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Industrial ecology in integrated assessment models

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[Abstract]

Technology-rich integrated assessment models (IAMs) address possible technology mixes and future costs of climate change mitigation by generating scenarios for the future industrial system. Industrial ecology (IE) focuses on the empirical analysis of this system. We conducted an in-depth review of five major IAMs (AIM/CGE, GCAM, IMAGE, REMIND, and MESSAGE) from an IE perspective, and revealed differences between the two fields regarding the modelling of linkages in the industrial system. Most IAMs ignore material cycles and recycling, incoherently describe the life-cycle impacts of technology, and miss linkages regarding buildings and infrastructure. Adding IE system linkages to IAMs adds new constraints and allows for studying new mitigation options, both of which may lead to more robust and policy-relevant mitigation scenarios.

Within climate change research there are two different but related families of integrated assessment models (IAM). One is cost-benefit-oriented and used, for example, by the IPCC Working Group II, to address questions regarding the optimal degree of global warming by weighing off the damage caused by global warming against the cost of mitigating it. The second family is technology-rich and scenario-based. It is used, for example, by the IPCC Working Group III, to model the industrial and consumption sectors that drive greenhouse gas emissions, to quantify the possible future effect of sustainable development strategies, and to identify optimal development pathways for climate change mitigation. It is the latter model family that is addressed here. Technology-rich IAMs are computer models that exhibit a comprehensive coverage of the global socio-ecological system (SES, Figure 1); they cover environmental mechanisms, in particular the climate system and natural vegetation; the biophysical basis of society, including industries, households, and infrastructure; the economic, political, and behavioural superstructure that governs human decisions; and major coupling mechanisms between these elements.

[Figure 1 about here]

The scenarios determined by IAMs are framed by storylines on the expected technical and economic characteristics of the industrial metabolism and constrained by limited natural resources, lock-in from existing technical installations, and emissions mitigation targets and climate policies such as carbon taxes. One group of technology-rich IAMs determine economically optimal solutions for energy supply (partial equilibrium models) or economy-wide (general equilibrium models). Another group does not optimize future outcome but extrapolates empirically verified patterns into the future (econometric and simulation models). The usefulness of IAM results is widely recognized by the scientific community and policy makers, for example, in the latest IPCC Assessment Report.[1] IAMs are applied to study the nexus between socio-economic drivers, energy services, climate, food, water, and land,[2–6] and are used by nongovernmental bodies such as the International Energy Agency for scenario development.[7] The IAM community has developed a vivid culture of interaction between models,[8] which is bundled in projects such as the Energy Modeling Forum,[9] the EU AMPERE project,[10] the Global Energy Assessment,[5] and the EU ADVANCE project.[11] As a result, an extensive database of scenario results has been compiled and made available to the wider public.[12]

While technology-rich IAMs generate future scenarios for the global SES, industrial ecology (IE) research quantitatively analyses specific linkages in the biophysical basis of society, which is the subsystem of the global SES where natural resources are transformed into materials and products,[13] where physical services to humans, like thermal comfort or mobility, are generated, and where emissions to the environment occur. In particular, IE researchers have identified the following linkages in society's biophysical basis as important determinants of sustainable development: global supply chains and their environmental, economic, and social impacts,[14,15] the linkage between capital services, capital stocks, and capital formation,[16] material cycles and their development over time,[17,18] co-production, industrial symbiosis, and waste processing,[19,20] and the link between the urban fabric and consumption patterns.[21,22] Unlike the IAM community, which centres around the different integrated assessment *models*, researchers in the IE community study linkages in society's biophysical basis from the perspective of different *methods*, each with a unique perspective on the global SES that is complementary to the perspective offered by IAMs. (Figure 2). The IE methods follow specific modelling principles. They work at high levels of process and commodity detail and respect the market and process balances. The different age-cohorts (vintages) of fixed assets and material stocks are tracked through time, and material flow analysis respects the system-wide closure for specific materials (Figure 2).

[Figure 2 about here]

Despite the overlap in scope between IE and IAMs the two fields have remained largely disconnected,[23] although recent years have seen studies that integrate detailed knowledge of industrial processes gained from life cycle assessment with aggregated representations of the whole economy, sometimes labelled as consequential life cycle assessment.[24–27] A systematic comparison of the IAM and IE approaches to assessing transformation strategies is still lacking. To fill that gap, we first compiled the core insights on linkages and principles for modelling society's biophysical basis established by IE research. Second, we performed a detailed review of five widely used technology-rich IAMs, covering how they model the industrial system and to what extent they incorporate insights from IE. Third, we identified potential benefits of a closer interaction between the IAM and IE communities and describe how this interaction could happen.

Recent examples for subject-specific reviews of IAMs include an identification of inconsistencies of some IAMs regarding bioenergy deployment,[23] the necessity of IAMs to include natural capital,[28] and improvement options for making IAMs suitable for modelling biodiversity futures.[29] This review of IAMs from an industrial ecology perspective contributes to the wider scientific debate[30–32] about improvement options for IAMs and potential synergies between IAMs and more specialized research fields.

Principles of industrial ecology

We describe the state of the art of the research on the central IE system linkages and list major limitations relevant for the interaction of IE research with IAMs.

Global supply chains and the life cycle perspective: Global supply chain analysis provides a full environmental assessment of the life cycle of products and services and identifies possible burden shifting between countries and industrial sectors, or across time.[33] Supply-chain models are applied in consumption-based accounting, where impacts of household consumption on climate change,[34,35] land use change,[36] and biodiversity loss[37] are studied. Supply chain models are especially important for correctly assessing indirect emissions from fossil fuel extraction[38] and for assessing products with low use-phase emissions but high impacts from production and disposal. Electric vehicles[39] and renewable electricity generation[38,40] represent important examples of products where capital production can dominate life cycle impacts. The low carbon fuel standards issued by several countries are the first policies that regulate supply chain greenhouse gas emissions.[41,42] Adding the carbon costs of life cycle emissions to climate policy scenarios can double the marginal abatement costs.[26] In IE supply chains are commonly studied with life cycle assessment (LCA) and environmentally extended multiregional IO (MRIO) analysis, with the physical (LCA) and monetary (MRIO) industry and market balances are central modelling principles. Most of LCA and MRIO research fails to account for future changes in energy supply and other industries, which is a major limitation when applying those methods for prospective technology assessment and scenario analysis.

Linkage between capital service, capital stocks, and capital flows: The provision of housing, mobility, and production services requires capital stocks, whose lifetime determines the speed at which new technologies can replace old ones, and the investment flows necessary to maintain stocks.[16,43] The service-stock-flow linkage is a central element of all dynamic models that connect the benefits of providing services to people, such as electricity from renewable sources, to the impacts of the investment flows into the production and distribution infrastructure of services, such as GHG emissions from steel and copper production. Within

IE research this linkage is studied at high levels of detail in dynamic LCA,[44] dynamic material flow analysis (MFA),[45,46] and urban metabolism studies,[47] with mass and capacity balances as well as vintage tracking of in-use stocks as central modelling principles. With the exception of stock-driven modelling[45] the different dynamic IE methods rely on exogenous demand scenarios as model drivers.

Mass-balance-consistent modelling of material cycles: In 2010, about 50% of industrial GHG emissions stemmed from the production of four material groups: steel, other metals, cement, and chemicals.[48] Dynamic MFA research has shown that three salient parameters need to be known to quantify the emissions mitigation potential of material cycles: (i) the level of in-use stocks as proxy for the service provided by materials, (ii) the amount of postconsumer scrap determining the recycling potential, and (iii) the level of primary production, the main determinant of GHG emissions from material production.[49,50] Physical MFA models are needed to develop future scenarios for material cycles as only they can determine scrap supply based on historic investments and the long lifetime of metal-containing products,[45] investigate the different substitution and light-weighting options for these materials,[51] and use material service demand rather than economic output as driver for material consumption.[45] MFA has shown that per capita affluence (PPP-GDP) is a poor predictor of the three major material cycle parameters (Figure S1-2) because there is little apparent correlation between the economic and physical indicators. The current dynamic material cycle models in IE lack a description of costs, which limits their relevance for decision making. They need to be linked to scenarios for future demand for buildings, vehicles, infrastructure, and industrial assets.

Accounting for the complexity of industrial processes: Co-production, industrial symbiosis, and waste management: Waste and by-product generation is a characteristic of every industrial activity,[52] and the description of waste generation and treatment, recycling, and by-product use is well established in the IE methods LCA,[53,54] MFA,[49,55] MRIO,[56,57] industrial symbiosis,[58] and urban metabolism studies.[59] To estimate the economic and environmental impacts of future waste flows and the contribution of co-production to sustainable development existing waste studies need to be extrapolated under different socioeconomic scenarios.

The structure of the urban fabric and consumption patterns: Urban form directly impacts transportation patterns and energy and material consumption of the urban population,[59,60] and the inertia of urban infrastructure is a key determinant of energy consumption and emissions pathway lock-ins.[61] There is no single factor that explains variations in per-capita greenhouse gas emissions across cities and mitigation options depend on the specific urbanisation trajectories,[61] which means that some detailed modelling is needed to better understand and quantify the different trajectories for sustainable urban development. To that end a better integration of 'micro-models' of building and vehicle types, 'meso-models' of the urban fabric, and 'macro-models' of the economy and policies beyond the urban sphere is needed.[62]

IAMs from an industrial ecology perspective

Model inter-comparison efforts of the IAM community focus on the juxtaposition and comparison of scenario drivers and results and not on the systematic comparison of model structures per se. The lack of structural comparison of IAMs was pointed out by Rosen in particular,[63,64] while Strachan et al. criticise the lack of documentation and replicability of technology-rich IAMs.[30] Throughout their history, the industrial subsystems of some IAMs and the related energy system models were reviewed, especially regarding their coverage of specific energy technologies and policies,[65–68] their suitability for describing a low-carbon society,[69] and the way they consider technological change.[70,71] The recently compiled wiki on the structure and resolution of ten widely applied IAMs under the EU-ADVANCE project is to our knowledge the only systematic comparative documentation of the technology-rich IAMs.[72] Still, the rich information provided by the ADVANCE-wiki was often insufficient to understand how the IE linkages and principles are modelled by IAMs, and a more detailed model review was necessary.

Reviewing the structure of IAMs poses a triple challenge: First, IAMs draw upon the specific knowledge of many scientific disciplines ranging from ecosystem science to macroeconomics and integrate it into a unique modelling structure. Second, IAMs with global scope are a very diverse group of models with more than 30 members. Third, since many IAMs have been developed over several decades, their documentation is often scattered across many different journal articles, reports, and other documents, and for several central aspects of some models, no publicly available documentation exists. We addressed the first challenge by narrowing down the scope of the review to the representation of society's biophysical basis, the research subject of IE. We dealt with the second challenge by adapting a two-level approach. We chose 30 IAMs that were part of recent model comparison projects and compiled a coarse description of these models regarding their resolution of the industrial system. We then performed an in-depth review of the structure and resolution of the five widely used IAMs: AIM/CGE,[73,74] GCAM,[75,76] IMAGE,[77,78] REMIND-MAgPIE,[79,80] and MESSAGE.[81,82] These models were chosen because they represent prominent examples of technology-rich IAMs and at the same time they vary in their modelling approach. Our review covered about 150 specific items for each model, including their representation of capital stocks, their determination of energy and service demand and technology mix, their process and commodity resolution, and their biophysical consistency (mass and energy balances). We dealt with the third challenge by compiling information from a large number of literature sources and by inviting the developers of each of the five IAMs to check our findings and provide additional information during the preparation of this article. The complete review results are documented in the supplementary table S2. Here we focus on how the five IAMs deal with the core IE linkages and principles (Table 1).

Industrial ecology in IAMs

Global supply chains and the life cycle perspective on technology: All models reviewed include the use phase of energy conversion (and other assets in industry, buildings, and transportation for some models) in both physical and monetary units. Additional energy costs and GHG emissions of new resource extraction and energy conversion technologies are sometimes included, e.g., for unconventional gas reserves in MESSAGE.[3] The build-up or investment phase of assets is always covered by a cost factor as investment costs strongly influence the outcome of the investment decision routines. Whether the emissions of producing new capital are included depends on whether the model has a macroeconomic budget closure (AIM/CGE, MESSAGE, REMIND) or not (GCAM, IMAGE). For a given GDP scenario models without budget closure do not reduce the output and services available to final consumers (and thus welfare) due to increasing investment costs in the industrial system as consequence of sustainable development. This missing link may be problematic as it breaks an important linkage in the industrial system: environmental and industrial repercussions of technology deployment are omitted from the assessment,[83,84] e.g., the rising metal demand of new energy technologies.[38,39,85,86] While the supply chain impacts of new capital assets are included in the overall economic output in models with budget closure, they are not allocated to these assets and thus cannot enter the decision making routines in the energy system and industrial modules.

Link between capital services, capital stocks, and capital formation: This linkage is always present in IAMs as they link services to stocks and stocks to investments. In none of the IAMs reviewed, however, there is a physical linkage between the capital stock (industrial assets, buildings, and transportation devices) and the material flows required to build up the stock. Instead, capital investments may consist of one aggregated monetary commodity (MESSAGE, REMIND), about 30 commodities in monetary units (AIM/CGE), or they may not be converted from costs to actual commodities (CGAM, IMAGE).

Table 1: Coverage of central linkages in the industrial system and the related modelling principles for the five IAMs reviewed.

		AIM/CGE 2.0	GCAM 4.2	IMAGE 3.0	MESSAGE V.4 and MACRO	REMIND 1.6
Major industrial ecology system linkages	**Global supply chains**	Indirect coverage of all supply chains in aggregated form (31 sectors in monetary units) + electricy3)	Physical supply chains for six final energy carriers, cement, and fertilizers; supply chains not complete due to missing capital link.	Phys. supply chains for 8 final energy carriers, cement, steel, services, and agricult. products. Supply chains not complete due to missing capital link.	All supply chains indirectly covered in highly aggregated form (1 sector in monetary units) + all final energy carriers3)	All supply chains indirectly covered in highly aggregated form (1 sector in monetary units) + all final energy carriers3)
	Linkage capital service → capital stocks → capital formation	Capital service demand → capital stock demand → demand for capital goods (composition not documented)	Demand for transportation devices and production capacity for electricity and refined fuels → demand for production assets → investment costs4)	Demand for production capacity for electricity, hydrogen, cement, and steel → demand for production assets → investment costs4)	Demand for capital services, and energy conversion assets → capital stock demand → demand for investment of the aggregate good	Demand for capital services, energy conversion, and transport → capital stock demand → demand for investment of the aggregate good
	Material cycles	Not considered.	Not considered	Cement and complete steel cycle	Not considered	Not considered
	Co-production, waste generation and use	No information available.	Co-production of electricity from fuel in industries, biomass waste to energy	Combined heat and power, by-products from biofuels use as fodder, wastewater treatment	Combined heat and power, several more5)	Combined heat and power
	Urban fabric → consumption patterns	Not considered.	Not considered.	Urban population → N and P emissions from wastewater2)	Not considered.	Not considered.
Central industrial ecology modelling principles	**Physical market balance**	For primary and secondary energy carriers (monetary market balance for all other commodities)	For primary and secondary energy carriers and all agricultural products	For primary and secondary energy carriers, agricultural product, cement, and steel	For primary and secondary energy carriers	For primary energy carriers
	Physical process (industry) balance	energy balance for 28 energy conversion technologies	energy balance for 42 energy conversion technologies	energy balance for 31 conversion technologies, mass balance (steel) for manufacturing and the use phase	energy balance for 43 energy conversion technologies	energy balance for about 50 energy conversion technologies
	Vintage tracking	Depreciation of capital stock, no vintage tracking, implicit aging of age-cohorts via 4%/yr depreciation rate	Vintage tracking in electricity generation, refining and transportation sectors, S-shaped retirement curve	Vintage tracking for energy conversion assets, transportation and household devices, and steel, all in physical units.	Vintage tracking with fixed lifetime for energy conversion assets (20-60 years, depending on technology)	Vintage tracking (energy system assets), exponential depreciation for all other capital
	System closure	For energy (physical), for GDP (monetary)	For energy (physical)	For energy (physical)1)	For energy (physical), for GDP (monetary)	For energy (physical), for GDP (monetary)
	High regional and process detail	69 technologies deployed in 17 regions	102 technologies deployed in 32 regions	More than 103 technologies deployed in 26 regions	100 technologies deployed in 11 regions	More than 56 technologies deployed in 11 regions

Notes: 1) The steel cycle model in IMAGE is not linked to the models for the steel-containing products and technologies, like buildings, vehicles, and energy conversion assets.
2) IMAGE considers the urban built-up area which is excluded from land use modelling. The built-up area depends on urban population and a country- and scenario-specific urban density curve.

3) AIM, MESSAGE, and REMIND contain a macroeconomic balance, meaning that production of all capital requirements is included in the total output (at the level of aggregation of the model).
4) The investment costs for new assets in IMAGE and GCAM enter the algorithms for investment decisions but the resulting investment flows are not linked back into the macroeconomic module.
5) Co-production of synthetic liquid fuels and electricity, nuclear fuel reprocessing, energy recovery from agriculture and forest residues and landfill CH_4.

Material cycles: While the production of bulk materials is included in AIM/GCE (6 commodities in monetary units, including steel), GCAM (cement and fertilizers), and IMAGE (steel and cement), only IMAGE contains a physical model for the steel cycle and its emissions, which is partly based on the integrated energy system and material cycle model MARKAL-MATTER.[87] The steel cycle model of IMAGE is driven by GDP; it is not linked to the building and transportation sector sub-models, which are the main steel users. For all other models and materials the complex inter-industrial network of material production, manufacturing, in-use stocks, waste management, and recycling is aggregated together with other industrial activities. We see this aggregated representation as problematic in light of the insights from IE[50] and energy system model research[87] into the role of material cycles in sustainable development: Milford et al. (2013) show that the emissions mitigation potential of material efficiency in the steel cycle is up to 1.5 Gt CO_2/yr in 2050, which is about half of the sector total. Consequently, recycling, light-weighting, and other material efficiency strategies should be part of technology-rich IAMs, which would allow them to assess a wider spectrum of emissions mitigation strategies than is currently the case. Moreover, the trends shown in Figure S1-2 suggest that affluence alone is not a reliable driver for any of the salient material cycle parameters, especially not for postconsumer scrap generation. Therefore, material production and recycling should be physically linked to service indicators including settlement patterns, personal dwelling space, and transport levels, which partly is the case in GCAM and IMAGE already.

Co-production, waste generation and use: IAMs consider co-generation of heat and power (IMAGE, MESSAGE, REMIND) and the co-generation of electricity from fuel use in industries (GCAM, MESSAGE). Apart from the exceptions listed in Table 1 waste generation, waste treatment, and recycling – central strategies to reduce emission in the material cycles – are not explicitly taken into account by the five IAMs, and the emission mitigation potential of strategies aiming at waste reduction, re-use, and higher levels of recycling can currently not be assessed.

The **coupling between settlement structures and consumption patterns** is not considered by any of the IAMs we reviewed, thus a link between urban patterns and energy demand cannot be made.

Physical balances and vintage tracking: IAMs respect the energy balance both for energy conversion technologies and for the markets for energy carriers. Only IMAGE includes a mass balance for steel and cement at different stages of the material cycles. Vintage tracking is mostly applied to energy conversion assets (all models except AIM/CGE), transportation devices (GCAM and IMAGE), and household appliances (IMAGE). All other capital stocks are either not represented or modelled as a single homogeneous unit whose value increases with investment and decreases with annual depreciation. Only IMAGE applies vintage tracking to steel stocks in use. Through consequent application of physical balances and vintage tracking in IAMs the constraints posed by these two first order biophysical modelling principles could help to produce more realistic scenarios for society's future biophysical basis.

Regional and process detail: With 50-100 technologies deployed in 10-30 regions the technology-rich IAMs provide a detailed description of the possible future energy system in different parts of the world. Still, we found that higher levels of detail, especially regarding material stocks and flows, waste and its treatment, and buildings and infrastructure, would add robustness to the scenario engines by adding constraints; it would also extend the spectrum of mitigation options to include material-related strategies. The questions whether adding more detail is technically feasible and whether it will change scenario results requires discussion and further research.

Improving IAMs

Representation and resolution of society's biophysical basis across IAMs are very diverse. While the creation of long-term global scenarios with considerable detail on energy conversion, transportation technologies, and GHG are common to all models, there seems to be little consensus among IAM modellers regarding the macroeconomic budget closure, material cycles, vintage tracking, the routines for decision making, the level of detail and the dynamics of sectors other than energy conversion, and buildings and infrastructure. Based on our review from an IE perspective we suggest the following options for further model development.

A macroeconomic budget closure should be standard so that the global supply chain impacts of all capital investment are at least indirectly represented. Options for integrating the energy-capital linkage into scenario models are identified in the literature on the combination of 'bottom-up' energy technology and 'top-down' aggregated economic equilibrium models;[88,89] the solutions proposed there can be adapted to cover assets in other industrial sectors. There is a similar development in IE, where LCA studies are 'hybridized' by combining detailed physical process models with aggregated monetary IO models to allow for a complete but aggregated representation of supply chains.[90]

More attention should be paid to physical linkages in the industrial system. Suggested refinements include: the explicit physical description of products, industrial processes, buildings, infrastructure, and urban fabric to better depict the link between energy and material throughput and service provision; the link between fixed capital and material stocks; and vintage tracking to improve the representation of technology turnover as well as scrap and waste generation. Stronger physical linkages can increase the policy relevance of IAM scenarios as resource extraction and non-energy industry policies can be better depicted. The explicit representation of material cycles poses new constraints to mitigation trajectories, such as the limited availability of postconsumer scrap for recycling, but also the opportunity to expand the spectrum of mitigation strategies to include joint production, resource efficiency, material efficiency, and recycling. The linkage between urban structures, infrastructure patterns, transportation, and energy demand should receive more attention, potentially by soft-linking IAMs to more specialized models, or by using stylized facts,[91] like stock saturation in material cycles.[92]

Many improvement options for IAMs involve adding new features to the models or increasing their resolution, and the question of how many linkages and much detail are necessary to build credible future scenarios remains open. On one side, LCA research has shown that both specific technology choices and local environmental conditions largely determine the net climate impact of renewable energy supply, especially for biofuels. Many of the physical linkages, like full vintage tracking and the scrap balance, may increase the robustness of IAM scenarios as they tie the future state more closely to lock-ins created by investment decisions in the past. Contrarily, extrapolating consumer choices and technology descriptions far into the future introduces significant uncertainties. One can therefore argue that beyond 2050, an aggregate representation of socioeconomic metabolism may be more suitable as the socioeconomic IAM results become invalid before the geophysical results.[93] A systematic inquiry on the appropriate level of detail for prospective modelling of socioecological systems is necessary.

Community interaction

Integration of system linkages studied by IE and other industry-related modelling fields, like energy system modelling, into IAMs and better alignment of prospective IE studies with IAM scenarios would allow modellers of both fields to reach a higher degree of systems integration[94] to the mutual benefit of policy makers and the researchers involved. We describe three possible pathways for future co-development of the two fields and list the resulting benefits and challenges.

Soft-links between IAMs and IE models: The interaction of IE methods and IAMs can be seen as a multi-model ecology,[95] where a group of models co-evolve and interact with each another in a dynamic environment. IAM scenarios can supply to IE researchers descriptions of the future industrial system, such as the electricity mix, as input data to IE models for prospective assessment of specific emissions mitigation strategies not considered in IAMs. Recent examples of this approach include a study of the future impact of global consumption using a modified MRIO model[96] and an analysis of the possible impact of a global diffusion of renewable energies on European consumption-based emissions.[97] This post-processing of IAM scenarios could be one solution to the quest for more detail in prospective assessment. It could help IE researchers to widen the scope of their analysis in a way that is consistent with established scenario modelling approaches while at the same time, it would help to examine IAM scenarios regarding their plausibility and consistency. The IAM community could use the IE inventory data to add details to their models where appropriate, which requires IE data and results to be made more transparent and accessible. This approach requires only limited interaction between researchers of the two fields but would greatly benefit from mutual standards for open data and data exchange. It does, however, not resolve the more fundamental differences regarding the inclusion of certain system linkages.

A **systematic analysis of the different IE system linkages** is needed to better understand their relevance for climate change mitigation as well as for other aspects of sustainable development.[98] Such analysis would ideally combine empirical research on long-term development patterns of structural economic change[43,99] with theoretical interdisciplinary considerations on the model structure. It could become part of proposed schemes for evaluation of IAMs[91] and involve researchers from different communities dealing with prospective assessment.

A **'standard model' of society's biophysical basis** could be developed that contains a canonical description of production and consumption activities to facilitate maximal coherency across the scenarios generated by different models (Figure 3).

[Figure 3 about here]

Such an effort should build on the experience gained in different fields on the modelling of supply chains, combined energy-material descriptions of the industrial system,[87] and representations of the economy as a whole. Designed as canonical and open source, the industry module would respect basic biophysical and economic constraints, like the material balance of the use phase and the macroeconomic closure, but not pre-empt normative choices and decision mechanisms. By aggregation the module would be made compatible with the scope and resolution of the different IAMs, energy system models, and prospective IE models.

The proposed consolidation of the way IAMs describe society's biophysical basis allows for producing biophysically more consistent descriptions of society's future metabolism. It can help to provide better advice to policy makers and opens up new research opportunities in other scientific fields, for example, in IE, especially for consequential and prospective studies. The consolidation is needed if IAMs want to maintain their relevance as the focus of sustainable development is expanding from the technology-driven energy transition to a more comprehensive set of interlinked strategies formulated as sustainable development goals (SDGs), most of which directly affect society's biophysical basis and the linkages therein. The success of the strategies proposed depends on efforts in both the IAM and related communities like IE to provide better documentation and interfaces to their work and on the willingness of practitioners to change their habits and integrate their often isolated modelling efforts into a larger toolbox. Research funders play a special role in providing the resources for transparent and reproducible integrated scenario modelling that includes state-of-the-art insights from different fields. Many will benefit from the proposed development: the scientists involved, who can bundle their resources and make faster progress, policy makers, who are provided with more robust and transparent assessments, and the general public, who can continue to rely on sound science supporting the political decisions on sustainable development strategies.

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Author contributions

S.P. and E.H. designed the approach, A.A., K.S., and S.P. performed the review, and all authors contributed to writing the paper.

Competing financial interests

The authors declare no competing financial interests.

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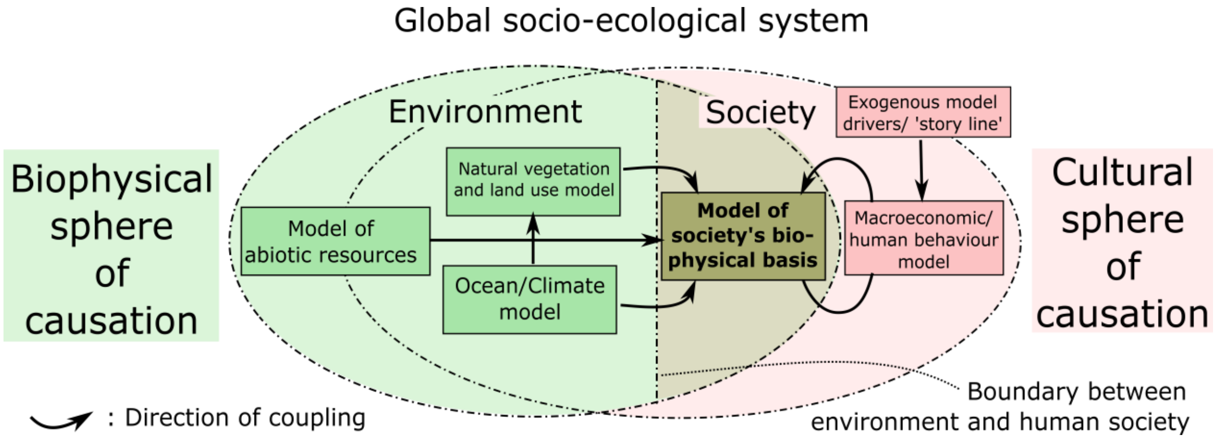

Figure 1: Scheme of the general structure of integrated assessment models (IAMs). IAMs represent the hybrid nature of the global socio-ecological system, which extends into the cultural/economic sphere of causation and the biophysical sphere of causation.[13]

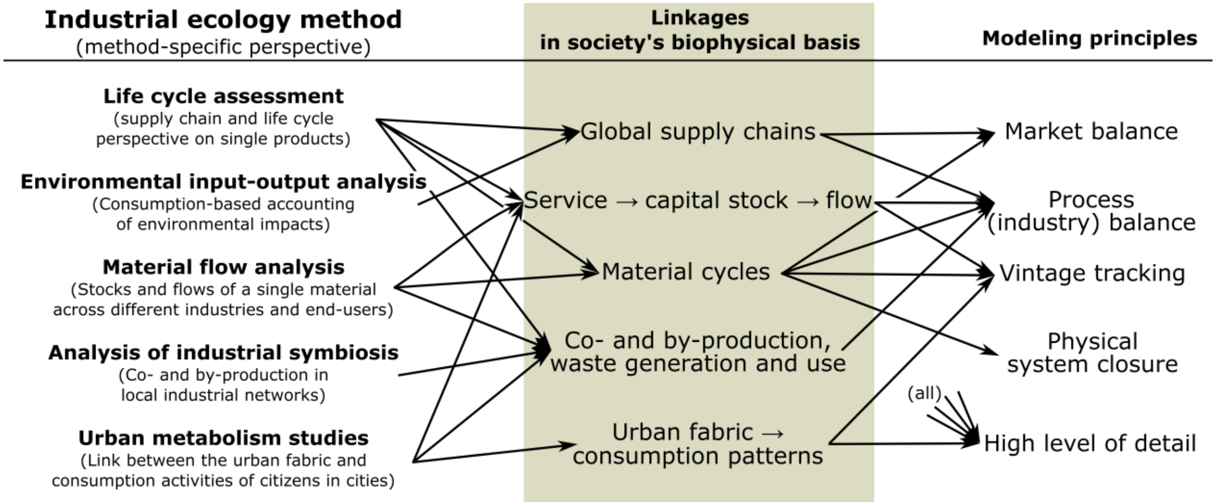

Figure 2: Overview of the main descriptive and assessment methods in industrial ecology. The methods are mapped to those linkages in the industrial system that IE research has identified as important determinants of sustainable development in society's biophysical basis. The linkages are then mapped to modelling principles adhered to by the different IE models. Both the linkages and the principles form the basis of our review of technology-rich IAMs in this work.

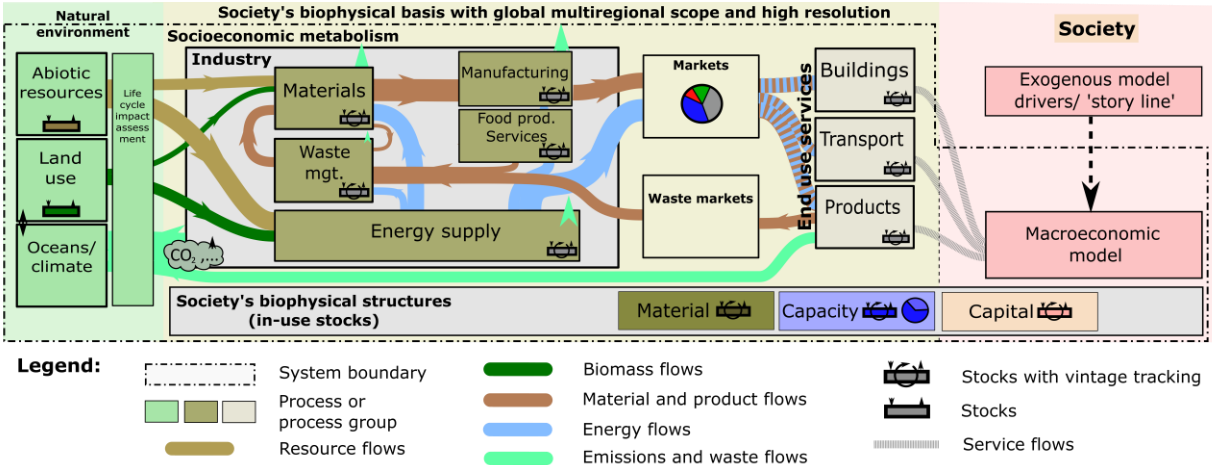

Figure 3: Sketch of the integration of the IAM and IE perspectives on the industrial system. The industrial sectors form a network that links environmental resources to final consumption of products and services. Industry has changed its role from an end-use sector of energy, as in many IAMs, to an intermediate sector that supplies goods for final consumption. Buildings, transport devices, products, and major material cycles are represented in physical units and vintage tracking is applied. Markets and treatment processes for waste and scrap are introduced, and environmental impact assessment is used alongside with the land use, ocean, and climate models. A detailed explanation of this figure can be found in SI1.