

Second revision of a Perspective invited for submission to *Nature Climate Change*

# *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.

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

45 [Figure 1 about here]

46 The scenarios determined by IAMs are framed by storylines on the expected technical and  
47 economic characteristics of the industrial metabolism and constrained by limited natural  
48 resources, lock-in from existing technical installations, and emissions mitigation targets and  
49 climate policies such as carbon taxes. One group of technology-rich IAMs determine  
50 economically optimal solutions for energy supply (partial equilibrium models) or economy-  
51 wide (general equilibrium models). Another group does not optimize future outcome but  
52 extrapolates empirically verified patterns into the future (econometric and simulation models).  
53 The usefulness of IAM results is widely recognized by the scientific community and policy  
54 makers, for example, in the latest IPCC Assessment Report.<sup>1</sup> IAMs are applied to study the  
55 nexus between socio-economic drivers, energy services, climate, food, water, and land,<sup>2-6</sup> and

56 are used by nongovernmental bodies such as the International Energy Agency for scenario  
57 development.<sup>7</sup> The IAM community has developed a vivid culture of interaction between  
58 models,<sup>8</sup> which is bundled in projects such as the Energy Modeling Forum,<sup>9</sup> the EU AMPERE  
59 project,<sup>10</sup> the Global Energy Assessment,<sup>5</sup> and the EU ADVANCE project.<sup>11</sup> As a result, an  
60 extensive database of scenario results has been compiled and made available to the wider  
61 public.<sup>12</sup>

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

80 [Figure 2 about here]

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

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

98

99

## 100 **Principles of industrial ecology**

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

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

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

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

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

150 **Accounting for the complexity of industrial processes: Co-production, industrial**  
151 **sympiosis, and waste management:** Waste and by-product generation is a characteristic of  
152 every industrial activity,<sup>52</sup> and the description of waste generation and treatment, recycling,

153 and by-product use is well established in the IE methods LCA,<sup>53,54</sup> MFA,<sup>49,55</sup> MRIO,<sup>56,57</sup>  
154 industrial symbiosis,<sup>58</sup> and urban metabolism studies.<sup>59</sup> To estimate the economic and  
155 environmental impacts of future waste flows and the contribution of co-production to  
156 sustainable development existing waste studies need to be extrapolated under different  
157 socioeconomic scenarios.

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

### 167 **IAMs from an industrial ecology perspective**

168 Model inter-comparison efforts of the IAM community focus on the juxtaposition and  
169 comparison of scenario drivers and results and not on the systematic comparison of model  
170 structures per se. The lack of structural comparison of IAMs was pointed out by Rosen in  
171 particular,<sup>63,64</sup> while Strachan et al. criticise the lack of documentation and replicability of  
172 technology-rich IAMs.<sup>30</sup> Throughout their history, the industrial subsystems of some IAMs  
173 and the related energy system models were reviewed, especially regarding their coverage of  
174 specific energy technologies and policies,<sup>65-68</sup> their suitability for describing a low-carbon  
175 society,<sup>69</sup> and the way they consider technological change.<sup>70,71</sup> The recently compiled wiki on  
176 the structure and resolution of ten widely applied IAMs under the EU-ADVANCE project is

177 to our knowledge the only systematic comparative documentation of the technology-rich  
178 IAMs.<sup>72</sup> Still, the rich information provided by the ADVANCE-wiki was often insufficient to  
179 understand how the IE linkages and principles are modelled by IAMs, and a more detailed  
180 model review was necessary.

181 Reviewing the structure of IAMs poses a triple challenge: First, IAMs draw upon the specific  
182 knowledge of many scientific disciplines ranging from ecosystem science to macroeconomics  
183 and integrate it into a unique modelling structure. Second, IAMs with global scope are a very  
184 diverse group of models with more than 30 members. Third, since many IAMs have been  
185 developed over several decades, their documentation is often scattered across many different  
186 journal articles, reports, and other documents, and for several central aspects of some models,  
187 no publicly available documentation exists. We addressed the first challenge by narrowing  
188 down the scope of the review to the representation of society's biophysical basis, the research  
189 subject of IE. We dealt with the second challenge by adapting a two-level approach. We chose  
190 30 IAMs that were part of recent model comparison projects and compiled a coarse  
191 description of these models regarding their resolution of the industrial system. We then  
192 performed an in-depth review of the structure and resolution of the five widely used IAMs:  
193 AIM/CGE,<sup>73,74</sup> GCAM,<sup>75,76</sup> IMAGE,<sup>77,78</sup> REMIND-MAgPIE,<sup>79,80</sup> and MESSAGE.<sup>81,82</sup> These  
194 models were chosen because they represent prominent examples of technology-rich IAMs and  
195 at the same time they vary in their modelling approach. Our review covered about 150  
196 specific items for each model, including their representation of capital stocks, their  
197 determination of energy and service demand and technology mix, their process and  
198 commodity resolution, and their biophysical consistency (mass and energy balances). We  
199 dealt with the third challenge by compiling information from a large number of literature  
200 sources and by inviting the developers of each of the five IAMs to check our findings and  
201 provide additional information during the preparation of this article. The complete review



202 results are documented in the supplementary table S2. Here we focus on how the five IAMs  
203 deal with the core IE linkages and principles (Table 1).

#### 204 **Industrial ecology in IAMs**

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

223 **Link between capital services, capital stocks, and capital formation:** This linkage is  
224 always present in IAMs as they link services to stocks and stocks to investments. In none of  
225 the IAMs reviewed, however, there is a physical linkage between the capital stock (industrial

226 assets, buildings, and transportation devices) and the material flows required to build up the  
227 stock. Instead, capital investments may consist of one aggregated monetary commodity  
228 (MESSAGE, REMIND), about 30 commodities in monetary units (AIM/CGE), or they may  
229 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
<b>Major industrial ecology system linkages</b>	<b>Global supply chains</b>	Indirect coverage of all supply chains in aggregated form (31 sectors in monetary units) + electricity <sup>3)</sup>	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 carriers <sup>3)</sup>	All supply chains indirectly covered in highly aggregated form (1 sector in monetary units) + all final energy carriers <sup>3)</sup>
	<b>Linkage capital service → capital stocks → capital formation</b>	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 costs <sup>4)</sup>	Demand for production capacity for electricity, hydrogen, cement, and steel → demand for production assets → investment costs <sup>4)</sup>	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
	<b>Material cycles</b>	Not considered.	Not considered	Cement and complete steel cycle	Not considered	Not considered
	<b>Co-production, waste generation and use</b>	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 more <sup>5)</sup>	Combined heat and power
	<b>Urban fabric → consumption patterns</b>	Not considered.	Not considered.	Urban population → N and P emissions from wastewater <sup>2)</sup>	Not considered.	Not considered.
<b>Central industrial ecology modelling principles</b>	<b>Physical market balance</b>	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
	<b>Physical process (industry) balance</b>	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
	<b>Vintage tracking</b>	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
	<b>System closure</b>	For energy (physical), for GDP (monetary)	For energy (physical)	For energy (physical) <sup>1)</sup>	For energy (physical), for GDP (monetary)	For energy (physical), for GDP (monetary)
	<b>High regional and process detail</b>	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<sub>4</sub>.

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

251 **Co-production, waste generation and use:** IAMs consider co-generation of heat and power  
252 (IMAGE, MESSAGE, REMIND) and the co-generation of electricity from fuel use in  
253 industries (GCAM, MESSAGE). Apart from the exceptions listed in Table 1 waste  
254 generation, waste treatment, and recycling – central strategies to reduce emission in the  
255 material cycles – are not explicitly taken into account by the five IAMs, and the emission

256 mitigation potential of strategies aiming at waste reduction, re-use, and higher levels of  
257 recycling can currently not be assessed.

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

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

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

## 280 **Improving IAMs**

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

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

297 **More attention should be paid to physical linkages** in the industrial system. Suggested  
298 refinements include: the explicit physical description of products, industrial processes,  
299 buildings, infrastructure, and urban fabric to better depict the link between energy and  
300 material throughput and service provision; the link between fixed capital and material stocks;  
301 and vintage tracking to improve the representation of technology turnover as well as scrap and  
302 waste generation. Stronger physical linkages can increase the policy relevance of IAM  
303 scenarios as resource extraction and non-energy industry policies can be better depicted. The

304 explicit representation of material cycles poses new constraints to mitigation trajectories, such  
305 as the limited availability of postconsumer scrap for recycling, but also the opportunity to  
306 expand the spectrum of mitigation strategies to include joint production, resource efficiency,  
307 material efficiency, and recycling. The linkage between urban structures, infrastructure  
308 patterns, transportation, and energy demand should receive more attention, potentially by soft-  
309 linking IAMs to more specialized models, or by using stylized facts,<sup>91</sup> like stock saturation in  
310 material cycles.<sup>92</sup>

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

#### 324 **Community interaction**

325 Integration of system linkages studied by IE and other industry-related modelling fields, like  
326 energy system modelling, into IAMs and better alignment of prospective IE studies with IAM  
327 scenarios would allow modellers of both fields to reach a higher degree of systems

328 integration<sup>94</sup> to the mutual benefit of policy makers and the researchers involved. We describe  
329 three possible pathways for future co-development of the two fields and list the resulting  
330 benefits and challenges.

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

348 **A systematic analysis of the different IE system linkages** is needed to better understand  
349 their relevance for climate change mitigation as well as for other aspects of sustainable  
350 development.<sup>98</sup> Such analysis would ideally combine empirical research on long-term  
351 development patterns of structural economic change<sup>43,99</sup> with theoretical interdisciplinary  
352 considerations on the model structure. It could become part of proposed schemes for



353 evaluation of IAMs<sup>91</sup> and involve researchers from different communities dealing with  
354 prospective assessment.

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

358 [Figure 3 about here]

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

367 The proposed consolidation of the way IAMs describe society’s biophysical basis allows for  
368 producing biophysically more consistent descriptions of society's future metabolism. It can  
369 help to provide better advice to policy makers and opens up new research opportunities in  
370 other scientific fields, for example, in IE, especially for consequential and prospective studies.

371 The consolidation is needed if IAMs want to maintain their relevance as the focus of  
372 sustainable development is expanding from the technology-driven energy transition to a more  
373 comprehensive set of interlinked strategies formulated as sustainable development goals  
374 (SDGs), most of which directly affect society’s biophysical basis and the linkages therein.

375 The success of the strategies proposed depends on efforts in both the IAM and related  
376 communities like IE to provide better documentation and interfaces to their work and on the

377 willingness of practitioners to change their habits and integrate their often isolated modelling  
378 efforts into a larger toolbox. Research funders play a special role in providing the resources  
379 for transparent and reproducible integrated scenario modelling that includes state-of-the-art  
380 insights from different fields. Many will benefit from the proposed development: the  
381 scientists involved, who can bundle their resources and make faster progress, policy makers,  
382 who are provided with more robust and transparent assessments, and the general public, who  
383 can continue to rely on sound science supporting the political decisions on sustainable  
384 development strategies.

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## 394 **Author contributions**

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

## 397 **Competing financial interests**

398 The authors declare no competing financial interests.

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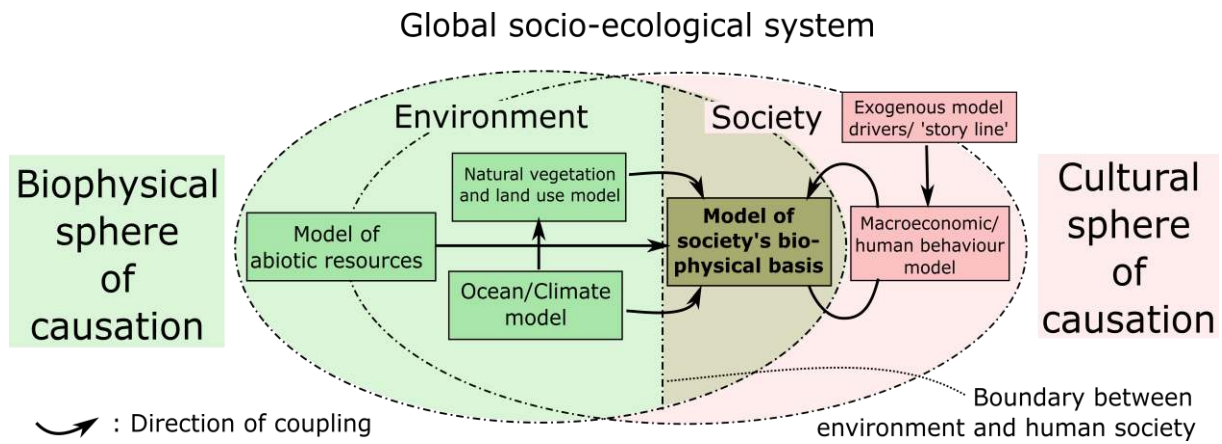
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599 **Figure 1: Scheme of the general structure of integrated assessment models (IAMs).** IAMs  
 600 represent the hybrid nature of the global socio-ecological system, which extends into the  
 601 cultural/economic sphere of causation and the biophysical sphere of causation.<sup>13</sup>

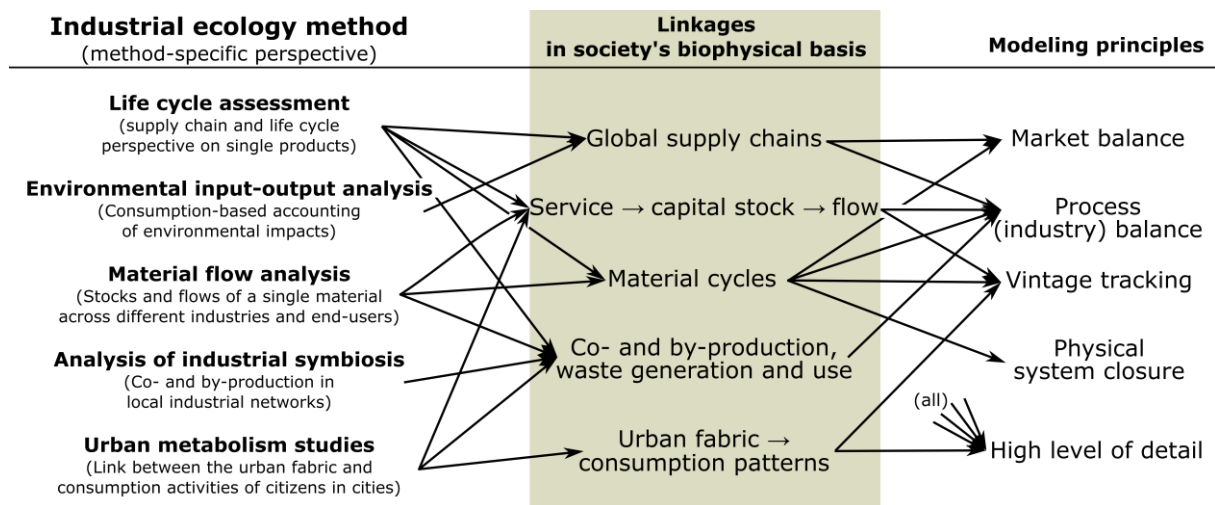
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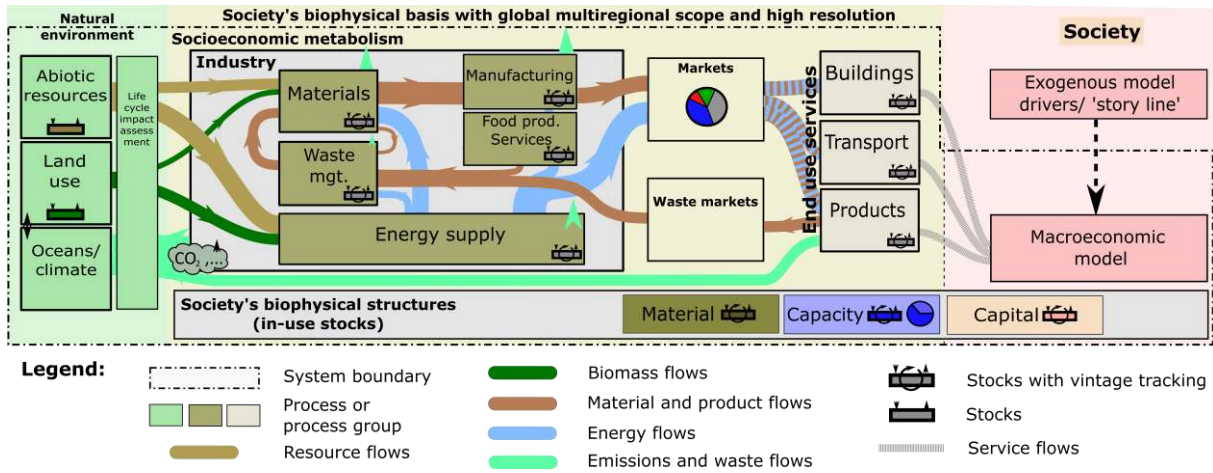


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608 **Figure 2: Overview of the main descriptive and assessment methods in industrial ecology.** The  
 609 methods are mapped to those linkages in the industrial system that IE research has identified as  
 610 important determinants of sustainable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

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

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625