Sustainable Production and Consumption 30 (2022) 269–277

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Research article

Coupling circularity performance and climate action: From disciplinary silos to transdisciplinary modelling science

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ARTICLE INFO

Article history:
Received 16 November 2021
Revised 9 December 2021
Accepted 10 December 2021
Available online 13 December 2021

Edited by Prof. K Tsagarakis

Keywords:
Circular economy
Decarbonization
Mitigation
Climate-economy modelling
Transdisciplinary science
Integrated assessment modelling

ABSTRACT

Technological breakthroughs and policy measures targeting energy efficiency and clean energy alone will not suffice to deliver Paris Agreement-compliant greenhouse gas emissions trajectories in the next decades. Strong cases have recently been made for acknowledging the decarbonisation potential lying in transforming linear economic models into closed-loop industrial ecosystems and in shifting lifestyle patterns towards this direction. This perspective highlights the research capacity needed to inform on the role and potential of the circular economy for climate change mitigation and to enhance the scientific capabilities to quantitatively explore their synergies and trade-offs. This begins with establishing conceptual and methodological bridges amongst the relevant and currently fragmented research communities, thereby allowing an interdisciplinary integration and assessment of circularity, decarbonisation, and sustainable development. Following similar calls for science in support of climate action, a transdisciplinary scientific agenda is needed to co-create the goals and scientific processes underpinning the transition pathways towards a circular, net-zero economy with representatives from policy, industry, and civil society. Here, it is argued that such integration of disciplines, methods, and communities can then lead to new and/or structurally enhanced quantitative systems models that better represent critical industrial value chains, consumption patterns, and mitigation technologies. This will be a crucial advancement towards assessing the material implications of, and the contribution of enhanced circularity performance to, mitigation pathways that are compatible with the temperature goals of the Paris Agreement and the transition to a circular economy.

1. Introduction

While the global climate agenda has gone through different stages during the last decades, bold promises for future breakthroughs in energy technologies are often in the spotlight (McLaren and Markusson, 2020). Recent scientific and policy dis-

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https://doi.org/10.1016/j.spc.2021.12.011

courses are increasingly revolving around large-scale technological interventions, including but not limited to the rapid decarbonisation of the power sector worldwide and the direct and indirect electrification of all other economic and industrial sectors (Rogelj et al., 2018). amongst other social and economic challenges, the material implications of such a transition (Capellán-Pérez et al., 2019), including for example for producing solar PV panels and wind turbines or batteries for storage and electric vehicles (Cronin et al., 2021), are generally overlooked; however, the needs associated with the transition may not only compromise decarbonisation efforts but also increase the rate of extraction and transformation of basic materials (Sovacool et al., 2020), and even cause geopolitical tensions over critical resources (Vakulchuk et al., 2020). To accompany large-scale technological interventions without compromising economic development, an increasing part of the literature highlights the potential lying in transforming linear economic models into sustainable closed-loop industrial ecosystems (Durán-Romero et al., 2020) and what is fundamentally being termed as a transition to a circular economy.

However, there currently is not only a lack of consensus on the conceptualisation and operationalisation of circularity principles and measures (Reike et al., 2018), but also an absence of a single commonly accepted concept of circularity in the literature (Kirchherr et al., 2017). Most definitions allude to resource efficiency as well as slowing, narrowing, and/or closing material flows for reduced material extraction and optimised use. But, despite the multitude of perspectives, a shared understanding lies in decoupling natural resource consumption from economic output (McCarthy et al., 2018). Likewise, responding to the climate crisis requires that economies achieve an absolute decoupling of economic output and greenhouse gas (GHG) emissions (Haberl et al., 2020). This shared goal of decoupling human activity, economic growth, and well-being from broad environmental pressures, along with the pivotal role of resource and energy efficiency in both decarbonisation and circularity, constitute the crossroads of these two seemingly separate yet in reality highly intertwined agendas (Hatfield-Dodds et al., 2017).

The link between the two agendas is partly reflected in science; for example, in the essence of the '3Rs' principle (reduce-reuse-recycle) (Yong, 2007) and its expanded scope (Kirchherr et al., 2017), the aims of a transition to a circular economy are defined to also include the reduction of demand for scarce materials and the minimisation of GHG emissions related to material extraction, primary production, and final use (Hertwich et al., 2019). In policy, one notable example can be found in the European Union: the impact assessment of its 2050 decarbonisation strategy showed that circularity and behavioural changes could promote a relatively cheap and efficient 1.5 °C-compliant trajectory, compared to high technological investments (European Commission, 2018), as also stressed by the private sector (Energy Transitions Commission, 2018). Following up, the European Green Deal now aims inter alia to carry out a series of initiatives amongst various policy areas in a shift from the traditional, take-make-waste, linear economic model to a climate-neutral, circular economy (European Commission, 2020), with the region's new circular economy action plan being a core building block of the deal. This policy-level link is even more pronounced in the increasing interest of tapping the potential of circular economy measures and decarbonisation policies in COVID-19 recovery packages (Lewney et al., 2021; OECD, 2021a; Schröder and Raes, 2021). Nevertheless, there hitherto exists a lack of coordination and widespread synergies amongst climate change mitigation and circularity in both modelling research (Durán-Romero et al., 2020) and policy (Calisto Friant et al., 2021).

Given the scope, speed, and timeframe in which the circular economy is considered attributional to meeting various sustainability goals, this calls for researchers to come out of their disciplinary silos and work on a more integrative and holistic perspective of transition options and their trade-offs and constraints. As the social dimension is frequently missing (Homrich et al., 2018), there is also a need for civil society and consumers, the private sector, as well as the policy framework within which it operates, to be included.

This perspective aims to reflect the common ground amongst the two agendas of circular economy and climate mitigation and their respective research and practice communities. It then sets out to explore how synergies can be established. It advocates for science beyond disciplinary silos, based on interdisciplinary approaches and transdisciplinary integration of voices from within and outside the scientific community, in line with recent typologies to bridge analytical approaches (Geels et al., 2016; Hof et al., 2020), and to enable modelling representation of societal transformations (Nikas et al., 2020). To successfully integrate methods, disciplines, and bodies of knowledge, including a wide variety of retrospective and forward-looking perspectives with different foci, this perspective draws/adapts from recent literature on strategies for linking mitigation models and social sciences (Trutnevyte et al., 2019), and proposes an outlook across three dimensions:

- Exchanging concepts used by the different scientific communities to reach a mutual understanding of circularity principles and measures and to identify the key sectors involved in circularity processes and climate action alike, thereby laying the interdisciplinary groundwork necessary for developing the capacity required to represent the circular economy in mitigation modelling (and vice versa).
- Co-defining the goals of and roadmap to establishing links between climate action and circularity performance, by co-creating and entangling together qualitative storylines, knowledge, motives, and concerns of different actors (scientists, policymakers, industries, citizens, etc.) into quantitative inputs, from a transdisciplinary perspective.
- Translating and integrating these interdisciplinary and transdisciplinary insights into new and/or structurally enhanced climate-energy-economy modelling capacity.

2. The common ground between circularity and climate action

The link between circularity performance and climate change mitigation is multi-dimensional. Both objectives may be largely defined, promoted, or hindered by similar socioeconomic and technological trajectories, in which the envisaged decoupling transitions can unfold, and both transitions are assessed from similar lenses and against similar criteria. Apart from energy efficiency being a common denominator (Jose et al., 2020), fossil fuels, basic materials such as steel and cement, and biomass from forestry and agriculture are vital reference points of decarbonisation and at the same time lie amongst the resources most emphasised in a circular economy transition (Mhatre et al., 2021). Conversely, sectors with significant potential for circularity—i.e., electronics, batteries and vehicles, packaging, plastics, textiles, construction, food, water, and nutrients—also feature considerable potential for decarbonisation, which is critical for a net-zero emissions economy (Mulvaney et al., 2021). Synergetic solutions to both objectives include substituting the core group of basic materials that lead to most industrial CO_2 emissions by secondary, less energy-intensive materials (Hertwich et al., 2019; IRP, 2020)—e.g., cement by biomaterials, such as wood in construction (Hafner and Schäfer, 2017). Better circulation of materials as well as advances in efficiency and substitution are also necessary to cover the substantial material requirements for producing the energy technologies and storage to transition to a low-carbon economy (Kouloumpis et al., 2015). Any interventions towards either goal can impact growth, employment, and social equity, as well as lead to new opportunities in specific sectors and countries, allowing them to become frontrunners in, and exporters of, game-changing technologies and knowledge (Johansson and Henriksson, 2020). In spite of this spectrum of linkages between the two objectives, circular solutions do not always directly result in emissions reductions or increased overall sustainability (Walzberg et al., 2021), much like frequently examined mitigation strategies do not necessarily or explicitly account for improved circularity performance (Pauliuk et al., 2017).

This observed lack of mainstream synergetic measures for achieving both climate change mitigation and circularity performance can be traced back to the limited interaction between the scientific perspectives underpinning these fields and the different methods and tools employed.

Research in support of climate policymaking is heavily dominated by integrated assessment models (IAMs) (Doukas and Nikas, 2020), which allow to quantitatively assess interactions within the spectrum of the highly intertwined pillars of technology, economy, environment, policy, and society (Trutnevyte et al., 2019). Despite an emerging focus on Nexus approaches (Brouwer et al., 2018), IAMs typically include models that analyse in detail specific high carbon value chains and their technological solution strategies (*energy system and partial equilibrium models*), including options that target both the carbon and material intensity of the represented value chain (van Sluisveld et al., 2021). However, they tend to poorly represent resources and their uses. IAMs may also include macroeconomic models in a top-down approach that provide broader cross-/sectoral coverage with less technological detail (*macroeconometric and general equilibrium models*) (Nikas et al., 2019). Such models typically used for climate policy analysis feature an aggregation of economic sectors that is too high to provide valuable circularity insights in a systemic context (Winning et al., 2017), in particular related to primary and resource-intensive manufacturing sectors. Further, they mostly focus on flows, while disregarding material stocks.

In contrast, as a circular economy can be implemented at the micro- (products, companies, and consumers), the meso– (eco-industrial parks) and the macro-level (cities, regions, nations), research endeavours to evaluate circularity performance have adapted to all these levels. In particular, research in the broad field of circular economy research has commonly orientated on life cycle assessment (LCA) (Sassanelli et al., 2019) and agent-based modelling (ABM) at the micro/*meso* level, as well as environmentally extended input-output analysis (Donati et al., 2020; Wiebe et al., 2019), material flow analysis (MFA), and accounting modelling (Wiedenhofer et al., 2019) primarily at the macro level (Mayer et al., 2019). However, in contrast to models used for energy and climate policy analysis, resource flow models only consider material energy carriers, with no explicit representation of the energy system. The use of economy-wide quantitative systems modelling frameworks in circularity has also been gaining attention (McCarthy et al., 2018), as these can assess spillover effects and interactions across sectors that are critical in the structural shifts entailed in a transition to a circular economy. Nevertheless, such models employed in circularity research generally do not represent climate feedbacks nor climate-explicit policies (Pauliuk et al., 2017).

This cultivates the need for an ambitious whole-system modelling approach (Pye et al., 2021) to fully understand climate action in consideration of resource, material, monetary, and energy efficiency and stocks, as well as technical progress, demand shifts, rebound effects, and inter-, intra-, and cross-sectoral flows. The call for integration of disciplines for sustainability research is not novel (e.g., Liu et al., 2015), and IAMs have in fact been viewed as a platform for breaking down disciplinary silos (Hamilton et al., 2015). There have been attempts to establish links between material cycles and energy/emissions as early as decades back (Giljum et al., 2008; Kram et al., 2001) or to describe material use and efficiency in relevant reference socioeconomic scenarios on which IAMs typically anchor (Pauliuk et al., 2021a; Schandl et al., 2020). However, the two modelling research communities remain fragmented, and their tools detached.

Another vital dimension of the circular economy lies in enhancing efforts towards a less materialistic way of living (Velenturf and Purnell, 2021), with reduced consumption and improved production efficiency, where product recycling and reuse loops are geared towards waste prevention and efficient material flows and management (Bassi et al., 2021), in line with an industrial ecology approach (Saavedra et al., 2018). At the same time, empowering both consumers and public buyers can enable long-lasting lifestyle changes that affect individuals' consumption habits, leading to whole-system changes that create a favourable environment for the implementation of circular economy actions (Parajuly et al., 2020). Nonetheless, the role of the consumption side in a circular economy remains a largely under-researched topic (Georgantzis Garcia et al., 2021). This is also true for climate-economy modelling practice: whatever their theory, structure, and coverage, models tend to focus predominantly on the supply-side action space (Wilson et al., 2012), even though most scenarios for keeping temperature increase well below 2 °C describe transformations in both energy supply and energy demand. This shared research gap requires going beyond the typical technocentric interpretation of transitions in models as scenario assumptions narrated outside the vividly modelled systems of energy, environment, policy, and economy (Braunreiter et al., 2021; McCollum et al., 2020), and straying from the business-as-usual modelling focus on technological options for energy efficiency improvements (Wilson et al., 2018) or assumptions on the maximum potential of technological breakthroughs (e.g., Grubler et al., 2018).

A shared research gap between the two communities can also be found in the assessment of action and actors involved at different scales: climate change mitigation and circularity performance are typically modelled at the global and/or national level; however, both are a core theme of action plans and practice at the local level (Kundzewicz et al., 2020; Petit-Boix and Leipold, 2018). Due to the complexity and interlinkages of global production and consumption systems, there is a need to not only quantify the impacts of implementing environmentally effective strategies at broad geographical levels, but also with a sub-national granularity (Hsu et al., 2019) to assess and upscale the impact on, and potential of, local communities (Christis et al., 2019; Gallego-Schmid et al., 2020).

Finally, despite climate action being a key goal of the 2030 Agenda for Sustainable Development, circularity is only indirectly represented via different Sustainable Development Goals (SDGs), in terms of responsible consumption and production, clean water and sanitation, community sustainability, infrastructure resilience and innovative industrialisation, etc. (Schroeder et al., 2019). Nevertheless, much like responding to the climate crisis (Cohen et al., 2021), the non-linear economic model has recently been described as a transformative mechanism that can aid in achieving overall sustainable development (Millar et al., 2019). This requires viewing the circular economy outside weak sustainability frames that orientate on resource efficiency (Bimpizas-Pinis et al., 2021) and substitutability (D'Amato et al., 2017), and considering the potential, cross-cutting implications of competing sustainability goals (van Soest et al., 2019), rebound effects (Zink and Geyer, 2017), and environmental or social trade-offs (Harris et al., 2021). Much like climate action (Nikas et al., 2021), the transition to a circular economy must thus be carefully but decisively reframed within the spectrum of sustainability, by investigating the trade-offs and synergies between them (Suárez-Eiroa et al., 2019).

It is, therefore, evident that the climate and circularity agendas share similar goals, drivers, barriers, and potential implications; however, their synergies remain underexplored, and their scientific common ground largely underexploited. Integrating the various available research paradigms together into a single exercise is a step towards closing this gap.

3. Building conceptual bridges

Systematically conceptualising and operationalising the various circular economy measures in terms of mechanisms relevant to decarbonisation remains a challenge, due inter alia to the diversity of reviews and debates around circularity (Kirchherr et al., 2017) and the various interplays that must be considered in climate change mitigation. Analysis of these interplays needs to be based on a clear definition of circularity and its shared goal with climate action, orienting on decoupling any human activity from pressures to the environment, and redirecting the socioeconomic system within planetary boundaries (Steffen et al., 2015). Moreover, beyond an adequate definition, the interconnection between circularity and mitigation should be analysed in the context of economic territory rather than geographic territory. Currently, the environmental pressures related to climate change are observed from the perspective of the territorial limits of countries (partially based on data on energy balances), whereas production and consumption activities, on which actions related to circularity essentially revolve, are quantified in the context of the limits of the economic territory (principle of residence according to the system of national accounts). This inconsistency not only makes it difficult to compare the progress made by different economies on the circular economy and climate change mitigation, but it also hinders the establishment of a solid analytical foundation that would allow for an adequate linkage between the two goals. Sectors with a high energy consumption pattern are at the same time the sectors where the greatest amounts of secondary products are used, while all productive activity is aimed at satisfying final demand. Therefore, analysing and understanding the connection between mitigation and circularity cannot be independent of understanding the structural characteristics of final use of products and services in each economy, which is determined in turn by changes in consumption habits related to mobility, food and housing, and other human necessities.

Clarifying the definitional boundaries of the circular economy and outlining its interfaces with climate action are important prerequisites to establishing a conceptual typology and mapping of circular economy measures onto emissions profiles (e.g., product characteristics and technical improvements (Glöser-Chahoud et al., 2021, 2019)), considering also shifts in production or consumption patterns, changes in user behaviour (e.g., sharing/secondary markets), and auxiliary parameters (e.g., surrounding energy systems). This conceptual mapping between circularity and climate action must be supplemented with a thorough understanding of the objectives and scale of existing models for climate change mitigation and their advantages and limitations in measuring circularity performance and its interrelations with climate change (e.g., McCarthy et al., 2018). This process can help match conceptual aspects with model parameters, as well as identify gaps between conceptual requirements for comprehensive modelling of the circular economy in climate mitigation and existing modelling capabilities.

Effectively implementing circular economic measures and climate action requires strong policy direction and monitoring. Sets of monitoring indicators have been recently proposed in the European Union to assist member states in evaluating circularity performance (Eurostat, 2021), and by the OECD to assess effects of the circular economy on the environment, governance, economy and business, infrastructure and technology, and civil society (OECD, 2021b). To sufficiently understand the impact of circularity on climate change, and vice versa, as well as its broader sustainability implications, firm interconnections should be established amongst circularity criteria, emissions mitigation indicators, and sustainability criteria—for example, those defined for IAM analysis of SDG progress (van Vuuren et al., 2021). Operationalising such a set of integrated indicators enables a better understanding of the circular economy and decarbonisation and establishes a common language with integrated assessment modelling, allowing members of both communities to quantitatively assess future trade-offs and synergies amongst circular economy and mitigation measures (Rodriguez-Anton et al., 2019) and collectively assess holistic sustainable development pathways (Soergel et al., 2021).

Transition pathways towards circular carbon neutrality usually stipulate a balanced interplay of environmental and economic systems (Ghisellini et al., 2016). Before implementing the policy measures required to ensure this interplay, it is crucial to comprehend the most significant linkages between key manufacturing sectors and other economic activities. And, although the link between critical sectors (steel, cement, and chemical industries, etc.) and key demand sectors (transport, buildings, agriculture, power generation, etc.) is typically understood, data availability for detailed assessments remains limited while interlinkages with waste management, recovery, repair, remanufacturing, leasing/rental, etc. are less established. Integrating such processes in these conventional supply-demand ties, as well as coupling them with emissions removal activities through natural and synthetic processes, comes as a key challenge towards building feasible carbon-neutral and circular transition pathways that consider implications for energy and material usage (e.g., Lee et al., 2017).

Apart from technical improvements in the design of products and production processes currently in use that aim at material efficiency, the transition to a circular economy also requires profound transformations of both society and existing production systems. Through this technical and socio-economic transformation, all necessary systemic changes should be triggered to guide the shift to multi-sectoral meta-regimes based on updated global economic models as part of a deep transition (Kern et al., 2020). These transformations initially entail the diffusion of innovation that enables the transition from linear to circular models, with actor-based approaches being key to enhance acceptability and uptake of radical and disruptive innovations. However, there is yet a lack of understanding on the core components of social innovation in the circular economy and the role of agency in multi-sectoral environments, including actors' decisions at the household and industry level. This highlights that non-modelling developments and their integration are also critical: although socio-political aspects are to some extent rooted in IAMs, a broad variety of socioeconomic and political factors are not always represented well in modelling—e.g., distributional impacts, interaction with development priorities other than climate, structural inertia and path dependencies, psychological and socio-cultural inertia, lack of information, etc. This limited representation of such factors points to the need for the modelling community to engage deeply with the broad range of disciplines comprising social sciences and humanities (Braunreiter et al., 2021; van Beek et al., 2020). Employing different sustainability transition frameworks such as Systems of Innovation, the Multi-Level Perspective, and Strategic Niche Management (and combinations of them; e.g., Koasidis et al., 2020) can bridge these gaps. It can also shed light on the impacts of lifestyle changes related to the transition to a circular economy, including socioeconomic, gender, and cultural dimensions as well as broader behavioural shifts, such as dietary selections (Mylan et al., 2016), energy and material consumption profiles, investment decisions, and choices with direct implications for circularity (reduction of food waste and energy use, product reuse, etc.). Overall, sociotechnical analyses enable the establishment of realistic qualitative narratives that meaningfully inform research and quantitative systems modelling exercises (Rogge et al., 2020; van Sluisveld et al., 2020), ensuring that the bridges between circularity performance and climate action are well tied with the societal implications of the transition.

4. The critical role of non-scientists in science

Designing and implementing effective strategies for a transition to a circular, climate-neutral economy requires the participation of multiple stakeholders, including policymakers, industry representatives, cities and local communities, and the wider public (Stahel, 2016). Therefore, relevant research activities, including modelling, must be qualitatively guided, supported, and legitimised through co-creation activities with all stakeholder groups, as broadly argued for all knowledge systems that are used to inform sustainable development (Cash et al., 2003). For example, policy makers can provide directions for the transition at a macro level, industry experts can provide on-the-floor knowledge and tacit information on applicability at a *meso* level, and citizens can provide insights on their willingness to adopt different solutions at a micro level. Strategies for co-creation with diverse stakeholder groups have been broadly framed as a way to increase the desirability and societal relevance of sustainability transitions (Nikas et al., 2020), based on transdisciplinary research processes and methods (Pohl et al., 2017) and innovation models (Durán-Romero et al., 2020). If not for co-production of knowledge and policy, stakeholder involvement can at least act as a communication channel and inform stakeholders about the benefits of circular and climate-related interventions, thereby boosting the uptake of research outputs (Galende-Sánchez and Sorman, 2021).

In particular, when it comes to policy, discourses amongst high-level policymakers and scientists are not uncommon in developing national targets and policies for climate change, circular economy, and sustainability in general, but the different policy levels remain fragmented (e.g., Calisto Friant et al., 2021). Multi-level governance and deliberation can provide valuable insights on bridging the existing high-level targets with the capacities and needs of countries and local communities, which can be pivotal in (the acceptability of) circular economy and climate mitigation initiatives alike (Fuso Nerini et al., 2019; Prendeville et al., 2018). For instance, many European cities (e.g., Amsterdam, Brussels, and Paris) have been at the forefront of such initiatives, focusing on material-related measures (like waste management and recycling), sharing economy initiatives, and communication campaigns to promote behavioural changes (Fratini et al., 2019). Local governments and decision-makers can also form a link between national and European policy, industry, and the wider public for actions targeting emissions cuts and circularity performance (Petit-Boix and Leipold, 2018).

From an industrial perspective, existing climate and circular economy policies have focused on technological solutions and innovations on the supply side (O'Neill et al., 2020), mostly targeting a select few industries (Durán-Romero et al., 2020). While some of these solutions include industrial symbiosis (Petit-Boix and Leipold, 2018), recent calls indicate the need for broader supply and value chain transformations (Mateus and Martins, 2020). In this direction, close collaboration amongst researchers, industrial partners, and policymakers is needed to develop and evaluate transformation strategies for existing production sites and analyse the role of regional industrial clusters in future value chains and towards industrial symbiosis. Field studies in close collaboration with industrial, research, and policy actors can offer insights to be integrated in the modelling frameworks used by researchers and policymakers and facilitate a realistic and robust representation of industrial transformations, while at the same time ensure the feasibility, ownership, relevance, and uptake of findings for industry (Okorie et al., 2021).

On the demand side, citizens can be central in the efforts towards enhancing both decarbonisation efforts and circularity performance, by changing lifestyles and energy/material use profiles, thus complementing and legitimising technological and policy change. The behavioural dimension relates not only to the consumption rates that determine energy and material demand in the economy but also to cultural and habitual aspects that affect or block the uptake of material and energy reduction strategies (Ellen MacArthur Foundation, 2019). For example, the food system constitutes one of the most salient sectors where behavioural change directly impacts a transition to a circular economy (i.e., flexitarian diets and food waste reduction) (Springmann et al., 2018). Additionally, lifestyle changes have the potential to significantly reduce both material use and emissions across the buildings and mobility sectors (Christis et al., 2019; Petit-Boix and Leipold, 2018), e.g., through sharing economy schemes that can optimise the utilisation of cars, bikes, and building spaces. While behavioural aspects have been introduced in macroeconomic and integrated assessment models (Aguilar-Hernandez et al., 2021; Niamir et al., 2020; van de Ven et al., 2018; van Vuuren et al., 2018), they remain largely underrepresented or merely represented as simplified exogenous assumptions for consumption rates and participation in sharing activities (McCarthy et al., 2018). However challenging (Sovacool et al., 2021), recent calls for a shift in the transitions research and policy agenda (Nikas et al., 2020) have argued for approaches to involving citizens in climate governance (Dryzek and Niemeyer, 2019) and science (Doukas and Nikas, 2021), and the same has been argued for circularity research (Geissdoerfer et al., 2017).

5. Developing new modelling capacity

Modelling the circular economy requires a comprehensive representation of end-to-end supply chains and a profound understanding of the physical and monetary flows throughout the economy (Pauliuk et al., 2021b). Although studies have begun assessing circularity and its regional and global impacts on emissions and energy demand (e.g., Hertwich, 2021), a more detailed and consistent quantitative and consistent investigation of impacts, costs, and policies is still missing. Currently, models used to produce mitigation pathways, such as IAMs and other macroeconomic models, do not include a sufficiently detailed representation of the material flows throughout the entire product life cycle, nor do they portray material or product stocks, while the representation of secondary markets and recycling tends to lack granularity (McCarthy et al., 2018). Depending on the modelling structure, many key sectors are lacking detailed modelling or are absent in IAMs (Keppo et al., 2021)—e.g., the mineral extraction and food industries. In addition, many of the relevant products are too clustered to allow modelling activities associated with specific changes in the respective production and consumption pathways. Implications of increased digitalisation, electrification, and dietary and other behavioural changes, with impacts on waste reduction and material reuse, require thorough representation of production technologies and interlinkages amongst these sectors and products via global and regional supply chains. Additionally, some models have relatively detailed representations of the industrial manufacturing sector (e.g., Fleiter et al., 2018; Nechifor et al., 2020) however, with few exceptions and to some extents (e.g., in the E3ME-FTT model, see Lee et al., 2018), there is usually no coupling to the energy sector to model endogenously how energy technology deployment patterns will impact the industrial manufacturing sector. Existing models may also lack functionalities to endogenously represent how changing consumption patterns impact the industrial manufacturing of goods and business supply of services. Enhanced representation of these interlinkages along with a shift from technology-rich to both technology- and material-rich models are necessary steps towards exploring how increasingly resource-conserving, circular activities can contribute to emissions cuts.

Both the models typically used for analysing climate-economy interactions (e.g., IAMs) and those employed in circularity research must, therefore, be enhanced to incorporate modelling features that are currently missing. One such example is detailed representation of economic activities related to enhanced circularity performance (i.e., material recycling, repair, share, and re-use) in the form of detailed bottom-up material flows, technological options, and their costs. Via better representation of key technologies and production systems, scientists will be better equipped to quantify how circularity performance contributes to energy, emissions, and material savings. For example, recent studies have shown that circular economy strategies can yield promising results in the decarbonisation of steel (Luh et al., 2020; Nechifor et al., 2020), cement (Rehfeldt et al., 2020), and ammonia industries (Budinis et al., 2020). Such developments enable better resolution of the production processes of product groups relevant to both production and consumption activities that are central to the lifecycle impacts of a low-carbon transition—e.g., recycling of batteries, renewable power components (wind turbines, solar panels), and electric infrastructure (copper, etc.).

Finally, model coupling can be used to further improve the representation of value chains in the various modelling frameworks used to produce mitigation pathways. Establishing links between the various assessment tools will allow to expand current modelling capacities to thoroughly assess closed-loop economic systems and interactions with the climate system (Volkart et al., 2018). One example lies in reinforcing commonly used models for mitigation, based in general on monetary data of the global economy, by hard-linking them to other datasets, representing economic activities in physical terms. Such material and energy flows through the economy are normally presented in the form of (global, multi-regional) Physical Supply and Use Tables (PSUTs) of materials and energy or are compiled in the format of Physical Input-Output Tables (PIOTs). By means of linking both datasets the analytic possibilities are increased allowing hybrid analyses of economy-environment interactions (Schoer et al., 2013). This characteristic of the hybrid models—i.e., representation of material and energy flows in a high sector and process resolution within the monetary datasets on the economy—improves the representation of relevant production and consumption activities in the models. But it also allows reducing uncertainties in models, based on monetary data, caused by market prices distortions. This flexible representation of flows is the first step for harmonising physical flows and monetary databases to enable hard and soft linkages with climate change mitigation models (Pollitt et al., 2020). Global PIOT models have recently been used to assess agriculture and food products (Bruckner et al., 2019) as well as iron and steel (Wieland et al., 2021).

However, there is still significant ground to cover other climate-intensive metals, such as copper or aluminium, construction materials such as cement, and biomass-related sectors such as textiles and pulp/paper. Covering all international supply chains in physical terms will enable to significantly enhance the representation of material use in mitigation models (Sun et al., 2019). Conversely, via a two-way integration of material and energy flows, physical tables on material flows can be extended with data on GHG emissions calculated using information on the physical energy flows for all processes and products, enabling higher-level mitigation potential associated with different types of materials and products. Coupling can also contribute to reducing epistemological uncertainties surrounding the broader environmental pressures resulting from the diffusion of mitigation technologies, for instance via LCA-IAM links (Arvesen et al., 2018; Ichisugi et al., 2019; Mendoza Beltran et al., 2020).

6. Concluding remarks

Even the most ambitious technological breakthroughs and conventional top-down policies will be insufficient to deliver Paris-compliant mitigation trajectories. The decarbonisation potential lying in linear-to-circular economic model transformations and in fostering more sustainable lifestyle patterns has been increasingly gaining attention; nevertheless, critical aspects remain underexplored. This perspective has outlined key similarities between the climate and circular economy agendas, as well as highlighted the gaps between their modelling communities and methodologies. While calls to reconcile these modelling communities are not new, our perspective outlines a novel paradigm to holistically inform the modelling integration through diverse inter- and transdisciplinary interactions both amongst scientists and with non-scientific stakeholders.

With a view to providing recommendations as key takeaways of this perspective, an outlook for future research is further suggested towards achieving the proposed integration. First, the different scientific communities should build bridges with one another and adopt an interdisciplinary approach that draws from diverse methods and models that are typically used independently to address questions on circularity, climate action, and sustainability. Second, employing a transdisciplinary paradigm, in which these communities co-produce knowledge with non-scientific stakeholders (policy, industry, and civil society), will allow to co-develop Paris-compliant, circularity-enhanced scenarios to systematically assess the contribution of the circular economy to decarbonisation, while enhancing their scientific credibility and legitimacy. Third, the integrated assessment modelling community should then translate these interdisciplinary and transdisciplinary insights into new modelling capabilities in the IAMs, which are typically used to project human-earth interactions in response to climate and policy shocks and to inform decision processes. This will allow policymakers and scientists to explore mitigation pathways that lead to a circular, net-zero economy with improved industrial value chains, physical flows, and sectoral reconfigurations, energy-, material-, and climate-conscious individual lifestyles and societal behaviours, and broader sustainability.

Considerable progress can be claimed for modelling research on sustainability transitions in the past decade. But, if circularity performance and decarbonisation are to be viewed as two pieces fitting together in the sustainability jigsaw, breaking down disciplinary silos must be the ambitious next step.

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.

Funding

This work was supported by the H2020 European Commission projects “PARIS REINFORCE” (Grant Agreement No. 820846), “LOCOMOTION” (Grant Agreement No. 821105), “NDC ASPECTS” (Grant Agreement No. 101003866), and “newTRENDS” (Grant Agreement No. 893311); the European Research Council (ERC) project “FINEPRINT” (Grant Agreement No. 725525); the Hellenic Foundation for Research and Innovation (HFRI) and General Secretariat for Research and Technology (GSRT) project “ATOM”

(Grant Agreement No. HFRI-FM17–2566); the Spanish Ministry of Science, Innovation, and Universities projects RTI2018–099858-A-I00 and RTI2018–093352-B-I00; the María de Maeztu excellence accreditation 2018–2022 (Ref. MDM-2017–0714), funded by MCIN/AEI/10.13039/501100011033; and by the Basque Government through the BERC 2018–2021 program and BIDERATU project (KK-2021/00050, ELKARTEK programme 2021). The sole responsibility for the content of this paper lies with the authors; the paper does not necessarily reflect the opinions of the European Commission, the Basque Government, or the Spanish Government.

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