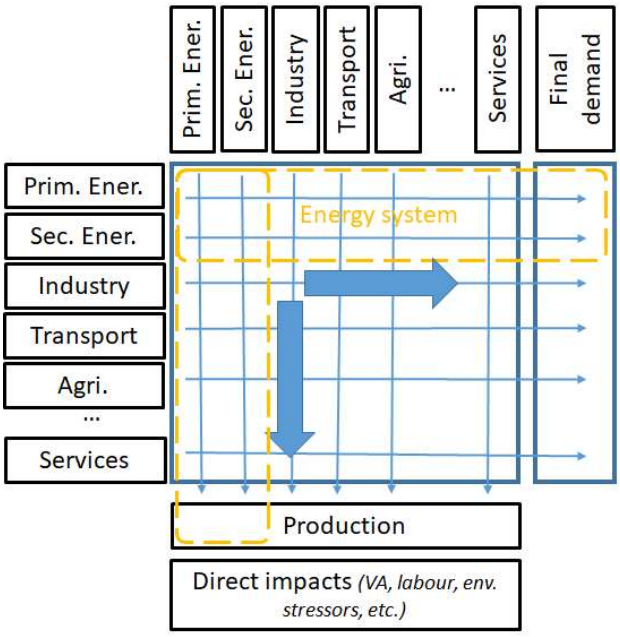

Figure 2 : Interdependence of economic sectors in IOA

Despite the richness of EE-MRIO methods and their potential for robust multi-dimensional sustainability analysis, the standard EEIO approach has intrinsic limitations. While it proves useful for disentangling key relationships in retrospective assessments based on past data, it falls short in exploring the implications of forward-looking scenarios. One of the primary reasons for this limitation is the static nature of the IO framework. It focuses on assessing consumption-based impacts of past trends or future exogenous changes in final demand while assuming fixed technical coefficients for intermediary consumption and environmental stressors, as well as fixed trade coefficients. Consequently, it does not account for technical improvements, input substitutions, and changes in trade relationships that are likely to occur in future scenarios. Furthermore, the EEIO approach does not capture intertemporal effects such as linked to capital formation and in-use stocks. While recent IO models endogenize capital (Södersten et al., 2018), they rely on data for a specific year and do not account for the technical changes occuring between the year of capital formation and the subsequent periods of capital utilization. This has implications for footprint estimates, particularly concerning long-lived assets. Additionally, it overlooks economic behaviors and price-induced mechanisms on both the supply and demand sides of the economy. As a result, the standard IO approach is inherently limited in its ability to explore transformation pathways and future scenarios. Furthermore, being a top-down approach based on macro accounting data, it tends to lack granularity in technological details.

Table 1 summarizes the main comparative advantages of IAM and EEIOA highlighting their complementary strengths for sustainability analysis.

	IAM	EEIOA
Comparative advantages	• System dynamics • Forward-looking scenarios • Technical change • Dynamic economic behaviours • High technology detail • Price effects	• System interdependence • Lifecycle impacts of technology • Multiple environmental impacts across supply chains • Consumption-based analysis • Intersectoral economic linkages

Table 1 : comparative advantages of IAM and EEIOA for sustainability analysis

3. Current state of IAM-IO integration

IAM and IO methods have been recently combined to address novel challenges in forward-looking scenarios. To evaluate the current state of integration between IAM and IO, I conducted a literature review within this emerging field. The review followed a staged approach. Initially, I conducted a search on Google Scholar using relevant keywords[1] and screened abstracts to select an initial set of papers. Additionally, I identified supplementary relevant papers by scrutinizing the reference lists of these initial papers. At the abstract screening stage, the inclusion criterion was that the paper should introduce a linking of methods within the domains of IAM (inclusive of energy system modeling and energy transition scenarios) and IOA (including EE-IO, MRIO, and hybrid LCA-IO[2]). Subsequently, during the in-depth reading stage, I focused on assessing the nature of the linking approaches employed (distinguishing between soft and hard linking and directionality) and the research questions studied. Based on these evaluations, I categorized and summarized the principal approaches employed for integrating IAM and IO methods, as presented in Table 2.

[1] Including *integrated assessment model, energy model, scenarios, input-output, lifecycle assessment*

[2] For constructing the core literature review which is focused on IO, I have only retained hybrid LCA-IO studies that include an explicit IO component. However, I have also considered some other papers more focused on LCA approaches to put IO approaches in perspective and to highlight the specific strengths of LCA methods compared to IO.

Link. type		Linking method	Objective of study	References
Soft-linking	From IAM/ESM to IO	Exogenous scenarios for energy technology development in hybrid LCA-IO model	Scenario-based LCA-IO assessment: life cycle environmental impacts (carbon, environmental pressures, materials, etc.) of energy technology development - individual technology and system-wide impacts	(Arvesen and Hertwich, 2011) (Wolfram et al., 2016) (Hertwich et al., 2015) (Gibon et al., 2017)
		Exogenous economy-wide climate and energy transition scenarios in MRIO/IO model	Consumption-based environmental impact assessment across global supply chains (including trade) of forward-looking transition scenarios (supply and demand-side transformations)	(Wiebe et al., 2018) (De Koning et al., 2016) (Teixeira and Lefevre, 2023) Demand-side : (Vita et al., 2019) (Moran et al., 2020) (Wood et al., 2018)
		PE ESM outputs as exogenous shocks to IO/MRIO model	Environmental (emissions) and socioeconomic (income, VA, output, jobs, etc.) impact assessment across economic sectors of energy system transition scenarios	(Siala et al., 2019) (Ju et al., 2022) (Oei et al., 2020) (Rady et al., 2018)
	From IO to IAM/ESM	Indirect emission factors (IEFs) estimated from hybrid LCA-IO model used in ESM / IAM	Assessment of optimal energy system decarbonization scenarios taking into account indirect lifecycle emissions	(Daly et al., 2015) (McDowall et al., 2018)
Hard-linking		IO-LP integrated model at country level	Assessment of optimal energy system (power) decarbonization scenarios taking into account indirect emissions (intermediate consumption of goods and services, capital goods for energy technologies, etc.)	(He et al., 2017) (Kang et al., 2019)
		IO-based macroeconomic IAMs - linking BU technical modules to CGE or macroeconomic demand-led IO models	Assessment of integrated technical and macroeconomic transformation pathways taking into account supply chain linkages across production and consumption, economic sectors and trade	(Mercure et al., 2018) (Distelkamp and Meyer, 2019) (Sassi et al., 2010)

Table 2 : Summary of the current state of IAM-IO integration

3.1. Soft-linking approaches

3.1.1. IAM to IO linking

The first main approach consists in soft-linking IAM and IO methods in a single direction by using information from one field to improve assessment based on the other. In the first direction, assumptions and results from IAMs and ESMs have been incorporated in IO models to perform different types of scenarios analysis.

A first type of scenario analysis explores the lifecycle environmental impacts of energy technology developments based on the implementation of exogenous energy technology scenarios in a hybrid LCA-IO model. For instance (Arvesen and Hertwich, 2011) and (Wolfram et al., 2016) implement power technology scenarios in two-region LCA-IO models (through exogenous shares of technologies in the IO matrix) to assess environmental impacts of large scale adoption of wind power in Europe for the former and the renewable electricity transition in Australia for the latter. (Hertwich et al., 2015) and (Gibon et al., 2017) develop a global hybrid LCA-MRIO model to assess the multi-dimensional environmental impacts of exogenous scenarios of large scale adoption of low carbon power technologies at global scale. Future technological change is captured with high detail through the hybrid approach combining lifecyle inventories and MRIO data. A vintage stock model is also used to account for the changes in the energy mix for manufacturing the future power plants. Incorporating detailed technical changes for upstream processes (e.g. manufacturing) in addition to that of the technology itself, becomes crucial when the objective is to quantify the lifecyle impacts of a specific technology in the future. This more precise aim is at the heart of prospective lifecycle assessment (pLCA) which involves modifying LCI data based on specific scenarios or IAM projections (van der Giesen et al., 2020). Recent pLCA studies have expanded the scope of LCAs to future passengers vehicles (Knobloch et al., 2020) and heating systems (Cox et al., 2020) and developed advanced methods for adjusting entire clusters of industrial activities, beyond the primary sector of interest, in the pLCI database (Sacchi et al., 2022).

A second type of analysis explores economy-wide climate transition scenarios and assess their implications for future environmental footprints of regions and sectors across global supply chains and trade. For instance (Wiebe et al., 2018) implement exogenous energy-economy scenarios, including technological and structural changes, in a global MRIO model. Exogenous scenarios information cover the level and structure of expenditure from households and capital formation (including investment for energy technologies) on the demand side and the input structure of energy supply and intermediary energy consumption – reflecting technical and technological improvements and substitutions – on the production side. Such a framework allows for exploring the implications of technology and production-oriented versus demand-side consumption-oriented scenarios (De Koning et al., 2016). A growing body of studies have been using this approach to explore the environmental efficacy of consumer-oriented policy measures and sufficiency lifestyles (Vita et al., 2019) (Wood et al., 2018) (Moran et al., 2020) building on the detailed final consumption structure of MRIO databases.

A third type of analysis directly feeds IO models with PE ESM outputs to evaluate the carbon and socio-economic impacts across economic sectors of energy system transition scenarios. In practice, the ESM provides information on the future changes in the energy system which are translated into changes of input requirements and final demand (fuel consumption, demand for capital goods, labour requirement, etc.) in the IO model. Existing studies use this method to assess the direct and indirect job and output impacts across economic sectors of various energy transition scenarios (Siala et al., 2019) (Oei et al., 2020) (Ju et al., 2022).

3.1.2. IO to IAM linking

To a lesser extent, IAM-IO soft-linking has been performed the other way around using IO results to improve IAM and ESM assessments. This approach has been used to compute optimal energy system decarbonization pathways taking into account the indirect lifecycle emissions of technologies embodied in capital goods (Daly et al., 2015) (McDowall et al., 2018). To do so, indirect emission factors (IEF) are estimated for the different technologies based on a hybrid LCA-IO model and further used in the optimization program of the ESM. This especially raises issues with sector to technology mapping and double counting. In (McDowall et al., 2018) some evolution of IEFs is taken into account which follows the average decarbonization rate of the ESM industry sector. Alternatively, similar studies use a bottom-up LCA database instead of top-down IO models to evaluate a range of lifecycle environmental stressors per technology that are further applied to IAMs for environmental impact assessment (Arvesen et al., 2018) (Rauner and Budzinski, 2017). For intance, (Pehl et al., 2017) use coefficients for embodied energy use (EEU) and IEFs derived from a prospective LCA model within the IAM REMIND to evaluate optimal future energy systems accounting for indirect energy use and emissions. Also, as for (McDowall et al., 2018), in this case the linkage to the IAM can be considered bidirectional, as certain scenario data from the IAM, in addition to external sources, is utilized in the pLCA model to derive the EEU coefficients. However, improvements are still needed to enhance harmonization of scenario data across the LCA and IAM.

3.2. Hard-linking approaches

Beyond soft-linking existing IAM and IO information or models, a few studies have sought to develop hard-linked IAM-IO or ESM-IO approaches. For instance, (He et al., 2017) and (Kang et al., 2019) develop input–output linear programming (IO-LP) models at country level based on energy system cost minimization under I-O balance constraint. This method enables to compute in a standalone model optimal energy and power system decarbonization while taking

into account the indirect emissions linked to consumption of intermediate goods and services (He et al., 2017) and capital formation (through the endogenization of capital goods for electricity technologies) (Kang et al., 2019).

Eventually, although the majority of IAMs are based on ESM, a subset of models under the IAM umbrella (e.g. 4 out of 20 global IAMs referenced in Annex 3 of IPCC AR6 WGIII report : https://www.ipcc.ch/report/ar6/wg3/) originate from multi-sectoral macroeconomic modeling with IO economic accounting at their core – hereafter IO-based macroeconomic IAMs. These models employ a hard-linking approach, integrating bottom-up technical modules for key sectors (such as energy extraction, power generation, transportation, buildings, industry, and land-use) with dynamic multi-regional multi-sectoral computable general equilibrium (CGE) models or macroeconomic demand-led IO models. IO-based macroeconomic IAMs are designed to assess integrated technical and macroeconomic transformation pathways, considering structural change effects and supply chain linkages across production, consumption, economic sectors, and trade (Lefèvre et al., 2022). Some of these models emphasize energy-economic linkages and price effects (e.g. IMACLIM (Sassi et al., 2010) or GEM-E3 (Capros et al., 2013)) ; for instance the impacts of energy prices variations due to technological changes in energy supply, on industries competitiveness and final consumption. Others models provide more detailed descriptions of trade mechanisms (Duchin and Levine, 2016) (Distelkamp and Meyer, 2019). IO-based IAMs do not contain full-resolution GMRIO datasets in general but usually include most of the information that is necessary to estimate a full GMRIO system (e.g. E3ME (Mercure et al., 2018)) and perform consumption-based assessments across global supply chains.

The review of the literature reveals that IAM-IO integration is still at a nascent stage. Methodologically, the majority of existing studies adopt a soft-linking approach wherein IAM or ESM and IO models are integrated in a unidirectional manner to enhance the analysis in one field based on insights from the other. While a few rare instances of two-way soft-linking between ESM and IO models have been explored (Heinrichs et al., 2017) this special issue includes several papers that offer a glimpse into the potential for more advanced IAM-IO model integration (Ju et al., 2023) (Budzinski et al., 2023). These and other methodological advancements hold the promise of unlocking new perspectives for advancing sustainability scenarios research in various directions. Notably, they could facilitate a deeper exploration of the energy-industry nexus in decarbonization pathways, enable more comprehensive and robust

multi-dimensional sustainability impact assessments, and enhance the accuracy of modeling demand-side solutions and post-growth climate mitigation scenarios.

4. Advancing IAM-IO integration and sustainability scenarios research

4.1. Advanced model integration

As outlined in the previous section, the current IAM-IO model integration is based on two main approaches : one involving loosely soft-linking independent models and data, and the other entailing the development of built-in approaches and strong model integration. We can expect these two tracks to evolve as complementary paths, facilitating the advancement of more sophisticated sustainability analyses.

Currently, soft-linking of IAM or ESM and IO models has primarily been developed for specific studies. We first propose fostering a more structured community interaction centered around a multi-model ecology, encouraging the co-evolution and interaction of various models, including IAMs, ESMs, MRIOs, and LCA-IOs (Pauliuk et al., 2017). Standardizing model linking practices and scenario assessments would be essential in this endeavor. For instance, MRIO models could enhance the quantification of SSP scenarios in dimensions that IAMs often inadequately cover, such as demand-side transformations and structural changes in industry sectors. Conversely, EE-MRIO and LCA-IO models could be leveraged to post-process IAM results, enabling more standardized and accurate assessment of SDG impacts through multi-dimensional environmental and socio-economic footprint estimates. IAM-IO soft-linking could also be expanded at the level of each modeling team through the development of complementary modules such as e.g. the IO-scenario builder of the MESSAGE model team (Qiyu, 2021). Overall, this process would both improve IAM-based scenarios and widen the scope of MRIO modelers in a way that is consistent with established forward-looking scenario modeling. Limited interaction between researchers from the two fields is sufficient for this approach, but it would greatly improve with the establishment of shared standards for open data and model interfaces. Collaborating on open source softwares would promote higher transparency and work quality, aligning for instance with the established practices within the IE research community (Pauliuk et al., 2015) (Stadler, 2021). However, IAM-IO soft-linking does not address the deeper disparities regarding the incorporation of specific system linkages.

Therefore, it is also highly relevant to advance built-in IAM-IO integration, tailoring different modeling techniques to address specific questions. A first promising direction is the development of more sophisticated ESM-IO linking, moving beyond simple one-way data

exchange. Recent examples of this approach include (Ju et al., 2023) and (Budzinski et al., 2023) in this special issue. (Ju et al., 2023) linked the GCAM model with a national IO model for Japan through an iterative approach. This iterative process involves exchanging data between the ESM and IO model at each time step to achieve convergence on common measuring points, i.e investment in power capacities and energy demand. This ensures an advanced integration of system linkages embedded in one model but weakly or not covered by the other. For example, it captures power generation dynamic investment choices from the ESM and feedback from power investment on industrial sectors and energy demand from the IO model. In contrast, (Budzinski et al., 2023) achieved full integration of ESM and MRIO data for a benchmark year within a common accounting system based on the Make and Use framework. This integration involved rearranging ESM energy flows data (primary, secondary, final, imports, exports, etc.) in the make and use logic, converting it into monetary units, and reconciling it with the broader economic Make and Use tables of the MRIO model. Expanding this approach to forward-looking scenarios would enable the generation of fully integrated ESM-IO projections without double accounting or overlapping of linkages representation.

A second general approach involves enhancing existing IO-based macroeconomic IAMs or develop new IAMs with a core IO framework. Current IO-based IAMs already encompass the essential system linkages of a standard IO framework, including demand-supply interdependence and supply chain connections across economic sectors and regions. Moreover, they offer additional descriptions of endogenous input substitution, economic behaviors, and feedback mechanisms, such as price and income effects, including rebound effects. However, their application has been limited in exploring inter-sectoral dynamics in future scenarios, e.g. in relation to structural change effects (Lefèvre et al., 2022). Strengthening the core IO framework of these models could significantly improve the representation of economic and biophysical linkages. Presently, while some hybridization of energy-economic IO data exists, energy flows are still primarily accounted for in money-based units within their macroeconomic core. To foster a more consistent integration of physical-macroeconomic dimensions, direct accounting of energy flows in hybrid units should be more systematically implemented. This would enable incorporating information on energy substitutability or energy efficiency potentials and constraints directly based on engineering expertise. Hybridization of IO data could also be expanded to encompass other physical flows, such as materialss and accounts of broader environmental stressors beyond GHG emissions should be more systematically incorporated (Econometrics, n.d.). Improving the supply chain linkages of fixed capital and

investment is another area of opportunity. Expanding the typical representation of an average investment vector to a matrix format would enable capturing the specific content of fixed capital formation in a given sector concerning investment goods. At a technology level, this investment matrix approach could better account for the lifecycle impacts of technologies and the energy system, such as net energy assessments (e.g., Energy return on investment – EROI (Brand-Correa et al., 2017)) or labour impacts (Dai et al., 2016).

Furthermore, the development of new IAMs based on the IO framework offers a promising avenue. Most existing IO-based macroeconomic IAMs are CGE models that adhere to a neoclassical oriented approach, emphasizing equilibrium, perfect markets, and high input substitutability with limited representation of finance. Beyond existing exceptions that challenge the standard CGE paradigm within IAMs (e.g. imperfect markets and limited substitutability (Sassi et al., 2010) or macroeconometric demand-led approaches (Mercure et al., 2018)), some scholars call for a new economic approach of energy transition models that embraces the features of modern economies encompassing complexity, non-equilibrium and uncertainty (Hafner et al., 2020). To achieve this goal, the emerging field of ecological macroeconomics proposes a diverse set of relevant modeling approaches, combining post-Keynesian and ecological economics (Hardt and O'Neill, 2017). Notably, the integration of IO with stock-flow consistent (SFC) models, which incorporate finance through consistent accounting of all monetary stocks and flows, as well as financial assets and liabilities (Lavoie and Godley, 2001), shows promise in assessing integrated concerns about ecological impacts, financial stability, and social progress (Hardt and O'Neill, 2017). Additionally, IO can be effectively combined with broader system dynamics approaches, incorporating the representation of stocks, flows, and feedbacks across complex systems (Radzicki, 2020). This integration allows for an improved representation of the dynamics of economic and biophysical linkages, by better capturing, for instance, the limitations to input substitutability through dynamic IO coefficients or the physical constraints linked to energy and resource availability (Nieto et al., 2020).

4.2. Advancing sustainability scenarios research

Overall, I see three important domains within sustainability scenarios research where advanced IAM-IO model integration could play a critical role.

4.2.1. Energy - Industry nexus

First of all, it could help to advance our understanding of the role of the industry sector in decarbonization pathways and to explore the energy-industry systems nexus beyond usual lifecycle analysis. While IAM-based scenarios often focus on the decarbonization of industrial processes (e.g., steel, cement, chemicals) based on assumptions about industrial demand trends, the industry sector is significantly influenced by various factors, including the lifecycle impacts of energy conversion and demand assets (such as power systems, transport equipment, buildings, etc.) through upstream and downstream supply chains involving intermediary consumption and investment. Particularly, manufacturing and construction of these assets have crucial supply chain linkages that feedback into industrial production and demand, with materials playing a significant role. Although existing linked IAM-IO studies already capture these linkages to a considerable extent (Hertwich et al., 2015) (Wiebe et al., 2018), they often do not thoroughly disentangle the detailed indirect impacts of energy technology development on industrial sectors and induced energy demand, mainly focusing on reporting carbon footprints. Hence, there is a need to comprehensively explore these feedbacks to better assess the role of the industry sector in decarbonization pathways, considering structural change perspectives and the broader socio-economic implications. The advanced IAM-IO modeling methods described in previous section can be utilized to address complementary aspects of this question. For instance, to explore the indirect and dynamically-consistent impacts of technology development on future material production and energy demand, an approach incorporating technology-specific vintage stock modeling and IO data would be favorable, for instance IAM hybrid LCA-MRIO soft- linking (Hertwich et al., 2015) or advanced ESM-MRIO linking (Ju et al., 2023) (Budzinski et al., 2023). Vintage stock modeling is important for accurately assessing the material and energy impacts at the year of capital formation. On the other hand, a more top-down approach based on MRIO (without LCA data) or IO-based IAMs could be sufficient to capture the primary long-run energy-industry lifecycle linkages in economy-wide scenarios, including aspects such as the future EROI of the energy system, without requiring full lifecycle resolution or dynamic effects of specific technologies. Moreover, the socio-economic implications for industrial sectors, including aspects like employment, value-added, and competitiveness, could be better evaluated using MRIO and IO-based IAMs, as these models focus on economic data and linkages.

4.2.2. Multi-dimensional sustainability impact assessment

A second research domain with significant potential for IAM-IO integration lies in the assessment of broader environmental interventions, extending beyond climate change, and

achieving a more consistent and comprehensive evaluation of Sustainable Development Goals and pathways. Presently, IAM-based scenarios primarily focus on energy and climate policy, with efforts to assess the implications of mitigation pathways for SDGs (Sörgel et al., 2021). However, these scenarios do not fully incorporate analysis of other environmental interventions beyond climate change on the one hand, and still perform incomplete assessment of SDGs by relying on indirect proxies or limiting assessments to impacts related solely to the energy system, on the other (Rauner et al., 2020).

The IO framework, by capturing industrial supply chains beyond the energy system, first enables investigation into additional environmental interventions. One such area is the circular economy, a crucial sustainability policy field that complements climate policy by aiming at greater circularity and resource efficiency in industrial processes (e.g., recycling, material efficiency, reuse)(Yang et al., 2023) (Gallego-Schmid et al., 2020). Recently, EE-MRIO approaches have been utilized to evaluate global circular economy scenarios (Wiebe et al., 2019), and IAM-EEMRIO linking could facilitate the exploration of integrated circular and mitigation scenarios, addressing both climate and resource-saving objectives. This integration is particularly relevant, considering that circular economy policies may also offer significant decarbonization potential (Serrano et al., 2021) (Cooper et al., 2017). While a fully integrated circular and climate policy IO-based IAM is an option (Econometrics and Bio, 2014), soft-linking IAM-EEMRIO approaches may be more suitable for disentangling the different effects captured by complementary models. One challenge in gaining deeper insights into the circular economy is the explicit modeling of stock formation, which is usually not done with EE-MRIO models. The potentials for material efficiency and reusing or the availability of secondary materials are indeed highly contingent upon the dynamics of in-use stocks.

Moreover, IAM-IO integration provides a foundation for a more consistent and comprehensive assessment of SDGs and quantification of Sustainable Development Pathways (SDPs) across environmental, social, and economic dimensions. The EEMRIO framework can serve as an integrative platform for various scenario information, enabling the derivation of environmental and socio-economic footprint indicators across global supply chains that can be further related to SDGs. To translate footprints (i.e., pressures) into impacts and damages and ultimately SDG indicators (e.g., water scarcity, ecosystem damage, human health, resource depletion), dedicated add-on models (e.g. health impacts (Zhang et al., 2017)) (Wiedmann and Lenzen, 2018)) could be utilized. Similar approaches have been employed by different EEMRIO models to track current progress towards SDGs (Malik et al., 2019) (Gómez-Paredes and Malik, 2018).

For instance, material footprint estimates have been used to quantify SDGs 8 and 12 (Lenzen et al., 2022), water footprinting for SDG6 (Vanham et al., 2018), social footprint for SDGs 3,5,6 and 16 (Xiao et al., 2017) including employment impacts (Montt et al., 2018), etc. Through IAM-EEMRIO integration, a similar approach could be applied in forward-looking scenarios, offering the advantage of consistent SDG assessment throughout global supply chains within the EEMRIO framework, including region-specific impacts. Here again, a soft-linking between IAM and MRIO might be the more relevant approach, mitigating the complexity of multi-dimensional analysis with a standalone IO-based IAM.

In addition, IAM-MRIO integration holds potential for advancing analysis in the field of inequality and equity. Recent studies have evaluated current global carbon inequality, examining the heterogeneity of carbon footprints across regions and individuals by combining EEMRIO data with household surveys (Zheng et al., 2023) (Chancel, 2022). These approaches can serve as a basis for evaluating the evolution of carbon inequality in transition scenarios, addressing equity issues related to the fair sharing of mitigation efforts across and within regions. To achieve this, IAM-EEMRIO linking can be combined with income inequality scenarios (Rao et al., 2019) and estimates of income elasticities of carbon footprints to project carbon inequality within regions in addition to average regional carbon footprints. Moreover, the MRIO framework can be utilized to project income inequality within regions by examining changes in the sectoral composition of economies in relation to income distribution factors, such as labor and capital ratios and skill structures of sectors. Some IO-based macroeconomic and ecological macroeconomic IAMs already incorporate endogenous income distribution by describing heterogeneous households and worker groups distinguished by skills, occupational status, income sources, and taxation (Fragkos and Fragkiadakis, 2022) (D'Alessandro et al., 2020).

4.2.3. Demand-side mitigation and post-growth scenarios

Eventually, we envision IAM-IO integration as a pivotal methodological approach for exploring demand-side transformations, demand-side solutions for mitigation (including sufficiency lifestyles), and post-growth climate mitigation scenarios. Despite recent efforts, demand-side transformations continue to be a major blind spot in IAMs, often represented only by the energy consumption of a few end-use sectors (such as industry, buildings, and transportation) as shown in Fig. 1. Energy projections in IAMs commonly rely on aggregated relationships between energy use and income per capita (Bauer et al., 2017). On the contrary, MRIO models offer a detailed description of final demand beyond energy and provide the

opportunity to project demand-driven structural change scenarios, even at the macroeconomic level, based on alternative assumptions of final demand levels and structure (Wiebe et al., 2018). Therefore, using MRIO frameworks can significantly expand the quantification of demand-side drivers in baseline scenarios like the SSPs. To achieve supply-demand integrated pathways, ESMs can be enriched with energy demand data derived from MRIO models. Additionally, built-in demand-side drivers of structural change can be effectively captured using standalone IO-based macroeconomic IAMs (Lefèvre et al., 2022).

In addition, while IAMs have explored demand-side mitigation measures towards reducing energy demand (Grubler et al., 2018) (van Vuuren et al., 2018), these measures have often been quantified outside the models and do not encompass the full scope of consumer-oriented solutions beyond the energy and food sectors (Creutzig et al., 2018). In contrast, the MRIO approach provides a consistent framework for more accurate and comprehensive exploration of consumer-oriented measures from an economy-wide perspective (Wood et al., 2018). Within this framework, three main options for consumption-based solutions can be tested : (1) changing detailed consumption patterns, including reducing overall consumption (i.e., altering consumption of individual products and services, including energy); (2) modifying the inputs required for production in industries (e.g., optimizing production recipes for improved efficiency); and (3) reducing direct emissions and environmental impacts. Therefore, detailed consumption-based measures in transition scenarios could be captured through IAM-MRIO linking, for comprehensively representing supply-demand transformations based on consistent supply chain linkages. For instance, IAM-MRIO linking would allow for the examination of structural transformations in industry sectors triggered by changes in consumption patterns, and the subsequent implications for energy demand and carbon emissions.

IAM-IO integration holds particular potential to explore sufficiency lifestyles. Sufficiency lifestyles are broadly defined as those that seek to minimize material and energy consumption, reducing environmental pressures while satisfying human needs and prioritizing well-being and quality of life (Jackson, 2005) (Vita et al., 2019) (Samadi et al., 2017). In practice, transitioning from unsustainable consumption to sufficiency involves directly reducing resource-intensive consumption (e.g., buying fewer clothes, minimizing long-distance leisure travels, reducing living space and indoor temperature) or indirectly through sharing and repairing practices, and adopting more sustainable consumption modes (e.g., shifting transportation from cars to bikes or embracing less meat-intensive diets) through individual and collective actions. While a few IAM studies have integrated some sufficiency measures into alternative scenarios (e.g.,

adopting less meat-intensive diets, implementing transport modal shifts, lowering indoor temperatures), emphasizing their benefits in mitigation pathways, including reduced reliance on uncertain technologies, positive impacts on other sustainability goals, and alignment with well-being considerations (Grubler et al., 2018) (van Vuuren et al., 2018) (Creutzig et al., 2022), the MRIO approach offers a more comprehensive representation of sufficiency lifestyles (Vita et al., 2019). It allows for a wide range of sufficiency scenarios, encompassing direct end-use energy sufficiency for transportation and housing, as well as a more granular differentiation between high versus low resource-intensive or luxury versus essential goods and services. Moreover, MRIO modeling can reflect various scenarios concerning changing preferences, beyond the scope of utility maximization, and quantify service provision and related consumption systems' implications on well-being. Here again, the advantages of MRIO can be harnessed through IAM-MRIO linking. Furthermore, IO-based macroeconomic IAMs, while representing sufficiency measures in less detail, can capture specific economic and behavioral feedback linked to sufficiency policies. For instance, they can account for potential unintended rebound effects that might lead to lower environmental benefits than initially anticipated (Sorrell et al., 2020) (Figge et al., 2014).

In addition, sufficiency lifestyles align with the concept of a post-growth economy, which represents a broader shift in the economic paradigm towards a prosperous system that does not rely on continuous economic growth (Kallis et al., 2012). Instead, the focus lies on principles of equity, sufficiency, and service provision to achieve strong social outcomes while minimizing environmental footprints. In post-growth climate mitigation scenarios for high-income countries, the emphasis is on scaling down energy use and material throughput through sufficiency-oriented consumption and production patterns. It aims to enhance social well-being by reducing inequality, ensuring full employment, and guaranteeing access to public services (Hickel et al., 2021). The primary goal of post-growth policies is not to stabilize or decline aggregated GDP, but given the historical coupling between material throughput and GDP, it is a likely consequence that need to be dealt with (Hardt and O'Neill, 2017). Post-growth scenarios build on the advantages of sufficiency lifestyles but also encompass a wider transformation of the economic paradigm, deliberately avoiding rebound effects and relying on uncertain decoupling between economic growth and energy use. Despite the appealing features, IAMs have not much explored post-growth mitigation scenarios so far (Hickel et al., 2021) and virtually all existing scenarios assume continuous economic growth in all countries from the outset (Dellink et al., 2017). Only a limited number of integrated modeling studies have

approached post-growth mitigation, often based on alternative assumptions of lower GDP and aggregated consumption (D'Alessandro et al., 2020) or homogeneous downscaling of useful energy demand across economic sectors (Li et al., 2023). While such studies allow exploration of uncharted areas in the existing scenario space such as the SSPs (Dellink et al., 2017), providing insights into the benefits and risks of lower growth and consumption (faster decarbonization, lower need for low carbon technologies, but possible macroeconomic and social risks, etc.) (D'Alessandro et al., 2020)(Li et al., 2023), they do not provide insights on the structural transformations induced by post-growth strategies : what is consumed and produced in the economy ? How is the provisioning system organized ? Where do people get income from ? etc. Yet, a post-growth economy fundamentally involves differentiated downscaling of production and consumption (Fitzpatrick et al., 2022). The IO framework, though not extensively used in this context thus far, could play a crucial role in describing the structural changes associated with a post-growth economy (Hardt et al., 2021) by integrating both consumption and production aspects. On the consumption side, IO mapping enables a clear understanding of shifts towards sufficiency lifestyles, minimizing energy and material throughput while meeting essential needs. On the production side, it can describe changes in production structures, promoting labor-intensive sectors and meaningful employment, such as in health, culture, education, and other service sectors (Hardt et al., 2021). Furthermore, by distinguishing between private and public consumption, the IO framework can shed light on changes in provisioning systems, moving from markets to government with sectoral differentiation. It can also analyze changes in 'welfare purchasing power' of income. In this context, aggregated consumption and economic output become a consequence of changes in consumption and production patterns, rather than an assumption from the beginning. The IAM-MRIO linking approach thus offers an integrated vision of the detailed structural changes associated with post-growth scenarios and their implications for energy demand and decarbonization pathways. The sectoral effects also offer insights for deriving economic and social implications, such as economic output, employment, and income inequality. IO-based macroeconomic IAMs can also contribute to describing structural change effects in post-growth scenarios, although with less granularity, while providing macroeconomic feedback and consistency related to the impact of changes in production levels and structure on income and final demand. Beyond structural change, post-growth raises important questions about macroeconomic and financial stability, work patterns, and redistributive fiscal policies. IO-based ecological macroeconomic IAMs are valuable tools to assess these issues and the macroeconomic transitions towards a post-growth economy (D'Alessandro et al., 2020). In

summary, the combination of IAM and MRIO modeling offers a comprehensive framework to explore post-growth scenarios, incorporating detailed structural changes, and understanding their wide-ranging implications on energy demand, decarbonization, economic stability, and social welfare.

		Soft-linking IAM/ESM and MRIO/LCA-IO	Advanced ESM-MRIO linking	IO-based (ecological) macroeconomic IAMs
Energy-industry nexus	Energy and technology linkages	XX	XX	X
	Economic aspects	X	X	XX
Sustainability impact assessment	Circular economy	XX	X	X
	SDGs	XX	X	X
	Inequality	X	X	XX
Demand-side mitigation and post-growth scenarios (PGS)	Demand-side transformations	XX	XX	X
	Sufficiency lifestyles	XX	XX	XX
	Structural change in PGS	XX	XX	XX
	Macroeconomy and finance in PGS	--	--	XX

Table 3 : Summary of research topics (rows) and corresponding modeling approaches (columns). For each column, 'XX', 'X' and '--' indicate that the modeling approach is respectively best adapted, adapted or not adapted to address each research topic in collumn.

Table 3 provides an overview of the outlook for advanced IAM-IO integration and its relevance to sustainability scenarios research, as explored in this paper. Specifically, the table highlights the modeling approaches that are best suited to address each specific research topic, as discussed in more detail in the main text. It can be seen as a reference to select the most suitable approaches for tackling future research issues with advanced IAM-IO models.

5. Conclusion

The further integration of IAM and IO modeling approaches holds tremendous promise for enhancing our understanding of the intricate biophysical and economic linkages that underpin human societies. By combining the strengths of IAMs in representing transformative processes with the comprehensive supply chain linkages and interdependencies of IO frameworks, advanced IAM-IO integration opens up new avenues for multi-dimensional analysis of forward-looking transition scenarios. Beyond technology-driven energy transition and decarbonization, this integration offers the potential to address a broader range of pressing sustainability challenges. In this paper, we have identified three main research domains needing urgent policy responses where IAM-IO integration can play a pivotal role : the energy-industry nexus, multi-dimensional sustainability assessment, and demand-side solutions, including post-growth climate mitigation scenarios. However, this list is not exhaustive, and other critical topics could be incorporated (e.g. climate change impacts across supply chains (Okuyama and Santos, 2014)). Moving forward, IAM-IO interaction and integration should be nurtured as a dynamic ecosystem of models and model linking methods, empowering researchers and practitioners to choose the most appropriate approach for addressing specific prospective questions across a wide spectrum of sustainability topics. This evolution will be bolstered by advanced community integration, fostering the sharing of data, model interfaces, and best practices. By cultivating such collaborations, policymakers and the general public would benefit from more advanced and transparent research, supporting collective decision-making for sustainable development strategies.

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