Material Cycles, Industry and Service Provisioning: A Review of Low Energy and Material Demand Modelling and Scenarios

Abstract

Developing transformative pathways for industry's compliance with international climate targets requires model-based insights on how supply- and demand-side measures affect industry, material cycles, global supply chains, socio-economic activities and service provisioning supporting societal wellbeing.

Herein, we review the recent literature modelling the industrial system for Low Energy and Materials Demand (LEMD) futures, resulting in lowered environmental pressures without relying on negative emissions. We identify 77 innovative studies drawing on nine distinct industry modelling traditions and critically assess system definitions and scopes, biophysical and thermodynamic consistency, granularity and heterogeneity, and operationalization of demand and service provision. We find large potentials of combined supply- and demand-side measures to reduce current economy-wide material use by -56%, energy use by -40 to -60%, and GHG emissions by -70% to net-zero. We call for strengthening interdisciplinary collaborations between industry modelling traditions and demand-side research, to produce more insightful scenarios and discuss research challenges and recommendations.

Keywords: climate change mitigation; sustainable resource use; integrated assessment modeling (IAM); ecological economics; industrial ecology;

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Summary points – highlight the central points of your review (max 8) in complete sentences.

- Modelling industry and service provisioning for Lower Energy and Material Demand (LEMD) is happening within all modelling traditions, and increasingly in interdisciplinary collaborations combining models and principles.
- Material cycles and stocks, as well as their dependence on energy use are usually not properly represented, except in those traditions focused on the biophysical basis of society.
- The granularity of industry and economic sectors, as well as materials differs substantially across traditions, with some input-output tables distinguishing up to 163 sectors and 69 materials.
- On the demand-side, up to ~10 end-use product groups are distinguished across modelling traditions, focusing on the groups of building and construction, transport, appliances and food. Less common but still prominent is modelling of functions such as square meter floor area or passenger-kilometers. Welfare and co-benefits beyond GDP are rarely addressed.
- Macro-economic traditions use endogenous economic growth theories to provide 'cost-optimal' pathways, incl. assumptions about autonomous efficiency improvements, regularly violating thermodynamics and ignoring or downplaying the 'costs' of escalating non-linear feedbacks, e.g., due to climate breakdown and ecosystem collapse in high growth scenarios.
- All other traditions use exogenous drivers such as population and economic growth and then simulate the technological, biophysical and behavioral GHG mitigation potentials of supply- and demand-side measures aiming to comply with emission reduction targets, however often excluding or simplifying macro-economic implications.
- We find a troubling lack of proper documentation and open data for more than half of the reviewed literature as well as a widespread lack of properly reporting model data inputs and model results, hindering comparability and evidence synthesis.
- We find various studies upscaling small-scale and/or static data to scenarios at national and global levels, which is a problematic oversimplification.

Future issues list – note where research may be headed (max 8) in complete sentences.

- Interdisciplinary combinations of modelling principles and traditions yield more robust, nuanced and policy-relevant insights, than any single tradition can provide.
- Thermodynamic and biophysical consistency at high granularity across material cycles, energy use and material stock turnover across industrial networks reacting to changes in final demand and socio-technological innovation is vital to understand time-dependent dynamics and efficiency potentials.
- Material stocks serve as constituents for service provision, as they are used to transform energy and material flows into functions and services in a context specific manner; what constitutes an acceptable and sufficient level of “low-demand“ is an open question requiring transdisciplinary approaches to derive justified targets.
- Widening the solution space for sustainable development and climate change mitigation by addressing a wider range of supply- and demand-side measures in combination is timely, utilizing optimization and simulation approaches drawing on a large set of possible measures beyond price-based instruments, acknowledging that LEMD transitions will induce dis-equilibrium, major structural changes and early retirement of some capital stocks.
- Assessing telecoupling in global supply chains is critical to identify potential rebound effects and burden-shifting, as well as economic winners and losers in LEMD transformations.
- Modelling should address the complex socio-ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations and the biosphere.
- Modelling should address the complex socio-ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations and the biosphere. The environment is more than a repository of resources to be extracted and a sink for waste and emissions. Complex trade-offs exist between different environmental aspects, ranging from the climate and biodiversity crisis to other Planetary Boundaries.
- Improved research infrastructure, open science principles, FaiR research and shared concepts and ontologies are needed to facilitate coupling of models, comparison of results and evidence synthesis.
- Connecting and contributing to ongoing efforts to improve the Shared Socio-economic Pathways (SSPs) framework is important so that future LEMD scenarios can be easily integrated into evidence synthesis by IPCC and others.

Terms and Definitions: definitions for max 20 most important abbreviations and key terms. 20 words max.

1. LEMD - Low Energy and Material Demand
2. Social Metabolism - Encompasses all materials and energy extracted and harvested, which are further processed, used and accumulated as material stocks by societies and their economies, necessarily resulting in waste and emissions
3. Material cycles and stocks - Physical flows from the extraction of raw materials to industrial processing and trade, to end-uses and accumulation as product stocks, resulting in (waste) by-products at each step as well as at the end-of-life
4. Material stocks - all long-lived in-use products utilized longer than one year, covering all socio-economically utilized products, machinery, buildings and infrastructure
5. Economy-wide - covering all economic production and consumption activities
6. System of National Accounts (SNA) – globally harmonized, socio-economic reporting system.
7. System of Environmental-Economic Accounts (SEEA) – globally harmonized, socio-economic and environmental reporting system.
8. SSP – Shared Socioeconomic Pathways: Set of scenarios used by the IPCC based on five narratives that describe plausible socioeconomic future trajectories
9. IAM – Integrated Assessment Model
10. ABM – Agent Based Model
11. SD – System Dynamics Model
12. MEFA – Material and Energy Flow Analysis, incl. dynamic stock-flow models
13. LCA – Life Cycle Assessment
14. PE – Partial Equilibrium macro-economic model
15. CGE – Computable General Equilibrium Model
16. MRIO – Multi-Regional Input-Output Model, covering the world economy

1) Introduction

This review addresses two concerns: Firstly, recent global assessment reports have clearly established that mitigating greenhouse gas (GHG) emissions and environmental impacts requires directly addressing the scale and composition of socio-economic material cycles and accumulated material stocks of buildings, infrastructure and machinery (IPBES, 2019; IPCC, 2022; UNEP-IRP, 2019). Improving energy efficiency and decarbonizing energy supply and industrial processes alone does not suffice to comply with internationally agreed upon efforts to limit the increase in global mean temperature to 1.5-2°C above pre-industrial levels (IPCC, 2022); furthermore, it does not address non-climate environmental impacts driving the transgression of five Planetary Boundaries (Richardson et al., 2023). Economy-wide material cycles include raw materials that originate from agriculture, forestry and mining and are processed by industry, manufacturing and construction; they include transport and waste management and, ultimately, final product demand, which accumulate as in-use material stocks (Haberl et al., 2019; Pauliuk and Hertwich, 2015). Material production and industry activity accounts for 20-34% of global GHG emissions (Hertwich, 2021; Lamb et al., 2021); material extraction is an important driver of land use change and biodiversity impacts (Giljum et al., 2022; UNEP-IRP, 2019). Crucially, recent reviews showed that many macro-economic Integrated Assessment Models (IAM) regularly violate the Laws of Thermodynamics and lack the granularity, resolution and framework to fully depict material cycles and material stocks (Bataille et al., 2021; Pauliuk et al., 2017; Stern, 2011). These gaps critically limit our understanding of the potentials, trade-offs and multi-SDG impacts of strategies aiming to reduce, slow and close socio-economic material cycles (Aguilar-Hernandez et al., 2018; Creutzig et al., 2022; Hertwich et al., 2019; Hickel et al., 2022; McCarthy et al., 2018; Muscat et al., 2021).

Secondly, global assessment reports have clearly established that expanding the solution space to demand-side measures and service provisioning is necessary (IPBES, 2019; IPCC, 2022; UNEP-IRP, 2019). Demand-side measures – defined as (Creutzig et al., 2021a): '*mitigation opportunities that involve individuals or industrial end users of products, services or processes.*' – aim to avoid, shift, and improve service provision to achieve Lower Energy and Material Demand (LEMD). (Wilson et al., 2022) state: "*Demand-side strategies change how services are delivered (e.g., more energy-efficient end-use technologies and infrastructure, digitalization, business models to increase efficient utilization of resources). […] Supply-side strategies change how resources are converted (e.g., precision agriculture, decarbonization of power production) [...]*".

Service provisioning for human needs and societal wellbeing can be grouped along material needs for food and water, mobility, shelter, thermal comfort and lighting, health, education, entertainment, social interaction and participation. All of these require material and energy flows as well as material stocks of products, infrastructure and buildings, resulting in waste and GHG emissions (Fell, 2017; Gough, 2015; Kalt et al., 2019; Lamb and Steinberger, 2017). Related research streams grounded in different theories about society and social change include, for example, sufficiency (Jungell-Michelsson and Heikkurinen, 2022; Sandberg, 2021), post-growth (Jackson, 2017; Hickel et al., 2021), steady-state economics (O'Neill, 2015; Victor, 2022), sustainable consumption corridors (Fuchs et al., 2021), as well as degrowth (Kallis et al. 2018; Hickel et al. 2022), and the circular economy (Aguilar-Hernandez et al., 2018; McCarthy et al., 2018). Independent of one's favorite theory, LEMD substantially increases the feasibility of addressing the climate crisis without relying on unproven large-scale negative emission technologies, reduces the costs of mitigation and decarbonization, and contributes to improving societal wellbeing (Creutzig et al., 2022, 2021b; Grubler et al., 2018b).

So far however, most climate change mitigation scenarios limiting climate heating to 1.5-2°C assume unprecedented efficiency improvements and rapid decarbonization of energy supply and other sectors, as well as gigantic amounts of negative emissions which is highly risky and prone to moral hazards (Anderson and Peters, 2016; Minx et al., 2018; IPCC, 2022). Most mitigation scenarios also assume endless economic growth and ever-increasing consumption, while perpetuating global inequality (Hickel and Slamersak, 2022). Existing mitigation scenarios report hardly any reductions in energy demand, partially because the underlying models lack heterogenous demand representations and usually do not consider service provision (Edelenbosch et al., 2020). They therefore explore only a narrow part of the solution space for sustainability transformations (Hickel et al., 2021; Keyßer and Lenzen, 2021; Lamb and Steinberger, 2017). Recently, the seminal 'Low Energy Demand (LED)' scenario with high service provisioning globally (Grubler et al., 2018b), as well as the dedicated IPCC chapter on services, demand and social aspects of mitigation (Creutzig et al., 2022) kick-started research into viable 'low-demand' futures with high wellbeing around the world, without resorting to technological silver-bullets.

This review addresses these concerns by surveying recent innovations in models aiming to address material cycles and stocks, industries, energy supply and GHG emissions, as well as final demand and service provision. We focus on Lower Energy and Material Demand (LEMD) scenarios and the underlying models. We do not aim for a general synthesis of mitigation potentials, which was recently done by (IPCC, 2022). *Herein, we summarize the status and research needs for modelling material cycles and industry in LEMD scenarios, answering the following research questions:*

- *Which aspects, principles, and system linkages of material cycles and industry need to be covered for LEMD scenarios and how are they addressed in the literature?*
- *How is service provisioning and its link to industry conceptualized and operationalized in the recent and relevant modelling literature?*

- *Which potentials of supply- and demand-side measures for LEMD have been shown so far?*
- *Which recommendations for modelling industry and material cycles for LEMD scenarios emerge?*

Literature deemed relevant was identified between 03/2022-09/2023 from scientific literature databases and via citation snowballing, to identify fully relevant and innovative studies, which aim to a) have biophysical and thermodynamic consistency between material cycles and stocks, energy use and GHG emissions, 2) treat industry not as end-user but as delivering to intermediate and final demand, 3) model demand and service provisioning ideally in non-monetary units, and 4) model scenarios with low(er) demand. We focused on recent, noteworthy studies published between 2014-2023, screened over 300 studies and selected 75 for in-depth review. We grouped all included studies according to their main modelling tradition, and assessed model scopes and results detail, including their operationalization of "service provisioning", using the Energy Service Cascade (Kalt et al., 2019) and the Stock-Flow-Service Nexus (Haberl et al., 2017) as analytical frameworks. Additional documentation about the research design and methods, as well as the full assessment of studies can be found in the supplemental information and data file.

2) Principles and purposes of the nine modelling traditions

We identify nine industry modelling traditions, each developed for specific purposes and based on different worldviews, theories, and modelling principles (Figure 1). For an introduction and overview for each tradition, we refer to the supplemental information section 2. These different foundations result in diverse terminologies, system definitions, model scopes and aims, data requirements, and computational complexity. Modeling society-nature interactions began in the 1960s, spurred by concerns about environmental degradation, energy security, and climate change, and the establishment of UNFCCC and IPCC. Macro-economic IAMs were developed to simulate emission scenarios and mitigation strategies, grounded in fields such as Energy- and Environmental Economics (Figure 3, in green). Alternative socio-ecological approaches focusing on a biophysical, non-monetary systems perspective emerged between the 1960s and 1990s, grounded in fields such as Industrial Ecology, Sustainability Science, Ecological Economics, and Complex Systems Science (Figure 3, in yellow).

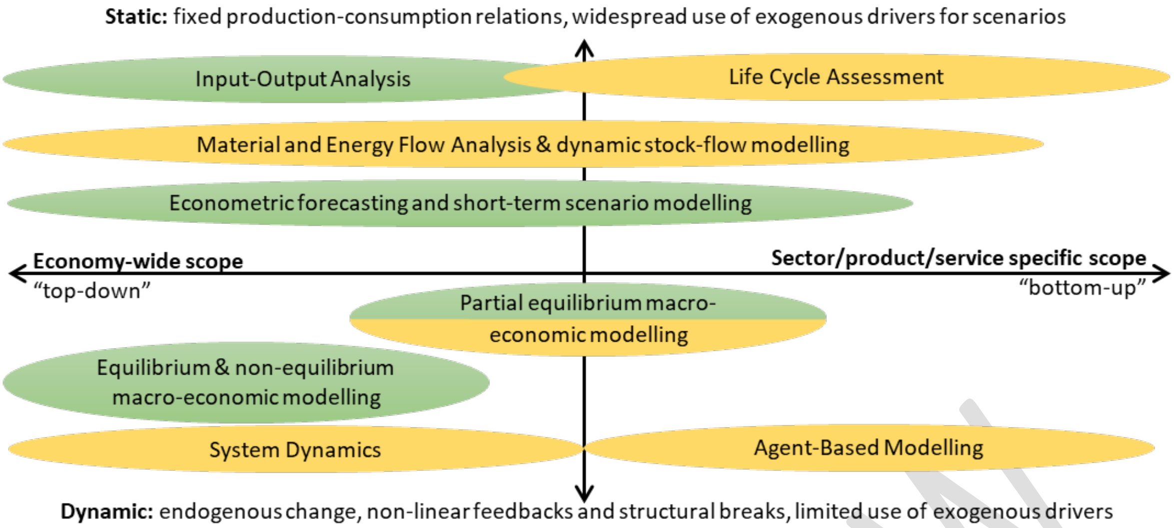

Figure 1: Foundational principles and typical scopes of the nine modelling traditions reviewed herein. Traditions in green originate from Energy and Environmental Economics, while yellow traditions originate from Engineering, Industrial Ecology, Ecological Economics, Socio-Metabolic Research and Complex Systems Science. The positioning of each tradition is based on the authors domain expertise and is only meant to provide orientation. We refer to the supplementary information for a more detailed discussion and literature sources for each tradition.

3) State-of-the-art models for LEMD scenarios

We identified 77 relevant studies published between 2014 – 2023. Two-thirds operate within their tradition, while one-third combines methods and data from engineering, Industrial Ecology, Ecological Economics and Complex System Sciences ('biophysical+'), ABM and other traditions ('ABM+'), as well as biophysical and macro-economic modelling ('economic+biophysical'; Fig.2a). Most studies have national, world-regional, or global scopes (Fig.2b). Two-thirds of regional and (sub)national studies focus on the Global North, while only one-third specifically investigates the Global South (Fig. SI-3). Around two-thirds of the reviewed studies are published Open Access and have supplementary information (Fig.2c). Only one-third provides machine-readable supplementary data and a mere 10 studies (13%) provide open model code, hampering assessment, comparison and evidence synthesis.

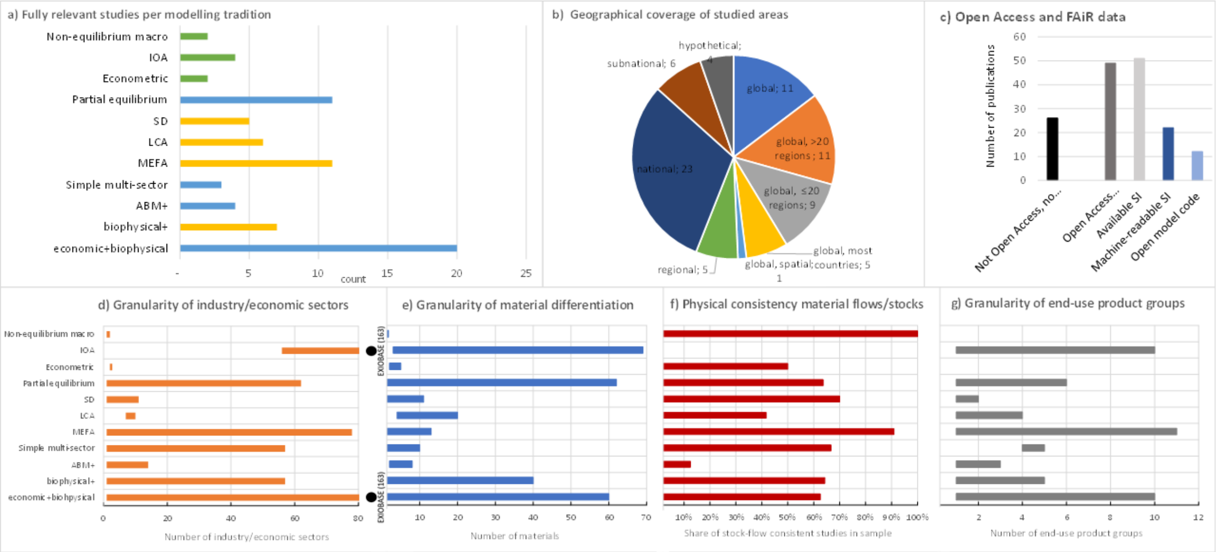

Figure 2: Overview of relevant studies by tradition and emergence from original research fields (a) coverage of geographical scopes (b), and implementation of FAiR open science principles across the reviewed literature sample (c). Ideally, studies, results and model code should be Findable, Accessible, interoperable and Re-usable (FAiR)(Wilkinson et al., 2016). Further documentation on coding and assessment can be found in the supplemental information section 2.

We find substantial differences in the resolution and granularity of industries and economic sectors modelled across the traditions (Fig.2d). Especially MRIOs and those using underlying data stand out, as they have been specifically developed to provide detailed sectoral classifications for extractive, manufacturing and service industries, with EXIOBASE at 200 products or 163 industries (Stadler et al., 2018), and GLORIA with 120 sectors (Lenzen et al., 2021). Others like WIOD or GTAP have lower resolution of 35-64 sectors. Models from the MEFA, LCA and SD traditions usually focus on specific industries and/or materials, resulting in relatively lower sectoral resolution, although recent synthesis studies compiled high resolutions of up to 78 industries/sectors. For the macro-economic traditions, we find an intermediate sectoral resolution of 1 – 57 sectors.[1]

MRIOs (69), partial (62) and general (60) equilibrium models, as well as model combinations using input-output tables (biophysical+, economic+biophysical) are most detailed in covering materials. Depending on scope and aims, some of these studies aggregated to only 1-3 materials (Fig.2e). For the other traditions, we find low (1-8) to intermediate (10-20) materials granularity. Regarding biophysical stock-flow consistency, we find that both non-equilibrium studies model material stock-flow relations, however only stylized. For MEFA, biophysical consistency is the core principle (some MEFA studies only look at either stocks or flows though). In contrast to the relatively higher resolution and granularity found for MRIOs, we find that they only partially comply with biophysical stock-flow consistency (Fig.2e): while environmentally-extended input-out analysis enforces mass-balances, it

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[1] Please note that the granularity of some studies based on LCA/MRIO combinations, which have substantial sectoral resolution in their ‘background system’, could not be assessed due to lacking documentation of the aggregation and truncation decisions common in LCA.

does not account material stocks, only specific variations account waste-by-products (waste and physical input-output analysis), and limitations arise from combining monetary and mass units (Streeck et al., 2023a). Regarding the coverage of modelled end-use product groups, we find that MEFA, MRIO and combinations of economic and biophysical traditions cover the most with between 10-11 end-use products groups (Fig.2f). Studies of the non-equilibrium macro and econometrics traditions do not model the number or material cycles of products explicitly, but depict resource use as intensity of macro-economic variables (e.g., per unit of aggregate or sectoral GDP).

When it comes to service provisioning, we find that across all studies what is most often modelled are end-use product stocks (amounts, weight, …) of appliances, food, motor vehicles, construction and residential buildings (Figure 3a). In summary, 'building & construction' is most often covered, followed by 'transport & vehicles'. For actual functions as physical 'action', the most prominent categories are housing, passenger transport, nutrition, heating and cooling, non-residential floorspace and freight transport (Figure 3b). Services as 'what is actually demanded' are substantially less quantified, mostly via employment and Decent Living Standards (DLS) (Figure 3c). Welfare, well-being and co-benefits are often approximated via GDP (Figure 3d).

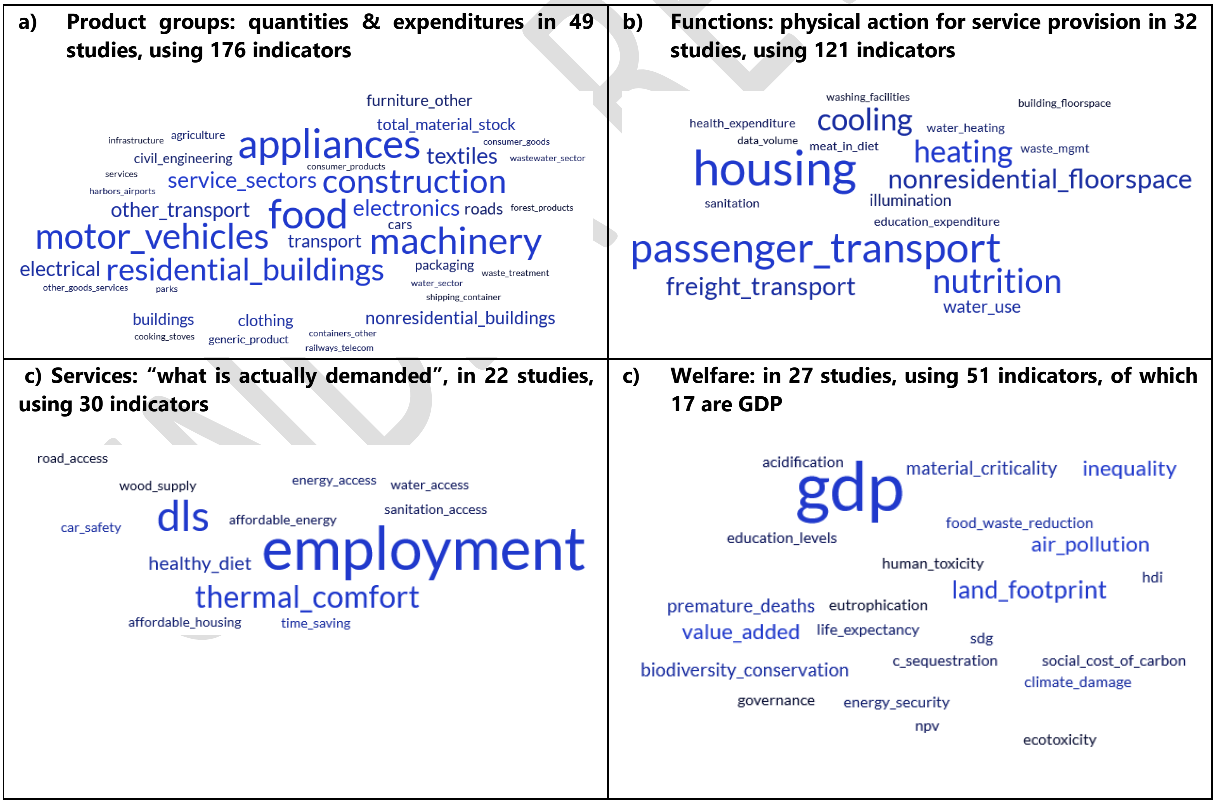

Figure 2: Indicators for product groups, functions, services and welfare & co-benefits used in the reviewed literature. For this grouping, we draw on the Energy Service Cascade (Kalt et al., 2019)*. We add welfare & co-benefit indicators which are defined at macro-level. For details on the definitions, accounting methodology of the cascade elements, and counts by item please see supplemental information section 2.*

3.1. State-of-the-art in non-equilibrium LEMD modelling

We identify substantial novelty in the emerging field of stock-flow consistent (SFC) Ecological Macro-Economics, which so far has mainly dealt with energy and GHG emissions (Jackson and Victor, 2020; Jacques et al., 2023; Nieto et al., 2020). These studies aim to use thermodynamically appropriate production functions including energy/exergy and materials, also complying with stock-flow consistency. Extending model scopes to material cycles has begun for global transport and the transition to electric vehicles (Pulido-Sánchez et al., 2022) and in a global IAM approach (Capellán-Pérez et al., 2020). This research line seems highly relevant for LEMD scenarios. See supplemental information section 4 for a detailed discussion of each study.

(Dafermos et al., 2017) apply the post-Keynesian, Stock-Flow-Consistent (SFC) approach with Georgescu-Roegen's flow fund model to the global economy. Highly innovatively, this model explicitly formalizes monetary and physical stocks and flows, complying with financial accounting rules and the Laws of Thermodynamics. The model encompasses material extraction, recycling, energy use, and GHG emissions in a stylized semi-empirical manner, used in exploratory scenarios. Similarly, (King, 2020) presents a stylized model with monetary and biophysical stock-flow consistency (SFC), implemented in System Dynamics using Input-Output Tables. They consider a finite, regenerating natural resource and energy availability already in their production functions, which indirectly constrains output due to its essential role for capital operation and sustaining the population, as well as labor availability constraints. Data-rich applications of the MEDEAS model built on these principles have been presented for electric vehicles (Pulido-Sánchez et al., 2022) and for a global IAM study (Capellán-Pérez et al., 2020).

3.2. State-of-the-art in Environmentally-Extended Input-Output Analysis LEMD modelling

IO studies usually exogenously impose reductions and shifts in final demand, using the static, demand-driven Leontief production function to model industry’s responses. Sectoral granularity is medium to high, depending on the choice of the multi-regional input-output model (MRIO). Economy-wide feedbacks are ignored, e.g., under-utilized capacity, (un)employment, industrial structural change (including industry material stocks), marginal technology adoption. Interactions between sectors and final demand are typically expressed in monetary terms. Rarely physical waste by-products in production are modelled, using hybrid IO technique of ‘waste input-output analysis’ (Nakamura and Kondo, 2009). However, substantial limitations exist, because statistics on industrial waste by-products and end-of-life waste suffer from considerable quality issues (Tisserant et al., 2017). Hybrid approaches combining MRIO with LCA are used for comprehensive supply chain coverage and detailed process representation, however due to high time and data requirements, this is usually only applied to specific products/industries/technologies. Next steps for EE-IO include better representing secondary materials processing and recycling, improving the robustness of IO tables esp. for the Global South, representing novel technologies and sectors, dynamic modelling of future industrial structures, including production capacity and material stock models; and developing physical IO models (Bruckner et al., 2019; Wieland et al., 2022). These steps will improve material stock-flow consistency beyond price assumptions, and enable linking production explicitly to service provisioning, rather than via monetary final demand alone. See supplemental information section 4 for a detailed discussion of each study.

The reviewed studies start by developing changes to final demand, based on stakeholder workshops on sufficiency and green consumption (Vita et al., 2019), the SDG target on access to 'all-season' mobility infrastructure (Wenz et al., 2020), hypothetical product light-weighting, lifetime extensions, and improved recycling (Donati et al., 2020; Wiebe et al., 2019), and food waste reductions (Garvey et al., 2021) (Hayashi et al., 2022). Some change the fixed Leontief 'production recipe' (input-output coefficients), while others hold them constant, to model the resulting economy-wide material and energy use as well as GHG emissions. Detailed LCA data is sometimes used to either disaggregate sectors, or translate specific measures into more aggregate sector and final demand categories available in an IO model.

(Gast et al., 2022) conduct a highly innovative global assessment of supply-side industrial symbiosis potentials for steel, cement, paper, and aluminum industries for the year 2017, hybridizing MRIO with MEFA. They find that even major changes to by-product utilization from cement production yields -7% GHG mitigation potentials. If industrial symbiosis is to be promoted, the top priorities are intensified utilization of other cementitious materials and flue gas heat recuperation for electricity generation and heat exchange.

3.3. State-of-the-art in econometric modelling and forecasting

The main strength of this approach is that it does not rely on restrictive assumptions regarding agents and firms' behavior. Three key limitations for LEMD modelling exist: models display high path-dependency and often require complementation with other models. Often simplified stock-flow dynamics are used, depicting materials-oriented measures only through changing demand-price elasticities. Energy use and rebound effects driven by general equilibrium dynamics are often not accounted for, potentially overestimating low demand potentials.

(Pollitt et al., 2020) employ the E3ME model to assess the impact of materials taxation for the carbon-intensive sectors basic metals (steel, aluminum) and cement. They draw on material use rates from

MFA (Pauliuk et al., 2016) to estimate sector unit costs and modify input-output coefficients and impose exogenous assumptions about energy intensity. They show that a €80/tCO2 materials tax reduces the EU's energy-related emissions by 6% and process emissions by up to 40%, without carbon leakage, with minimal GDP impacts and slight employment reductions.

(van Ruijven et al., 2016) 2016 rely on carefully selected regression models to build a relatively detailed bottom–up steel and cement model embedded in a long-term global energy system model. They generate future projections of steel and cement demand based on the SSP2 scenario. While they show rapid increases in absence of climate policies, by 2050 steel and cement demand can decrease by 80–90% and 40–80% below 2010 level if a carbon tax of 100 $/tCO$_2$ + 4%pa is imposed. Yet, availability of CCS plays a major role.

(de Souza and Pacca, 2023) evaluate the CO2 mitigation potential of circular economy strategies considering jointly the cement and steel industries in Brazil: recycled-based EAF and charcoal-fired BF in the cement industry; material efficiency, the substitution of supplementary cementitious materials for clinker and the substitution of petroleum coke with alternative fuels. They show that together, circular practices and industrial symbiosis can avoid 52% of the business-as-usual emissions up to 2050 at US$ 10/tCO2e.

A highly innovative and notable effort not yet addressing material cycles explicitly is the MARCO-UK model, first energy-economy-wide model to include thermodynamic (energy) efficiency, and the useful stage of energy consumption (as useful exergy). For example, (Sakai et al., 2019) use MARCO-UK and show that around a quarter of historical UK economic growth since 1970 could be attributed to gains in economy-wide thermodynamic energy efficiency.

3.4. State-of-the-art in equilibrium-based macro-economic LEMD modelling

This tradition usually models lower demand only compared to a growth-oriented business-as-usual scenario; see supplemental information section 4 for a detailed discussion. Most do not find actual absolute LEMD reductions, which is often confusingly communicated by mainly reporting modelled 'reductions' vis a vis a questionable growth BAU scenarios. In the simplest form, elasticities for materials-producing and using sectors are modified exogenously (Zhang et al. 2022). More innovatively, models are extended with the production of specific materials or raw material extraction, however without biophysical consistency across material cycles and stocks (Nong et al., 2023; OECD, 2019; Schandl et al., 2020). Those studies report that even highly ambitious, supply-side resource efficiency and climate change mitigation measures result in a +50-100% increase of global resource use, driving further ecological deterioration. Interestingly, (Nong et al., 2023) nest Leontief production functions into widely used CES functions by introducing 'technology bundles' for three key industries—

steel manufacturing, land transportation, and electricity generation, consisting of various technologies using distinct combinations of inputs, capturing practical constraints in substituting labor and capital between technologies, at least in the short-term. Material stocks and service provisioning are usually not included in non-monetary units, except when combined with an explicit material stock turnover model from the MEFA tradition (Cao et al., 2019). They assume perfect factor allocation, full capacity utilization and rational agents (‘homo oeconomicus’), which is questionable, esp. because LEMD probably results in under-utilized capacities, dis-equilibrium due to oversupply, e.g., fossil fuels and products using them, as well as early decommissioning of stranded assets. Widely used CES industrial production functions assuming full substitutability of energy violate thermodynamics, ignoring that final energy/exergy are complements in industrial production (Keen, 2021; Keen et al., 2019; Stern, 2011)~~.~~ Introducing full thermodynamic consistency for material cycles, energy use, material stocks, as well as extending service provisioning beyond monetary valuation are required.

CGEs can also be combined with dynamic MEFA to explicitly and biophysically model stock-flow dynamics. (Cao et al., 2019) combine a CGE model with a dynamic MEFA for residential buildings in China, considering service and stock saturation (m^2 per capita). Modelled construction material use feed into their CGE model to quantify economy-wide effects, ensuring both biophysical and monetary consistency. Exogenously assumed lower building service saturation levels and delayed stock development could save 25.4 Gt in embodied CO2 emissions in the construction sector, partially offset by economy-wide rebound effects of 18.8 Gt, assuming GDP remains constant and is re-distributed to other sectors. (Tong et al., 2022) investigate global shifts from internal combustion engines to battery electric and fuel cell vehicles, covering supply and demand for platinum group metals and GHG emissions, combining the IMED CGE with a dynamic MEFA for cars. They model several scenarios for future car stock saturation levels, structured via Multi-Level Transitions Theory. They highlight potential future mismatches between platinum group metals extraction, vehicle production, and end-of-life vehicles for recycling.

Highly innovatively, (Bachner et al., 2021) extend a CGE by explicitly modeling service demand using non-monetary indicators, construct an alternative wellbeing indicator, and quantify co-benefits and avoided burdens, for Austria. They model measures avoiding, shifting and improving demand for buildings and transport. They use an energy-focused building vintage model (m^2 of floor area), and represent transport modes and travelled distances, which are later converted to monetary units via stock-flow-service relations. Their alternative wellbeing indicator covers monetary welfare effects for private and public consumption, co-benefits such as avoided air pollution incl health impacts, and changes in leisure. In their ambitious climate transformation scenario, they find GDP to decline slightly, while societal welfare increases.

3.5. State-of-the-art in partial equilibrium LEMD modelling

PE sector models are technology-rich optimization models built on thermodynamic consistency for their respective sector, with exogenous demand either from GDP, population or specific material/energy demand dynamics using econometric methods, and often assumed automatic material and energy efficiency gains. PE models are increasingly combined with models from other traditions, especially for modelling demand for energy services, which has been presented at high granularity using physical service provisioning indicators (Gaur et al., 2022). PE often draws on data from other traditions, such as LCA, engineering, or industrial ecology, requiring complex and time-intensive data harmonization. Usually, there are little considerations of rebound effects (van den Berg et al., 2019). Future decoupling of economic growth from energy and material needs to be exogenously assumed. It is so far unclear, if a high level of detail for consistent service and material demand in PE IAMs is feasible, or if soft-coupling with other models or innovative multi-model analysis like e.g., applied in (Gaspard et al., 2023) is more advantageous. See supplemental information section 4 for a detailed discussion of each study.

(Grubler et al., 2018a) present the groundbreaking Low Energy Demand (LED) scenario, covering service provisioning not only for energy services but for thermal comfort, consumer goods, mobility, food, commercial and public buildings, as well as upstream freight transport and industry activities, quantified at the global level via the hybrid MESSAGEix-GLOBIOM model. The scenario combines reduced energy and material demand with substantially increased supply chain and end-use service provisioning efficiency, finding that final energy demand could decrease by - 40% until 2050. Focusing on one country, (Barrett et al., 2022) report a reduction of -52% in energy demand by 2050 compared to 2020 in the UK, resulting from technical and behavioral measures without compromising wellbeing. To consistently represent all services, they enrich the macro-economic model TIMES using an MRIO, apply dynamic MEFA for construction, buildings and the food industry, and a bottom-up transport model. In this 'whole-systems' model, industry interacts with transport services, construction, building stocks and their lifecycle, and nutritional requirements, as well as endogenous economic growth. A high level of detail for options to 'improve' energy efficiency, 'avoid' energy use and 'shift' to more efficient energy demand provision can be covered. Also modelling lower energy service demand for one country, (Oshiro et al., 2021) find a potential of -37% reduction in final energy demand by 2050 for Japan. They apply the technology-rich PE energy systems model AIM/Enduse for Japan, which is exogenously driven by GDP and population and as their industry sector is not linked to final demand, dematerialization and material efficiency factors (elasticities) are exogenously modified and no material cycles or stocks are depicted.

There are attempts to extend PE IAM models for an improved material representation either focusing on specific sectors like steel and iron (Zhang et al., 2019), food (Springmann et al., 2018), forests (Daigneault et al. 2022) or materials like plastics (Stegmann et al., 2022) or on specific measures like e.g., a global transition to autonomous shared vehicles quantifying operational and industrial energy use, basic materials (cement, iron/steel, plastics) and GHG emissions (Akimoto et al., 2022). There are also attempts to incorporate ores and metal extraction and processing sectors, typically absent in PE models, incorporating material availability constraints over time, addressing measures such as technology lifetime extension, recycling, and material intensity reduction (Tokimatsu et al., 2018). They find that metal requirements vary significantly across scenarios and uncertainties, with some metals, including Vanadium, consistently deemed critical. Combining dynamic MEFA with a PE leads to stock-flow consistency, which increases the credibility for medium- to long-term projections of structural change and material availability, in particular. (Kermeli et al., 2022) find steel demand for 2100 to be -75% lower than in flow-based estimations when explicitly modeling steel stock-flow dynamics, incl. end-of-life recycling and assumed per capita saturation of stocks. (Lechtenböhmer et al., 2015) assess how re-industrialization and energy-intensive industries can be aligned with the German Climate Protection Law. The study employs a technology-rich energy systems PE model and a simplified stock-flow MEFA model. Re-industrialization could impede Germany's energy and GHG targets due to limited efficiency potentials, requiring further demand-side measures. (Deetman et al., 2021, 2020, 2018) combine an IAM with dynamic stock-flow MEFA endogenously modeling global material requirements for electricity, buildings, vehicles and appliances under climate policy scenarios. Innovatively, this approach provides biophysical consistency between the demand for service provisioning, material cycles and stocks, including repercussions for industry.

Two multi-model studies driving PE energy system models with exogenously driven demand from other modules and/or demand-side measures are also identified. (Costa et al., 2021a) soft-couple PE, LCA, MEFA and MRIO modelling to assess European net-zero pathways. They find that behavioral changes could contribute -20% of the GHG reductions needed for net-zero by 2050. (Günther et al., 2019) combine resource efficiency and demand-side measures to model net-zero pathways for Germany. They present a technology-rich multi-model analysis driven by exogenous assumptions for sub-modules for transport, heating and cooling in buildings, agriculture and forestry, which then drive a PE energy optimization model, a waste module, and a global trade model. The most ambitious scenario combining phase-outs, supply-side efficiency and technological progress with demand-side measures shows that until 2050, GHG emissions can be reduced by -95%, raw material consumption by -56% and final energy consumption by -24%.

3.6. State-of-the-art in System Dynamics LEMD modelling

We find several studies integrating environmental, biophysical, economic and social considerations. System Dynamics models simulate dynamic interlinkages between multiple evolving parts of a system. The complexity and traceability of models limits system expansion, their simulation approaches are validated on historical relationships, and the structures of the models can limit which scenarios can be modeled, or would require exogenously overruling parts of the dynamic system. More systematic coverage of material cycles, stocks and esp. service provisioning could make this tradition highly interesting for LEMD scenarios. See supplemental information section 4 for a detailed discussion of each study.

(Allen et al., 2019) simulate supply- and demand-side measures for Australia, incl. economy-wide raw material extraction, final energy, and selected material stocks. Their 'Sustainability Transition' scenario achieves 70% progress towards the SDGs by 2030, while focusing either on economic growth, social inclusion, or green economy strategies achieves limited progress. (Moallemi et al., 2022) model low-demand pathways to achieve the SDGs, depicting service provisioning and socioeconomic wellbeing via a capability’s perspective, and use life expectancy and the Human Development Index as headline indicators. Industry and the economy are only represented via aggregate Cobb-Douglas production functions. They find that multiple early interventions are necessary to facilitate long-term SDG progress after 2030. (Neumann and Hirschnitz-Garbers, 2022) quantify how a 100% renewable energy system globally impacts material reserves and utilization of bulk- and precious metals. They find that improved recycling can reduce potential economic constraints due to the depletion of high-grade raw material reserves. (Sverdrup and Olafsdottir, 2023) extend the World7 IAM with complete cement, sand and metal cycles, incl. energy use and GHG emissions, complying with mass and energy balance. Their low-demand scenario assumes a global stabilization and then decline of concrete stocks per capita, low carbon energy and industrial processes, as well as improved recycling and material substitution.

(Kumar et al., 2021) present a noteworthy and innovative model of the energy and materials required to achieve development goals in India, e.g., food and water security, housing and clean energy for all, sufficient healthcare and access to clean cooking and transport. Sectoral growth is also driven by a soft-linked CGE model to ensure macro-economic consistency. Highly innovatively, they explore how urban built form shapes housing and transportation resource and energy demand.

3.7. State-of-the-art in Life Cycle Assessment LEMD modelling

Using detailed LCA for system-level modelling and LEMD scenario analysis requires methodological advancements and models from other traditions to overcome typical limitations, especially of attributional LCA. Recent advances include consequential LCA, as well as upscaling through combining LCA with dynamic MEFA and its stock-flow models. See supplemental information section 4 for a detailed discussion of each study.

(Verhoef et al., 2018) estimate the energy savings potential of additive manufacturing across multiple sectors using attributional LCA, and find substantial technical energy saving potentials, not considering rebounds nor shifts in demand. (Van der Voet et al., 2019) combine consequential LCA with a stock turnover model to assess metals production and recycling for future energy scenarios. They find that increasing secondary metals use could reduce life-cycle emissions substantially at the global level, but only in the second half of the 21st century when end-of-life metals increasingly become available from ageing material stocks. (Buschbeck and Pauliuk, 2022) use consequential LCA to assess when substituting emission-intensive materials with timber leads to net GHG savings, considering that growing forests are also natural carbon sinks. They find that short term (<25 years), intensive wood harvest is not climate beneficial, while long-term potentials depend on the speed of energy system- and industrial decarbonization.

An important contribution to LEMD futures is the modelling of the required resources and emissions for sufficient consumption, 'just' access to basic services, and DLS, using LCA. (Bjørn et al., 2018) use a hybrid of attributional LCA and MRIO to estimate the climate impact of surveyed household consumption baskets for ten service demand areas in Denmark, finding required reductions of supply- and demand-side emission intensities by factor 2-14 to comply with climate targets. (Rammelt et al., 2022) estimate life-cycle impacts of 'just access' to energy, water, food, housing and transport drawn from SDG indicators globally, and eclectically combine attributional static LCA factors. In 2018, eradicating severe deprivations could amount to 2–26% additional impacts on climate, water, land, and nutrients, amounting to similar impacts induced by the wealthiest 1-4%.

Recently, research on DLS has proliferated, with studies addressing a common set of products and services required for Decent Living, including housing, mobility, and nutrition, for some Global South countries (Mastrucci et al., 2020; Mastrucci and Rao, 2019; Rao et al., 2019) and globally (Jarmo S. Kikstra et al., 2021; Millward-Hopkins et al., 2020). Detailed LCA inventories for the DLS dimensions are directly linked to the use of materials and stocks by households, MRIO-based footprints address truncation errors and dimensions where the linkage with materials is less clear (nutrition, education, healthcare, and socialization), and IAMs such as MESSAGEix-GLOBIOM can be used to estimate impacts from energy supply and decarbonization. Food and transport dominate energy for decent living, while housing dominates upfront energy investment needs; in sum, 149-156 EJ/year of final energy would be needed after 2040, ~60% less than today (Jarmo S. Kikstra et al., 2021; Millward-Hopkins et al., 2020). Nutrition and mobility at DLS globally would require 6 t/cap tons of raw materials, and stocks of ~43 t/cap in buildings, infrastructure and industrial assets (Vélez-Henao and Pauliuk, 2023).

3.8 State-of-the-art in dynamic Material and Energy Flow Analysis LEMD modelling

Dynamic MEFA focuses on a thermodynamically consistent representation of material cycles and material stocks at national to global scales, either for sectors or materials, usually treating socio-economic dynamics as exogenous. A rapidly growing number of studies investigates how lower demand for material product stocks is a crucial demand-side measure, which combined with material efficiency, circular economy strategies, technological improvements in industry and energy system decarbonization can achieve 1.5-2°C compatible pathways. For this purpose, dynamic stock-flow modelling is often combined with energy statistics, LCA and EE-IO to model supply chain energy use and GHG emissions. First combinations with macro-economic models are also identified. See supplemental information section 4 for a detailed discussion of each study.

A common approach is to study the technical potential of reducing turnover across the entire material cycle, by combining possible technical changes in all process steps, including manufacturing (light-weighting and less scrap), longer and more intensive use, and better re-use and recycling (Ciacci et al., 2020; Kalt et al., 2022; Pauliuk et al., 2021; Song et al., 2023; Wang et al., 2022; Watari et al., 2022; Zhang et al., 2018). In those studies, material cycles and stocks are linked to energy use and GHG emissions, enabling thermodynamically consistent modelling of GHG mitigation potentials from materials-oriented strategies. As (Krausmann et al., 2020) show for 2015, ~40% of global energy use and GHG emissions were required by industry, transport and construction for stock-building, and ~60% for stock utilization and service provision.

In addition, it is common to exogenously assume lower stock growth or lower stock saturation levels in the future, which inevitably leads to lower material and energy demand, although with substantial delays (Zhou et al., 2022) (Watari et al., 2022) (Watari et al., 2020; Watari and Yokoi, 2021) (Krausmann et al., 2020) (Cao et al., 2020) (Cao et al., 2021) (Pauliuk et al., 2021; Zhong et al., 2021) (Kalt et al., 2021) (Ciacci et al., 2020). Saturated/stabilized material stocks, combined with longer lifetimes and high recycling would drive substantial reductions of raw material extraction and subsequent energy use. The socio-economic feasibility of lower in-use stocks is, however, assumed and not endogenously modelled nor explained. These scenarios therefore show the extent to which demand-side reductions would be needed to comply with global climate targets, under realistic supply-side improvements and industry decarbonisation pathways.

Dynamic MEFAs are also used to model land-use and the industries extracting and processing biomass for food, feed, biofuels, material use and as potential carbon sinks. (Mayer et al., 2022) model the

European food and land-use system, combining dynamic MFA and consequential LCA. Several low demand scenarios explore alternative diets and variable non-food product demand for biofuels and material use. They find that agroecology can mitigate some emissions, but only if combined with less meat consumption, a smaller-sized agri-food system, and if livestock systems are better aligned with regional feed production capacities. (Bailis et al., 2015) quantify the carbon emissions due to pan-tropical woodfuel supply and demand for subsistence cooking and commercial uses, using spatially-explicit information on supply, travel distances and demand. They find that 27-34% of woodfuel harvested exceeds annual biomass regrowth, resulting in ~2% of global and ~4% of pan-tropical GHG emissions. (Le Noë et al., 2021) analyze timber harvest and natural carbon stocks in forests from 1990-2020, using an ecologically-informed dynamic MFA for global forests. They find that if harvest had not increased since 1990, forests could have stored 4.9 Gt of additional carbon. A “no harvest” scenario would have increased biomass carbon stocks by 49.1 Gt, showing substantial mitigation potentials of lower wood use.

3.9. State-of-the-art in Agent-Based LEMD modelling

ABMs enable detailed representation of (inter)actions of heterogenous agents resulting in emergent non-linear dynamics, hence they can assess distributional aspects, diffusion and uptake of innovations, or shocks and climate damages (Lamperti et al., 2019, 2018) Many studies build on Post-Keynesian theory and evolutionary economics, or derive agent behavior from qualitative research and transdisciplinary co-production. Focusing on agent’s decision-making necessitates granular data, which so far results in less emphasis on industrial transformation, as well as data-rich scenarios for material cycles, stocks and energy use. At the national to global levels, ABMs resemble System Dynamics models, as only aggregate agents are considered. For LEMD scenarios, this tradition could be highly useful to model social dynamics and the diffusion of innovations beyond rational optimizers. Given the transdisciplinary, participatory potential to co-develop models and scenarios, this tradition could also be a useful to co-develop locally/regionally grounded LEMD pathways and service provisioning demand together with communities and stakeholders. (Safarzyńska and van den Bergh, 2022) study the impact of unemployment and inequalities on the social cost of carbon. (Yazan and Fraccascia, 2020) and (Koide et al., 2023) present concepts for building data-rich scenarios exploring how a more circular industrial system could be implemented at the household and the firm levels, including consumer and supplier decision-making in response to repairing and refurbishing.

3.10 Quantitative evidence synthesis of mitigation potentials

The reviewed literature finds substantial potentials for reducing material and energy demand, as well as mitigating GHG emissions (Figure 3). For material use, we find reduction potentials from -1 to -80% when considering all study scopes (Figure 3a). Economy-wide reduction potentials of combined supply- and demand-side measures were reported at 56% when compared to historical base year (i.e. last data-driven year), and 2-47% compared to BAU scenarios (i.e. last year of future scenario). The most effective single measure with a -52% reduction of material footprints compared to 2020 is a scenario of global contraction and convergence to DLS (Vélez-Henao and Pauliuk, 2023). For individual sectors, reductions of up to -63% of phosphorous fertilizer in food systems through a combination of technological and diet change (Springmann et al., 2018) and up to -80% reduction of steel demand through LED-type transformations combining supply and demand-side measures (Oshiro et al., 2021) were reported for annual use in 2050 compared to BAU scenario.

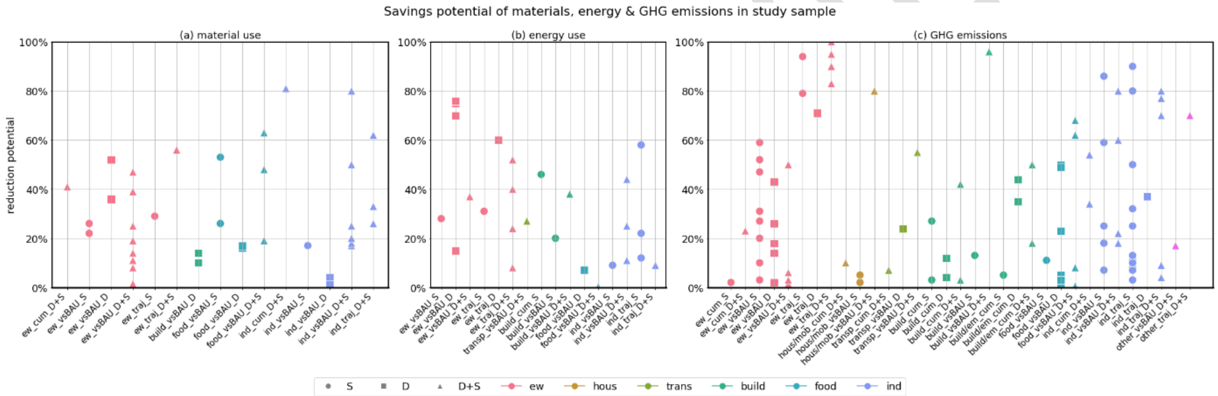

Figure 3: Summary of savings potentials for material and energy use, as well as GHG emissions across all relevant studies, grouped by sectoral and temporal scope, as well as supply-side (S), demand-side (D) and combined supply- and demand-side (D+S) measures. ew = economy-wide, hous/mob= housing & mobility, build = buildings, build/em = buildings embodied flows, food = agriculture & food, ind = industry; cum = cumulative, traj = trajectory from historical base year to scenario year, vsBAU = comparison of annual reduction to business-as-usual scenario). Please note that the exact time and sectoral scopes, as well as mitigation measures within categories might still differ (e.g., some studies accounting cumulative emissions from 2010-30 vs. 2010-50, or industry reduction potentials including estimates for different materials industries like steel, copper, etc.). Due to the comparison to either the historical base year, or a base scenario, values can still be compared. For a detailed account of scopes, we refer to SIX.

For energy use, we find reduction potentials of -0.3 to -76%, when considering all study scopes (Figure 3b). The strongest economy-wide reduction potential of up to -76% in 2050 annual global energy demand was reported for demand reductions to DLS (Jarmo S Kikstra et al., 2021), representing a ~60% reduction when compared to historical base years (Millward-Hopkins et al., 2020). These are followed by LED-type transformations combining supply- and demand-side measures with reduction potentials between 40-52% compared to historical base years (Barrett et al., 2022; Gaur et al., 2022; Grubler et al., 2018a). For buildings, we find material substitution to reduce cumulative energy use from 2020-50 in India by -46% (Kumar et al., 2021). For industry, we find global energy use for steel and cement production reduced by -22% and -58% though a carbon tax of 20-100$/tCO2 respectively (van Ruijven et al., 2016).

For GHG emissions we find reduction potentials from -1 to -100% when considering all study scopes (Figure 3c). Economy-wide emission reductions between -70% and -100% (i.e. net-zero emissions) are achieved in several studies through combined demand and supply-side measures (Barrett et al., 2022; Costa et al., 2021b; Gaur et al., 2022; Günther et al., 2019; Moallemi et al., 2022). Obviously, the decarbonization of the energy system plays a large role for reducing GHG emissions. Large reductions of economy-wide emissions of individual measures were reported for 3D printing (-27% annual), remote work and active travel (-26%), demand-reduction (-23% cumulative), local/sharing service economy (-18%) and vegan diets (-14%). For additional insights on sectoral potential, please consult the supplemental information section 3.

4. Discussion

4.1. Sector definitions, system boundaries, and modelling principles to depict industrial networks

We identify the below entry points to model the biophysical basis of LEMD scenarios in the reviewed literature, suggesting the need for a unified system definition and shared modelling principles to enable comparability, leverage model combinations, knowledge accumulation and facilitate evidence synthesis.

UNFCC emissions accounting defines the following broad economic sectors: energy supply, industry, agriculture and forestry and other land use (AFOLU), transport, and buildings (Lamb et al., 2021; IPCC, 2022). This “end-of-pipe” perspective on the ‘sources’ of emissions lacks a differentiation of supply and (final) demand and separates interconnected sectors, which jointly respond to demand by forming an industrial network. Depending on statistical practices across countries, extractive industries are variously allocated across energy supply, industry, construction and AFOLU, hindering systematic analysis of material cycles and energy use.

Energy statistics provide detailed information on supply and use of energy carriers for sectors, production processes and final demand, and distinguish between primary, final, and useful energy stages. Leveraging this information is highly relevant for LEMD modelling, to understand potentials and limits of fuel switching, electrification and energy efficiency (Cullen and Allwood, 2010; Sakai et al., 2019).

Raw material extraction and land use, which constitutes the ‘start‘ of material cycles, is reported along boundaries established in the System of Environmental-Economic Accounting (SEEA) and focuses on types of raw materials, e.g., biomass, non-metallic minerals, ores and metals, as well as fossil energy carriers, lacking inherent sector resolution (Krausmann et al., 2017). This data is increasingly used across traditions, requiring modelers to compile data on material cycles and waste by-products occurring at each production step, linkage to input-output tables for sector resolution, as well as differentiation into final products accumulating as stocks (Plank et al. 2022; Streeck et al. 2023a,b). Industry production statistics, such as those for cement or steel, focus on specific stages of the value chain and material cycle, often used eclectically for selective coupling into models.

Waste statistics, if available at all (Tisserant et al., 2017) (United Nations Environment Programme and International Waste Management Association, 2015), cover only what is officially collected and managed in institutionalized waste management systems, leaving large unknowns. Systematic use requires time-intensive mass-balancing and harmonization to quantify the end-of-life part of material cycles. Some models therefore resort to estimating waste flows as a function of GDP or population, violating thermodynamics i.e. mass-balanced consistency with material extraction, industrial processing, and material stock dynamics.

To model material cycles for LEMD scenarios, we suggest an economy-wide system definition for industry following the SEEA[2] framework which covers extractive sectors and basic industries (agriculture, forestry, mining, refining, processing), manufacturing, construction, energy supply to industries and to final demand, as well as service sectors (transport services, health, financial sectors, etc.), and repair, recycling and waste management sectors. LEMD modelling could be substantially advanced via a consistent depiction of the industrial system regarding physical and monetary layers, supply and demand, interactions between industries, as well as stock vs. flows, at least enabling a clear documentation of any specific model scope to facilitate comparability (Figure 5). Ideally, LEMD scenarios are based on a consistent model of material cycles, from extractive industries to industrial assets and infrastructure to the waste management and circular industries, which is essential for delineating and capturing the implications for energy use and emissions.

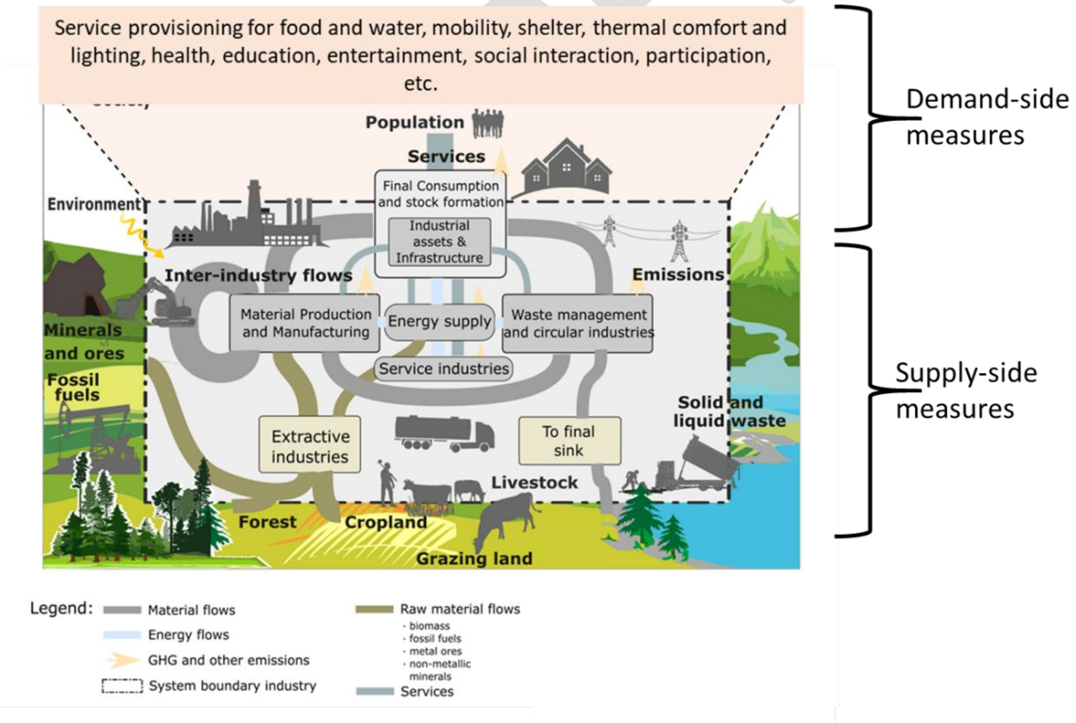

Figure 5: Conceptualizing socio-economic material cycles, energy use, economic sectors and service provisioning, drawing on (Chen and Graedel, 2015; Haberl et al., 2019; Kalt et al., 2019).

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[2] The SEEA draws on economy-wide material flow accounting for raw material extraction, energy statistics for sectoral energy use, as well as UNFCC emissions reporting (Krausmann et al., 2017; OECD, 2008) into a (relatively) coherent framework integrating economic, social and environmental information (UN, EU, FAO, IMF, OECD, WB, 2014), however not reporting full material cycles yet.

4.2. Modelling industrial production for LEMD modelling

LEMD modelling of industrial networks needs to depict how supply reacts to changes in demand and service provisioning. At the level of the industrial sector, so-called ‘production functions’ model the input of labor, capital, energy, and materials in response to intermediate and final demand for each sector’s output. A shared understanding and use of appropriate production functions that are consistent across aggregation levels is crucial for LEMD modelling (Keen et al., 2019; Pauliuk et al., 2017; Stern, 2011) (see supplemental information section 6). For a consistent description of material and energy flows and stocks, the mass und energy balance of industrial sectors needs to be respected, which includes a proper accounting of by-products, waste, and emissions. Engineering limits to efficiency need to be respected by the different modelling traditions to prevent the inclusion of unrealistic or even infeasible efficiency gains, including aggregate decoupling of economic growth from energy and materials. Production models should discern different quality grades of energy, such as primary vs. final energy/exergy or high, medium and low temperature heat as well as the different material quality grades required for production. Production functions should allow for varying or incomplete capacity utilization, a common phenomenon in LEMD futures. An option to include more realism in production modelling is to split inputs into fixed inputs that scale with capacity and operating input that scale with the output.

While production functions model individual sectors, models of markets and market mechanisms are needed to determine the market share of different suppliers. A crucial feature of interdisciplinary LEMD industry modelling is to explicitly consider market mechanisms not only for the industrial commodities but also for production factors labor and capital as well as materials and energy carriers. Here, market models from the different disciplines can be combined to accurately reflect the nature of individual markets (equilibrium, disequilibrium, controlled or free).

4.3. Service provisioning and demand modelling

Demand-side LEMD transformation options become visible when making the relations between human wellbeing, service provisioning, product stocks, industry and environmental impacts explicit and assessing decoupling potentials at each step of the so-called Energy Service Cascade[3] (Fig. 5). The reviewed literature predominantly focuses on the demand for shelter, mobility, nutrition and thermal comfort, and less on sectors like health, education and leisure activities (Figure 2). What is actually modelled in most studies are product stocks such as the number of appliances, or weight of buildings (per capita), as well as functions provided by stocks and energy use, such as square meter of well-tempered living space. Service provisioning of 'what is actually demanded' is usually done via exogenously imposed levels of functions, either derived from policy targets, trans-disciplinary deliberations aiming at political legitimacy, or via the researcher's choices.

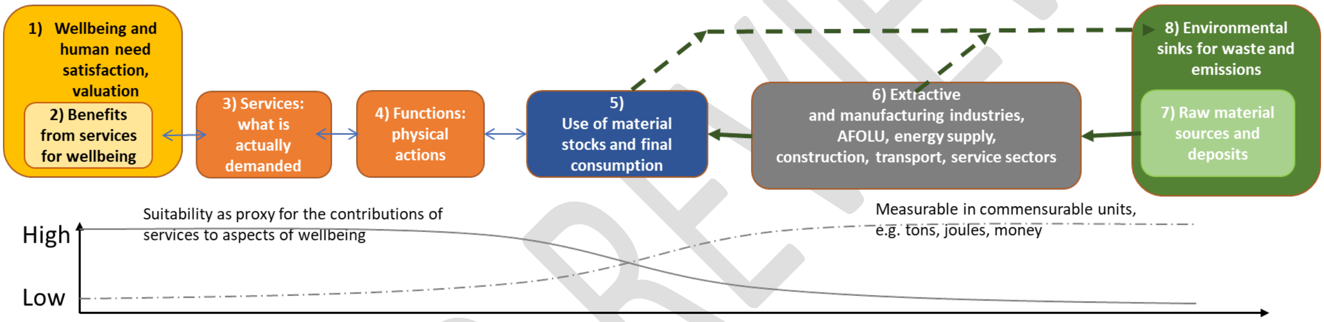

Figure 4: Relations of wellbeing, human needs, to service provisioning, material stocks and economic production, drawing on natural resources, resulting waste and emissions. Adapted from (Kalt et al., 2019).

In the reviewed literature, we find three approaches to modelling demand in general and for service provisioning specifically, via 'consumption functions', which expresses how a basket of goods and services is chosen under constraints. This requires a choice of commensurable units, as well as theoretical assumptions about how actors decide among competing alternatives. First, optimization which is widely used in macro-economic traditions uses variations of (bounded) rational choice theory and monetary valuation, assuming maximization of 'utility' (consumption). Expanding the notion of utility to leisure, unpaid care work, quality of life and wellbeing, as well as non-monetary values seems necessary. Second, exogenously given policy-relevant targets, or extrapolations based on observed economic dynamics are also used, providing useful what-if insights, however often lacking behavioral foundations about who, how and why. Third, policy measures as well as future consumption baskets

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[3] As Virág et al. (2022) demonstrate for mobility, more distances travelled don't translate into a better service ('being able to reach places'), or higher wellbeing contributions, and a more explicit representation of the link between human wellbeing, needs satisfaction, the required product functioning and in-use stocks is needed to better understand decoupling potentials on the social side. Such research on low demand scenarios the stock-flow-service-wellbeing nexus is only in its infancy.

developed via transdisciplinary co-creation efforts, such as in citizen assemblies or stakeholder workshops, are highly innovative and promising to achieve transformative impacts and insights.

4.4. A roadmap for improved LEMD scenario modelling

We summarize our insights as eight recommendations for future LEMD modeling to contribute more nuanced, biophysically consistent, and policy-relevant scenarios and insights for climate change mitigation and sustainability. For an extended discussion, see supplemental information section 7.

Interdisciplinary combinations of modelling principles and traditions yield more robust, nuanced and policy-relevant insights than any single tradition alone can provide. Combining models requires carefully considering and potentially harmonizing differences in system definitions and modelling principles (see section 5.1.). Collaborating with the social sciences helps to understand how demand and service provisioning are organized, what acceptable and just low-demand futures could be like, and how they might be achieved.

Thermodynamic and Biophysical Consistency: To capture economy-wide and time-dependent implications of LEMD scenarios, it's crucial to achieve consistency across material cycles, material stocks, energy use, by-products and waste, and emissions. Ideally, this is achieved at high granularity, spanning from primary extractive sectors, industry and manufacturing, final consumption, recycling, and waste management, to service provisioning. Ideally, economic, biophysical, and social data layers are consistently integrated, complying with their respective rules of consistency.

Stock-Flow-Service Nexus: The efficiency of transforming material and energy into services hinges on existing material stocks in products, buildings, and infrastructure. Ideally, these relations are consistently represented in models. The SDGs and other policy targets are useful starting points. Transdisciplinary co-creation approaches can be useful to develop context-specific "low-demand" scenarios. Non-monetary service provisioning indicators improve our understanding of the links between wellbeing, human needs, and service provisioning systems.

Wider Spectrum of Supply and Demand-Side Measures: Enlarging the solution space is necessary to develop net-zero compliant LEMD pathways, which might result in dis-equilibrium, stranded assets, and early decommissioning. This includes standard economic instruments, as well as regulatory measures, product standards, institutional changes, government activities, financial markets, changes in settlement patterns and urban forms, as well as socio-behavioral dynamics.

Assess Telecoupling in Global Supply Chains: Modeling global supply chain interactions is critical to identify potential rebound effects and burden-shifting, as well as economic winners and losers in LEMD transformations. The different layers of industrial assets (capacity, capital, material stocks), as well as the different stages in supply chains (resource extraction, material production, manufacturing, waste management, recycling, energy supply and service sectors) should therefore be explicitly represented, to understand capital constraints for LEMD scenarios and potential global re-allocations of capital, labour, and natural resources, as well as their transport implications, across global supply chains.

Resource Constraints, Vulnerability, and Resilience: Modelling should address the complex socio-ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations and the biosphere. The environment is more than a repository of resources to be extracted and a sink for waste and emissions. Complex trade-offs exist between different environmental aspects, ranging from the climate and biodiversity crisis to other Planetary Boundaries. Some of the reviewed models can address some of these concerns (see supplemental information section XX). Ideally, the social implications of deep structural changes as well as societal crisis for labour, incomes, skills, and inequality are also assessed.

Improved Research Infrastructure, Open Science and Community Standards: Findable, Accessible, Interoperable, and Reusable (FAiR) research findings and models are crucial for cumulative research and evidence synthesis (Hertwich et al., 2018; Pauliuk, 2020; Wilkinson et al., 2016). Ongoing community efforts, for example by the Integrated Assessment Modeling Consortium[4] (IAMC), the International Transport Energy Modeling (iTEM) network[5], and the Energy Demand changes Induced by Technological and Social innovations (EDITS) network[6] aim to diversify and broaden contributions to the 7th IPCC assessment cycle and beyond. We recommend that LEMD modelers consider the data reporting requirements of such assessments early on in their model development, ideally developing a shared ontology across traditions and models, to facilitate comparability and evidence synthesis.

Connecting to the updated Shared Socioeconomic Pathways (SSPs) is timely, so that LEMD scenarios can readily contribute to evidence synthesis and global assessments reports. The SSPs are a common framework connecting research on mitigation, adaptation, and impacts. Since their inception in 2014 they have been developed further (Green et al., 2022; van Ruijven et al., 2022), with substantial quantitative updates[7] to be released in 2024. More fundamental revisions are also being discussed. Ideally, future LEMD modeling takes up the most recent SSP version and contributes to ongoing discussions about a new low-growth/low-demand SSP. Explicitly quantifying service provision levels in the SSPs is essential for comparability across LEMD models. Additionally, a significant challenge for

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[4] https://www.iamconsortium.org

[5] https://transportenergy.org/

[6] https://iiasa.ac.at/projects/edits

[7] https://depts.washington.edu/iconics/, https://www.iamconsortium.org/event/iconics-and-iamc-joint-webinar-shared-socioeconomic-pathways-ssps-update/

new entrants in IPCC scenario submissions is ensuring their models generate sufficiently consistent data for comparison with larger-scale models, while maintaining sectoral or national specificity.

5. Conclusions

We assessed the findings and underlying models of 77 state-of-the-art studies originating from nine modelling traditions published between 2014-2023, which explore Low Energy and Material Demand (LEMD) futures. Interdisciplinary combinations of modelling traditions are on the rise, leveraging their respective strengths for more nuanced and robust insights. We do find large mitigation potentials for materials, energy and GHG emissions across studies, given substantial challenges in extracting, harmonizing, and synthesizing findings. We recommend the development of shared concepts and ontologies, as well as widespread adoption of open science and FaiR data principles, to facilitate comparability as well as systematic and robust evidence synthesis.

We find that service provisioning and demand are increasingly represented via non-monetary indicators for end-use products and the physical actions they provide. An important next step is to assess how much is sufficient for decent living and wellbeing, to develop justified and acceptable scenarios across different contexts. Few models fully link material cycles, material stocks, energy use, waste and emissions in a thermodynamically consistent manner. Those who do are rather coarse in their representation of socio-economic interdependencies and dynamics driving changes. Models with comparatively better representation of socio-economic complexity and dynamics often do not fully comply with thermodynamic principles. In summary, the reviewed models seem to be either too aggregate, or too specific. When considering the multiple properties which are important for modeling industry transformation (detailed physical and economic representation of industrial assets and production flows, detailed representation of the political and legal framework and form behavior given these circumstances, etc.) comprehensiveness at sufficient detail is a criterion hardly achieved.

To improve LEMD modelling, we herein propose a general comprehensive system definition and eight suggestions for future work. A question for further exploration is how the required comprehensiveness and granularity can be achieved in a resource-efficient way, so that real life decisions can be robustly informed.

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