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Bridging modelling and policymaking efforts to realize the European bioeconomy

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Abstract

The European Bioeconomy Strategy aims to facilitate the transition from a take–make–dispose fossil economy into one fostering circular bio-based value chains linking sustainable land use with cutting-edge products. Optimized designs, implementation and monitoring rely on continuous interactions between policymakers and modellers who run multiple scenarios for environmentally, economically and socially desirable futures. This paper leverages a multi-layered framework that cross-references 39 policies and 32 models to assess how they address the five principle objectives of the Bioeconomy Strategy in terms of accompanying sectors, value chains and multi-dimensional indicators. The framework identifies gaps in bioeconomy knowledge both in policy and modelling. Overall, the analysis found little mention of the wide range of bio-based products, technologies and processes, bio-refineries, waste and land conservation. Bio-based product policies can be simulated only in a limited number of models, compared, for example, to the wide range of modelling capacities that can model bioenergy. Additionally, in both policy and modelling realms, integration of market and biophysical drivers within the full scope of the value chain is scarce. Multidisciplinary studies combining multiple models perform best in this respect by integrating a more comprehensive range of relevant policies, bioeconomy drivers and indicators. Findings point to a more significant issue in policy-modelling information exchange, and this paper discusses the challenges and opportunities for future improvements in this collaboration.

KEYWORDS
bio-based products, bio-based value chains, bioeconomy, biorefineries, European Bioeconomy Strategy, modelling, models, policy, value chains

1 | INTRODUCTION

Natural resources crucial to the survival of people and keystone species have been extracted in a 'take–make–dispose' development model. At the same time, global atmospheric greenhouse gas (GHG) emissions have not stopped increasing since humans began measuring them. Based on a socially and environmentally responsible vision of prosperity, the European Bioeconomy Strategy seeks to address these challenges by revitalizing land

and connecting a suite of sectors to produce and convert biological resources into innovative products. The bioeconomy represents a building block within the circular economy, which pairs sustainability with innovation to ensure future economic growth (Stegmann et al., 2020). The Bioeconomy Strategy forms part of the Circular Economy Action Plan, a central tenet of the Green Deal (European Commission, 2019).

The bioeconomy encompasses all sectors and systems relying on biological resources (e.g. plants, animals, microorganisms and derived biomass, including organic waste), their functions and principles. It interlinks land use (e.g. agriculture or forestry) and ecosystem services with all the economic and industrial sectors that process biological resources to produce food, feed, bio-based products, energy and services (European Commission, 2018a) circularly and sustainably.

The five societal objectives of the European Bioeconomy Strategy (Table 1) govern its updated action plan and consist of scaling-up bio-based sectors, deploying bioeconomy at the local level, and measuring ecological boundaries. The Strategy has set multi-term and spatially explicit 2030 targets to achieve these objectives, including cutting food waste by 50%, achieving land degradation neutrality, rolling-out bioenergy as a sustainable competitive energy source and deploying over 300 new biorefineries (European Commission, 2018a).

A suite of models and policies exists to support the implementation of these goals. Models can steer future policy support to optimize the performance of bioeconomy value chains (Panoutsou & Singh, 2020) and inform both biophysical and market factors (Keegan et al., 2013; Philippidis et al., 2018) or competitive priorities that can accelerate future deployment (Panoutsou, Singh, et al., 2020). Models are integral to policymaking and can help produce legally binding numbers for government budgets (Kolkman, 2020). As such, model experts have the opportunity to integrate policymaking priorities when formulating findings, while policymakers can benefit from having a rudimentary understanding of modelling tools when interpreting outcomes. Indeed, at the European Commission, Acs et al. (2019) reveal that reliance on models used within 'evidence-based' integrated quantitative impact assessments has been gathering pace. The EU Commission's Knowledge Centre for Bioeconomy (KCB) produces forward-looking analysis employing modelling scenarios that integrate a sustainable, resource-efficient bioeconomy with climate change issues and sustainable development goals (Verkerk et al., 2021). Existing modelling capacities help justify large funding programmes such as Horizon Europe (European Commission, 2020a) for bioeconomy research and innovation activities and influence the creation of public and private partnerships such as those enacted by the Standing Committee on Agricultural Research (Soini et al., 2018). Multi-stakeholder workshops are held annually in Brussels hosted by the Directorate-General for Agriculture and Rural Development (DG AGRI), where new agro-food baselines and model results are discussed (European Commission, 2020b).

TABLE 1 The five objectives of the European Bioeconomy Strategy

Objective I: Ensuring food and nutrition security: *by turning organic waste and food discards into valuable and safe bio-based products, deploying small-scale biorefineries and fostering revenue sources for rural workers.*
Objective II: Managing natural resources sustainably: *by restoring and enhancing ecosystem functions to increase food and water security while improving capacity to monitor and forecast the status of natural resources.*
Objective III: Reducing dependence on non-renewable, unsustainable resources: *by rolling-out bio-based products through innovative industrial bio-based processes and circular value chains.*
Objective IV: Mitigating and adapting to climate change mitigation: *by reducing greenhouse gas emissions, promoting resource efficiency within primary production practices and enhancing ecosystem climate resiliency.*
Objective V: Strengthening European competitiveness and creating jobs: *by deploying technologies and fostering commercial opportunities for bio-based products, including economic development in remote or peripheral areas.*

The five core objectives of the European Bioeconomy Strategy mirror the sustainable development goals (SDGs) and target several dimensions of sustainability and growth. Policies and models can equally target environmental, economic and social dimensions of sustainability (Wang et al., 2016). Meanwhile, the Bioeconomy Strategy entails collaboration and integration to produce robust, cross-sectoral evidence (European Commission, 2018a). However, decision-makers have limited guidance on which model(s) to select for policy planning (Allen et al., 2016). When linking the Bioeconomy Strategy with the SDGs, Ronzon and Sanjuán (2020) found that increasing agricultural production, industrial use of biomass, economic growth and domestic material consumption all at once proves challenging. Wesseler (2022) highlight the multiple policy targets within the EU Farm to Fork strategy and derived complexity in producing modelling impact studies. Decision-makers can pose the following question: are modelling capacities that simulate available policies and policies that shape the narrative and societal priorities for models sufficient in informing the cross-cutting objectives of the Bioeconomy Strategy?

This paper aims to evaluate how a selective mix of current modelling capacities and policies address the five objectives of the European Bioeconomy Strategy both separately and jointly. The first section lists bioeconomy objectives, sectors, value chain stages and indicators as the basis for the classification assessment of this paper. Appendices A–C include a comprehensive aggregation, definition and sourcing of this classification. Overall, the analysis uses the value chain approach to frame key challenges, competitive advantages and disadvantages of bioeconomy deployment across all stages—from the use of natural resources to produce feedstock and further conversion to bio-based products used by consumers (Panoutsou, Singh, et al., 2020; Sevigné-Itoiz et al., 2021). The second section assesses the capacity of models and policies independently from one another to understand the extent to which they address the five core objectives facing the bioeconomy. Model and policy reviews capitalize on original work, the Horizon 2020 Biomonitor Project (https://biomonitor.eu/) and previous work from the authors (Singh et al., 2021). The third section carries out the same exercise; however, this time looking at policy representation within models and assessing their capacity to respond to the five Bioeconomy Strategy objectives. Figure 1 illustrates the methodological framework.

The proposed framework seeks to shed light on the adequacy of current policy designs and modelling capacities in addressing the five objectives of the European Bioeconomy Strategy, as well as bioeconomy sectors, value chain representation and indicators as defined here. It equally assesses whether the bioeconomy can be analysed through a single one-size-fits-all model specification and the quality of policy representation available in the current modelling capacity to inform the aims of the Bioeconomy Strategy. Furthermore, it evaluates the degree to which models and policies adequately integrate ecological or biophysical dimensions with socioeconomic and economic considerations. Finally, it seeks to identify gaps between policymaking and modelling and discuss how each respective camp can better coordinate data acquisition, priorities and harmonized methodologies for bioeconomy needs.

2 | MATERIALS AND METHODS

2.1 | Bioeconomy sectors, value chain stages and indicators

Bioeconomy sectors stem both from an aggregation of NACE (Statistical Classification of Economic Activities in the European Community) sectors (Cingiz et al., 2021; Kardung et al., 2021; Lier et al., 2018; Ronzon et al., 2017), including agriculture, forestry, energy, bio-based industries, and two cross-sectoral areas of the bioeconomy: waste and environment. Verkerk et al. (2021) find that existing models do not appropriately capture the aquaculture and fishing sector (idem for textiles, pharmaceuticals, plastics and chemicals). Their recommendation is to link these models to broader sectors, an approach followed by this paper. The waste sector defines bio-waste as a product linkable to the agricultural sector (primary waste), industries (secondary waste) or retail/consumer (tertiary waste). The environment comprises biophysical dynamics such as land, soil, water, biodiversity and atmospheric resources. It is an area where the Member States can legislate and adopt legally binding acts (Official Journal of the European Union, 2012).

Bioeconomy value chain stages (Figure 2) begin with land use, which involves land productivity, direct and indirect displacement of other land-based activities and soil quality. The second stage is biomass production, which includes crop establishment and management, harvesting, pre-treatment, storage and transport. Sustainability measures centre on avoiding the disruption of food

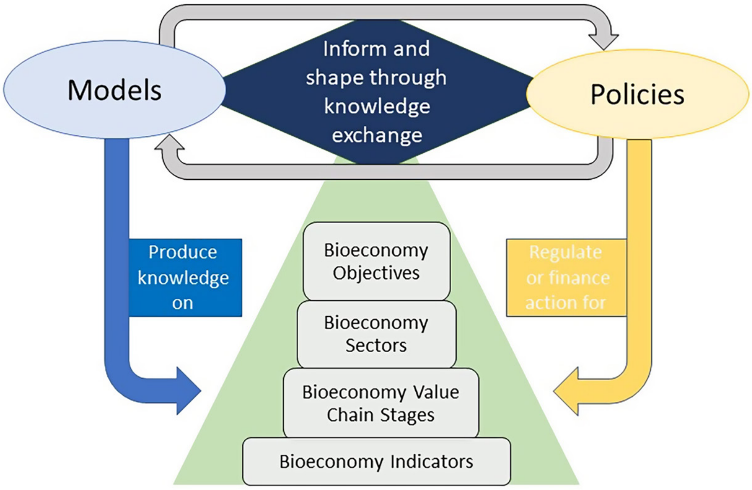

FIGURE 1 Methodological approach.

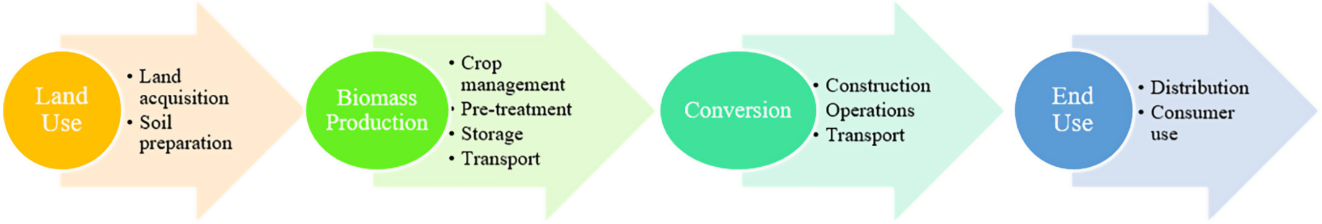

FIGURE 2 Bioeconomy value chain stages.

production, natural capital or carbon sinks. Valorization of biomass depends on innovations at the cultivation level and rural capital growth (Panoutsou, 2017), as well as the emergence of new feedstock such as bio-waste, residues and discards (European Commission, 2018a). The following stage is biomass conversion into bio-based products and includes biochemical, thermochemical, physical or chemical depolymerization pathways. The relation of this stage to the previous and next rests in its ability to handle mixed volumes of feedstocks, optimize synergies for the valorization of residues and co-products and reliably produce high-quality products (Panoutsou, Arrekul, et al., 2020). Finally, end-use products must comply or compete with existing infrastructure, standards and distribution channels. Their value is driven by consumer behaviour and perception (McCollum et al., 2017; Wesseler & von Braun, 2017).

Individual *indicators* can track the performance of multiple facets of the bioeconomy. Internationally recognized and scientifically robust with tangible metrics, indicators can appropriately monitor and evaluate the progress and impact of bioproducts (Bracco et al., 2019). Kardung and Drabik (2021) analysed 41 indicators for the circular bioeconomy. In this paper, indicators remain at a broad level (see Appendix C for quantitative and qualitative indicator definitions): for instance, instead of ‘employment rate of recent graduates’, we use ‘full-time employment’. This approach facilitates the cross-referencing exercise (i.e. comparing the incidence of an indicator between model A and model B) and copes with the limited capacity of available indicators in models or policies relevant to the bioeconomy. The international projects Biomass Policies (Pelkmans et al., 2014) and MAGIC (Panoutsou et al., 2018), as well as a Food and Agriculture Organization report (Bracco et al., 2019), provide a basis for the selection of indicators in this study (Table 2). They provide comparable measures of sustainability and performance and follow the ‘triple bottom line’, namely environmental integrity, economic resilience and social well-being (Elkington, 1998), in addition to a technical dimension measuring natural resource availability, technology level and energy needs.

2.2 | Relevant models and policies

First, we selected 39 bioeconomy policies based on a review of over 90 policies (Singh et al., 2021). The selection filtered out cross-cutting and strategic policies without precise, measurable interventions. The selection aggregated policies into 13 groupings according to their overall scope (see Tables 3 and 4) and reviewed their relevance to bioeconomy objectives, sectors, value chain stages and indicators.

Second, models were selected and aggregated based on an original review complemented by the one conducted by the BioMonitor Project (Panoutsou, van Leeuwen, et al., 2020; Varacca et al., 2020). From the selected 32 models, we grouped 21 into seven congruent ‘umbrella’ groupings based on analogous objectives and drivers. The remaining 11 models are standalone, generating 18 model groupings (see Tables 3 and 4). Their relevance to respective bioeconomy objectives, sectors, value chain stages and indicators is reviewed (Appendices D and F include a complete list of models and policies and Appendix E contains the original review of indicators from modelling scenarios). The indicators review is supported by recent ongoing research (Kardung et al., 2019; Panoutsou, Arrekul, et al., 2020) and individual modelling scenarios.

Third, the relevance of policies and models for informing the European Bioeconomy is determined. Models can simulate the effects of policy interventions by comparing the same output under a situation in which that policy is absent from shaping an evidence base for policymakers (Pinter et al., 2004). A cross-referencing framework is used to screen which policies can be used in specific models and which model-based knowledge is relevant for policies. Policy outcomes are compared with model inputs, assumptions and built-in parameters, while model technical documentation and case study literature are reviewed. The framework also compares how each policy and model assigns bioeconomy objectives, sectors and value chain stage.

Where some models are relevant for policymaking in one specific sector, other models can inform on the broader impacts of a policy, including on other bioeconomy sectors and value chain stages not directly targeted by such policies. For instance, sustainable forestry policies do not cover the agricultural sector. However, models with

TABLE 2 Model indicators paired with bioeconomy objectives (roman numerals and corresponding colour codes from Table 1 are repeated)

Dimension	Indicator	Availability in models	European bioeconomy strategy objectives
Technical	Land, biomass or water availability	12	I II
	Technology level	5	I III V
	Energy need	2	III IV
	Conversion capacity	3	III V
Environmental	Land use	12	I II IV
	Nutrient levels	6	I II
	Life cycle GHG	12	IV
	Carbon stocks	7	II IV
	Inputs	7	I II III
	Harvest and litter	4	I II V
	Pollutants	5	I II III IV
	Water use	8	I II
	Ecosystem services and productivity	5	II IV
Economic	Biomass production	14	I II III IV V
	Energy supply carrier production	10	III IV V
	Costs and return	12	I III V
	Import and export	7	I III V
	GDP	4	I III V
	Price	9	I III V
Social	Demand/consumption	11	I III V
	Farm income	4	I III V
	Employment	5	I III V
	Welfare	4	I V

Abbreviation: GDP, gross domestic product.

built-in data and functions for both sectors can simulate the impact of such policies on agriculture.

3 | GAP ANALYSIS AND RESULTS

This section seeks to shed light on whether current policy designs and modelling capacity adequately address the five objectives of the European Bioeconomy Strategy and their representations of sectors, value chains and indicators. Adequacy of policies and models is first analysed separately (Sections 3.1 and 3.2, respectively), then determined by the level of policy representation currently available in modelling capacities (Section 3.3).

3.1 | Bioeconomy policies

The policy review builds on Singh et al. (2021), who interpreted the adequacy of available regulatory or financial policies responding to bioeconomy aims. The study analysed policies for their relevance to biomass, bioprocessing and bio-based product groups for each value chain stage and activity and the main issues they regulate based on their scope, objectives and instruments. Most of the 39 European policy interventions reviewed (listed in Tables 3 and 4) that were found relevant to the bioeconomy centre around environmental sustainability and climate issues as most target biophysical drivers. Among bioeconomy objectives, sectors and value chain stages, there is fair coverage for each. However, objective I (food security and waste valuation) and the waste sector have limited representation.

The Farm to Fork Strategy appears in some studies as central to the bioeconomy (Trigo et al., 2021). However, this paper is structured around the strict definition of the Bioeconomy Strategy objectives, whereby objective I states the need for tangential, wider or complementary efforts to traditional food systems and economies, namely organic waste as bio-based products, biorefineries and rural incomes.

TABLE 3 Matching bioeconomy models and policies (1)

Models	**InVEST**	**G4M CBM-CFS3, EFDM & EFISCEN**	**PRISM-ELM & EPIC**	**MAgPIE**	**MITERRA**	**CLUMondo & Dyna-CLUE**	**FARMIS**	**BeWhere**	**MESSAGE TIMES & MARKAL**
Policies									
Conservation Designation	🟩	🟩		🟩	🟩	🟩	🟩	🟩	
Soil Quality Improvement	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
Sustainable Forestry	🟩	🟩	🟩	🟩				🟩	
Sustainable Agriculture	🟩		🟩	🟩	🟩	🟩	🟩	🟩	
Industrial Decarbonization								🟩	🟩
Sustainable Biobased Products									🟩
Sustainable Biofuels								🟩	🟩
Vehicles Emission Reduction								🟩	🟩
Water Regulation	🟩		🟩	🟩	🟩	🟩			
Waste Regulation			🟩	🟩	🟩			🟩	🟩
Land Use Change Impact Mitigation		🟩		🟩		🟩	🟩	🟩	
Energy Efficiency				🟩			🟩	🟩	🟩
Advanced Bioenergy Uptake		🟩		🟩		🟩	🟩	🟩	🟩

TABLE 4 Matching bioeconomy models and policies (2)

Models	**GCAM**	**REMIND**	**IMAGE**	**BIOSAMs**	**MAGNET MIRAGE & GTAP**	**GLOBIOM**	**AGMEMOD ESIM & CAPRI & AgLink-COSIMO**	**GFTM GFPM & EFI-GTM**	**IMPACT**
Policies									
Conservation Designation	🟩	🟩	🟩		🟩	🟩	🟩	🟩	
Soil Quality Improvement	🟩		🟩	🟩			🟩		🟩
Sustainable Forestry	🟩	🟩	🟩	🟩	🟩	🟩		🟩	
Sustainable Agriculture	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩
Industrial Decarbonization	🟩	🟩	🟩		🟩	🟩			
Sustainable Biobased Products				🟩	🟩				
Sustainable Biofuels	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Vehicles Emission Reduction	🟩	🟩	🟩		🟩	🟩			
Water Regulation	🟩	🟩	🟩		🟩	🟩			🟩
Waste Regulation			🟩		🟩		🟩		🟩
Land Use Change Impact Mitigation	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩
Energy Efficiency	🟩	🟩	🟩		🟩	🟩	🟩		
Advanced Bioenergy Uptake	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

The Common Agricultural Policy (CAP) is included in this review as it captures the broader socioeconomic context and underlying land use and ecological drivers (Ehrmann, 2010; Helming & Tabeau, 2018; Leclère et al., 2014; Malek & Verburg, 2018; Rosegrant et al., 2014; Wąs et al., 2014) and impacts objective I directly.

Although the land use indicator is broadly used across policy areas, for instance, in sustainable agriculture policies (Louhichi et al., 2017), marginal land designations (Banja et al., 2019; Panoutsou & Singh, 2020) are not explicitly mentioned. Marginal lands can serve a crucial role in harbouring innovative non-food crops that do not disturb food systems or conservation areas (Panoutsou et al., 2018). Additionally, there is a lack of supporting policies for mobilizing biomass feedstock from waste sources.

There is little policy support for optimizing complex conversion processes that convert biological materials of varying content (including bio-waste) into bio-based products. For instance, lignocellulosic feedstock types are suitable for thermal or biochemical conversion based on a specific established set of chemical characteristics (Hoefnagels & Germer, 2018). Finally, regarding the end-use stage, policy interventions targeting the distribution and standardization of the vast, available range of bio-based products and services remain limited (Singh et al., 2021).

These gaps are repeated within available modelling capacity (reviewed in the next section).

While policies may address each value chain stage, they often lack value chain integration. For instance, there is a strong focus on reducing emissions (decarbonization) at specific stages, yet no mechanism integrating innovation across the value chain and how this may, in turn, impact sustainability goals. This is illustrated, for instance, by the Medium Combustion Plant Directive (European Union, 2015).

3.2 | Bioeconomy models

Among models reviewed for this study, 4 are top-down economic models, and 13 are bottom-up economic models. Economic models include the following: 'top-down' economy-wide (input–output, CGE, and macro-econometric models), 'bottom-up' (sector- or product-specific partial equilibrium, optimization simulation models and life cycle assessment) and hybrid. Additionally, 10 are environmental models specializing in spatial land coverage and dynamic vegetation, and 5 are integrated assessment models, which provide environmental, economic and social impact policy analyses. At first glance, there appears to be modelling capacity informing on all bioeconomy objectives. However, analysing models at the level of their output indicators (Table 2) provides a more detailed view.

Regarding bioeconomy sectors, most of the models are capable of simulating agricultural and environmental dynamics (three-quarters of models), followed by energy and forestry (two-thirds of models), and lastly, the bio-based industries and waste sectors (less than one-fourth of models). Concerning value chain stages, most models can represent the first two stages, with 16 of the total 18 model groupings in the selected sample capturing land use and 17 capturing biomass production. Meanwhile, 11 capture the end-use stage, while only 7 capture the conversion stage.

Table 2 links model output indicators across different dimensions to the five objectives of the Bioeconomy Strategy. Figure 3 shows which indicators and objectives individual model groupings can target. The models appear to have a strong capacity to inform objective I (through food availability and security indicators), followed by objectives III and V, and finally, with the least capacity, objectives II and IV.

Table 2 highlights the inherent cross-dimensional nature of indicators and their medium to high distribution within models. As such, there is potential to handle trade-offs or promote synergies across sustainability and performance dimensions. However, Figure 3 shows a much more varied (and limited) picture of modelling capacity in this respect. The economic MESSAGE/TIMES/MARKAL model grouping lacks indicators that inform environmental factors for objective II. In contrast, BIOSAMs and BeWhere, two models that explicitly simulate bioeconomy growth, have limited capacities to inform objectives II and IV. This fact mirrors the lack of policy harmonization of economic and sustainability dimensions. Some models such as EPIC or MITERRA are strictly environmental and restricted to the first two stages of the value chain (land use and biomass production) and exclude energy and bio-industrial sectoral considerations. However, cross-dimensional synergies exist; for example, a study determined the productivity and global market impacts of land-based dynamics such as soil health (Sartori et al., 2019). Integrated assessment models (such as MAGNET or GLOBIOM) can combine economic, environmental and technical indicators and thus capture a broader range of objectives.

In the bioeconomy, performance indicators aim to appropriately monitor and evaluate the progress and impact of bioproducts and the different dimensions of their development (Bracco et al., 2019). Wąs et al. (2014) measure welfare changes for agricultural price changes, including the impact of ecologically restorative measures (e.g. permanent grassland or crop diversification) with the CAPRI model, addressing objectives I, II and

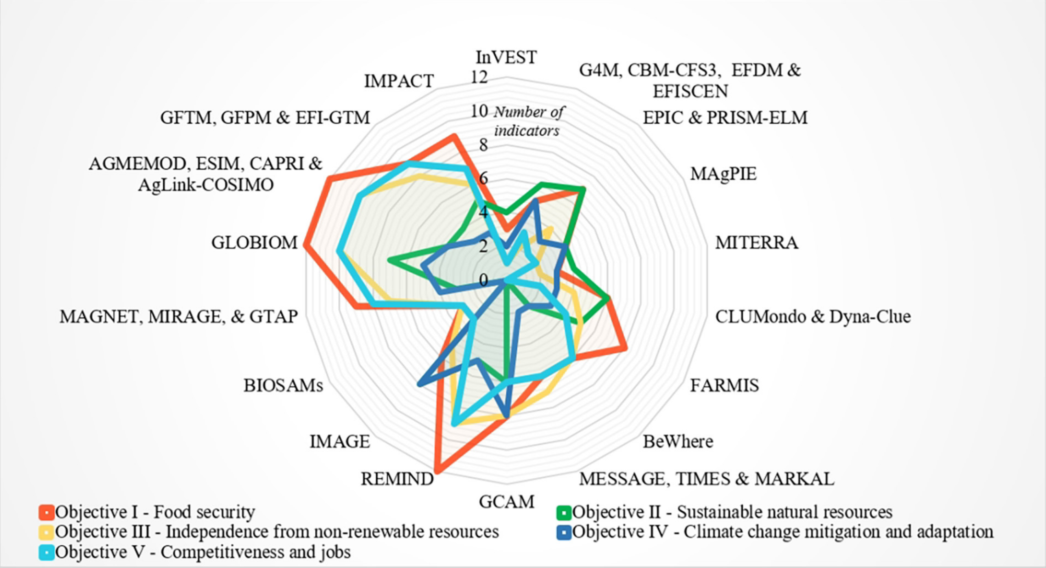

FIGURE 3 Indicators available for each model grouping and the bioeconomy objectives they inform.

V. However, at a more refined level, bioeconomy products do not feature, which is seen in other studies as well addressing objective I (Gocht et al., 2011; Rutten et al., 2013; Salamon et al., 2017). Similarly, Helming and Tabeau (2018) ambitiously address four bioeconomy objectives with both CAPRI and MAGNET by looking at the impacts of agricultural labour subsidies on employment, emissions, agricultural production, sectoral value and welfare. However, there is no explicit distinction between mineral and bio-based sectors, nor accounting of carbon in bio-based materials, which act as fundamental measures of objectives III and IV, respectively (O'Brien et al., 2017). However, GHG metrics are more widely available and, at times, linked to costs (Moiseyev et al., 2014). They are the standard for measuring climate change mitigation (IPCC, 2015).

Regarding impacts on natural resources, Rosegrant et al. (2014) employ soil fertility management measures such as no-till effects (absence of ploughing, use of cover crops and crop rotation) with IMPACT. However, the impact on ecosystem resilience or groundwater is not measured. The handful of models that do contain land inputs and ecosystem dynamic output indicators—InVEST, PRISM-ELM, EPIC and GLOBIOM—combine these with innovative biomass practices (Daly et al., 2018; Deppermann et al., 2019; Izaurralde et al., 2012; Lee et al., 2018), yet exclude market growth factors. This last study addresses four objectives with GLOBIOM, assessing the impacts of a carbon tax, expansion of protected areas, technological progress, reduction of waste and bioenergy on land use, emissions and biodiversity (Deppermann et al., 2019). At a metric level, land use (in hectares) interprets impacts on biodiversity. While this is a crucial impact indicator at a policy level (Louhichi et al., 2017), indicators for the spatial distribution of species occurrence, abundance and change over time are missing.

Moreover, spatially explicit ecosystem (Maes et al., 2018) and biodiversity footprint (Moran & Kanemoto, 2017) indicators are scarce among models. Additionally, there is no measurement of set-aside (conservation) land in economic terms. Diaoglou et al. (2015) employ IMAGE to measure land use and economic implications of residues used as feedstock for bioenergy production, addressing four bioeconomy objectives and lacking objective IV for climate change mitigation potential. Thus, analysing modelling capacity at the indicator (metric) level provides a clearer picture of the challenges in working cross-dimensionally to address several or all bioeconomy objectives. The analysis of indicators continues in the next section and looks at how modelling capacities integrate policy mechanisms.

3.3 | Combined bioeconomy models and policies

3.3.1 | Knowledge produced by policies simulated in models

Policies and models relevant to each other (Tables 3 and 4) are assessed jointly to determine what knowledge around the bioeconomy they can generate and whether gaps stressed in Sections 3.1 and 3.2 are resolved or unchanged. Aside from expected incompatibility between models targeting the first two stages of the value chain (land use and biomass production) and policies targeting the latter two stages (conversion and end use), overall, there is substantial alignment and relevance between models and policies, and thus significant potential to combine modelling and policymaking efforts to inform on the bioeconomy objectives.

Policies that target land use, biomass production or all value chain stages at once (e.g. water regulation) have more modelling support than those targeting the conversion and end-use stages. In line with the findings of the preceding sections, gaps in the intermediary steps of the bio-based value chain and well-defined end products remain. Indeed, sustainable bio-based product policies and their economic potential can be simulated in only a limited number of models (BIOSAMs, MESSAGE/TIMES/MARKAL and MAGNET/MIRAGE/GTAP). The opposite is true for the representation of conservation, sustainable agriculture, bioenergy uptake and land use change policies, for which more robust modelling capacities exist.

In Figure 4, coverage of bioeconomy objectives from both models and policies is determined based on:

- alignment of policies with objectives (e.g. conservation designation policies impact objective II),
- alignment of models and objectives and
- Tables 3 and 4 pairing of models and policies based on their relevance.

Findings indicate that models can simulate policies predominantly to inform objectives II and IV (environment and emissions), followed by III and V (alternatives to fossil fuels and economic growth), and finally, I (food security). Four policy areas can be integrated into modelling to inform objective I, including sustainable agriculture, land use change, soil quality and waste regulation. The coverage of objectives by modelling capacities for specific policy goals varies substantially.

Models have limited capacity in incorporating land conservation policies, soil protection, industrial decarbonization, bio-based product certification, vehicle emission reduction or waste and water regulation to uncover new fossil-free bio-based value chains (objective III) and foster economic growth (objective V). Exceptions include the MARKAL model, which can perform a cost- and emission-optimization pathways for biochemicals and deployment of biomass conversion technologies (Tsiropoulos et al., 2018). Additionally, Choi et al. (2019) study the impacts of bioeconomy growth (notably waste and perennial biomass crops for producing bioenergy and biomaterials/chemicals) on agricultural markets, prices, emissions and direct land use change. This is one of few studies incorporating waste processing and valorization, as policy mechanisms available to models fail to consider waste streams as valuable sources of feedstock mobilization (Singh et al., 2021). Finally, Figure 4 shows that objective I is not well targeted, as models only simulate a limited number of policies employing indicators of waste or residues, biorefinery entities and rural income.

On objective III, few studies integrate both traditional and bioeconomy-based pathways. Philippidis et al. (2018) analyse EU bioeconomy challenges in harmonizing emissions reduction and economic growth by integrating a GTAP database in MAGNET to disaggregate and differentiate sources of biomass supply, conversion pathways and bio-products with traditional pathways. This study enhanced the modelling architecture. Models can combine different modules, for instance, adding a code for biophysical or environmental considerations to an economic model, such as MAGNET (Woltjer & Kuiper, 2014). They can also be calibrated with output from others in the form of exogenous constraints or conditions or expanded with additional products, sectors, policies and regions. Implications of such structural flexibility are further explored in the discussion.

Within the knowledge capacity generated by models incorporating and informing policies, the agricultural, forestry, and energy sectors, environmental dynamics, and the two first stages of the value chain—land use and biomass production—are most targeted (Figures 5 and 6). Some knowledge is available for the end-use stage and, to a lesser extent, the conversion stage. Indeed, more studies are needed to incorporate conversion technology maturity, learning curves and capital investment costs (Karka, Petersson, et al., 2020; Wesseler & von Braun, 2017). The concept of a value chain as a driver of economic transformation remains under-utilized and misunderstood, especially concerning the intermediary steps, as models implicitly assume that primary producers directly supply consumers through complete and competitive markets (Barrett et al., 2020). Moreover, the absence of bio-refineries in the scenario literature as technological or commercial entities demonstrates the underdeveloped nature of the bio-based industry sector in models and policies. Bio-refineries are central to bioeconomy growth by converting biomass into a spectrum of marketable products and energy (De Jong et al., 2012; Pleissner et al., 2016). In one exception, Leduc et al. (2012) address objectives III, IV and V by employing the model BeWhere to compare combined heat-and-power and biofuel conversion technologies for a set of carbon costs and biofuel support policies.

Commonly available indicators in models simulating policies (full table available in Appendix G) include resource availability (e.g. amount of growing stock), land use change, economic performance (e.g. energy supply carriers or costs and return) and market factors (e.g. price).

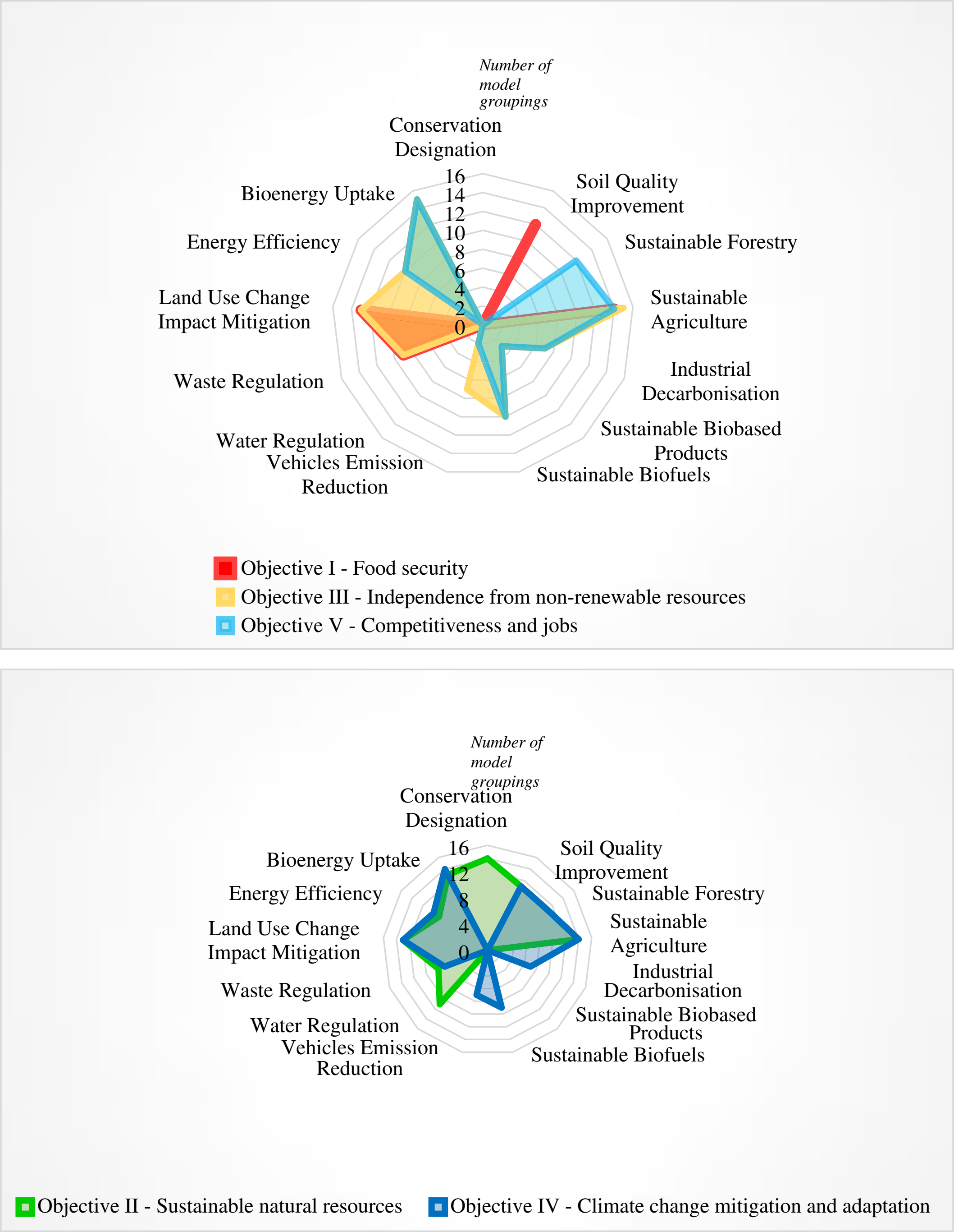

FIGURE 4 Number of models relevant to policies and how both address bioeconomy objectives.

Models and policies can, therefore, jointly deliver information on the bioeconomy at a metric level. Additionally, cross-dimensional knowledge can be generated, for instance, conservation, soil, water or waste regulation policies being measured in economic competitiveness terms or land use change being used in energy efficiency policies. However, gaps and challenges raised by the previous section (3.2) also exist here: bio-based product metrics, ecosystem and land input indicators suffer from poor representation.

Only seven individual models can integrate bio-based product policies and measure their environmental or economic impacts: BIOSAMs, MESSAGE, TIMES, MARKAL, MAGNET, MIRAGE and GTAP. Agricultural, biophysical and climactic impacts, in the form of crop subsidies for bioplastics and associated global real gross domestic product change as well as global land use change emissions, are studied through GTAP (Escobar et al., 2018) and bio-fuels, bio-chemicals and bio-electricity through a combination of these models (Philippidis et al., 2018). However, in one

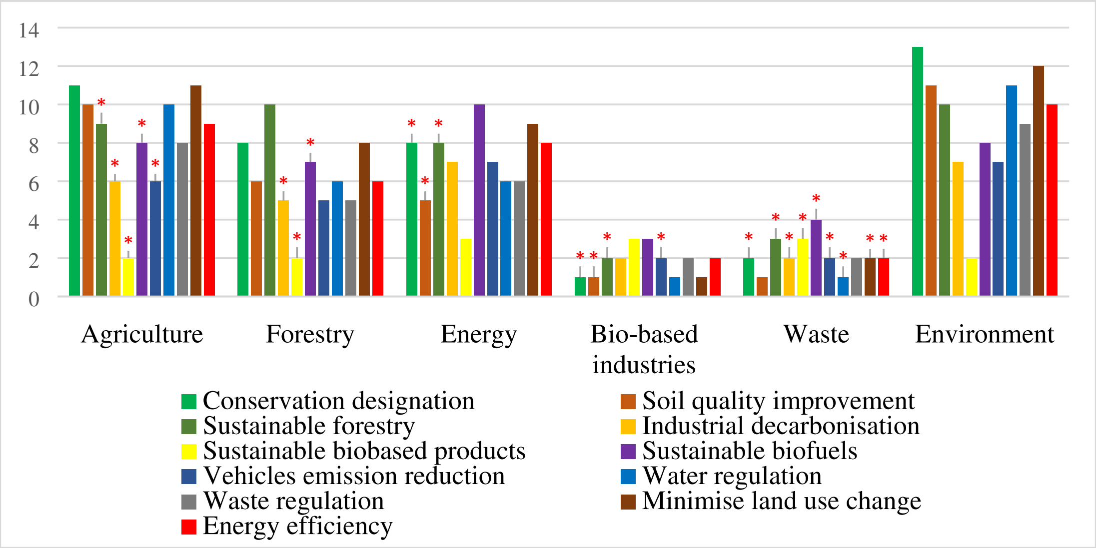

FIGURE 5 Number of models relevant to policy groups (colour coded) and their combined coverage of bioeconomy sectors. Red asterisks denote a policy area that falls outside of the scope of the sector but that can still be simulated through modelling capacities integrating both the policy area and sector. In the case of the environment area, all reviewed policies are relevant to its scope.

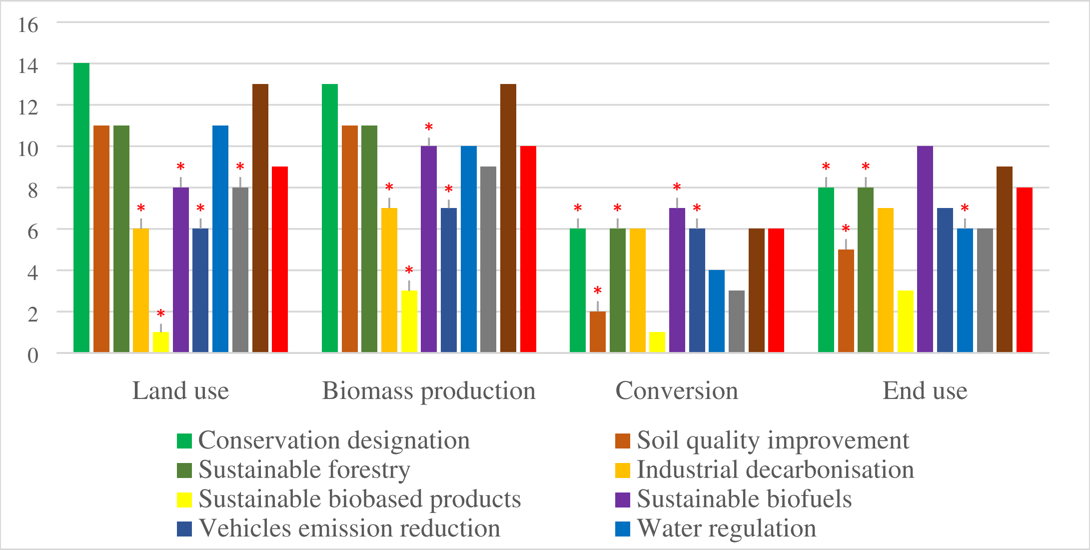

FIGURE 6 Number of models relevant to policy groups (colour coded) and their combined coverage of bioeconomy value chain stages. Red asterisks denote a policy area that falls outside of the scope of the value chain stage but that can still be simulated through modelling capacities integrating both the policy area and value chain stage.

study employing TIMES, biochemical demand and production are determined exogenously (Choi et al., 2019). Lastly, results underline the capacity of models to analyse policies within a broader context: they can simulate a policy and compare its impact on other bioeconomy sectors and value chains beyond those targeted by the policy in question.

Available bioeconomy models can integrate policies that target energy or bio-based industry with additional land, soil and forestry dynamics (Deppermann et al., 2019). Conversely, impacts of agriculture and forestry policies can be integrated with downstream stages of the value chain (conversion and end use) and the energy and bio-based industry sectors. Diaoglou et al. (2015) compare scenarios of agriculture and forestry production to determine long-term, global supply curve projections of the available residue potential for renewable energy.

3.3.2 | Knowledge produced by agriculture and bioenergy policies simulated in models

This section continues the analysis using the same framework and focusing on two policy areas—sustainable agriculture, defined here by the CAP (European Commission, 2018b), and bioenergy uptake, defined by the Renewable Energy Directive (European Union, 2018) and the 2030 Framework for Climate and Energy (European Union, 2014). The analysis informs how modelling scenario studies integrate them to inform the bioeconomy objectives. These policy areas generate the most modelling studies of all policies reviewed and are relevant for most European Bioeconomy Strategy objectives.

The literature shows that while studies can handle multiple policy areas at once, including conservation designation, land use change mitigation and bioenergy mandates (Deppermann et al., 2019; Van Vuuren et al., 2010), only a few comprise the majority of bioeconomy objectives at once (Table 5). Moreover, these usually combine and link different modelling approaches, which raises a question of technical complexity in accurately handling multiple modelling frameworks and assumptions (Böttcher et al., 2012; Popp et al., 2014). Leclère et al. (2014) combine GLOBIOM and EPIC to study the impact of land, infrastructural and labour changes in agricultural systems on climate change mitigation, and Popp et al. (2014) compound GCAM, IMAGE, REMIND and MAgPIE to evaluate direct land and economic competition of bioenergy with other energy technology options for GHG mitigation.

Among studies employing the models reviewed in this paper that incorporate sustainable agriculture policies, objective III (reducing dependence on fossil fuel sources) was explicitly addressed once (Helming & Tabeau, 2018). On the other hand, CAPRI can integrate agriculture with conservation designation (Wąs et al., 2014), IMPACT can pair it with soil quality improvements (Rosegrant et al., 2014) and CLUMondo can do so with water regulation (Malek & Verburg, 2018). Thus, circularity principles and technologies tied to bio-based processes are scarce, while the interaction between agricultural activities and natural resources is supported by modelling capacity. Although studies incorporate land use and biomass production innovations (Diaoglou et al., 2015; Rosegrant et al., 2014), they do not explicitly link these with ecosystem indicators such as soil organic matter or farmland bird index used in the Common Monitoring and Evaluation Framework of the CAP 2014–2020 (European Commission, 2015). Additionally, while some scenario projections aim to inform future agriculture policies beyond 2020 (Verburg & Overmars, 2009), none currently employ multidimensional indicators relevant to the whole bio-based value chain as outlined in the future CAP of 2021–2027 (van Doorslaer et al., 2019), such as soil carbon, renewable energy and cascading biomass.

Regarding studies analysing bioenergy uptake policies, models are well-equipped to produce cross-value chain analyses of bioenergy policies and inform on multiple objectives. EFI-GTM simulates both the cost of forest-based feedstock and the price of biofuels as critical drivers for allocating biomass between different renewable energy sources (Kallio et al., 2018). Although bioenergy uptake policies do not directly relate to the objective I (food

TABLE 5 Modelling studies incorporating agriculture and bioenergy policies and the bioeconomy objectives these target (detailed table available in Appendix H)

Policy area	Number of modelling studies incorporating policy	Bioeconomy objectives targeted	References
Sustainable agriculture [Common Agricultural Policy, European Commission (2018b)]	1	I and V	Salamon et al. (2017)
	4	I, II and V	Ehrmann (2010) Rosegrant et al. (2014) Wąs et al. (2014) Malek and Verburg (2018)
	1	I, II, IV and V	Leclère et al. (2014)
	1	I, III, IV and V	Helming and Tabeau (2018)
Bioenergy uptake [Renewable Energy Directive (European Union, 2018) and the 2030 Framework for Climate and Energy (European Union, 2014)]	3	III, IV and V	Leduc et al. (2012) Moiseyev et al. (2014) Smeets et al. (2014)
	2	I, II, III and IV	Valin et al. (2015) Deppermann et al. (2019)
	3	I, II, III and V	van Vuuren et al. (2010) Blanco et al. (2012) Diaoglou et al. (2015)
	2	I, III, IV and V	Philippidis et al. (2018) Choi et al. (2019)
	1	I, II, III, IV and V	Popp et al. (2014)

security), several models broaden the scope of such policies to integrate economic, environmental and socioeconomic trade-offs between bioenergy production and the agricultural sector (Barreiro-Hurle et al., 2021; Beckman et al., 2020; Choi et al., 2019; Deppermann et al., 2019; Diaoglou et al., 2015; Valin et al., 2015).

Although the Farm to Fork strategy was not included in this framework, a bioeconomy knowledge base can benefit from the research, industry and policy nexus around sustainable food production. The use of the CAP in this paper to assess the quality of available bioeconomy knowledge shows (a) that researchers and policymakers are confronted with the issue of complex multi-model frameworks to address the multiple dimensions of the bioeconomy and that (b) bioeconomy products and services are largely absent. Nevertheless, modelling studies have insights on how to reduce production footprints and address socioeconomic challenges (Barreiro-Hurle et al., 2021; Beckman et al., 2020; Wesseler, 2022) and can foster synergies between food and bioeconomy systems. For instance, the bioeconomy produces biochemicals that can help drive out the use of chemical pesticides (a key quantitative Farm to Fork strategy target). Equally, an effective bioeconomy would attribute value to products created from waste streams, which could address another Farm to Fork strategy target of reducing per capita food waste. Finally, advances in ecological restoration techniques in farm systems contributing to thriving biodiversity (Wesseler, 2022) can generate transferable lessons for sustainability measures within non-food crop (bioeconomy) systems.

4 | DISCUSSION

The knowledge made available by current modelling capacities integrating policy measures to inform how to implement the European Bioeconomy Strategy is assessed through an analytical framework employing bioeconomy objectives, sectors, value chain stages and indicators. Among policies themselves, economic competition and sustainability dimensions, as well as value chain stages, are often kept apart. Concerning models, cross-dimensional and cross-value chain studies do exist. However, they often demand complex multi-model research. Given the similarities in gaps between models and policies (Sections 3.1 and 3.2) and shared relevance in the targeted scope of the bioeconomy (Tables 3 and 4), a critical question arises on how both communities can help each other address these gaps.

Bio-based and waste products and processes (distinct from traditional food products) have a marginal presence within available policies and models, especially compared to bioenergy. This does not reflect the state of play within the industry (Beims et al., 2019; Markedal et al., 2017; Mohan et al., 2019), though international waste trade requires further development as a renewable source of energy (Junginger et al., 2019). Briassoulis et al. (2021) propose various modelling metrics for mechanical recyclability. Policies regulating bio-based products require more harmonized standardization at a European level and investment support (Singh et al., 2021) compared to established energy-focused legislation, metrics and resources (Mai-Moulin et al., 2017). Technological growth factors relating to the conversion stage (e.g. whether a biorefinery is at a demonstration or commercial stage), which serves as a fundamental capital asset in the production of bio-based products, are given scant attention. While broad policy frameworks such as the European Green Deal support biorefineries and technology valorization pathways, they still lack actionable policies related to conversion logistics (Singh et al., 2021). Models producing knowledge on new value chains and their market growth (Objectives III and V) more often target traditional policy areas (bioenergy, land-use, agriculture, forestry, energy efficiency) than other areas such as conservation, water and waste, bio-based industries or industrial decarbonization.

Ecosystem and biodiversity footprint indicators are scarce, especially tied to value chain operations or market productivity. Current dominant policy frameworks, such as the Renewable Energy Directive, do not include detailed guidance on tree retention, endemic species protection or specially designated land (Mai-Moulin et al., 2021). Conversely, model indicators that should reflect endogenous bioeconomy change through biodiversity, the circularity of biomass, consumer demand and technological maturation (Pyka et al., 2022) are primarily nascent (Christensen & Panoutsou, 2022). Species distribution modelling, which uses geographical space data, suffers from a lack of harmonized standards (Araújo et al., 2019). Given the widespread use of conservation designation and land use, models and policies can benefit from additional biodiversity data layering. Comprehensive biodiversity conservation plans such as the Biodiversity Strategy for 2030 and the Green Deal require better integration with socioeconomic sectors (Hermoso et al., 2022).

While there are opportunities to leverage modelling tools and generate broader knowledge on the impact of a single policy or even a package of policy measures, findings indicate there is no single, one-size-fits-all model specification addressing all five bioeconomy objectives. Bioeconomy research is witnessing the development of larger and more complex models spanning many disciplines (Allen, 2016; Pyka et al., 2022). Indeed, results indicate that studies most successfully informing multiple bioeconomy objectives are typically characterized using multiple modelling frameworks and types. As such, the model and policy collaboration process to address such complexity is in question. Partly institutional and partly technical obstacles remain that may hamper model-based intelligence on the efficiency of policies targeting the Bioeconomy Strategy. These include barriers to entry for modelling expertise and inclusive approaches in high-level cross-government reports, data availability and lags, and the relatively slow uptake of interdisciplinary modelling efforts.

High-level reports produced by cross-governmental networks and large scientific consortia routinely integrate modelling insights. For example, the OECD used IMAGE in its global Environmental Outlook study (Allen, 2016), while the JRC employs MAGNET to address multi-sustainability nexus issues (M'Barek et al., 2019). While these models and CAPRI enjoy a high degree of usage within such consortia (Thiel, 2009), barriers exist for policymakers to diversify or improve the use of modelling tools. Improving research capacity and removing institutional barriers can improve the contribution of the bioeconomy to 11 SDGs (Trigo et al., 2021). Barriers include fast-moving and high-pressure policy environments (Kolkman, 2020). Long-term relationships are needed to create coalitions for change (Cairney & Oliver, 2017), yet lead model developers often switch roles and leave gaps in expertise and knowledge (Jansson et al., 2020).

Additionally, governing bioeconomy research bodies are resource intensive (Fritsche et al., 2020). These include the Nova Institute (Piotrowski et al., 2018) and the JRC (Ronzon et al., 2017). The latter coordinates the KCB, which handles risk assessment studies for ecosystem services and biodiversity (indicators that were found to be lacking) and global and long-term sustainable biomass potential, supply and demand (European Commission, 2018a). Expert groups such as the one recently launched by the European Commission to improve global food system governance (European Commission, 2021) can be extended to or reproduced for the bioeconomy. Over 3000 employees lead the JRC research capacity with a budget of nearly 400 million EUR (Triollet et al., 2019), which underlines the challenge of smaller, more specialized modelling and policymaking to access high-level reporting. Model entry costs, such as the level of capacity training required or licence restrictions, also add to funding challenges. According to the Horizon 2020 SUPREMA project findings, creating governing legal entities (e.g. MAGNET operates with a formalized consortium agreement) and data-sharing schemes can help overcome high costs and coordination efforts associated with data updating and modelling management (Jansson et al., 2020). CAPRI and AGMEMOD models could benefit from these practices in addition to their open code access and expansive developer and market expert networks. These latter two characteristics could also benefit MAGNET and GLOBIOM.

Furthermore, funding barriers and time lags lead to data gaps. Collecting new data for new products, such as processing residues from biorefineries or manufacturing chemical products, is long and expensive (Kardung et al., 2019). Official statistics cannot keep pace with 'current' modelling needs. The continuous emergence of new technologies within bio-industrial and energy sectors fall under the radar of the minimum requirements for the approval of new products or industrial classifications in official statistical databases. One example is the case of categorizing marginal land types (Humalisto, 2015). Bio-based shares from parent NACE industry classifications are usually inferred through methodologies that add a burden of integration and peer-review consensus.

Moreover, in cases where microdata accounts are developed through statistical office questionnaires, data confidentiality issues often prevent public access. While specialist market reports provided by commercial enterprises are undoubtedly a valuable source of data, these expensive pay-per-view options remain inconsistent with the knowledge-sharing networks of modellers. Publicly funded bodies have the opportunity to address data challenges through the organization of workshops, technical assessments and bilateral consultations between modelling experts, member state representatives from national statistical offices and high-level policy groups (Böttcher et al., 2012). Initially under the auspices of the JRC and the KCB of the European Commission, a platform was launched granting public access to data sources to monitor the bioeconomy (M'Barek et al., 2014). Through partnerships with established expert groups (e.g. Nova Institute, Biomass Technology Group) and via subsequent 'in-house' data developments, this platform grants access to (inter alia): time-series datasets of bioeconomy indicators (e.g. Ronzon et al., 2020), balances of biomass flows (Gurría et al., 2017), macroeconomic member state accounts including bio-based activities and commodities (Mainar & Philippidis, 2018) and recently, a report on biochemical sectors (Spekreijse et al., 2021).

Lastly, harmonizing interdisciplinary concepts and multi-scale considerations can become a slow and iterative process (Van Delden et al., 2011). As such, dedicated, collaborative platforms exist to address that challenge. The LUISA Territorial Modelling Platform links macroeconomic and biophysical components to evaluate the territorial impact of policies effectively connecting CAPRI, CBM, GFTM and EU-TIMES (Ronzon et al., 2017). Similarly, the JRC Integrated Modelling Platform for Agroeconomic Commodity and Policy Analysis (iMAP) combines AGMEMOD, CAPRI and AGLINK to generate spatially explicit market intelligence. This effort required joint coordination between modelling teams and national market experts (Salamon et al., 2017). Additionally, the Sustainability Impact Assessment Tool combines EFISCEN, CAPRI, Dyna-CLUE and other macro-econometric models to simulate trade-offs among different sectors through 80 economic, climatic and biodiversity and biophysical indicators (Sieber et al., 2013). One study combines MAGNET with a soil erosion model (RUSLE) to measure the impact of soil erosion on the global economy owing to land productivity loss (Sartori et al., 2019). Modellers and policymakers alike should leverage such cross-cutting approaches and tools and learn by their example to pursue the realization of the bioeconomy objectives. Initiatives like The Knowledge Management for Policy under the JRC can build expertise in handling such complex methodologies by supporting training for experts combining research, policymaking, management and communication (Topp et al., 2018).

5 | CONCLUSION

This paper evaluates whether current policy and modelling capacities are adequately addressing the five objectives of the European Bioeconomy Strategy. In detail, the analysis presented here discusses how efficient the information exchange and collaboration of models and policy planning are in terms of integrating bioeconomy sectors (Kardung et al., 2021; Lier et al., 2018; Ronzon et al., 2017), value chains (Lokesh et al., 2018; Panoutsou & Singh, 2020) and indicators (Bracco et al., 2019; Kardung et al., 2021; O'Brien et al., 2017). It posits whether single, one-size-fits-all model specifications exist for these purposes and whether policies or models adequately combine biophysical with social and economic considerations. The level of policy representation currently available in modelling capacities to inform the Bioeconomy Strategy is tested across these hypotheses.

While many models and policies were found relevant to each other in terms of generating bioeconomy-relevant knowledge, significant gaps exist:

Policies tend to keep economic competitiveness and sustainability dimensions, as well as value chain stages, apart.

There are limited policy mechanisms and modelling frameworks covering both the market uptake and sustainability of bio-based products, technologies and processes (including biorefineries). Their distinction from traditional sectors (agriculture, forestry and energy) remains fuzzy.

Ecosystem and biodiversity footprint indicators are equally scarce and usually unrelated to value chain operations or market valuation.

These shortcomings are mirrored in assessments of policies under the Farm to Fork Strategy, where impacts on biodiversity and biotechnology advances are poorly understood or considered (Galanakis et al., 2022; Wesseler, 2022).

As models are not designed in an ideological silo (Kolkman, 2020), and policies that impact market functions are not created in a vacuum (Smith et al., 2021), optimizing knowledge exchange between the modelling and policymaking arenas remains a crucial way forward. Workshops facilitated by large public organizations can increase openness and transparency and build upon previous bioenergy and biofuels frameworks to target biochemical and biomaterial sectors (Junginger et al., 2019). They can also integrate traditional industries to accelerate an economic transition. Karka, Papadokonstantakis, et al. (2020) highlight the temporary but essential role that fossil fuel infrastructure plays in supporting the roll-out of advanced biofuel production facilities by reducing initial start-up risks. To ensure technological progress, traditional industries should be subject to the same stringent science-based criteria as nascent ones (Smith et al., 2021). Jander and Grundmann (2019) suggest hybrid modelling approaches that distinguish demand and resource flows between fossil- and bio-based products and sectors. Concerning socioeconomic change, policies and modelling literature lack skillset specifications for bioeconomy jobs (Clube, 2022) and social impacts of innovative technologies (Rafiaani et al., 2018), especially concerning rural areas and actors (Ronzon & M'Barek, 2018). A concerted effort is thus required to encourage the alignment of modellers and policymakers in setting clear priorities and funding goals.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.f4qrfj6zz.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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