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Industry Transformations for High Service Provisioning with Lower Energy and Material Demand: A Review of Models and Scenarios

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Abstract

Developing transformative pathways for industry's compliance with international climate targets requires model-based insights into how supply- and demand-side measures affect industry, material cycles, global supply chains, socioeconomic activities, and service provisioning that support societal well-being. We review the recent literature modeling the industrial system in low energy and material demand futures, which mitigates environmental impacts without relying on risky future negative emissions and technological fixes. We identify 77 innovative studies drawing on nine distinct industry modeling traditions. We critically assess system definitions and scopes, biophysical and thermodynamic consistency, granularity and heterogeneity, and operationalization of demand and service provisioning. We find that combined supply- and demand-side measures could reduce current economy-wide material use by 56%, energy use by 40% to 60%, and greenhouse gas emissions by 70% to net zero. We call for strengthened interdisciplinary collaborations between industry modeling traditions and demand-side research to produce more insightful scenarios, and we discuss challenges and recommendations for this emerging field.

Contents

1. INTRODUCTION

Global material and energy use and the resulting environmental impacts and greenhouse gas (GHG) emissions are increasing, intensifying the climate crisis (1–3) and transgressing five of nine planetary boundaries (4). Time is running short to mitigate these multiple environmental crises before irreversible tipping points are crossed. This "great intergenerational robbery" (5) requires concerted and transformative action. As three decades of climate mitigation efforts have failed to deliver, a deep transformation away from the prevalent material- and energy-intensive development paradigm and lifestyles seems necessary (2, 6). Industry is at the heart of this transformation.

Yet, most climate change mitigation scenarios that limit the climate crisis to 1.5–2°C of warming explore only a narrow range of the solution space for sustainability transformations (7–9), limiting our collective outlook on desirable, feasible, and sustainable futures. Specifically, they assume unprecedented efficiency improvements (10), rapid decarbonization of energy supply and industry, and gigantic amounts of negative emissions, which are risky and prone to moral hazard (2, 11, 12). As most of these scenarios relate to the shared socioeconomic pathway (SSP) framework (13), they assume substantial economic growth and ever-increasing consumption, with minimal reductions in energy demand (14), and perpetuate global inequalities in energy access (15). These scenarios also do not take into account that materials are required as the biophysical basis of production, consumption, and well-being (16); materials also drive environmental impacts and could be mitigated via materials-oriented strategies (3, 17).

Therefore, alternative perspectives focusing on high well-being with lower energy and material demand have recently gained prominence, widening the solution space. For example, the seminal Low-Energy-Demand scenario introduced the idea that high service provisioning for well-being can be combined with a limit of global warming to 1.5°C without relying on negative emissions (18). The latest report by the Intergovernmental Panel on Climate Change (IPCC) contains a chapter dedicated to a survey of the growing research field of "demand, services and social aspects of mitigation" (19): Large GHG mitigation potentials exist that do not compromise service provisioning but rather bring about improvements in well-being and strong synergies with the Sustainable Development Goals (SDGs) (19, 20). This research on so-called demand-side measures enables the development of novel scenarios of sufficient service provisioning for high well-being with low energy and material demand (LEMD), providing novel transformative perspectives for policy, science, and the public (21–23).

Demand-side measures are "policies, interventions, and measures that modify demand for goods and services to reduce material and energy requirements and associated GHG emissions, while also contributing to other policy objectives including improved well-being and living standards" (23, p. 1). They aim to avoid, shift, or improve upon the demand for material- and energy-intensive service provisioning, complementing traditional supply-side technology- and efficiency-oriented mitigation efforts (22, 23). The service provisioning and demand-side perspective focuses on the material and energy requirements of the provisioning systems for food and water, mobility, shelter, and thermal comfort, as well as lighting, health, education,

Shared socioeconomic pathways (SSPs): a set of scenario narratives that describe five future socioeconomic trajectories for climate change mitigation and adaptation research

SDG: Sustainable Development Goals

LEMD: low energy and material demand entertainment, social interaction, and participation. Demand-side measures can have multiple benefits for health, quality of life, resilience of socioeconomic systems, lowered economic costs of mitigation, and equity (20, 23). They can also reduce risks from supply constraints and geopolitics; materials criticality; and land use competition between food, feed, fuels, mining, and settlements (23). This emerging field of demand-side research draws upon multiple concepts and efforts, for example, beyond gross domestic product (GDP) (24), sufficiency (25, 26), postgrowth (7, 27), steady-state economics (28, 29), sustainable consumption corridors (30), degrowth (31, 32), sustainable circular economy (33, 34), and material and resource efficiency (17).

Gross domestic product (GDP): measures the monetary market value of all final goods and services produced in an economy; it is often misleadingly used as an indicator of societal welfare

Material cycles: physical flows of materials and energy carriers from the extraction of raw resources through 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

Material stocks: all long-lived products used longer than 1 year, covering all socioeconomically utilized buildings, infrastructure, machinery, and other products

IAM: integrated assessment model

This review assesses the state of the art of industry-oriented LEMD scenario modeling and aims to provide a reference point for this emerging interdisciplinary field (23, 35). We address two specific concerns. First, we assess how service provisioning and its links to industry and supply chains are conceptualized and modeled. Doing so is important because service provisioning serves as a productive boundary concept for interdisciplinary research on demand-side measures (36), but its measurement and model implementation are challenging; the concept has been interpreted in multiple ways (37, 38). Second, we assess which aspects, principles, and system linkages of material cycles and industry need to be addressed for LEMD scenarios with high service provisioning, and how they are modeled in the literature. These aspects are important because service provisioning requires stocks as well as flows of materials and energy, resulting in waste and GHG emissions. In 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 provisioning (39). Material production alone accounts for 20% to 34% of global GHG emissions (40, 41), some of which are hard to abate (42). Resource extraction is also an important cause of land use change and biodiversity impacts (1), as growing demand intensifies land use competition (3). So-called material cycles originate from agriculture, forestry, and mining and are processed by industry, manufacturing, and construction; they also include transport and waste management. All of these material cycles use energy and cause process emissions (41). Ultimately, physical products accumulate as in-use material stocks of buildings, infrastructure, machinery, and various short-lived products, which also require energy to be used and to provide services (e.g., heating a building or using public transport) (41, 43). Crucially, recent reviews have shown that many macroeconomic integrated assessment models (IAMs) regularly violate the laws of thermodynamics and lack the granularity, resolution, and framework to properly depict material cycles and material stocks of buildings, infrastructure, machinery, and other short-lived products (16, 44, 45). These gaps critically limit our understanding of the potentials, trade-offs, and multi-SDG impacts of materials-oriented GHG mitigation strategies (16, 17, 35, 46, 47).

In this review, we introduce the research frontier of LEMD modeling across nine modeling traditions, present an evidence synthesis, and identify future research needs and recommendations. We collected the relevant literature from scientific literature databases and via citation snowballing between March 2022 and September 2023. From more than 300 screened studies, we selected 77 for in-depth review that (*a*) aim for biophysical and thermodynamic consistency between material cycles and stocks, energy use, and GHG emissions; (*b*) treat industry not as an end user but as a means of delivery to intermediate and final demand, resulting in supply chains reacting to demand-side measures; (*c*) model demand and service provisioning, ideally in nonmonetary units; and (*d*) model some form of LEMD scenario. For documentation of the research design, extended introductions of all model traditions, and detailed discussions of each study, see the **Supplemental Material** and **Supplemental Data**.

Supplemental Material >

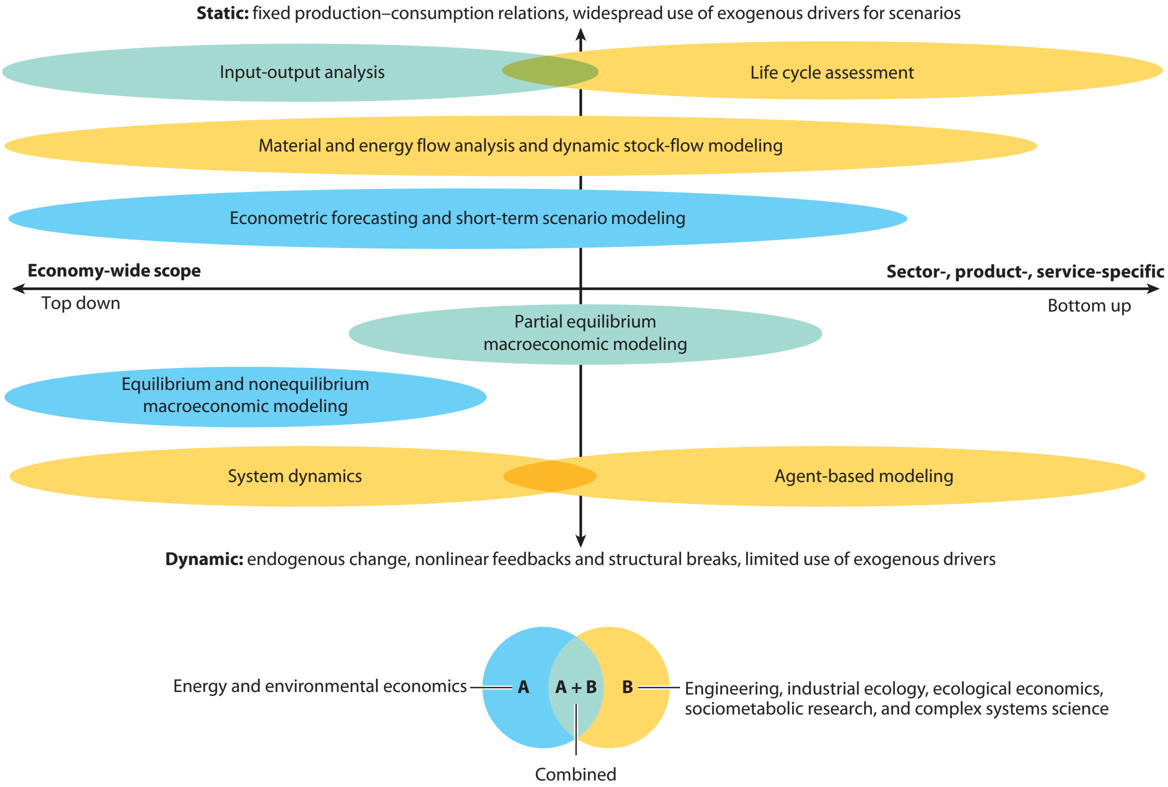

Figure 1

Foundational principles and typical scopes of the modeling traditions reviewed in this article. Traditions in blue originate from energy and environmental economics, and traditions in yellow originate from engineering, industrial ecology, ecological economics, sociometabolic research, and complex systems science. The ninth tradition identified in this review eclectically combines traditions and submodels and therefore cannot be directly located herein. The positioning of each tradition is based on the authors' domain expertise and is intended solely to provide orientation. For a detailed discussion of each tradition and references, see section 2 of the **Supplemental Material**.

2. LEMD SCENARIOS ORIGINATE FROM NINE DIFFERENT MODELING TRADITIONS

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Efforts to model society–nature interactions began in the 1960s, spurred by concerns about environmental degradation, energy security, and climate change. These efforts resulted in the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), the IPCC, and more recently the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Nonequilibrium, input–output analysis and equilibrium-based macroeconomic approaches have increasingly been used to simulate mitigation strategies, grounded in energy and environmental economics (**Figure 1**). Alternative socioecological approaches inspired by biophysical systems perspectives emerged between the 1960s and the 1990s from fields such as industrial ecology, sustainability science, ecological economics, and complex systems science (**Figure 1**). Overall, we identify nine modeling traditions, each developed for specific purposes based on different worldviews, theories, and modeling principles (for an introduction to each tradition, see section 2 of the **Supplemental Material**). As a result, different fields use different terminologies, system definitions, model scopes and aims, data requirements, and computational

UNFCCC: United Nations Framework Convention on Climate Change complexity. These traditions differ in how statically or dynamically they model production–consumption relations, as well as in their typical scope—from economy-wide to sector-, product-, or service-specific (**Figure 1**). While this diversity makes them useful for different types of questions related to service provisioning and LEMD scenarios, it also hinders evidence synthesis and complicates interdisciplinary collaboration.

Economy-wide: covering all socioeconomic production and consumption activities within an economy.

ABM: agent-based model

Table 1 summarizes several typical aspects of these modeling traditions. The table presents each tradition's theoretical assumptions about the limits of monetary valuation (9, 49, 50) vis-à-vis the need for a biophysical perspective and concerns that cannot be priced in markets (e.g., the value of a life or of biodiversity, ecosystems, or future climate change–induced damages and biodiversity loss), model drivers, emphasis on consistency, granularity of industry and supply chain representations, and heterogeneity of demand representations.

We highlight two crucial considerations for this emerging literature: simulation versus optimization on the one hand and consistency, heterogeneity, and granularity on the other. The distinction between optimization and simulation in the context of modeling LEMD pathways is crucial to assess transformative and disruptive changes (**Table 1**). Optimization models vary in their temporal scope—from myopic to intertemporal optimization—and aim to find the mathematically optimal solution by defining an objective function, decision variables, and constraints; they often incorporate equilibrium conditions where supply matches demand. These models tend to predict earlier uptake of novel technologies as a result of their inherent assumptions of market efficiency and rational actors maximizing utility; they rely heavily on assumptions about future monetary costs, including those from environmental impacts such as climate change (50). In contrast, simulation models, which are typically characterized by limited foresight and a focus on reproducing the dynamics of a system under various conditions, can display more inertia and strongly rely on exogenous scenarios assumptions. Simulation models are highly valuable for what-if exploratory scenarios that explore the full range of (im)possible futures.

Modeling traditions also place a different emphasis on consistency, granularity, and heterogeneity because of differences in their theoretical backgrounds and data availability (**Table 1**). Economic traditions (**Figure 1**) emphasize monetary consistency within (dis)equilibrium frameworks, while other traditions emphasize biophysical consistency. Granularity pertains to the detailed representation of sectors, technologies, and processes: Bottom-up models offer high specificity at the cost of increased data and computational demands, while top-down models provide broader, less detailed economic relationships. Heterogeneity concerns the models' ability to depict diverse consumer behaviors and market dynamics. Economic models usually assume some form of rationally optimizing agents, while the alternative biophysical traditions typically use exogenous scenario assumptions. Agent-based models (ABMs) emphasize the variability of decision-making processes.

These distinctions underscore the models' applicability and limitations in capturing the complexity of industrial systems, service provisioning, demand, and potential entry points for modeling LEMD strategies. Top-down models are useful for macroeconomic analyses but mostly lack the detail needed to accurately model technological transitions or the intricacies of sector-specific mitigation measures. Conversely, bottom-up models excel in technological specificity but often overlook broader socioeconomic effects. Hybrid models attempt to reconcile these differences by combining detailed technological and biophysical insights with economic dynamics, but they require large quantities of data and result in substantial model complexity.

3. STATE-OF-THE-ART MODELING OF LEMD SCENARIOS

Two-thirds of the 77 studies reviewed here operate within their tradition, while one-third combine methods and data from engineering, industrial ecology, ecological economics, and complex

Table 1 Assessment of nine modeling traditions vis-à-vis key low energy and material demand considerations[a]

	Nonequilibrium macroeconomic models	Input–output analysis	Econometric forecasting	Equilibrium macroeconomic models	Partial equilibrium macroeconomic models	System dynamics models	Life cycle assessment	Material and energy flow analysis	Agent-based models
(Limits of) monetary valuation	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Primary drivers	Demand	Demand	Supply	Supply–demand equilibrium	Demand	Both	Demand	Both	Both
Emphasis on consistency	Monetary	Monetary and biophysical flows	Monetary	Monetary	Monetary and commodity specific, biophysical	Monetary and biophysical	Biophysical, but supply chain truncation errors	Biophysical stocks and flows	Study specific
Simulation versus optimization	Optimization	Simulation	Optimization	Optimization	Optimization	Simulation	Simulation	Simulation	Simulation
Sectoral/ technological granularity	Low to medium	Medium to high	Low to medium	Low to medium	Medium to high	Low to medium	Medium to high	Low to medium	Low to medium
Demand heterogeneity	Low to medium	Medium to high	Low to medium	Low to medium	Low	Medium	Low to medium	Low	High

[a] Table is based on data from References 16 and 51 and on the authors' domain expertise. These assessments are about typical research from the respective traditions. Many of studies we review do advance beyond their respective standard assumptions (for discussion, see sections 4 to 7 of the **Supplemental Material**).

Supplemental Material >

system sciences (biophysical+); ABMs and other traditions (ABM+); and biophysical and macroeconomic modeling (economic+biophysical) (**Figure 2*a***). Study scopes range from national and world regional to global (**Figure 2*b***). Two-thirds of regional and (sub)national studies focus on the Global North, while only one-third investigate the Global South (**Supplemental Figure 3**). Around two-thirds of the reviewed studies are open access and have supplementary information (**Figure 2*c***). Only one-third provide machine-readable supplementary data; a mere 10 (13%) provide open model code, hampering comparison and evidence synthesis. For a full assessment of all 77 studies, see the **Supplemental Data**.

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Multiregional input–output (MRIO) model: model covering the world economy

Material and energy flow analysis (MEFA): includes dynamic stock–flow models

LCA: life cycle assessment

We find substantial differences in the resolution and granularity of industries and economic sectors modeled across traditions (**Figure 2*d***). Multiregional input–output (MRIO) models and models using the same underlying data stand out, as they were developed specifically to provide detailed sectoral classifications for extractive, manufacturing, and service industries. Among the detailed MRIO databases, EXIOBASE contains information on 200 products and 163 industries (53), while GLORIA includes 120 sectors (54). Others, like WIOD and GTAP, have an intermediate resolution of 35–64 sectors. Models from the material and energy flow analysis (MEFA), life cycle assessment (LCA), and system dynamics traditions usually focus on specific industries and/or materials, resulting in lower sectoral resolution, although recent synthesis studies compiled intermediate resolutions of up to 78 industries or sectors. The macroeconomic tradition is characterized by low to intermediate sectoral resolution (1–57 sectors).[1]

MRIO models (69), partial (62) and general (60) equilibrium models, and model combinations using input–output tables (biophysical+, economic+biophysical) offer the most detailed descriptions of materials. Depending on their scope and aim, some of these studies aggregate only one to three materials (**Figure 2*e***). Other traditions are characterized by low (1–8) to intermediate (10–20) material granularity. Nonequilibrium studies align with biophysical stock–flow consistency because they model material stock–flow relations, albeit only in a stylized way. Biophysical consistency is the core principle of MEFA—although some MEFA studies look only at either stocks or flows. In contrast to their high resolution and granularity, MRIO models only partially comply with biophysical stock–flow consistency (**Figure 2*e***); while they ensure mass-balanced flows, they do not account for material stocks and account for waste by-products only in specific applications.

Regarding the granularity of modeled end-use product groups, MEFA models, MRIO models, and combinations of economic and biophysical traditions achieve 10–11 end-use product groups (**Figure 2*f***). Studies of the nonequilibrium macro and econometrics traditions usually do not model material cycles or products; rather, they depict resource use simply as intensities of macroeconomic variables (e.g., per GDP or sectoral value added). This approach becomes problematic when trying to model materials-oriented GHG mitigation strategies; it hinders the depiction of service provisioning beyond monetary consumption.

3.1. Nonequilibrium LEMD Modeling

The emerging field of stock–flow consistent ecological macroeconomics could offer a new approach to LEMD modeling, but so far such studies have focused mainly on conceptual issues, energy, and GHG emissions (55–57). This tradition uses thermodynamically appropriate production functions—including energy and, increasingly, materials—and aim to comply with biophysical stock–flow consistency. They endogenously model economic growth through bounded

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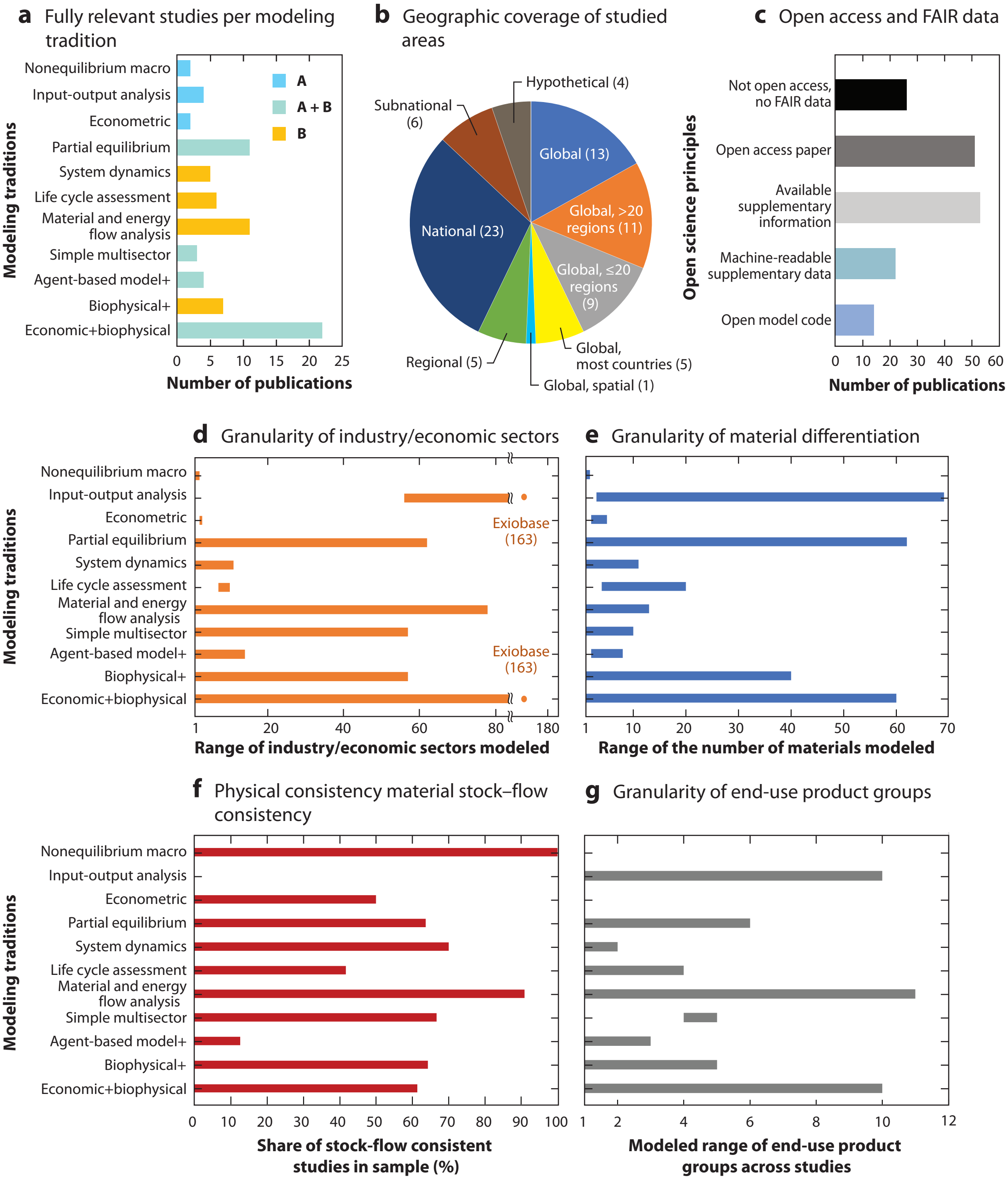
[1] The granularity of some studies based on LCA/MRIO combinations, which have substantial sectoral resolution in their background system, could not be assessed because they lack documentation of the aggregation and truncation decisions common in LCA.



(Caption appears on following page)

Figure 2 (*Figure appears on preceding page*)

(*a*) Overview of reviewed studies by research tradition and their combinations (*plus signs*), as described in **Figure 1** (A, energy and environmental economics; B, engineering, industrial ecology, ecological economics, sociometabolic research, and complex systems science). (*b*) Geographic coverage of the reviewed studies. (*c*) Implementation of open science principles, as studies, results, and model code should be findable, accessible, interoperable, and reusable (FAIR) (52). (*d–g*) Within each tradition and their combinations, models have a varying range of granular representations of (*d*) industry/economic sectors, (*e*) different materials, and (*g*) end-use product groups, in which higher resolution generally improves robustness. (*f*) Physical stock–flow consistency is crucial to understand time-dependent system dynamics and end-of-life waste potential. Agent-based model+ refers to agent-based models and other traditions. Biophysical+ refers to studies that combine data from engineering, industrial ecology, ecological economics, and complex system sciences. Economic+biophysical refers to biophysical and macroeconomic modeling studies. For details of each study, see the **Supplemental Data**.

Supplemental Material >

rationality, disequilibrium between supply and demand, and potential underutilization of capital and labor. Models are being extended to material cycles for global transport and the transition to electric vehicles (58), as well as in a global IAM (59).

3.2. Environmentally Extended Input–Output Analysis LEMD Modeling

Over the last decade, researchers have developed multiple MRIO models, which enable simulations of LEMD futures for the global economy. The studies we review model changes to final demand on the basis of stakeholder workshops on sufficiency and green consumption (60), the SDG of access to all-season mobility infrastructure (61), hypothetical product lightweighting, lifetime extensions and improved recycling (62, 63), and food waste reduction (64, 65). To model economy-wide material and energy use and GHG emissions, some researchers exogenously change the fixed Leontief production recipe, while others hold it constant. Detailed LCA data are sometimes used to either disaggregate sectors or translate specific measures into the more aggregate sectors and final demand categories available in an MRIO model. One study hybridizes input–output with MEFA (66) to assess supply-side industrial symbiosis potentials for the steel, cement, paper, and aluminum industries.

3.3. Econometric LEMD Modeling and Forecasting

Econometric forecasting models usually display high path dependency and are often used to complement models from other traditions. Biophysical stock–flow dynamics are usually simplified; materials-oriented measures are depicted only through changing price elasticities. Energy use and rebound effects due to general (dis)equilibrium dynamics are often not accounted for. Importantly, these models generally do not account for material stocks and service provisioning in nonmonetary units.

Innovative studies (67–69) have assessed the impact of materials taxation on basic metals (e.g., steel, aluminum) and cement in the European Union, showing that a materials tax of €80 per ton of CO_2 (tCO_2) reduces energy-related emissions by 6% and industry process emissions by up to 40%, without carbon leakage and with minimal GDP impacts and employment reductions. van Ruijven et al. (69) use econometric regression models and a bottom-up steel and cement model embedded in a long-term global energy system model to show that a carbon tax of $100/$tCO_2$, increased by 4%/year until 2050, could decrease use of steel by 80–90% and use of cement by 40–80% in comparison to 2010 levels. However, the availability of carbon capture and storage plays a major role in decarbonization. de Souza & Pacca (68) show that circular economy measures can avoid 52% of business-as-usual (BAU) emissions in Brazil up to 2050 through increased recycling, material efficiency, the substitution of clinker with supplementary cementitious materials, and the substitution of petroleum coke with alternative fuels.

3.4. Equilibrium-Based Macroeconomic LEMD Modeling

CGE: computable general equilibrium

PE models: partial equilibrium macroeconomic models

The computable general equilibrium (CGE) tradition models optimal lower demand only in comparison to a growth-oriented BAU scenario. CGE models usually do not find absolute LEMD reductions, a result that is often confusingly communicated by prominently stating reductions that, however, occur only in comparison to questionable high-growth BAU scenarios (50). They assume perfect factor allocation, full capacity utilization, and rational agents. This assumption is problematic because LEMD likely results in underutilized capacities and disequilibrium due to oversupply of, for example, fossil fuels and fossil fuel–intensive products as well as early decommissioning of stranded assets. Widely used industrial production functions that assume full substitutability of energy violate thermodynamics, ignoring the fact that energy plays a central role in industrial production and economic growth (45, 70).

In the simplest approach, price elasticities for material-related sectors are modified exogenously (71). Some studies explicitly add specific material flows or economy-wide raw material extraction, but without biophysical consistency across material cycles and stocks (72–74). They find that even highly ambitious supply-side resource efficiency and climate change mitigation measures result in a 50–100% increase in global resource use, driving further ecological deterioration.

More innovatively, Cao et al. (75) and Tong et al. (76) combine a CGE with a dynamic MEFA model. Cao et al. (75) exogenously assume a saturation of building stock in China (square meters per capita) and model potential rebound effects, holding the total economy—measured via GDP—constant. Such a saturation could save 25.4 Gt in embodied CO_2 emissions in the construction sector, which would be partially offset by economy-wide rebound effects (18.8 Gt) due to respending of savings. Tong et al. (76) investigate how global shifts from internal combustion engines to battery electric and fuel cell vehicles could result in substantial future mismatches between supply and demand for platinum group metals.

Even more innovatively, Bachner et al. (77) extend their CGE model with service provisioning via nonmonetary indicators and use it to model several measures that avoid, shift, and improve upon the material and energy intensity of service demand for buildings and transport. They use a well-being indicator that goes beyond GDP and covers monetary welfare effects for private and public consumption, cobenefits such as air pollution and avoided health impacts, and changes in leisure. In their ambitious climate transformation scenario, these authors show that GDP declines only slightly, while societal welfare increases and GHG emissions decrease substantially.

3.5. Partial Equilibrium LEMD Modeling

Partial equilibrium (PE) macroeconomic models are widely used for specific industrial sectors and the energy system and are driven by exogenous scenario assumptions; they are often coupled with other model traditions. The most straightforward are modifications to price elasticities in specific industrial sectors to approximate materials-oriented measures (e.g., 78).

More innovative efforts introduce explicit service provisioning indicators, simplified material cycles and stocks, and soft coupling with other traditions. Grubler et al. (79) present a groundbreaking Low-Energy-Demand scenario that quantifies highly efficient service provisioning for thermal comfort, consumer goods, mobility, food, and commercial and public buildings globally, and use a PE energy systems model to show that final energy demand could decrease by 40% until 2050. Barrett et al. (80) soft-couple several models, including the macroeconomic model TIMES; an MRIO model; a dynamic MEFA model 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 life cycle, and nutritional requirements, as well as with endogenous economic growth, allowing highly detailed options to improve energy efficiency, avoid energy use, and shift to more-efficient energy demand provisioning. Without compromising well-being, Barrett et al. find potential absolute reductions of 52% in energy demand by 2050 compared with 2020 for the United Kingdom.

Costa et al. (81) soft-couple PE, LCA, MEFA, and MRIO models 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. (82) combine resource efficiency and demand-side measures to model net-zero GHG pathways in Germany, using a technology-rich multimodel analysis driven by exogenous assumptions on transport, heating and cooling in buildings, agriculture, and forestry, which drive a PE energy system model, a waste sector model, and a global trade model. By combining technology and fossil fuel phase-outs, supply-side efficiency, and technological progress with demand-side measures, these authors achieve significant reductions of GHG emissions (95%), raw material consumption (56%), and final energy consumption (24%) by 2050.

A combination of PE models with dynamic MEFA leads to material stock–flow consistency, increasing the credibility for medium- to long-term projections of structural change and material availability. Kermeli et al. (83) model steel stock–flow dynamics, including end-of-life recycling and assumed per capita saturation of stocks. They find steel demand in 2100 to be 75% lower than in purely flow-based estimations. PE models have been selectively extended to specific materials such as steel and iron (84), food (85), forests (86, 87), and plastics (88) and with the material requirements for a global transition to autonomous shared vehicles (89). Some models incorporate the ore and metal extraction and processing sectors, which are typically absent from PE models, including material availability constraints over time to model technology lifetime extension, recycling, and material intensity reductions (90). Lechtenböhmer et al. (91) use a technology-rich energy system PE model and a simplified dynamic MEFA model to assess how reindustrialization and energy-intensive industries can be aligned with the German climate protection law. Reindustrialization could impede Germany's energy and GHG targets as a result of limited efficiency potentials, requiring further demand-side measures. Highly innovative studies (92–94) have combined a global PE IAM with dynamic MEFA to model material cycles and stocks for electricity, buildings, vehicles, and appliances under climate policy scenarios. These studies achieve biophysical consistency among demand for service provisioning, material cycles, and stocks and include repercussions for industry, finding substantial LEMD potentials.

3.6. System Dynamics LEMD Modeling

System dynamics LEMD modeling contributes to a better understanding of nonlinear dynamics and feedbacks by simulating dynamic interlinkages between multiple evolving parts of a system; thus, it provides several innovative and interesting LEMD contributions. Allen et al. (95) simulate supply- and demand-side measures for Australia, including economy-wide raw material extraction, final energy, and selected material stocks. Their sustainability transition scenario achieves 70% progress toward the SDGs by 2030. Conversely, a focus on economic growth, social inclusion, or green economy strategies achieves only limited progress. Moallemi et al. (96) model LEMD pathways to achieve the SDGs, depicting service provisioning and socioeconomic well-being via a capability's perspective, and use life expectancy and the Human Development Index as headline indicators. They show that multiple early interventions are necessary to facilitate long-term SDG progress after 2030. Neumann et al. (97) quantify how a 100% renewable energy system globally affects 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 et al. (98) extend the World7 model with the entire cement, sand, and metal cycles—including 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, and improved recycling and material substitution.

Kumar et al. (99) present a highly innovative model of the energy and materials required to achieve the SDGs in India, covering food and water security, housing and clean energy, sufficient health care, and access to clean cooking and transport. Sectoral economic growth is soft-linked to a CGE model to ensure macroeconomic consistency. These authors show that the urban form shapes housing and demand for transportation resources and energy.

DLS: decent living standards

3.7. Life Cycle Assessment–Based LEMD Modeling

LCA can be useful for system-level LEMD modeling when combined with other traditions to overcome some of its standard limitations, such as its focus on specific product systems, its often attributional static approach, and truncation errors. Recent advances include consequential LCA, which depicts system-level feedbacks, and combinations of LCA with dynamic MEFA.

For example, Verhoef et al. (100) show some energy reduction potential of additive manufacturing, although they do not consider rebounds or shifts in demand. van der Voet et al. (101) combine consequential LCA with a dynamic MEFA model to assess metal production and recycling in future energy scenarios. Increasing use of secondary metals could substantially reduce life cycle emissions at the global level, but only in the second half of the twenty-first century, when end-of-life metals become increasingly available from aging energy system stocks. Buschbeck & Pauliuk (102) use consequential LCA to assess the conditions under which substituting emissions-intensive materials with timber leads to net GHG savings, given that growing forests are also natural carbon sinks. They find that short-term (<25 year) intensive wood harvesting is not climate beneficial, while long-term potentials depend on the speed of energy system and industrial decarbonization.

Bjørn et al. (103) address sufficiency in consumption by combining attributional LCA with an MRIO to estimate the global climate footprint implications of surveyed household consumption baskets for 10 service demand areas in Denmark. They show that supply- and demand-side emissions intensities need to be reduced by a factor of 2–14 to comply with climate targets. Rammelt et al. (104) combine attributional LCA factors and upscale them globally to approximate the life cycle impacts of "just access" to energy, water, food, housing, and transport drawn from SDG indicators. Eradicating severe deprivations could amount to 2–26% greater impacts on climate, water, land, and nutrients, comparable to the impacts from the wealthiest 1–4%; however, they ignore rebound effects and socioeconomic dynamics.

The universal minimum decent living standards (DLS) have led to substantial innovations in LEMD modeling. Such models address a common set of products and services including housing, mobility, nutrition, education, health care, and socialization for countries both in the Global South (105–107) and globally (108, 109). Food and transport dominate energy use for decent living, while housing dominates up-front energy investment needs. Nutrition and mobility for universal DLS globally would require 6 t/capita of raw materials as well as stocks of ∼43 t/capita in buildings, infrastructure, and industrial assets (110). By simulating a global contraction and convergence to DLS, Kikstra et al. (108) and Millward-Hopkins et al. (109) show that, after 2040, ∼60% less final energy than today could be required.

3.8. Dynamic Material and Energy Flow Analysis LEMD Modeling

A growing number of dynamic MEFA studies simulate combinations of lower demand for material product stocks and service provisioning with material efficiency, circular economy strategies, and technological improvements in industry and energy system decarbonization. They focus on a thermodynamically consistent representation of material cycles and material stocks at national to global scales, usually treating socioeconomic dynamics as exogenous assumptions. Dynamic MEFAs are increasingly being combined with LCA, MRIO models, and macroeconomic models.

MEFA studies have shown that saturated and stabilized material product stock levels are a key lever for LEMD futures, which, combined with longer product lifetimes and higher recycling, enable substantial reductions in raw material extraction and energy use (39, 43, 111–119). Technical efficiency potentials across material cycles and supply chains are receiving considerable attention, covering manufacturing (lightweighting and less scrap), longer and more intensive product use, and better reuse and recycling (43, 113, 115, 120–123).

Dynamic MEFA models are also used to model land use and the industries extracting and processing biomass for food, feed, biofuels, and material use, as well as ecosystems as potential carbon sinks. Mayer et al. (124) combine dynamic MEFA and consequential LCA to analyze LEMD scenarios for the European food system. They show that alternative diets with much less meat, low demand for biofuels and material use by nonfood products, and production systems aligned with regional biocapacities can substantially mitigate GHG emissions. Bailis et al. (125) show that pan-tropical wood-fuel demand for subsistence cooking and commercial use accounts for ~2% of global and ~4% of pan-tropical GHG emissions. Le Noë et al. (126) show that not harvesting forests could have resulted in 49 Gt of natural negative carbon emissions due to regrowth.

3.9. Agent-Based LEMD Modeling

ABMs enable detailed representations of (inter)actions of heterogeneous agents, resulting in emergent nonlinear dynamics. ABMs are useful for assessing distributional aspects, diffusion, and uptake of innovations or of shocks and climate damages (127–129). We did not find any macro-level empirical LEMD scenarios; the studies closest to the scope of this review include that by Safarzyńska & van den Bergh (130), who study the relations of unemployment, inequality, and the social cost of carbon, and those by Yazan & Fraccascia (131), Koide et al. (132), and Safarzyńska et al. (133), who model aspects of a sustainable circular economy across industrial and household systems.

3.10. Quantitative Evidence Synthesis of Mitigation Potentials

Evidence synthesis is complicated by the heterogeneity of study scopes and measures modeled, as these often lack supplementary data, as well as by differences between scenario simulations starting from current material and energy use and optimization scenarios including comparisons against various BAU growth scenarios. After substantial harmonization efforts, we find that the literature reviewed here shows substantial LEMD and GHG mitigation potentials (**Figure 3**), with similar or higher levels of service provisioning.

We find potential reductions in industrial material use by 80% and potential reductions in combined supply- and demand-side measures of economy-wide material use by 56%, both compared with historical base years, and by 2% to 47% compared with BAU scenarios (**Figure 3*a***). The most effective scenario shows a decrease in material use by 52% compared with the year 2020 as a result of a global contraction and convergence to DLS (110). In comparison to BAU, individual sectors achieve potential reductions of up to 63% in phosphorus fertilizer by combining technological measures and dietary changes (85), and they achieve a reduction of up to 80% in steel demand by combining supply- and demand-side measures (78).

For energy use, we find potential reductions of up to 76% (**Figure 3*b***). The strongest economy-wide reduction potential is for a global contraction and convergence to DLS, resulting in ~60%

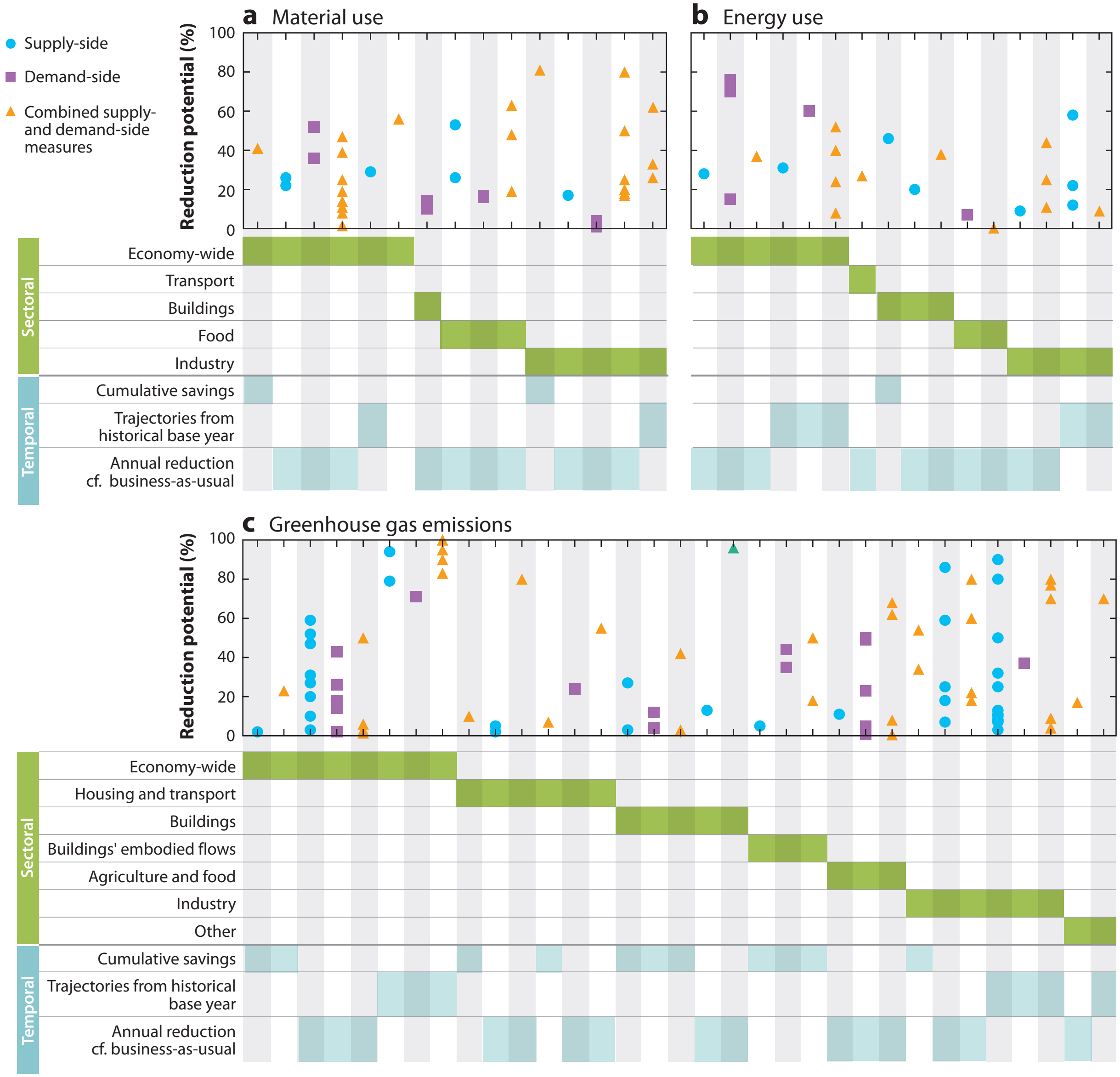


Figure 3

Summary of (*a*) material use, (*b*) energy use, and (*c*) greenhouse gas emissions reduction potentials across sectors and study scopes, where each point represents a mitigation scenario result. The reduction potentials are grouped by sectoral and temporal scopes, as well as if supply-side, demand-side, or combined supply- and demand-side measures were modeled. Studies report reduction potentials along three different temporal scopes: cumulative savings, trajectories from historical base years, and annual reductions compared to a business-as-usual baseline. The exact temporal and sectoral scopes of each study can still differ, making only an intermediate level of synthesis feasible. For details of each study, see the **Supplemental Data**.

lower final energy use compared with today (109, 134). Combinations of various supply- and demand-side measures yield potential reductions of 40–52% for various countries compared with historical base years (79, 80, 135). For buildings, we find that material substitution reduces cumulative energy use by 46% from 2020 to 2050 in India (99). For industry, global energy use for steel

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and cement production could be reduced by 22% to 58% through a carbon tax of \$20–100/tCO_2, respectively (69).

Regarding GHG emissions, we find potential reductions of 1% to 100% (**Figure 3*c***). Economy-wide estimates range from 70% to 100% when demand- and supply-side measures are combined (81, 82, 96, 135). Obviously, decarbonizing the energy system is crucial; additional reduction potential from individual measures is due to 3D printing (27% annually), remote work and active travel (26%), demand reduction (23% cumulatively), local/sharing service economy (18%), and vegan diet (14%).

4. DISCUSSION

Industry needs to drastically transform itself to comply with agreed-upon climate targets as well as with global and regional environmental constraints, while still being able to provide the goods and services required to satisfy human needs, well-being, and other social goals (9). LEMD policies can accelerate the transformation of service provisioning and demand, and induce behavioral change in industrial stakeholders (136), which will require model-based assessments of potential reductions and unintended consequences, ideally from intercomparisons among different modeling traditions. This review aims to solidify the connection across these highly heterogeneous model traditions to lay the groundwork for policy-relevant and robust future research building on core model principles and shared concepts. Ideally, LEMD scenarios will reveal how service provisioning can be achieved more efficiently and justly, complementing traditional technology- and supply-side efficiency measures. LEMD scenarios therefore contribute to expanding our collective imaginary about sustainable futures within planetary boundaries, beyond betting on future technological fixes.

Various LEMD approaches are increasingly being applied across all nine modeling traditions; many highly innovative studies combine the strengths of different traditions (see Sections 3.1–3.9). This development suggests two things. First, a growing number of research groups are developing transformative scenarios and models to show how high service provisioning can be achieved with LEMD. Second, we lack a common conceptual and ontological framework to connect these models and their scenarios into a shared evidence base with high policy relevance. Shared scenario narratives and assumptions about key drivers and service provisioning levels could constitute such a bridge (7, 21, 23), similar to the established SSP framework that connects most mitigation and adaptation research (2, 13). In the following subsections, we explore two specific challenges for improved LEMD modeling, then summarize recommendations for this emerging field.

4.1. Toward Harmonized Definitions for Industry and Materials in LEMD Scenarios

The literature we review here suffers from highly heterogeneous system definitions, study scopes, and scenario assumptions. We identify five entry points that influence how LEMD scenarios are modeled, resulting in partial perspectives on the potential and unintended consequences of supply- and demand-side measures. This wide variety shows that shared system definitions and modeling principles are needed to enable comparability, leverage interdisciplinary model combinations, and facilitate evidence synthesis.

First, UNFCCC emissions accounting defines the following broad economic sectors: energy supply; industry; agriculture, forestry, and other land use (AFOLU); transport; and buildings (2, 41). This widely used end-of-pipe perspective on the sources of emissions lacks a differentiation of supply and (final) demand and treats industry as an end user. However, industry responds to demand from other sectors. Furthermore in current modeling and accounting, extractive industries are usually allocated across energy supply, industry, construction, and AFOLU, with further differences depending on statistical practices in each country. These inconsistencies hinder systematic analyses of how material cycles, energy use, and GHG emissions interconnect as well as analyses of how materials-oriented mitigation strategies can be modeled.

System of Environmental Economic Accounting (SEEA): a globally harmonized socioeconomic and environmental reporting system

Second, energy statistics show the supply and use of energy carriers for sectors, production processes, and final demand and distinguish among primary, final, and useful energy stages. This information is highly relevant for understanding the potentials and limits linked to fuel switching, electrification, and energy efficiency (137, 138), as well as for linking energy use to material cycles and service provisioning.

Third, fully integrating material cycles and stocks remains a key challenge for all modeling traditions, despite recent substantial innovations. Raw material extraction and land use, which constitute the beginning of material cycles, are reported according to the boundaries established in the System of Environmental Economic Accounting (SEEA) and focus on types of raw materials, such as biomass, nonmetallic minerals, ores and metals, and fossil energy carriers, thus lacking inherent sector resolution (139). These data are increasingly being used across traditions, requiring modelers to allocate raw materials to extractive industry sectors and compile data on material cycles and waste by-products occurring at each production step, for example, via input–output tables or material–flow analysis (140, 141). Industry production statistics, such as those for cement or steel, focus on specific stages of the value chain and material cycle; they are often eclectically and selectively coupled into existing models. Waste statistics, if available at all (142, 143), cover only what is officially collected and managed in institutionalized waste management systems, leaving large unknowns. Some models resort to estimating waste flows as a function of GDP or population, violating mass-balanced consistency between material extraction, industrial processing, and material stock dynamics. These different entry points and inconsistent data sources therefore hinder our ability to depict how different supply- and demand-side measures affect material extraction, land use, material cycles, and energy use.

We claim that an economy-wide system definition for industry and the socioeconomic system, following the SEEA[2] framework, is needed to improve the modeling of material cycles and their interdependence on energy and service provisioning (**Figure 4**). Ideally, LEMD scenarios are based on a consistent depiction of material cycles, from extractive industries to industrial assets and infrastructure to waste management. LEMD modeling of industrial networks also 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. Shared understanding and use of appropriate production functions that are consistent across aggregation levels and for monetary and biophysical layers are crucial for LEMD modeling (16, 45, 70) (see section 5 of the **Supplemental Material**). These improvements will be essential for delineating and capturing how supply- and demand-side measures affect materials, energy use, and GHG emissions.

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4.2. Demand, Service Provisioning, and Sufficiency

Interpretations of service provisioning diverge substantially across the studies reviewed here, as do the representations and granularity of demand (see Section 3.1). Transformative options become visible when relations between human well-being, service provisioning, physical functions and

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[2] The SEEA draws on economy-wide material flows, accounting for raw material extraction, energy statistics for sectoral energy use, and UNFCCC emissions reporting (139, 144), into a (relatively) coherent framework integrating economic, social, and environmental information (145). However, it does not yet report full material cycles.

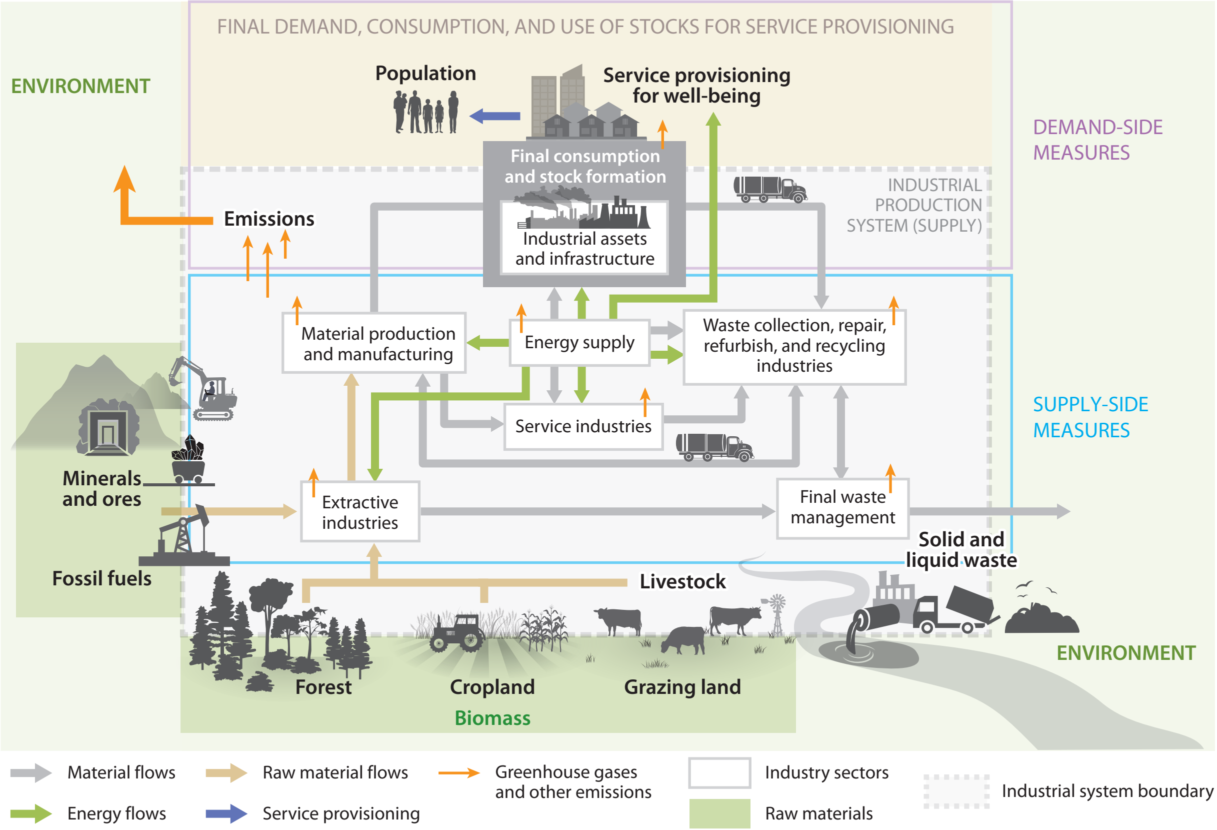

Figure 4

Conceptualizing a biophysically consistent perspective on the industrial production system as it transforms materials and energy to supply goods and provide services to demand, including for basic needs such as nutrition and water, mobility, shelter and thermal comfort, lighting, health, education, entertainment, social interaction, and participation. Figure based on concepts described in References 37, 146, and 147.

product stocks, and industry and environmental impacts are made explicit. The energy service cascade (37) helps disentangle how well-being rests on services often defined as what is actually demanded, which is provisioned via physical actions performed by product stocks and energy use (**Figure 5*a***). Because functions require product stocks and energy, industry and the energy system are needed upstream to process natural resources. Clearly, then, what is actually demanded can be provisioned in multiple ways and with various industrial and environmental implications (48). For example, for the case of mobility, Virág et al. (148) show that more distance traveled (i.e., a function) does not automatically translate into better service (i.e., being able to reach places) or contributions to greater well-being. Indeed, most people do not aim to travel as far as possible to maximize their well-being; rather, they aim to reach places quickly and safely. At the same time, having a sufficient level of mobility services for everyday life has clear benefits for well-being (148).

The literature reviewed herein primarily addresses products and functions, with much less emphasis on what is actually demanded, or overall contributions to well-being (**Figure 5*b–e***). Studies focus on the demand for shelter, mobility, nutrition, and thermal comfort and less on sectors like health, education, and leisure. What is mostly modeled are product stocks, such as the number of appliances or weight of buildings, with 49 studies using 176 indicators referring to product

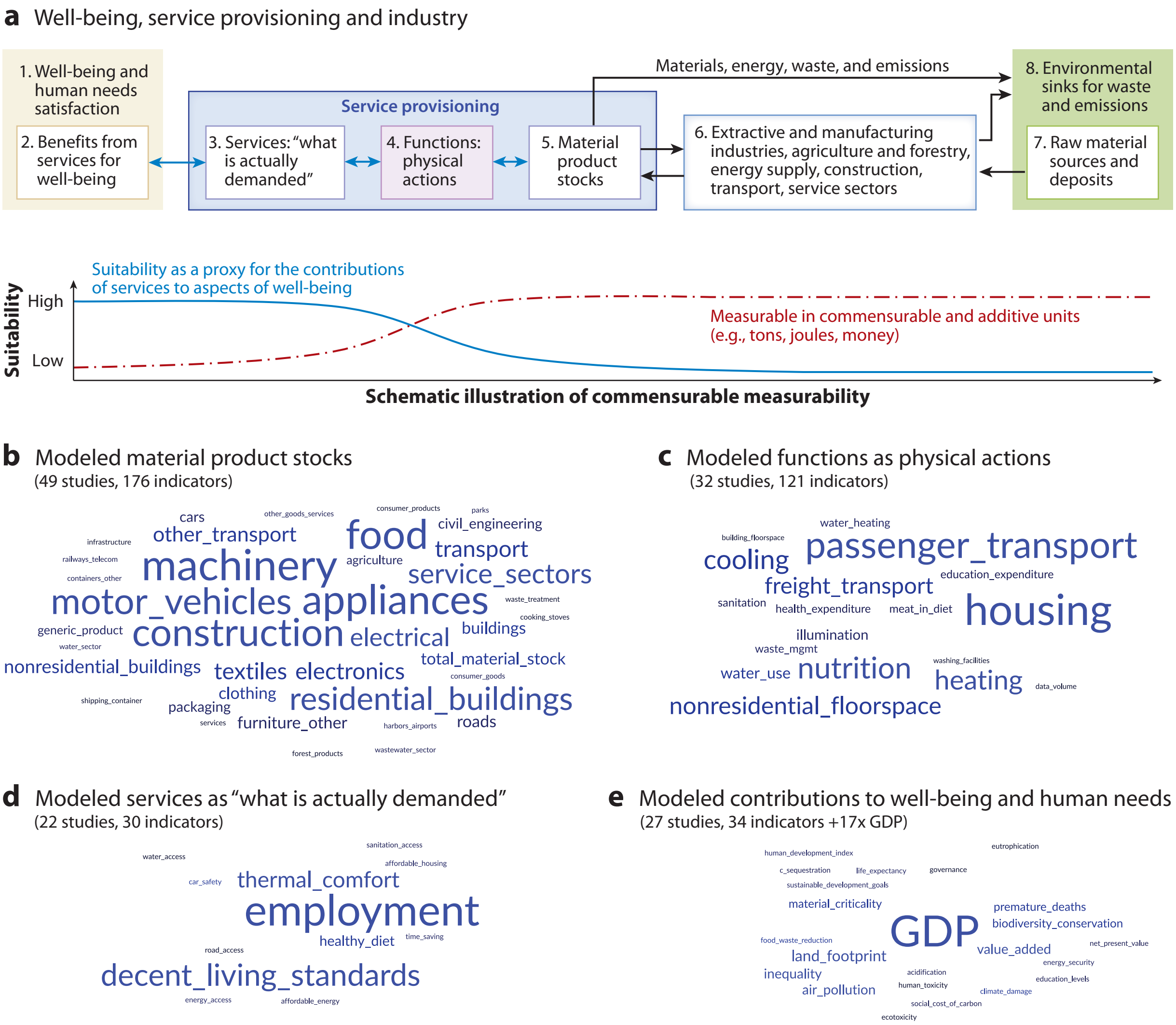

Figure 5

(*a*) Conceptualizing how service provisioning links well-being, human need satisfaction, and demand to the industrial production system supplying goods and services by drawing on the environment for resources and as sinks for waste and emissions (37). (*a*, *top*) Service provisioning can be conceptualized as linking "what is actually demanded," e.g., thermal comfort, to the physical actions performed by product stocks that convert energy and materials, whose configuration can be more or less resource efficient. (*a*, *bottom*) Along this relationship from well-being to service provisioning to industry and the environment, measurability and commensurability increase while the suitability of these measurements as a proxy for the contributions of services to aspects of well-being declines. Tackling this trade-off requires trans- and interdisciplinary approaches to understand feasible, desirable, and context-specific minima and maxima of service provisioning. Black arrows represent physical flows of resources and waste, and blue arrows show interactions of elements. (*b*–*e*) The word clouds show the frequency of indicators used in the reviewed literature to operationalize these relationships, with the majority of studies assessing only (*b*) product stocks (number 5 in panel *a*), while (*c*) physical actions required for service provisioning (number 4 in panel *a*), as well as (*d*) services as "what is actually demanded" (number 3 in panel *a*) are addressed much less often. (*e*) Finally, contributions to well-being (number 2 in panel *a*) are modeled least frequently and then mainly via economic indicators only. For the details of each study, see section 1 of the **Supplemental Material**.

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quantities and expenditures (**Figure 5*b***). A total of 32 studies focus on actual functions using 121 indicators, most prominently those related to housing, passenger transport, nutrition, heating and cooling, nonresidential floorspace, and freight transport (**Figure 5*c***). Service provisioning as what is actually demanded is the focus of only 22 studies using 30 indicators, mostly via employment and the minimum universal DLS (**Figure 5*d***). Only 27 studies link to well-being, mainly using GDP as proxy, and to various complementary indicators (**Figure 5*e***).

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We also find three approaches to modeling demand for service provisioning, showing how the theoretical background of each tradition influences its perspective on consumer decisions and sufficiency of service provisioning (see section 6 of the **Supplemental Material**). So-called consumption functions are used to model how a basket of goods and services is chosen under constraints; they imply a choice of commensurable units and require theoretical assumptions about how actors decide among competing alternatives. First, researchers in macroeconomics commonly employ optimization, using variations of (bounded) rational choice theory and monetary valuation and assuming maximization of utility (e.g., consumption, GDP). Expanding the notion of utility to leisure, unpaid care work, quality of life, and well-being, as well as properly including disbenefits, would be a useful step toward fully addressing questions of well-being (9, 77). Second, exogenously given policy targets and extrapolations of observed dynamics are employed to provide useful what-if insights. However, these studies do not discuss the behavioral foundations of the who, the how, and the why. Third, future consumption patterns are developed from, for example, minimum universal DLS (107, 109, 110, 134) or via transdisciplinary cocreation efforts in citizen assemblies or stakeholder workshops (60, 81). These efforts constitute innovative and promising avenues for transformative insights on justifiable minimum and maximum levels of service provisioning consistent with high well-being.

4.3. A Roadmap for Improved LEMD Scenario Modeling and Scenario Development

A primary goal of LEMD modeling efforts for industry should be to achieve higher-level interdisciplinary consistency and resolution in order to show industry transformation pathways for LEMD futures that will meet multiple SDGs and help shape a new understanding of the role of industrial sectors. We summarize eight recommendations for future research (for an extended discussion, see section 7 of the **Supplemental Material**).

Overall, interdisciplinary combinations of modeling traditions yield more robust, detailed, and policy-relevant insights than any single tradition alone can provide. Combining models requires that we carefully consider and potentially harmonize differences in system definitions and modeling principles. Transdisciplinary research and collaborations among the social sciences will help us understand how service provisioning is organized and could be transformed, as well as what acceptable and just LEMD futures could look like.

4.3.1. Thermodynamic and biophysical consistency. Consistency across material cycles, material stocks, energy use, by-products, waste, and emissions will be crucial to capture economy-wide and time-dependent implications of LEMD scenarios. Ideally, such consistency would be achieved at high granularity, ranging from primary extractive sectors, industry and manufacturing, final consumption, recycling, and waste management to service provisioning. In this way, the potential and unintended consequences of LEMD scenarios could be modeled.

4.3.2. Stock–flow–service nexus. The efficiency of transforming material and energy flows into service provisioning hinges on existing material stocks in products, buildings, and infrastructure. Especially in higher-income countries, transformation of already existing material product stocks will be necessary to break up technological and infrastructural lock-ins and improve the efficiency of service provisioning. Nonmonetary service provisioning indicators will improve our understanding of the links between well-being, human needs, and service provisioning systems.

4.3.3. Wider spectrum of supply- and demand-side measures. Developing net-zero-compliant LEMD pathways requires enlarging the solution space, which includes not only standard economic instruments but also regulatory measures, product standards, institutional changes, government procurement, financial markets, changes in settlement patterns and urban forms, and sociobehavioral changes. Modeling these measures and their interactions is significantly more complex than modeling price-based instruments and rational agents.

4.3.4. LEMD-induced changes in industrial assets and supply chains. LEMD transformations will create economic winners and losers. Assessment of the socioeconomic and environmental repercussions across global supply chains will be critical to understand potential rebound effects, burden shifting, and unintended consequences. An explicit representation of industrial assets and supply chains will help us understand capital constraints; early asset retirements; and reallocations of capital, labor, and natural resources in LEMD scenarios. Ideally, the social implications of deep structural changes as well as societal crises in labor, incomes, skills, and inequality will also be assessed.

4.3.5. Resource constraints, vulnerability, and resilience. Complex socioecological dynamics, feedbacks, and nonlinearities are inherent in LEMD transformations, including the changes that are already occurring in the Earth system and their impacts. The environment is more than a repository of resources to be extracted and a sink for waste and emissions. Complex trade-offs exist between the climate, biodiversity, and land use as well as the other planetary boundaries.

4.3.6. 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 (52, 149, 150). Research efforts aiming to diversify and broaden contributions to the seventh IPCC assessment cycle and beyond include the Integrated Assessment Modeling Consortium (see **https://www.iamconsortium.org**), the International Transport Energy Modeling network (see **https://transportenergy.org**), and the Energy Demand Changes Induced by Technological and Social Innovations network (see **https://iiasa.ac.at/projects/edits**). To successfully engage, LEMD modelers need to consider the reporting requirements for such assessments early on. A shared data ontology across traditions and models is necessary to facilitate comparability and evidence synthesis.

4.3.7. Shared understanding of LEMD decarbonization pathways. LEMD modeling can readily contribute to evidence synthesis and global assessment reports only if reference decarbonization pathways and frameworks, such as the SSPs, are appropriately updated and modified to account for the potential role of demand-side measures. Since their inception, the SSPs have been further developed (13, 151), and substantial updates will be released in 2024 (see **https://depts.washington.edu/iconics**, **https://www.iamconsortium.org/event/iconics-and-iamc-joint-webinar-shared-socioeconomic-pathways-ssps-update**). More fundamental revisions are also being discussed. Ideally, future LEMD modeling will connect to the most recent SSPs and contribute to ongoing efforts to develop a new low-growth/low-demand SSP (7). Explicit quantification of service provisioning will be essential for comparability across LEMD models (21, 23, 152).

5. CONCLUSIONS

Industry's response to LEMD futures is a crucial sustainability lever. Model-based assessments help design effective policy for deep sustainability transformation in this crucial sector.

LEMD modeling is on the rise and is particularly relevant to show the mitigation potentials and well-being benefits of transformative supply- and demand-side measures that address multiple environmental crises and multiple SDGs. LEMD scenarios avoid betting on future technological solutions, such as large-scale negative emissions technologies. The mitigation potentials of materials, energy, and GHG emissions are substantial across LEMD studies, indicating that LEMD futures can be achieved with sufficient service provisioning for high well-being.

Yet these studies suffer from several shortcomings, stemming from differences in modeling approaches—simulation versus optimization—and linked to issues of model consistency, heterogeneity, and granularity. A crucial issue is to better understand how much provision of goods and services is sufficient to promote high well-being. We will need to develop justified and acceptable scenarios of minimum levels, such as the DLS, as well as ecologically feasible maximum levels of service provisioning across different contexts. Another important need in LEMD modeling for industry is to improve models to link material cycles, material stocks, energy use, waste, and emissions in a thermodynamically consistent manner. Most studies do not do so, and those that do are rather coarse in their representation of the socioeconomic interdependencies and dynamics underlying changes. Models with comparatively better representation of socioeconomic complexity and endogenous dynamics often do not comply with thermodynamic principles. In summary, many of the industry models reviewed herein seem to be either too aggregated or too specific. Shared concepts, ontologies, and scenario narratives, as well as more open science and FAIR data, are clearly required to facilitate collaboration and evidence synthesis.

Opening up the solution space for addressing the climate crisis and the transgression of multiple planetary boundaries is a crucial endeavor that requires new visions and strategies. Coupling industry transformation with LEMD futures could be such a pathway. Advancing LEMD modeling for industry plays a crucial part in informing the policy and business communities and the wider public about our collective options for transforming the industrial sector, aside from betting on risky future technological fixes.

SUMMARY POINTS

1. The emerging field of low energy and material demand (LEMD) modeling aims to broaden our collective understanding of the solution space for mitigating the climate crisis without relying on risky future technological fixes.
2. Scenarios showing LEMD-oriented industry futures are generated through various models and methods and increasingly via interdisciplinary combinations of modeling traditions.
3. Material cycles; stocks of buildings, infrastructure, machinery, and other short-lived products; and their dependence on energy use need to be more consistently represented to understand the potential of different supply- and demand-side measures for sustainable development in industry.
4. On the demand side, up to 10 end-use product groups approximate service provisioning, mainly for buildings, transport, appliances, and food, whereas well-being implications beyond gross domestic product (GDP) are rarely addressed.
5. Various studies extrapolate small-scale and/or static data to the national or even global level, which is a problematic oversimplification of industrial systems dynamics.

6. Macroeconomic traditions use endogenous economic growth theories to provide cost-optimal pathways, including assumptions about autonomous efficiency improvements and future costs of the climate crisis. They regularly violate thermodynamics and ignore or downplay the costs of escalating nonlinear feedbacks arising from, for instance, climate breakdown and ecosystem collapse in high-growth scenarios.
7. Other industry modeling traditions use exogenous drivers such as population and economic growth and then simulate the technological, biophysical, and behavioral greenhouse gas (GHG) mitigation potentials of supply- and demand-side measures. However, they often exclude or oversimplify macroeconomic and social implications.
8. Industry transformation pathways need to be plausible and consistent in both monetary and biophysical terms, including fixed capital and investment needs as well as material cycles, material stocks, and energy use, to depict the substantial demand reductions that could result from significant improvements in end-use service provisioning efficiency.
9. Proper documentation and open data are lacking for more than half of the studies reviewed here, hindering reproducibility, comparability, and evidence synthesis.

FUTURE ISSUES

1. Interdisciplinary combinations of modeling traditions yield more robust, detailed, and policy-relevant insights than any single tradition can provide.
2. Biophysical consistency across industries, material cycles, energy use, material stocks, and service provisioning are important to understand time-dependent system dynamics, supply- and demand-side mitigation potentials, and possible unintended negative consequences.
3. While minimum levels of service provisioning are receiving increasing attention—for example, via decent living standards (DLS)—what constitutes ecologically feasible and socially acceptable maximum levels is an open question, as are ways to address inequality.
4. Studies that show the potentials and impacts of a larger range of supply- and demand-side measures beyond only price-based instruments are crucial, because LEMD transitions would induce disequilibrium, major structural changes with repercussions for employment, and early retirement of some capital stocks.
5. Addressing LEMD repercussions across global supply chains is important because there will be rebound effects and burden shifting, as well as socioeconomic winners and losers.
6. LEMD scenario modeling should address ecological feedbacks and dynamics, which are already occurring as a result of the intensifying climate crisis. Complex trade-offs exist between different environmental factors, ranging from the climate and biodiversity crises to other planetary boundaries.
7. Shared understanding and development of appropriate production functions for industry that are consistent across aggregation levels and for monetary and biophysical layers are crucial for modeling and designing sustainable industry futures.
8. Shared concepts and scenario narratives—as well as improved research infrastructure; open science principles; and findable, accessible, interoperable, and reusable (FAIR)

research data—are needed to facilitate the combination of models, comparison of results, and synthesis of evidence.

9. Connecting with efforts to extend the shared socioeconomic pathway (SSP) framework is important so that the Intergovernmental Panel on Climate Change and other assessment efforts can easily integrate LEMD scenarios into their evidence synthesis.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

D.W. contributed to the article's conceptualization, methodology, formal analysis, investigation, resources, data curation, writing of the original draft, visualization, and supervision as well as to project administration and funding acquisition. J.S. contributed to the article's conceptualization, methodology, formal analysis, investigation, resources, data curation, and writing of the original draft. F.W. participated in validation, investigation, data curation, and writing and editing of the article. E.V. and N.B. participated in the conceptualization, investigation, and review and editing of the article. A. Mastrucci, J.M., J.N., M.F.G.L., L.M., A. Mayer, S.G., A.H., and J.J. contributed to the investigation, data curation, and reviewing and editing of the article. Y.J. participated in the conceptualization, investigation, data curation, and review and editing of the article. B.B.-K. and B.v.R. participated in the article's conceptualization, investigation, supervision, and writing and editing, as well as project administration and funding acquisition. H.W. participated in the formal analysis, investigation, data curation, visualization, and review and editing of the article. G.Ü., L.N., T.C., M.Z.-Z., and B.P. participated in investigation and data curation. J.V.-H. participated in investigation and data curation. E.M. participated in the investigation, validation, and review and editing of the article. V.K. participated in the validation and review and editing of the article. K.A. contributed to supervision and funding acquisition. A.G. participated in the article's conceptualization and supervision. S.P. contributed to the article's conceptualization, methodology, formal analysis, investigation, resources, data curation, writing of the original draft, and visualization.

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