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Unlocking circular economy policies in integrated assessment models

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ABSTRACT

The circular economy (CE) has emerged as a promising strategy to simultaneously address climate change and the over-exploitation of Earth's resources. Yet, most Integrated Assessment Models (IAMs) lack the capacity to fully assess the potential benefits and drawbacks of CE policies in the context of climate change. This paper provides a structured approach to improve the representation of CE in IAMs and guides their application in climate policy assessments. To this end, we first propose a framework to organize the multiple layers and policy dimensions involved in CE. We then review the current state of CE modeling in IAMs and identify critical gaps, including limited attention to policy mechanisms, lack of material-level granularity, and insufficient coverage of downstream and upstream supply chain sectors. Lastly, we identify priority areas for improvement, such as coupling IAMs with material flow and sectoral models, refining data and structural assumptions, and developing more coherent CE policy narratives. Together, these steps establish pathways for the scientific community to better integrate CE into IAMs and strengthen understanding of its role in global climate mitigation strategies.

1. Introduction

The circular economy (CE) has emerged as a promising strategy to jointly tackle issues of climate change and the over-exploitation of Earth's resources (Cantzler et al., 2020), two interconnected key challenges that our societies are faced with. Integrated into the broader agenda of sustainable development, CE policies aim to reduce pollution and resource overexploitation while increasing products' value within the economy (Ghisellini et al., 2016). By promoting a range of strategies – such as reduce, reuse, recycle, and recover – CE impacts supply chains in a variety of ways and offers substantial potential for reducing GHG emissions (Material Economics 2018). However, it may also generate unintended effects that could undermine decarbonization efforts.

Integrated Assessment Models (IAMs) - which inform and shape climate policy (IPCC 2023) - are crucial tools to explore the intersection of CE and climate change. These models present very heterogeneous frameworks, using diverse methodologies to explore low-carbon pathways compatible with climate targets, such as those outlined in the Paris Agreement (Krey 2014; Nikas et al. 2019; Weyant 2017). Detailed process (DP) IAMs, which offer more granular projections of climate mitigation strategies across different technologies, regions, and sectors (Weyant 2017; Bosetti 2021), have only recently begun incorporating CE strategies (Fragkos 2022; Stegmann et al. 2022). Still, important challenges must be overcome to ensure effective evaluation of CE policies.

First, assessing the benefits of CE within the climate context lies in the fundamental complexity and multidimensional nature of CE itself. The concept of circular economy is notably complex, and not unique definition is established in the literature (Deutz 2024; Kirchherr et al. 2023). In this paper, circular economy refers to the implementation of a set of practices that lowers the quantity of primary material resources necessary at any point in time to achieve a certain level of services in the economy. These practices are labelled "circular economy strategies" and are classified according to Potting et al. (2017) using the 10R hierarchical framework as follows: Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8), and Recover (R9). Importantly, the 10Rs can be grouped into three main CE objectives each relating to loops—the process of cycling materials within the economy. These objectives are: (i) Reducing primary materials' demand to narrow the loop; (ii) Increasing product use phase to slow the loop; and (iii) reintroducing materials back to the economy to close the loop (Bocken et al. 2016).

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Second, unintended effects – such as those linked to negative spillovers, rebound effects, trade-offs and feedback loops - may arise from the implementation of CE strategies, potentially hindering the joint achievement of mitigation and circularity objectives (Aguilar-Hernandez et al. 2021; Fitch-Roy et al. 2021; Rizos et al. 2019). Such consequences are governed by distinct mechanisms, many of which remain insufficiently understood - making it hard for IAMs to capture all of them (Joltreau et al., 2025). For instance, recycling may inadvertently cause negative spillovers, such as burden shifting, by relocating carbon emissions to other stages of the product life cycle, potentially offsetting the intended environmental benefits. Also, possible rebound effects are usually not accounted for as, for example, lower production costs from recycled materials or material efficiency measures can stimulate higher consumption of the same product (direct rebound) (Castro et al. 2022; Metic and Pigosso 2022; Zink and Geyer 2017). In addition, increasing recycling can also boost economic activity and lead to more energy consumption and transportation, which can ultimately increase local CO_2 emissions (Boonman 2023), as well as, savings generated from circular practices (e.g., buying second-hand products) may be redirected to other goods and services with high environmental impacts, such as air travel (indirect rebound) (Castro et al. 2022). Moreover, large-scale recycling policies can reduce material costs across multiple industries, stimulating economic growth and production in other sectors, which increases overall resource use and emissions at the macroeconomic level (economy-wide rebound) (Ferrante et al. 2024; Zink and Geyer 2017). Trade-offs may emerge when circular strategies compete with climate mitigation goals. For instance, in cases where recycling certain materials reduces their potential to store carbon during their (longer) use phase, a strategy that could help avoid carbon emission overshooting (de Oliveira et al. 2021). Along similar lines, extending appliance lifetimes reduces material demand, but keeping less efficient products in use may increase energy consumption and emissions (Zink and Geyer 2017). Finally, feedback loops are crucial to understanding the dynamic behavior of CE strategies (i.e., circular cause-and-effect relationships where changes in one subsystem trigger cascading effects in others, which can either amplify or counteract the original CE strategy). For example, a balancing loop may happen when increasing product reuse lowers demand for new products, reducing production and resource extraction, which decreases environmental pressures and, over time, diminishes the urgency and opportunities for additional reuse, gradually stabilizing the system (Bassi et al. 2021).Therefore, efforts to promote the uptake of CE strategies by economic agents require accompanying policies that address the negative consequences and externalities associated with resource extraction, use and disposal.

Third, the representation of multiple policies is not straightforward (Peñasco et al. 2021), particularly if applied at multiple scales along supply chains, while accounting for economic and biophysical limits, and respecting thermodynamics law. These policies – often implemented as part of portfolios - provide economic and regulatory incentives to narrow, slow and close the loop, and boost investment and innovation to overcome technical, economic, institutional, and cultural challenges (Grafström and Aasma 2021). Yet, most IAMs rely on a simplified policy representation: changing prices to represent taxes and subsidies, or limiting model parameters (Roelfsema et al. 2020).

Several key studies on material analysis laid the groundwork for reviewing, understanding and improving models' representations of CE policies in IAMs' low carbon scenarios (Aguilar-Hernandez et al. 2021; Kullmann et al. 2021; McCarthy 2018; Nikas et al. 2022; Pauliuk et al. 2017). They suggest that IAMs alone are unable to fully capture the broad spectrum of CE policies and their interactions (Nikas et al. 2022). Importantly, CE measures are intimately connected to the use and management of materials; they thus require a full understanding of the material-energy-climate nexus — a capability often absent in IAMs (Pauliuk et al. 2017). Secondary markets and the possibility of representing endogenously the effects of material substitution at the regional level are also a fundamental feature which is currently absent in macroeconometric and general equilibrium models (CGE) (McCarthy 2018). IAMs have also been subject to broader critiques, including the need for a shift beyond technology-centric views to embrace demand-side measures and a diverse representation of mitigation actions across different scales (Pye et al. 2021; Keppo et al. 2021).

While research on CE development in IAMs has expanded over the past years, a critical gap remains: the inability to take a system-wide perspective and consider interlinkages between CE strategies. This means embedding the complexity of circular economy strategies across multiple interlinked stages of material extraction, production, use and end-of-life while also accounting for unintended effects across environmental, economic, and social subsystems. Yet, such system-wide perspective is instrumental to assess the interdependencies between different CE policies, targets and constraints across the supply chain (Milios 2018; Steenmans and Lesniewska 2023). Consider, for instance, (i) incentives to the recycling sector, (ii) a percentage requirement of recycled plastic in packaged goods in industry, and (iii) a policy that educates consumers to reduce plastics consumption. Policies targeting recycling and production phases might contribute to one another: as the first increases the demand for recycled plastics and the second creates a market for recycled material in industry. However, in the opposite direction the policy applied to the consumers can reduce the quantity of plastics available for recycling and, consequently, for further use in industry. Alternatively, in absence of educational policies, recycling and production incentives result in higher plastics consumption.

This paper addresses this gap by developing a structured framework which details the key dimensions of the assessment of CE strategies. Such framework is then used to investigate the state of the art of CE representation in IAMs and to identify the key developments necessary to improve CE policies evaluation in IAMs. To achieve this, we first develop a conceptual framework grounded in key definitions and classifications of CE policies, and which incorporates the principle of life cycle thinking. This perspective – which is widely adopted in CE policymaking, e.g., the EU Circular Economy Action Plan (European Comission, 2020) - accounts for environmental and resource impacts across all stages of materials or products' lifecycle - from raw material extraction through production, use and end-of-life managing and reprocessing. Second, based on this framework we present an in-depth review of how CE strategies have been evaluated in IAMs. Lastly, we comprehensively discuss the current challenges and potential improvements needed in IAMs, focusing on different approaches, novel model capabilities and couplings.

The rest of the paper is organized as follows. Section 2 details the conceptual framework and outlines the methodological approach used to conduct the review. In Section 3 the results are presented, detailing the current state of IAMs in incorporating CE policies. Section 4 discusses potential options for improving CE policies in models and provides insights into future research and modelling improvements. Section 5 concludes.

2. Methods

The methodology of this paper is based on two consecutive steps. First, a conceptual framework was developed to organize the key dimensions of the CE and serve as the basis for understanding the state-of-the-art of IAMs modelling of CE and to identify key avenues for future research (Fig. 1). Second, a literature review was conducted to examine how CE policies have been represented in IAMs. Based on this review, and using the framework as an analytical lens, key gaps and limitations in current modeling practices were identified. The subsections below describe each step in further detail.

2.1. Organizing the problem: A CE framework for modelers

The conceptual framework developed in this study draws from established concepts in industrial ecology and climate and energy policy

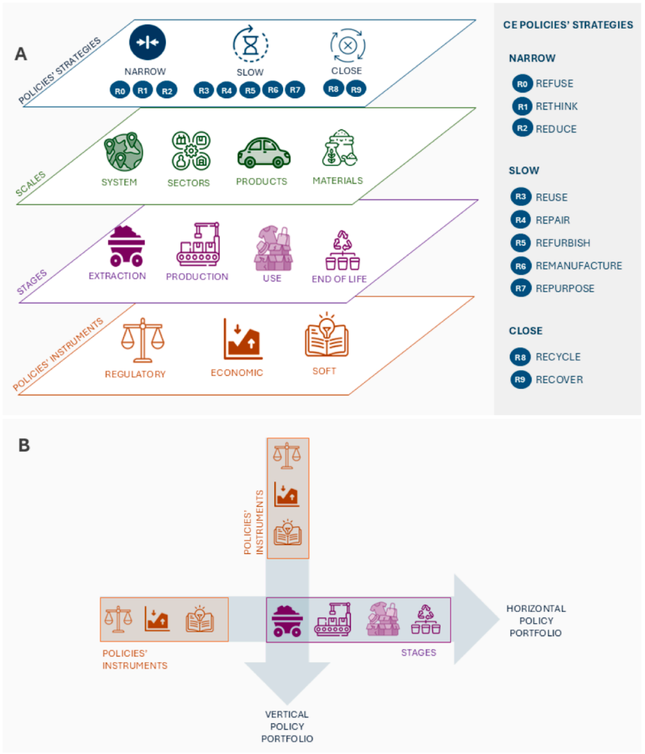

Fig. 1. Conceptual framework for CE policy evaluation in energy-climate models.

analysis. It details the key elements and layers to provide a comprehensive assessment of the mitigation potential of CE policies. It also highlights how the different elements/layers interact with each other in the context of promoting circularity. Modelers should then be aware of, and account for, these interactions.

The framework distinguishes four key layers. First, in the terminology of Bocken et al. (2016), CE policies differ in terms of strategies: they can promote narrowing, slowing or closing strategies. . *Narrowing* policies focus on strategies to reduce material use, incentivizing companies to adopt servitization or sharing economy principles. This includes designing products that minimize material and energy use, such as lightweight and multi-functional items, encouraging consumers to choose versatile over specialized products. These policies should also drive consumer behavior towards reduced consumption and preference for sustainable options. *Slowing* policies are primarily centered on adding value to products to extend their economic lifespan. This strategy is mainly achieved by improving product durability and repairability during the production phase. It is essential to push the development of new services and markets and encourage consumers to utilize these services. *Closing* policies promote the reintegration of materials into the economy following their post-consumer phase. In the production phase, product design policies can enhance the effectiveness of these policies by prioritizing recyclable materials and easy disassembly. Additionally, policies that curtail landfill-bound waste and promote the creation of new markets for post-consumer products contribute to the success of these efforts. Eco-parks and the promotion of industrial symbiosis further serve as significant incentives for closing policies.

Second, independently of whether they target the narrowing, the slowing or the closing of material loops, policies differ by nature. Following the classification framework from Bemelmans-Videc (2017), as applied in climate and energy policy studies (e.g., Skillington et al. 2022), we organize CE policies in three main categories. *Regulatory* policy instruments, encompassing codes, standards, and quotas, establish mandatory environmental benchmarks and practices - as is the case for the EU Single-use Plastic Directive (European Commission 2019). *Economic and Financial instruments*, including taxes, user charges, subsidies, and tax reductions such as Sweden's Reduced VAT on Repairs (European Commission 2021), aim to internalize environmental externally by altering the costs associated with material use, nudging the market towards resource efficiency and sustainable innovation. Lastly, *Voluntary* – or *Soft* – policies aim at influencing the behavior of economic agents through information provision, education and awareness and behavioral change, as in the case of the EU Ecolabel certifying goods and services with a reduced environmental impact (European Commission 2024).

Third, all policy instruments can be applied at different and multiple scales. We draw on terminologies used in industrial ecology and CE policy field (e.g., Linder et al., 2017; Pauliuk and Heeren, 2020; European Comission, 2020) to classify these scales as: *Material-level* initiatives promote the reuse or recycling of specific components, like electronic parts or packaging, aiming to increase recycled content in products like plastic bags. *Product-level* policies focus on the entire lifecycle of products, implementing eco-design principles to improve durability, recyclability, and reparability, exemplified by the France Reparability Index (European Environmental Agency 2024) *Sectoral-level* policies apply to entire industries, advocating for sustainable practices, resource efficiency, and circular business models within sectors such as manufacturing and energy, as seen in the U.S. Solid Waste Infrastructure for Recycling Grant Program (US EPA 2022). *System-level* policies adopt a holistic approach, encouraging closed-loop systems and Extended Producer Responsibility (EPR) schemes (OECD 2024).

Fourth, given the breadth of CE strategies, to successfully achieve macro-level material demand reduction policies in support of CE should consider the entire product life cycle (Joltreau et al., 2025). For instance, a policy might target either consumers (demand-side policy) or manufacturers and end-of-life management sectors (supply-side policy). This differentiation leads to very different impacts on material demand, flows, stocks, and potential rebound effects. For this reason, it is important to understand in which stage of the supply chain a given policy instrument is applied - namely extraction, production, consumption, and end-of-life management. *Extraction* involves the initial procurement of resources, *production* covers the transformation of primary resources into final products or services, *consumption* pertains to the end-use of these products and services, and *end-of-life management* encompasses the post-consumption processes related to post-consumption transformation. This four-phase classification summarizes the main stages typically used in cradle-to-grave and cradle-to-cradle life cycle thinking and material flow analysis (Curran 2012).It is important to distinguish between life cycle thinking, which is a conceptual approach for assessing environmental impacts across all stages of a product's life, and supply chain management, which focuses on the coordination and operational capacity across these stages. In the modeling context, both are complementary: life cycle thinking ensures consistency in environmental accounting and helps prevent burden shifting, while supply chain management highlights the need for technical and economical coherence between stages. For example, end-of-life processing systems considered in models might not be realistically feasible in some regions (e.g. post-consumption flows are not managed properly to sort and recycling facilities). Both perspectives require that all stages of the supply chain be coherently represented and interconnected within the models.

Importantly, CE policy instruments, when applied at different levels, can be integrated into a policy portfolio with a specific objective, such as the reduction of primary critical metal extraction. As shown in Fig. 1**B**, this policy portfolio can be implemented in a vertical approach, whereby distinct instruments are employed to achieve one or more CE strategies within a single stage of the supply chain. In contrast, a horizontal policy portfolio entails the implementation of instruments and, subsequently, CE strategies across the various stages of the supply chain. In both cases, instruments can target different scales, from material-level measures to broader product- or system-level interventions by using different R strategies. For the sake of visual clarity, Fig. 1B focuses on the structural logic of policy layering and interaction across the supply chain, while strategy types and scales are detailed in Fig. 1**A**.

2.2. *Literature review*

Using the theoretical framework from the previous subsection, we carry out a systematic literature review to identify approaches used to model the intersection of climate mitigation and CE in IAMs, as well as gaps that remain to be addressed. To this end, we select a sample of publication as detailed below, classify each publication depending on the objectives of CE policies, the policy mechanisms employed, the CE strategies utilized, the scales of application, the stages of the supply chain addressed, and the interdependence and cross-sectorial analysis of CE strategies. Our final sample includes 31 articles that evaluated the impact of CE strategies on climate mitigation within IAMs (Fig. 2), encompassing 15 distinct models of varying complexity.

The sample selection for our review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology (Page et al. 2021). First, we searched the Scopus and Web of Science database using keywords related to ’circular economy’, ’energy-climate models’, ’integrated assessment model*’, ’macroeconomic models’ as well as the 10R framework**.** We focused on peer-reviewed papers published between 2014 and 2024, as this period marks a shift in IAM research following the Paris Agreement, with increasing emphasis on demand-side mitigation strategies and the integration of circular economy considerations (e.g. Cantzler et al. (2020); Creutzig et al. (2024)). Additionally, we applied the forward snowballing technique to ensure that relevant articles were included (Wohlin 2014). Details are provided in Annex A.

Papers were eligible for inclusion in the review if they (i) were original research articles (excluding meta-analyses and review articles) and peer-reviewed, (ii) considered CE strategies focused on material and non-energy use feedstocks and (iii) examined their impacts on at least energy use and greenhouse gas emissions in energy-climate low carbon scenarios. The second selection criteria implies that we excluded articles focusing solely on the switch of energy generation technology from fossil to renewable energy or biomass on supply-side energy efficiency mitigation options, which are common mitigation strategies. Additionally, we did not consider papers in which the scenarios resulting from the IAMs were used as inputs for other models to carry out their analyses (as is the case for Pauliuk et al. 2021 and Sacchi et al. 2022).

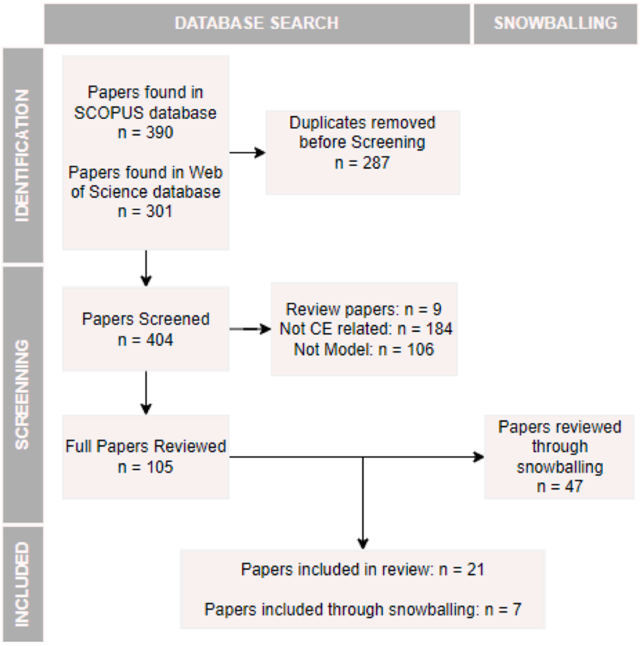

Fig. 2. Reviewing process conducted in this paper.

Given the heterogeneity of IAMs, we classify papers based on the grouping proposed in Wiedenhofer et al. (2024): Computable General Equilibrium (CGE) models, Partial Equilibrium models (PE), and Macroeconometric models and System Dynamics (SD) models. CGE models offer a detailed economic representation, examining policy impacts aiming for optimal economic closure. PE models focus on the interaction between environmental impacts and specific economic sectors, often integrated with CGE models for comprehensive analysis. Macroeconometric models, distinct from CGE models, base their simulations on historical data to capture dynamic, nonequilibrium economic behaviors, suitable for evaluating diverse climate policies. SD models are usually based on simulation of non-linear dynamics between actors in a specific system and they are rooted in causal feedback structures.

The framework presented in subSection 2.1 was used as the basis for a structured analysis of the selected papers, with the aim of identifying gaps and thus shaping future research priorities. This process involved examining which dimensions of circular economy are underrepresented or inconsistently addressed in existing modeling approaches. From this, a set of research directions was formulated by assessing where improvements are both most needed and most feasible. The suggestions were not derived arbitrarily but emerged through a systematic evaluation of existing gaps and a targeted search for literature, including from adjacent fields, that proposed methodological pathways or policy strategies to address them.

The methodological approach described so far is certainly subject to some limitations. Firstly, the papers selected for review were based on a set of keywords that are typically used in the field of circular economy research, as cited in references such as Kirchherr (2023) and Reike et al. (2018). However, it should be acknowledged that some models may represent the circular economy using different names or classifications that were not captured by the research query. The application of the snowballing method was specifically intended to mitigate this potential limitation, thereby reinforcing the robustness of the results in relation to the research objectives. Moreover, the lack of transparency regarding the specifics of how particular variables and assumptions are incorporated into models partially prevents us from discussing certain facets of CE representation and modelling assumptions. This is a well-documented issue in the literature (Keppo et al. 2021; Robertson 2021).

3. Representation of circular economy in IAMs

Four main insights emerge from our analysis. First, modelling efforts focus on narrowing and closing **strategies**, but largely overlook policies aimed at slowing. Second, with respect to **scales**, it is evident that IAMs lack the granularity necessary to model detailed CE options. Third, with respect to **stages**, IAMs are currently limited in their ability to account for the full supply chain effects and cross-linkages of CE strategies. Fourth, IAMs lack the ability to model specific **policy instruments** and face challenges in evaluating policy portfolios. We discuss each of these results in detail below.

Fig. 3 illustrates the characteristics of our sample. Fig. 3**A** demonstrates that the prevalence of CE measures in decarbonization scenarios has been increasing over time. Furthermore, Fig. 3**B** depicts that PE models represent the largest category of investigated models, followed by CGEs, System Dynamics models and Macroeconometric models. **Annex B** contains a detailed discussion of these papers in our sample.

3.1. *Strategies: narrow and close, but not slow enough*

Most articles in our review focus on modelling how ’Narrow’ and ’Close’ CE policies affect GHG emissions (Fig. 4). CE strategies aimed at narrowing the loop are the focus of most of the contributions, representing half of all strategies mapped in this review, and focus on

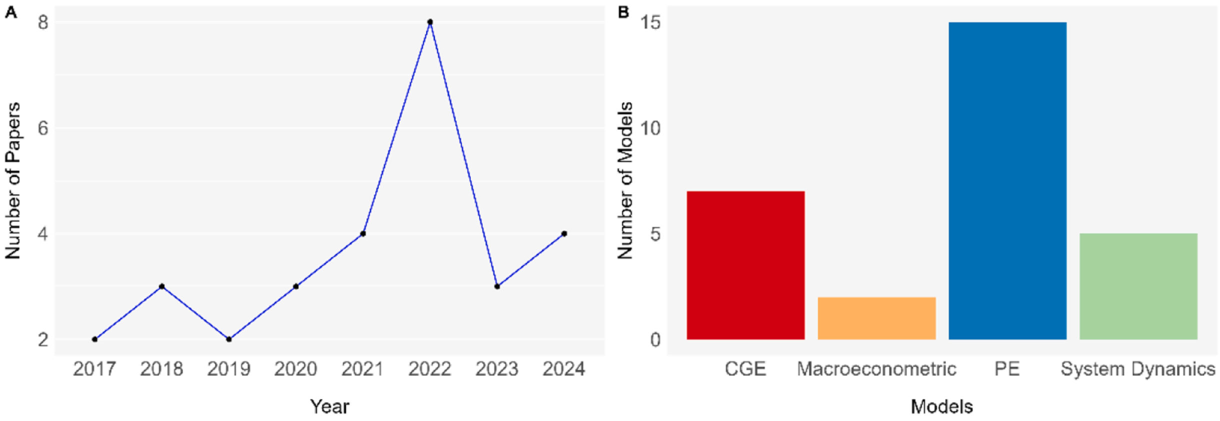

Fig. 3. Number of publications review by publication year (**A**) and by Models (**B**).

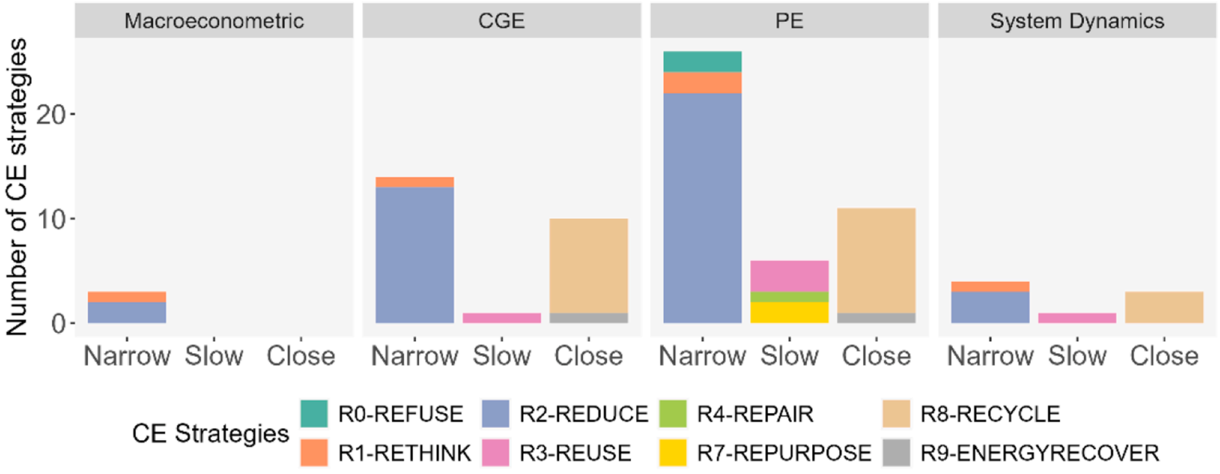

Fig. 4. CE strategies mapped in this review by model type.**Figure.**

Reducing primary material feedstock for industries and material services demand for end-use sectors. The second most modelled strategy is *Recycling* (28 %), that is predominantly considered in industry scenarios as an increase in the utilization of recycled feedstock during production (Fig. 4). All other strategies are addressed only in a handful of contributions. Some CE strategies such as *Refuse* and *Rethink* sum together roughly 7 % of the strategies examined in our sample. They are predominantly applied in the transport and building sectors, meaning that (i) narrow strategies, which present less economy-wide and rebound effects, are underexplored, (ii) the scarcity of these options poses a significant knowledge gap regarding understanding and evaluating the impacts of new business models in industry. In some cases, the interest in CE is also motivated by the hope of reducing the dependency on imported critical materials, which is crucially important debate related to the energy transition (Blas et al. 2020; Capellán-Pérez et al. 2019; Hu et al. 2024; Tokimatsu et al. 2018).

’Slow’ policies are largely under researched. This is partly because they rely on end-user behaviors, which are highly heterogeneous and involve complex dynamics between prices and income that are difficult to capture in IAMs. In the few cases in which they are considered, they are only included as a component in the mix of CE policies options described in what-if scenarios’ narratives (Barrett et al. 2022; Hu et al. 2024; Tokimatsu et al. 2018) or implicitly considered through the use of sensitivity analysis to estimate the potential effects of increasing the lifespan of energy generation technologies (Tokimatsu et al. 2018). *Reuse* options represent around 6 % of all strategies only and considered as part on narratives that together with other strategies set a reduction in primary feedstocks in industry (Boonman et al. 2023; Barrett et al. 2022; de Oliveira et al. 2021). *Repurpose* represented only 2.5 % of the CE options essentially comprising cascading batteries (Hu et al. 2024a) and industrial symbiosis (van Sluisveld et al. 2021) or repurposing oil refining infrastructure to process biomass (Bergman-Fonte et al. 2023). Neither *Refurbish* nor *Remanufacture* were considered in any of the articles investigated.

3.2. Scales: lack of granularity in CE modelling options

With respect to the scale dimension, policies promoting CE often target materials, components, and products (e.g. the new EU batteries regulation (European Union 2023)), but models typically represent CE strategies at the sector level. IAMs, in their original framework, lack the necessary granularity to capture these policies effectively due to insufficient detail on economic sectors and physical and economic flows between them. As shown in Fig. 5, around 6 % and 29 % of reviewed papers focus on the product and material levels, respectively, while all others focus on the sectoral level. This limitation hinders the accurate assessment of factors such as waste availability, regional recycling capacities, and investment costs, making it difficult to develop material-balanced, low-carbon scenarios.

The ability to focus on product and material level is much higher when IAMs are coupled with other models. Among the analyses based on single models, product and material-levels account for just 7.4 % and 3.7 %, respectively; these numbers raise to 42 % for material-level and reduce to 5.8 % to product-level percent when in the same of analyses in

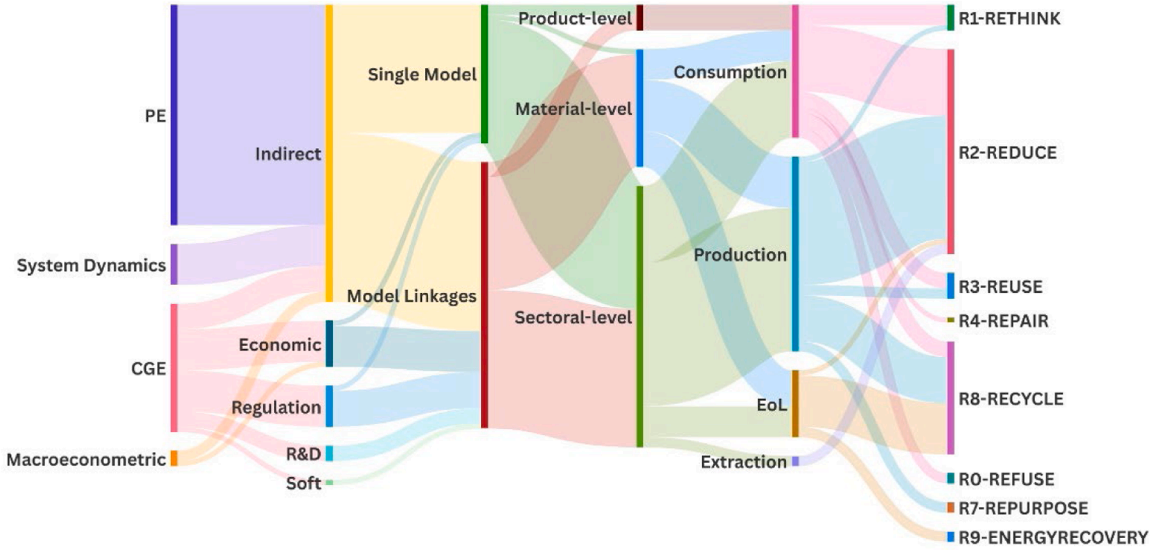

Fig. 5. Flow of CE strategies mapped in the reviewed literature, organized by model type, policy instrument representation, model coupling, scale, supply chain stage, and CE strategy. The Sankey diagram visualizes how circular economy strategies are represented across IAMs. The width of each flow corresponds to the number of CE strategy representations that move from one node to the next—indicating, for example, how many strategies are modeled endogenously, applied at a given scale, or linked to specific supply chain stages.

which IAMS are linked with bottom-up models. Similarly, while production remains the most analyzed sector, model linkages significantly increased the representation of the consumption stage. Without linkages, CE strategies were predominantly applied to the production sector (63 %) and consumption (37 %). However, with model linkages, the focus shifted: production accounted for 40 %, consumption 31 %, EoL 25 %, and extraction 4 %. Notably, evaluating CE strategies at the material level during the consumption phase was only possible through coupled models.

The Sankey diagram presented in Fig. 5 reveals several important insights. First, CGE models are more likely to endogenously assess different types of policy instruments, while PE and SD models tend to neglect this aspect. Second, Fig. 5 highlights the limited representation of the extraction and EoL stages, underscoring the current difficulty IAMs face in fully applying life cycle thinking. The predominance of measures focused on the production stage further illustrates that CE modeling, like traditional mitigation modeling, often centers on supply-side interventions. Third, the underrepresentation of CE strategies that act outside the production stage suggests that improving the modeling of these strategies depends on developing the representation of other supply chain stages. This, in turn, is more effectively achieved through model linkages with tools that offer greater sectoral and material detail.

3.3. Stages: limited ability to account for the full supply chain

The effective implementation of CE depends on the participation of a diverse range of stakeholders within the supply chain (Elia et al., 2020). Yet, most available analysis lacks the granularity and heterogeneity needed to accurately represent complex supply chains and the CE policy mix applied to them. With respect to stages, Fig. 5 also highlights a disproportionate focus on CE strategies in the consumption and production stages, with less attention to end-of-life and extraction sectors. PE models and SD frameworks face challenges in capturing the full supply chain, particularly when not linked with other models. Even when model linkages are applied, they fall short in adequately representing extraction sectors, often accounting only for available reserves of specific resources, such as rare earth minerals. CGE and macroeconometric models are particularly well-suited to representing entire supply chains due to their structural characteristics; however, as noted, they largely lack material-level granularity.

From our review, no IAM has successfully detailed both extraction and End-of-Life sectors comprehensively. Specifically, current IAMs lack an integrated approach to account for resource availability, ore decaying and the energy expenditures associated with processing and refining resources in extraction sectors. Similarly, most models provide either limited or sector-specific material and energy-balanced representations of EoL sectors, often omitting the energy costs related to the trade and transport of materials and products post-consumption.

3.4. Instruments: limited modelling of specific policy instruments and challenges in evaluating policy portfolios

Most studies (70 %) relied on stylized CE narratives with limited or highly aggregated CE strategies, thus failing to incorporate policy mechanisms in a detailed manner (Fig. 5 and Fig. 6). Rather, exogenous adjustments are made to reflect directly the policies' outcomes, a common practice in PE models (Álvarez-Antelo et al. 2024; Fragkos 2022; Fritzeen et al. 2023; Oliveira et al. 2021; Oshiro et al. 2021; Pulido-Sánchez et al. 2022; Sluisveld et al. 2021; Speizer et al. 2023; Stegmann et al. 2022; Tokimatsu et al. 2018; Ven et al. 2018). Only 30 % of

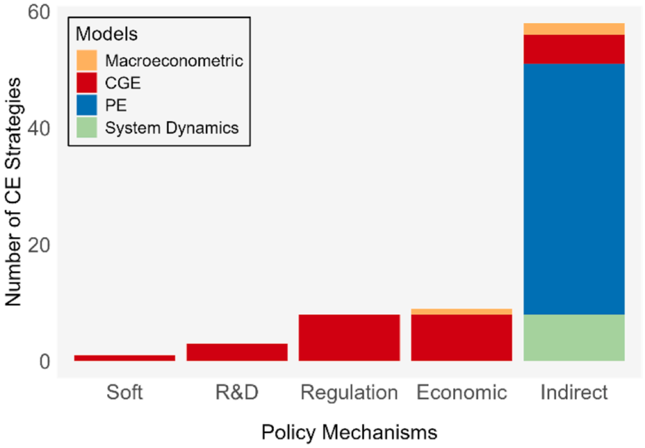

Fig. 6. Type of policy mechanisms were considered by model type or whether there is no specific policy mechanism were directly modelled (Indirect).

the studies apply endogenous CE strategies; most of them use CGE and Macroeconometric models (Fig. 6). Of these, 43 % investigate economic policy instruments, 38 % focus on regulations, 14 % on R&D investments and only 5 % on soft mechanisms. This suggests that linking detailed-process and economic models can be a valuable strategy to improve CE analysis, particularly for evaluating the effectiveness of different policy instruments. Papers focusing on economic instruments usually refer to (i) taxes on waste or carbon-intensive primary feedstocks (Hatfield-Dodds et al. 2017; Pollitt et al. 2020), (ii) subsidies to increase recycling (Freire-González et al. 2022), and (iii) economic incentives to consumers to encourage the replacement of batteries instead of the acquisition of new cars (Hu et al. 2024b). The regulatory mechanisms most studied are bans and targets towards the consumption of bio-based feedstock, reduction of primary materials use and waste prevention (Hatfield-Dodds et al. 2017; Boonman et al. 2023). Modelling efforts focusing on R&D considered financial incentives to increase recycling and material efficiency rates (Lu et al. 2024). Soft mechanisms are considered in narratives to promote behavioral shifts regarding waste sorting (Boonman et al. 2023).

Models represent CE policies in three ways: altering monetary values (e.g., Boonman et al. 2023), adjusting elasticities of substitution to reshape input relationships (e.g., Pollitt et al., 2020), or imposing constraints on material or technological availability and consumption (e.g. Stegmann et al. 2022). However, IAMs do not incorporate the monetary costs of policy implementation into their pricing frameworks, and there are limited studies on the effectiveness of alternative policy mechanisms, whether applied individually or in combination (e.g. Hatfield-Dodds et al., 2017).

Another noteworthy insight is that existing models are deficient in adequately representing the interactions between CE strategies when implemented concurrently. This is true both in the case of policy portfolios implemented within a given scale and stage, or across different scales and stages. The only exception is Boonman et al. (2023), which was the sole study to investigate together the impact of enhanced waste collection systems by integrating waste sorting with recycling rates to project the use of recycled material in production processes. However, no analysis was conducted to evaluate the performance of individual CE strategies in comparison with the policy mix. A comparable gap is evident with respect to the vertical policy portfolio, wherein a combination of CE strategies is implemented at the same stage of the supply chain.

3.5. Understanding models' specificities and research focus

We find that the IAMs identified in this review differ significantly in their capacity to represent the multiple dimensions required for robust CE policy assessment, as outlined in the conceptual framework. PE models, particularly detailed process models linked with sectoral bottom-up tools, offer a more granular representation of technologies and, in some cases, materials, making them suitable for simulating narrow, demand-side CE strategies such as product reduction or substitution. However, they lack detailed representations of heterogeneous behaviors, economic feedbacks, and diverse policy instruments, often relying on exogenous assumptions implemented through "what-if" scenarios. Their sectoral scope is also limited to production and consumption stages, constraining system-wide analysis and integration of life cycle thinking.

Macroeconomic IAMs, including CGE and macroeconometric models, are more effective in capturing price-based policy instruments and economy-wide feedbacks. Their system-level structure enables the assessment of cross-sectoral interactions and distributional impacts. Nevertheless, they usually rely on aggregated representations of materials and technologies, limiting their ability to assess product- or material-specific CE strategies. Although these models can evaluate certain social impacts of CE strategies, such as effects on income and employment, they struggle to incorporate non-price behavioral instruments and detailed agent heterogeneity. System Dynamics models are well-suited for simulating complex CE strategies as they can capture nonlinear feedback between subsystems and dynamically represent biophysical and socioeconomic constraints (Pulido-Sánchez et al. 2022). However, their high spatial and temporal aggregation and reliance on sensitive causal assumptions make empirical validation challenging. In addition, the absence of explicit market mechanisms limits their capacity to assess broader economic trade-offs. A more detailed analysis of how different IAMs implement CE, including specific instruments, strategies, and modeling approaches, is provided in Annex B, which includes a sector-by-sector breakdown of CE implementation based on the reviewed literature.

Across the reviewed literature, all IAMs focused on evaluating the benefits of CE strategies primarily in terms of reductions in CO_2 emissions and energy use. CGE and macroeconometric models extended this evaluation to include economic indicators, most notably GDP impacts. When it comes to material demand reduction, such benefits were typically captured by SD and PE models or, in a more aggregated way, by CGE models. However, this was the case in less than half of the models analyzed. Importantly, social outcomes remain largely absent from current CE-integrated modeling efforts. Among the studies reviewed, only one SD model considered changes in employment because of the implementation of CE approaches (Allen et al., 2022), as well as the benefits to Sustainable Development Goals (SDGs).

This lack of attention to social dimensions reveals a critical gap in current CE modeling. Although CE strategies have the potential to influence job creation, equity, and well-being (Vanhuyse et al. 2022), these impacts are rarely addressed. Incorporating such dimensions is essential to provide a more holistic assessment of CE policies and to align modeling efforts with the broader objectives of the SDGs.

While no single model type can fully capture all dimensions of CE policy analysis, each has strengths within specific layers of the framework. This highlights the need for further research on model integration and hybridization.

4. Advancing CE policy modeling in IAMs: key challenges and future prospects

IAMs hold great potential as suitable tools for the evaluation of CE policies and their impact on climate mitigation. Yet, critical gaps described in Section 3 need to be addressed. Key opportunities for enhancing IAMs include model development and coupling, better integration of high-quality data and empirical insights, and development of new scenarios. Table 1 summarizes these opportunities, identifying specific gaps and highlighting areas where an integrated approach could be particularly beneficial. It also illustrates how addressing the identified gaps through the suggested research pathways can contribute to improving IAMs.

The classification presented in the Table is based on three main criteria: (i) **consistency**, which refers to whether the model maintains a material-balanced framework, meaning that all material flows (including extraction, production, use, recycling, and disposal) are coherently tracked and aligned with the principle of mass conservation, ensuring that stocks and availability for reprocessing match inflows and outflows; (ii) **accuracy**, defined as the extent to which the implementation of CE policies in the model reflects empirical and system-level conditions, particularly whether assumptions (e.g., on recycling rates, behavioral change, or technological feasibility) are grounded in observed data or supported by industrial ecology literature and applied case studies, thereby reducing the gap between modeled outcomes and policy outcomes; and (iii) **comprehensiveness**, referring to the model's capacity to evaluate a wide range of CE policies strategies, whether across multiple life-cycle stages (e.g., design, consumption, end-of-life), through different types of policy instruments (e.g., regulatory, economic, behavioral), applied vertically and horizontally. Notably, some identified gaps overlap with proposed solutions, indicating that certain

Table 1
Main gaps and future research pathways. Accuracy in blue, Comprehensiveness in orange, Consistency in green.

Framework	Main Gap	Future Research Focus			
		Model Improvement	**Coupling Models**	**Data & Structural Changes**	**Scenarios**
CE strategies	• Lack of representation of CE strategies other than reduce and recycle • The potential consequences of applying different CE strategies together along supply chains have not been fully explored	🟦🟧 • Enhance CE evaluation by capturing compounded effects of coordinated CE interventions along supply chains	🟦🟧 • Link macroeconomic models and bottom-up models with detailed process IAMs to enhance sectoral detail • Link IAMs with Agent-based models to endogenize heterogeneity and behavioral dynamics	🟦 • Enhance regional assumptions on socio-technical, economic, and cultural barriers to improve understanding of potential obstacles to CE adoption.	🟧 • Assess "what-if" scenarios to understand how spillover and rebound effects, feedback loops and/or trade-offs may impact the effectiveness of CE measures in reducing CO_2 emissions
Scales	• Lack of material level and material flow representation, which limits CE strategy options	🟦🟧 • Development of material flows from end use sectors to intermediate sectors (industry)	🟦🟩🟧 •Link IAMs with MFA models to enable material-balanced analysis and improve granularity through multi-scale coupling 🟦🟧 •Link IAMs with bottom-up sectoral models to improve industrial demand, and technological and behavioral	🟦 • Improve data on material contents of products on a regional scale	🟧 • Develop multi-scale scenarios evaluating regional versus global impacts of CE policies
Stages	• Limited representation of whole supply chain interactions	🟦🟩🟧 • Enhance representation of all life cycle stages in models and interlinkages of material flows between them 🟧🟦 • Link industry output endogenously to end-use sector demand to reflect material needs more accurately	🟦🟧 • Link EE-MRIO and macroeconomic models to improve sectoral representation 🟧 • Link macroeconomic models and bottom-up sectoral models with detailed process IAMs to enhance sectoral detail	🟦 • Improve available data on extractions phase and EoL phases 🟦 • Include data on policy outcomes, effectiveness, and regional application differences.	🟧 • Develop what-if scenarios addressing the trade-offs and burden shifts of CE strategies across all life cycle stages
Policy Instruments	• Policy instruments, their associated costs and other barriers are often overlooked. When considered, policy mixes are rarely explored in depth	🟧 • Enhance internal IAM structures to simulate diverse policy instruments across sectors (horizontal) and governance levels (vertical)	🟧 • Couple economic models with policy simulation tools and detailed process IAMs to improve policy instruments evaluation	🟦 • Develop more empirical data on policy outcomes, effectiveness, and regional application differences.	🟧 • Explore new scenarios to assess policy mixes and economy-wide or rebound effects on climate mitigation. • Explore SSP3 scenarios incorporating policies focused on national resource sovereignty

challenges require an integrated approach. In the remainder of this section, we discuss in detail key approaches which can be implemented to shift the focus of the IAMs community from the modelling of CE as a collection of marginal changes to its representation as a structural change implying new business models, dematerialization and servitization.

4.1. Model improvements

Model improvements should focus on enhancing the ability to consider comprehensively and consistently the impact of CE policies. This can be achieved by improving granularity (e.g., from material-level scale to the aggregate macro-scale) and better capturing trade-offs, burden shifts, and rebound effects. Improvements should also offer opportunities to overcome the dominant approach of evaluating CE policies and strategies in isolation.

We mapped six main challenges that need to be tackled. First, models need to be improved to include material flows between upstream sectors (manufacturing and extraction) and downstream sectors (end-of-life management) at material level, effectively establishing connections between material flows in a way that extends beyond the conventional boundaries of consumption and production. The potential of this solution is shown, for instance, by the recently developed MESSAGEix-Materials model (Ünlü et al. 2024), which enhanced the industrial representation of the MESSAGE model by adding an accounting for stocks and flows of steel, cement, and aluminum. Additionally, IAMs should develop innovative methods to obtain estimates of future material consumption that transcend the traditional approach based on econometric regression models – as the latter may otherwise lock model exercises to portray a trajectory of resources consumerism tied to economic growth rather than one more in line with the implications brought about by circular practices.

Second, the range of Rs strategies portrayed in models needs to be expanded. Although narrow and slow strategies related to behavioral choices are typically the most effective in terms of mitigation potential (Wolfram et al., 2021), this review shows that most CE strategies focus on *Recycling* and *Reduce*, which demonstrates an underexplored space in IAMs. Some recent contributions provide guidance on incorporating CE strategies into IAMs. For instance, the International Resource Panel (IRP) report on the RECC model (UNEP, 2020) outlines methods to quantify the effects of resource efficiency strategies, such as remanufacturing and repurpose, on greenhouse gas reduction.

Third, parameters representing CE policy instruments and strategies in models require refinement to better reflect regional socio-technical, economic, sectoral and cultural factors. Instead of using generic, fixed values (e.g., a uniform recycling rate in all model regions), models should incorporate region-specific parameters that capture local drivers and barriers to CE adoption. As pointed out by Bassi et al. (2021), CE levers and barriers are strongly related to local specificities. These local specifics can include logistics, material and energy penalty costs, technical availability of transformation processes (e.g. recycling, refurbishing), market acceptance considering lifestyles and cultural values. For example, Lessard et al. (2021) has demonstrated that the availability and cost of by-products vary across regions, which can impede the implementation of CE strategies at the local level. Furthermore, it is important to recognize that the same policy mechanism can have different impacts across sectors. For instance, Meglin et al. (2022) show that levies are less effective than bans in the landfill sector, while the opposite is true in the cement sector, highlighting the need to account for such sector-specific differences.

Fourth, it is imperative that models better capture the behavioral dimensions of CE and their effects on emissions reduction. Models must improve in representing the diversity of consumers' lifestyles and firm behaviors. Accounting for these differences enables more realistic model outcomes, as access to resources, preferences, and willingness to adopt sustainable practices are influenced by cultural and economic contexts (Creutzig et al., 2018; Geels et al., 2017). While progress has been made in integrating lifestyle factors into IAMs (van den Berg et al. 2019), current models still rely heavily on stylized, exogenous narratives and lack frameworks to endogenize emerging trends, such as the sharing economy and shifts toward sustainable consumption. New frameworks to understand the impacts of lifestyle on mitigation (e.g. as in Pettifor et al. (2023)) could provide guidance for further developments of CE in IAMs.

Fifth, IAMs should be developed to evaluate direct and indirect impacts of CE policies on climate mitigation. From our review, many gaps persist, especially regarding indirect effects across economic sectors. For example, the substitution between cement and wood in the construction sector can impact the forestry sector and, consequently, land availability for other uses such as food cultivation or energy crops. Other negative impacts such as burden shifts and rebound effects can further complicate the evaluation of the secondary impacts of CE strategies in IAMs. Improvement can come from the coupling of models, particularly if efforts are focused on endogenizing to the extent possible the responses of heterogeneous actors to these policies.

Sixth, model improvements should also focus on better capturing the compound effects of coordinated interventions across supply chains, as highlighted by Milios (2018). This shift helps move beyond evaluating CE strategies in isolation, which often results in a fragmented view of CE's decarbonization benefits. For instance, economic mechanisms, such as incentives for recycling market development, EPR schemes, education policies, and waste import bans, can influence the recycling rates assumed in models but are often overlooked. Therefore, it is essential to gain a deeper understanding of the operational mechanisms through which diverse policies operate across different sectors and regions. This could be achieved by examining the findings of existing studies that have explored the potential outcomes of different CE policies, as illustrated by Larrain et al. (2022), Meglin et al. (2022) and Balleer et al. (2024). Few studies have examined the effectiveness of policy portfolios, whether individually or in combination (e.g., Hatfield-Dodds et al., 2017). This gap highlights the need for further exploration of the different horizontal and vertical policy implementations that might impact CE outcomes.

Although several model improvements have been discussed in this subsection, some can be considered particularly foundational. The first step is to disaggregate the industrial sector into relevant sub-industries, followed by its representation as an intermediate sector whose output is endogenously determined by demand from end-use sectors. This structural change enables a more consistent analysis of how CE measures implemented in end use sectors affect material production, energy requirements, and industrial emissions. Moreover, it facilitates the explicit representation of material flows.

Incorporating a full, multi-layered depiction of CE strategies into IAMs might require substantial structural modifications that may not align with their original purpose. Considering these constraints, adopting a modular modeling approach, in which IAMs interface with external tools such as dynamic MFA models, can offer a flexible and technically feasible pathway. These strategies are further elaborated in the following subsection on model coupling.

4.2. *Models coupling*

Many IAMs are based on static optimization or simulation approaches originally designed to model energy flows and emissions. Over time, these models have evolved to include land-use and water systems, but their architecture often remains constrained when it comes to incorporating material flows with sufficient granularity. Incorporating detailed material flows within these models frequently requires substantial modifications that may not align with the model's initial design or technical feasibility. As such, model coupling emerges as a solution, allowing IAMs to be complemented by external models without necessarily compromising internal consistency. Coupling enables the integration of CE-relevant insights while maintaining the strengths of both modeling approaches.

A range of external models can be linked to IAMs to support different layers of CE analysis. For instance, model linkages have been recently considered in reviewed papers through integrating in IAMs of industrial ecology frameworks such as Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Environmental Extended Multi-Region Input-Output tables (EE-MRIO), Agent-Based Models (ABM) or by liking sector-specific bottom-up models into their main structure. MFA frameworks track material flows and stocks across sectors, ensuring consistent consideration in terms of material availability. LCA helps (i) the calculation of material demand for low-carbon technologies due to material intensities coefficients available in life cycle inventories (e.g. Pulido-Sánchez et al. 2022) and (ii) the choice for less carbon-intensive feedstock and processes in industries (e.g. Peng et al. 2022). EE-MRIO frameworks expand sectoral representation in macroeconomic models, facilitating the analysis of environmental impacts from consumption (e.g. Freire-González et al. 2022). ABMs simulate heterogeneous agents and their interactions, showing how individual behaviors shape system outcomes. Linking them with IAMs introduces behavioral diversity, social influence, and innovation diffusion (Rizzati and Landoni 2024). Frameworks such as Giarola et al. (2022) provide a foundation for developing ABMs that simulate consumer and producer decisions on CE adoption, improving the representation of micro-level dynamics in long-term CE policy analysis. Bottom-up models provide precise calculations of material and energy demand in housing, mobility and industry sectors assessing the impact of consumption patterns on materials and energy use. When combined with MFA, these models evaluate CE strategies like waste reduction and material reuse with a mass-balanced perspective, significantly reducing emissions (Fritzeen et al. 2023; Stegmann et al. 2022).

Further integration between different IAMs is essential to better analyze CE strategies. While CGE and macroeconomic models capture economy-wide effects, they struggle with long-term technological changes. PE models, with detailed technological analysis, are ideal for studying material flows and can better be integrated with macroeconomic models for a more comprehensive approach.

Fruitful avenues of future research on CE evaluation are the creation of iterative processes not only between IAMs and industrial ecology models but also between macroeconomic and PE models to refine evaluation of CE effect across supply chains. This includes linking models to better represent price fluctuations of resources and their availability. These linkages would enable researchers to advance their understanding of how CE policies might reshape global trade and might reduce the risk of supply disruptions for critical materials considering economical and geopolitical barriers.

Several approaches can be used to operationalize model coupling, depending on the level of integration and the direction of information flow. These include: (i) *Hard-linking*, where two models are fully integrated into a single framework and solved simultaneously. This approach allows for dynamic feedback between systems but is technically complex and requires deep compatibility between model structures (e.g., Barret et al. 2022); (ii) *Soft-linking*, in which models operate independently but exchanging data between them. This exchange can occur in one direction or iteratively until convergence or a maximum number of iterations is reached (e.g. as in IMAGE-Materials (Arp et al. 2024), which is a dynamic MFA model that receives service demands from IMAGE model and provides back material demand data) (iii) *Harmonization*, in which parameters or assumptions from one model are used to calibrate another. For example, sectoral service demands, material efficiencies, or recycling potentials from bottom-up or MFA models can be used to inform IAM scenarios; (iv) *Pre-processing*, where circular economy assumptions are incorporated into the input data or scenario definitions before model execution. For instance, material intensity trajectories from different product designs can be imposed in IAMs as exogenous assumptions; (v) *Post-processing*, in which outputs from IAMs are used as inputs for other models such as dynamic LCA tools, enabling the evaluation of environmental impacts across broader system boundaries (e.g., see Sacchi et al. (2022) for an example of integrating IAM outputs into prospective LCA).

Among these options, coupling IAMs with MFA tools is particularly foundational, as it enables consistent and dynamic evaluation of secondary material availability over time, sectors, and regions, replacing arbitrary assumptions about recycling rates with physically consistent estimates. Despite their advantages, coupling strategies face practical challenges. A key difficulty lies in harmonizing spatial and temporal resolutions, which are often complicated by differences in scales, sectoral disaggregation, and data structures across models. For IAM–ABM integrations, it is often difficult to empirically validate results, as behavioral data are scarce at large scales and aggregation makes difficult to account for local variations. These efforts demand not only time and coordination but also clarity and transparency in how assumptions, such as material lifetimes, technological uptake, or policy implementation timelines, are aligned, transferred, or adjusted across models.

4.3. Improving data availability to better inform modeling efforts through empirical insights

Several challenges in modeling CE policies arise from data limitations**.** The lack of high-quality data hinders models from accurately reflecting CE strategies, limiting their granularity and preventing them from accounting for regional specificities. Without detailed data, models struggle to capture the unique capacities, prices, behaviors, and transformation processes of each region accurately. Furthermore, the lack of reliable estimates of the demand price elasticities, because of limited data availability, constrains accurate model calibration. Consequently, the ability to model how changes in demand for materials or services, like repair, affect overall demand is limited, hindering realistic assumptions about CE adoption and potential unintended effects.

Material intensities and efficiency potentials often rely on assumptions due to limited empirical research (Calderon et al., 2024). CGE models, for instance, rely heavily on price and demand elasticity assumptions, which should be grounded in robust empirical studies to improve accuracy (Skelton et al., 2020). More empirical research is also needed to better capture dynamics like household decisions between buying new products or repairing existing ones. Similarly, IAMs require real-world data to refine assumptions. For instance, empirical evaluations of recycling efforts—such as those driven by labeling initiatives or extended producer responsibility programs—can provide crucial inputs for modeling CE strategies more effectively.

Another critical challenge in assessing the benefits of reducing primary resource consumption lies in the limited availability of extraction-sector data, particularly for rare earth metals (REEs). REE data is often considered market-sensitive due to geopolitical and economic factors (Jowitt 2018), leading to a lack of proper representation of the extraction sector in IAMs and the effects of CE strategies in this sector.

The use of high-quality data allows models to more accurately reflect CE strategies by enhancing their granularity and accounting for regional specificities. It enables models to better capture the capacities, prices, behaviors, and transformation processes unique to each region.

Technological progress plays pivotal roles in shaping the success of CE policies. However, their representation in IAMs often faces challenges associated with the unpredictability of technological advancement and the complex interactions between technology adoption and lifestyle or cultural differences. Traditionally, technological progress and innovation in IAMs have been based on limited stylized narratives (Grubler et al. 2018; Barrett et al. 2022) that drive assumption of consumption reduction. These narratives lack a better understanding of the public acceptance of technological innovation, structural changes driven by new business models, that may differ considerably between regions and the possibility of increasing consumption of products due to technological change (Kasulaitis et al., 2019).

Better data and empirical evidence are also needed to improve the way in which IAMs capture the interplay between consumer choices and technological developments, which is crucial for effective policy analysis. Changes in consumption patterns drive innovation, while technological advancements influence consumer preferences. This bidirectional relationship requires careful modeling. Also, scenarios and models must consider possible CE innovation spillover effect that could change the rate of adoption of a certain CE strategy.

4.4. Reimagining decarbonization narratives: from climate mitigation efforts to comprehensive sustainability and structural shifts

Current CE narratives often rely on the Shared Socioeconomic Pathways 2 (SSP2 - Middle of the Road) ,[1] SSP1 (Sustainability) scenarios and Low Energy Demand (LED) scenarios. However, they lack depictions of policies current in place that might set back CE objectives. Additionally, CE scenarios usually do not fully consider the potential of slow policies and structural changes, that are typically necessary to support comprehensive CE implementation.

For instance, the U.S. Inflation Reduction Act promotes (IEA 2022) domestic industry, signaling a shift towards protectionist policies that align more with an SSP3 (Regional Rivalry) scenario. This highlights the need for modelling new scenarios in which international cooperation is not or only partially achieved. Since the CE success also relies on global flow of materials, protectionist measures can disrupt these flows, impacting end-of-life recycling and reuse processes (Helbig et al. 2021). Accounting for these in the narratives would enable better exploration of potential rebound effects, price shocks, and disruptions in supply chains may undermine CE.

Another important point is that CE fundamentally involves structural changes, although IAMs have focused mainly on representing marginal changes. Structural changes broad about by circularly include the rise of new business models – promoting dematerialization and servitization - along with digitalization's effects on consumption. Such aspects prove challenging to model because they necessitate shifts in sector outputs, industry composition, cultural and value systems and trade flows. To address this issue, narratives must reflect changes on both the demand and supply sides, manifesting as novel consumption behaviors and new product and service combinations.

Similarly, 'Slow' policies that are designed to extend product lifecycles, such as repair policies, which could have a significant impact on sustainability efforts, are not yet fully explored. This gap is especially evident when shifting from meso-level (firm-level) analyses to assessments of macroeconomic impact. Incorporating the potential outcomes of slow policies into CE scenarios is essential for understanding how such measures could transform consumption and production systems.

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[1] Shared Socioeconomic Pathways (SSP) are scenarios that explore how the world might change over the remainder of the 21st century. They are based on five narratives that describe the potential socioeconomic trends that could shape future society. They encompass a spectrum of possibilities, including a world characterized by sustainability-focused growth and equality (SSP1), a "middle-of-the-road" scenario where trends align with historical patterns (SSP2), a fragmented world shaped by resurgent nationalism (SSP3), a world where inequality persists (SSP4), and a world of rapid and unconstrained economic growth and energy consumption (SSP5) (Riahi et al. 2017)

5. Conclusion

This study reviews the state-of-the-art modelling of CE policies and strategies in Integrated Assessment Models with the aim of highlighting fruitful directions for improvements. Our analysis shows that IAMs have so far focused on modelling CE actions in isolation, largely overlooking the interconnectedness of material flows and the broader economic, environmental and social impacts of CE policies. Current IAMs lack the capability to evaluate comprehensive CE policy portfolios, both horizontally (across sectors) and vertically (through the supply chain), and to account for regional barriers to the adoption of these policies.

The findings of this study point to several key areas for improvement in IAMs. First, models must represent the entire material lifecycle, from extraction and production to consumption and end-of-life management. Second, they need to account for the interdependencies of CE strategies across supply chains, and also consider potential spillover effects (cross-sectoral or cross-regional impacts that can be positive or negative), feedback loops (self-reinforcing cycles that amplify or reduce the outcomes of a CE strategy), rebound effects (when CE strategies intended to reduce consumption or primary production unintentionally lead to their increase) and possible trade-offs. Third, models should explore more CE strategies other than *Reduce* and *Recycling* and better assess the wider economic, environmental, and social impacts of CE strategies for a more holistic perspective.

The main contribution of this paper is threefold. First, this paper contributes to the circular economy and climate policy modeling literature by offering a structured way to organize the complex and multi-layered challenges of assessing CE strategies within IAMs. Drawing on concepts from industrial ecology, life cycle thinking, and policy analysis, the framework synthesizes four key analytical layers (policy instruments, CE strategies, supply chain stages, and scale levels) into a structured, policy-relevant approach. This conceptual structure allows researchers to better understand how CE can be modeled, identify inconsistencies, and ensure alignment with principles such as system-wide and life cycle thinking.

Second, the paper makes an empirical contribution by applying this framework to a systematic review of recent literature, revealing how different types of IAMs, such as partial equilibrium, macroeconomic, and system dynamics models, vary in their ability to represent the multiple dimensions of CE.

Third, building on this evidence, the paper proposes clear research avenues for enhancing the investigation of CE policies within IAMs. This includes recommendations for improving data collection, integrating diverse modeling frameworks, and addressing sectoral interconnections with regional and cultural specificity. Additionally, the paper proposes "what-if" narratives to explore CE spillover and rebound effects, feedback loops, trade-offs and geopolitical implications, especially in reducing dependence on critical materials for energy security.

While this paper takes an important step in the analysis of CE representation in IAMs, some areas for future improvement remain. These include an in-depth review of the integration of industrial ecology models with IAMs and future perspectives to strengthen the linkages between the two. An additional area for potential enhancement is the establishment of a comprehensive CE policy database. This could be organized according to the conceptual framework outlined in this paper and would support more realistic CE scenarios in IAMs. In addition, it would offer insights across related disciplines.

Finally, CE must also be evaluated in relation to other SDGs, as its principles align with broader SDG objectives beyond the typical focus on energy and emissions in IAMs. While IAMs are primarily used for energy and climate policy research, there is an increasing need to incorporate SDG considerations, since these goals are interconnected and can involve trade-offs, particularly between climate action and other objectives. CE strategies could help mitigate some of these trade-offs, such as reducing biodiversity loss while pursuing zero hunger, but they might also introduce new conflicts, especially between economic growth and sustainable consumption versus climate goals.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) declare that no AI and AI-assisted technologies were used.

CRediT authorship contribution statement

Leticia Magalar: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elena Verdolini:** Writing – review & editing, Writing – original draft, Supervision. **Alexandre Szklo:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108614.

Data availability

Data will be made available on request.

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