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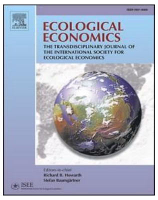

The development of bio-based industry in the European Union: A prospective integrated modelling assessment

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ABSTRACT

Quantitative bioeconomy simulation models aid our understanding of the complex market driven dynamics accompanying the transition to a net-zero economy. This research addresses knowledge gaps in EU bioeconomy modelling capacity, particularly representations of contemporary bio-based industrial markets. Encompassing a comprehensive selection of biomass types and bioeconomy activities, an integrated model toolbox is constructed consisting of five state-of-the-art bioeconomy simulation models. Focusing on a public-policy driven bio-based industrial transformation, exploratory scenarios examine the synergies and trade-offs for the EU through the prism of its five bioeconomy pillars. Results indicate that the promotion of biomass for industry reduces fossil dependence, although if enacted globally, may result in a substantial increase in biomass demand. In addition, carbon taxes further accelerate market opportunities for bio-based alternatives, although a bio-based industry transformation contingent, at least in part, on woody and agricultural biomass feedstocks, will not achieve important reductions in emissions. Finally, in addition to a strict adherence to the principle of circularity in biomass usage, a socially responsible change in consumption behaviour represents an essential strategy for easing (agricultural) biomass market tensions.

1. Background

The bioeconomy is seen as a vehicle for achieving the goals of the European Green Deal (EC, 2019) and the transition toward a net-zero economy (EC, 2023a). The European Commission (EC) Bioeconomy Strategy (EC, 2018) posits a sustainable bioeconomy for Europe, addressing the competing uses of biological resources (e.g., animals, plants, micro-organisms and derived biomass, including organic waste) and encompassing multiple sectors and policies to achieve policy coherence and synergies. Underpinning the strategy are five interlinked bioeconomy objectives, namely (i) ensuring food and nutrition security, (ii) managing natural resources sustainably, (iii) reduced dependence on non-renewable resources, (iv) mitigating and adapting to climate change, and (v) strengthening European competitiveness and creating jobs. Given the variety of bio-based activities that impact upon land-use practises, the food system, energy and materials provision for high-end uses, the challenge of developing a policy coherent framework that matches the five bioeconomy strategy objectives is immense (Singh

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et al., 2021). In addition, international strategies and initiatives (e.g., Sustainable Development Goals (United Nations, 2015); Paris Agreement (UNFCCC, 2018) that call for a socially responsible sustainable model of human development, further highlight the role and importance of the bioeconomy.

A recent EC document (EC, 2022a) on the progress in implementing the Bioeconomy Strategy, however, reports knowledge gaps, particularly on sustainable biomass needs between competing uses, as well as potential trade-offs between environmental, social and economic objectives. To address these shortcomings, further development and implementation of forward-looking bioeconomy modelling capacity is needed (EC, 2022b). Unfortunately, the fragmented and eclectic nature of bioeconomy activities described above and the lack of a consensually accepted bioeconomy definition (Tassinari et al., 2021), have led to only 'partial' bioeconomy coverage in hitherto modelling endeavours (Verkerk et al., 2021a; see Section 2).

Furthermore, a review of the relevant modelling literature (Section 2) exposes a dearth of research focused on characterising high-value industrial applications of biomass. As an initial step in this direction, the key objective is to fill this knowledge gap by employing a suite of enhanced bioeconomy models with EU and global coverage that capture both the vertical and horizontal dimensions of biomass usage (i.e., biomass supply chains across different activities and biomass competition effects between food, feed, energy and materials). A comprehensive and harmonised (across models) baseline scenario to 2030 and 2050 is constructed. With an emphasis on high value bio-based industrial applications, three foresight scenarios characterising ambitious bio-industrial driven bioeconomy futures are implemented. The key questions relate to the availability of biomass; the economic ramifications for bio-based industries and the bioeconomy at large; and the resulting environmental impacts arising from an ambitious bio-based industrial policy. The aim is to quantify these questions through the lens of the EU's five EU bioeconomy pillars.

2. Literature review of EU bioeconomy modelling

Quantitative simulation models can help to better understand complexity, trade-offs, and potential scenarios to achieve the transition to a net-zero economy (Angenendt et al., 2018). Recent reviews of existing bioeconomy modelling capacity (Verkerk et al., 2021a; Christensen et al., 2022) highlight important gaps in existing bioeconomy modelling capacities. Whilst models exist that cover certain bioeconomy activities (i.e., agriculture, forestry and bioenergy), bioeconomy modelling capacity elsewhere (e.g., textiles, leather and wearing apparel, construction, pharmaceuticals, plastics, and the chemical sector), remains relatively sparse. Furthermore, there is a limited capacity to capture the cross-cutting activities within the bioeconomy transition or provide meaningful metrics across multiple bioeconomy objectives. Consequently, the modelling literature focus is very 'localised', where many bioeconomy models do not cope well with competition effects between different (industrial and energy) areas of the bioeconomy.

In contemporary EU focused agriculture and food modelling studies (e.g., Beckman et al., 2020; Barreiro-Hurle et al., 2021), the ramifications for agricultural production systems arising from the EU's Farm to Fork (F2F) strategy (EC, 2020), is examined. Most studies limit their attention to economic performance with expectations of negative output and price effects arising from F2F mandated targets on (inter alia) fertiliser and pesticide usage, reductions in agricultural land and more widespread organic farming practises. Indeed, Barreiro-Hurle et al. (2021) observe a trade-off between worsening economic performance and improved environmental and climate performance of the agricultural sector.

Bioeconomy-related forest sector modelling has focused on structural change in traditional forest product markets (e.g., Hurmekoski et al., 2014; Chiba et al., 2017; Rougieux and Damette, 2018), as well as on the impacts of increased use of wood biomass for energy purposes (e.g., Moiseyev et al., 2014; Johnston and van Kooten, 2016). More recently, modelling efforts examine the market implications of emerging or new wood and wood-based products for applications in construction, textiles and chemicals (e.g., Jonsson et al., 2021; Kallio, 2021; UN and FAO, 2021), while other work investigates the market impacts of recent climate and biodiversity policies (e.g., Päivinen et al., 2022; Schier et al., 2022).

In bioenergy modelling research, attention has focused on the role of biomass in the transition to a low carbon economy while meeting EU policy targets (RED, REDII) and national policy objectives (Uslu et al., 2013; van Stralen et al., 2013). Other work examines the suitability, carbon neutrality, sustainability, cost efficiency and potential competition for biomass resources across energy sectors (heat, power and transport) (Panoutsou et al., 2013). More recently, with a move toward net zero emissions, modelling work has further focused on assessing bioenergy scenarios that can deliver lower carbon intensity for sectors that are 'hard-to-abate' (i.e. aviation, marine), for heavy duty road transport and sectors that process heat in highly energy intense industries (i.e. steel and cement) (e.g., Baležentis et al., 2019; Mandley et al., 2020).

EU bio-based industrial policy has gained further traction through the 'Green Deal Industrial Plan' (EC, 2023a) and the 'Transition pathway for the chemical industry' (EC, 2023). These initiatives promote green investment programmes geared toward the conceptualisation, development and commercial application of innovative bio-based technologies and public-private collaborations, within risk-free environments (Singh et al., 2021). Examples of supporting modelling studies of contemporary bio-based industry are scarce. One example is by Escobar and Britz (2021) who modify a top-down macroeconomic simulation model, with additional sector splits identifying drop-in[1] bio-based plastics and their fossil counterpart with representation of food-based feedstocks (i.e., starch, sugar, maize and cassava). They examine rising consumption of bio-based plastics (via support subsidies or fossil taxes). The authors conclude that increased extra-EU imports of biomass may lead to undesirable leakage effects, whilst indirect land use impacts may offset GHG emissions savings from the decarbonisation of EU plastics. With a focus on bio-based chemicals, two further studies (van Leeuwen et al., 2022; Sturm et al., 2023) present and discuss detailed backward-looking trends based on a dedicated EU Member State focused 'bottom-up' partial equilibrium simulation model database and accompanying model framework ('BIOMAT' – see Section 3.1), with a validatory discussion of the model's usefulness for forward-looking market research.

3. Methods

3.1. Modelling toolbox framework

To answer our research questions, a bioeconomy model toolbox (Fig. 1) is developed, consisting of five simulation models. The toolbox models employ, where possible, a consistent narrative of macroeconomic, market balance-, price-, biophysical- and energy market projections from published forecasting sources based on specialist models adjacent to the suite of models used directly in the toolbox. The direction of the arrows (Fig. 1) indicates the 'soft' links when aligning the five models to each of these external model drivers. A further discussion of these links is provided in Section A3 of the Supplementary Online Materials (SOM).

The toolbox consists of, firstly, the AGricultural MEmber state MODelling (AGMEMOD) framework, is an econometric, dynamic,

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[1] 'Drop-in' chemicals are bio-based variants of already existing petrochemicals. In contrast, 'dedicated' bio-based chemicals are uniquely bio-based products.

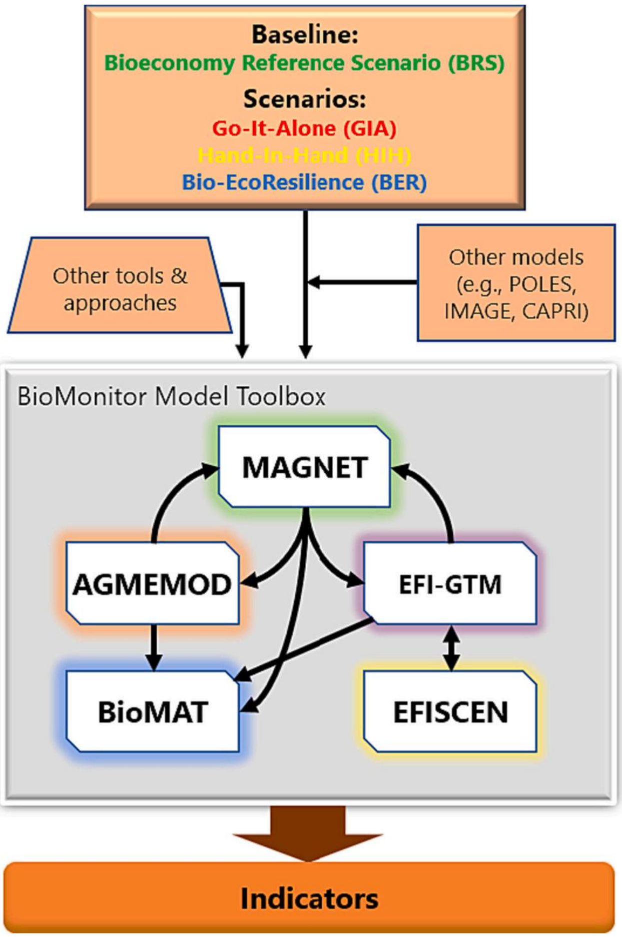

Fig. 1. Graphical overview of the Bioeconomy Model Toolbox (adapted from Verkerk et al., 2021b).

partial-equilibrium multi-country model developed for EU agricultural crop markets. Secondly, the European Forest Institute Global Trade Model (EFI-GTM) is a multi-regional and multi-periodic partial-equilibrium model of the global forest sector. Thirdly, the European Forest Information SCENario model (EFISCEN) is a large-scale forest model that projects forest resource development from regional to European scale. Fourthly, the Modular Applied GeNeral Equilibrium Tool (MAGNET) is a recursive dynamic, multi-region, macroeconomic simulation model with a focus on natural resources and multiple bio-based activities. Fifthly and finally, the Bio-based MATerials (BioMAT) model is a new bottom-up multi-regional partial-equilibrium model of bio-based product groups as well as for associated biological feedstock needs. These five models were carefully selected based on their combined coverage of the bioeconomy, covering EU member state biomass production systems (AGMEMOD and EFISCEN), as well as relevant bio-based industrial activities (BioMAT and EFI-GTM) and the bioeconomy as a whole within the broader macroeconomy (MAGNET). The toolbox and improvement made to the models is described in detail by Verkerk et al. (2021b) and a brief description of the models is given in Section A1 of the SOM.

3.2. Scenarios

An incremental system of scenarios is implemented to gain insights on possible developments in EU bioeconomy markets. Summary Table 1 summarizes the design of the scenarios, which are further discussed below. Details on the implementation of the scenarios in the models are given in Tables A1-A4 in Section A2 of the SOM.

Table 1
Overview of the incremental scenario design from 2020 to 2050. For details on the implementation of the scenarios in the models see Tables A1-A5 of the SOM.

Scenario:	Descriptor:
Bioeconomy Reference Scenario (BRS)	Maintenance of 'Business-as-usual' trends for biomass usage and consumer attitudes.
'Go-It-Alone' (GIA): EU enacts measures to upscale biomass for bio-industry and promotes food biomass conservation behaviour.	**BRS PLUS:** (i) Bio-industrial policy driver: Public support measures to drive upscaling of biomass use in bio-based industries. (ii) Bio-industrial technology driver: Additional input-saving technology changes in upscaled bio-based industrial sectors. (iii) Biomass availability driver: Assumes rises in woody biomass availability owing to measures aiming to enhance forest productivity and wood mobilisation. (iv) Consumer engagement driver: Halving of household food waste by 50% by 2030 vs 2020 levels.
Hand-in-Hand (HIH): Global co-operation toward bio-industrial driven growth and food biomass conservation behaviour.	**GIA PLUS:** Policy, Technology, Biomass availability and Societal engagement drivers in GIA applied world-wide.
Bio-EcoResilience (BER): Greener world order policies consistent with the 'two degree' target.	**HIH PLUS:** Rising carbon taxes aiming for GHG emissions reductions consistent with a "two-degree scenario". Eliminate conventional bioethanol and biodiesel support Doubling (vs. BRS) of advanced (cellulosic feedstock) generation liquid biofuel mandates by 2050.

Firstly, a Bioeconomy Reference Scenario (BRS) characterises a continuity of existing trends and social attitudes in the absence of any drastic course change by society. The thirty-year time horizon beginning in 2020 reflects the policy arena in the EU in which 2030 and 2050 serve as points of reference. As a consistent and official European source for economic, population, climate and energy market outlooks for the EU and the world, the BRS is based on the Global Energy and Climate Outlook (GECO) 'reference scenario' (Keramidas et al., 2021). More specifically, the BRS borrows projections for real GDP, population, fossil price changes, energy market transformations and carbon taxes. The GECO reference scenario embeds some degree of energy market decarbonisation driven by the dynamics of market forces (i.e., depletion of fossil resources) and anticipated technology change, whilst no additional climate agreements beyond 2017, nor investment strategies that promote a more responsible and sustainable model of growth, are included. The BRS is further enriched with specific assumptions (targeted agricultural policy support payments, agricultural production outlook trends, crop yield assumptions, potential woody biomass availability, conventional and advanced biofuels projections etc.) from additional secondary data sources. As indicated in Fig. 1, inter model links are employed to harmonise the BRS driver assumptions (see Section A3 of the SOM document for more details).

Departing from the BRS, three alternate bioeconomy scenarios are implemented that concern the updated Bioeconomy Strategy. The EU policy push toward the implementation of the 'cascading principle' (Fritsche and Iriarte, 2014) of biomass requires that high value-added material applications be prioritised, before being recycled or burnt for fuel. As a result, to unlock the bioeconomy's potential, the focus here is on the active mobilisation and upscaling of biomass for bio-industrial led growth. Under the auspices of the EU's Green Deal, the switch to publicly driven green investments is deemed as a 'win-win' for establishing low-carbon sustainable growth. Moreover, as identified in the updated Bioeconomy Strategy (EC, 2019), the successful commercialisation and upscaling of (nascent) bio-industrial uses of biomass hinges on "*research and innovation and the deployment of innovative solutions*" (pp6, EC, 2019). On the demand side for biomass markets, to relieve (food) biomass market tensions, the EU's Farm to Fork strategy envisages the socially responsible halving of household food waste by 2030, consistent with Target 12.3 of the SDGs.

To enumerate these concepts within the models, they are mapped to the specific settings of four key model drivers (see Table 1). Thus, changes are implemented for (i) an accelerated upscaling of biomass and biotechnology in bio-based industries (construction, textiles, packaging materials and chemicals); (ii) medium-term incremental input-saving technological improvements in bio-based industries resulting from policy driven upscaling; (iii) improvements in conversion technologies increasing harvestable sustainable potentials for woody and cellulosic biomass; and (iv) sustainable food consumption behaviour, characterised by the halving of household food waste by 2030.

Compared with the BRS, by 2050, 'Go-It-Alone' (GIA) envisages sustained proactive biomass mobilisation and use in the EU in construction (following Churkina et al., 2020), wood-based textiles (tripled EU demand) and packaging materials (tripled EU demand), that are implemented and harmonised in EFI-GTM and Magnet.[2] Public driven investments are translated into input-saving productivity gains in EU upscaled bio-based industries based on the parameterisation of a rate-of-return estimate.[3] The halving of EU household food waste is modelled employing taste shifters. According to Eurostat, EU27 household food waste in 2020 was approximately 31 million tonnes, which when paired with estimates of food consumption in 2019 (De Laurentiis et al., 2021), corresponds to approximately 6.5% of household food consumption. Woody biomass availability is assumed to increase as a result of research and development efforts in enhancing forest productivity and improved mobilisation (Verkerk et al., 2018).

The 'Hand-in-Hand' (HIH) scenario builds on the GIA scenario by extending the four GIA model driver settings for the EU to the whole world (see Table 1). Global initiatives to halve household food waste are expected to relieve agricultural market tensions, particularly through the reduced impact on indirect land usage. The upscaling of the industrial use of biomass world-wide, will intensify global market pressure, particularly for non-food biomass provision (e.g., wood, lignocellulosic crops).

The 'Bio-EcoResilience' (BER) scenario explores the resilience of, and opportunities afforded to, the EU bioeconomy resulting from a greener global world order, consistent with the two-degree scenario of Keramidas et al. (2021). The scenario employs the same driver settings as HIH, but also explores a more stringent climate-policy and a sustainable policy reform in global bioenergy markets. Thus, the modelling includes higher carbon taxes to achieve the global GHG emission reductions consistent with a 'two-degree' scenario,[4] based on projections from Keramidas et al. (2021). Moreover, to free up biomass for higher value-added (industrial) uses, and following from the proposals of the EU's Renewable Energy Directive III (RED III),[5] all global public support for conventional liquid biofuels is removed and a doubling of the mandates for advanced liquid biofuels compared with the BRS in 2050, is assumed.

4. Results

As noted above, a key strength of the bioeconomy modelling toolbox is the ability to represent the intricate dynamics of the bioeconomy from biomass provision to competing uses. To provide insights on the synergies and trade-offs that arise under different explorative scenarios, the results are presented through the prism of the five bioeconomy strategy objectives, as described in the introduction (EC, 2019) and using the indicator framework developed by Kardung et al. (2021).

4.1. *Ensuring food and nutrition security*

4.1.1. *Agricultural crop prices*

The BRS price trend (Fig. 2 – green line) for EU agri-food commodities reflects assumed drivers from GECO and the DG-Agriculture and Rural Development (EC, 2022c) outlook.[6] In the remaining three scenarios, the shape of the curve remains broadly unchanged, due to the prevailing assumed market conditions of the BRS. Notwithstanding, the halving of household food waste in the EU (GIA) and world-wide (HIH) reduces crop market price tensions, despite the simultaneous presence of industrial biomass promoting policies in the EU (GIA) and world-wide (HIH). Finally, in BER, the average agricultural crop price falls even further than HIH due to the additional removal of world-wide public support for conventional biofuels, leading to further oilseed and cereal price falls.

4.1.2. *Crop production*

EU crop production in cereals and oilseeds is expected to rise (Fig. 3) as yield increases more than compensate declines in cultivated areas. Agricultural land use in the alternative scenarios compared to BRS remains quite rigid and consequently crop production patterns follow similar steady trends. Meanwhile, falling crop demand due to the halving of food waste benefits EU self-sufficiency in GIA and HIH, when compared with the BRS (not shown), with cereals self-sufficiency rising from 1.25 in the BRS, to 1.30 in GIA and HIH. In BER, a similar trend is observed, although with the additional phasing out of 14 million tonnes of dry matter (dm) for first-generation liquid energy biomass, EU cereals self-sufficiency increases to 1.34.

4.2. *Managing natural resources sustainably*

4.2.1. *Agricultural land use*

In the EU, the BRS reveals an estimated 93.2 million hectares (mha) of agricultural cropland and 70.1 mha of pastureland in 2020 (Fig. 4, left hand column). With assumed moderate declines in the EU population, slow per capita rises in food demand for nutrients and (exogenously) projected increases in land productivity, utilised agricultural land (i.e., cropland and pastureland) declines from 163.3 mha in 2020 to 161.0 mha in 2050. Driven by fossil price rises and rising carbon taxes, dedicated energy crop land rises marginally from 0.12 mha in 2020 to 0.13 mha by 2050 (not shown).

Compared with the BRS in 2050, the EU household food waste reduction in GIA generates an additional EU agricultural land saving of 0.53% (0.86 mha). HIH also exhibits a (albeit smaller) relative agricultural land saving effect (0.41%; or 0.66 mha), reflecting the opposing forces of world-wide household food waste reductions (land saving) and world-wide promotion of biomass for bio-based industrial applications (land demanding).

In BER, the EU's relative agricultural land saving effect (0.22% or 0.36 mha) is less than in HIH. Despite reduced land market stress arising from the abolition of conventional biofuels support, the supply of biofuel

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[2] Further discussion on the modelling of these four drivers is given in section A2 of the SOM.

[3] The assumptions and modelling of upscaled bio-industrial technology change is described in section A2 of the SOM.

[4] A scenario which limits temperature rises to 2 degrees above pre-industrial levels by 2100.

[5] The RED III envisages only until 2030 a liquid biofuel target, with advanced biofuels shares strongly increased. However, the development of biofuels related policies after 2030 is not further defined.

[6] Given the medium to long-run character of the simulation, the BRS does not include the (unpredictable) impacts of the Ukraine conflict, nor does it consider unforeseen extreme weather events or disease outbreaks.

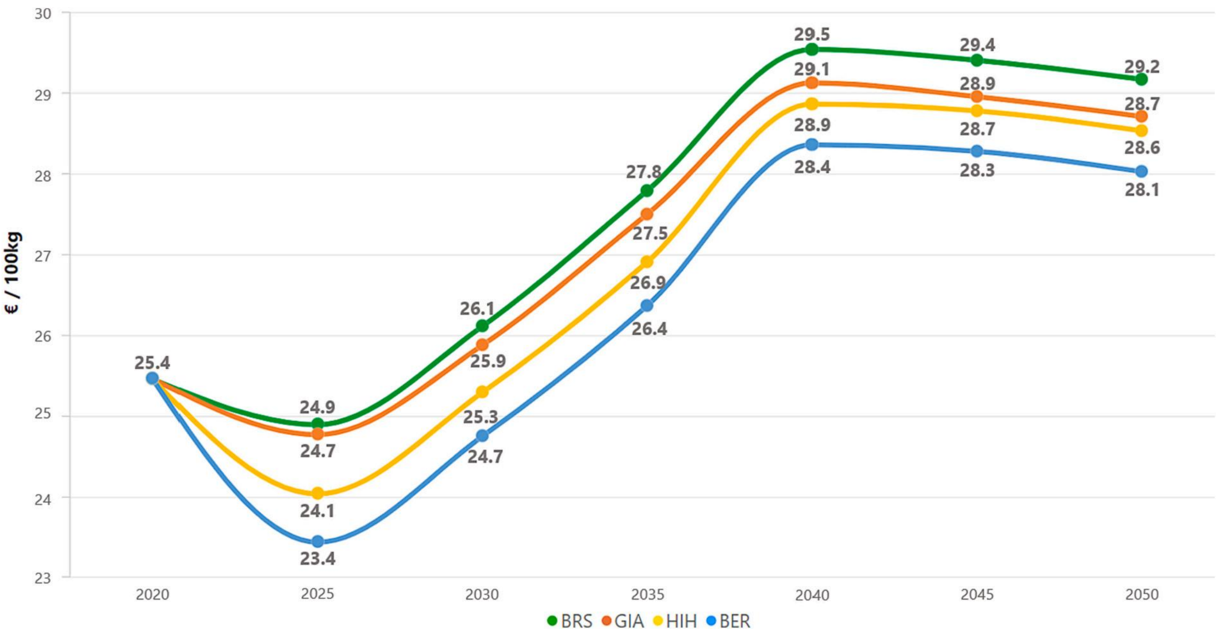

Fig. 2. Development of EU agricultural crop prices by scenarios from 2020 to 2050.

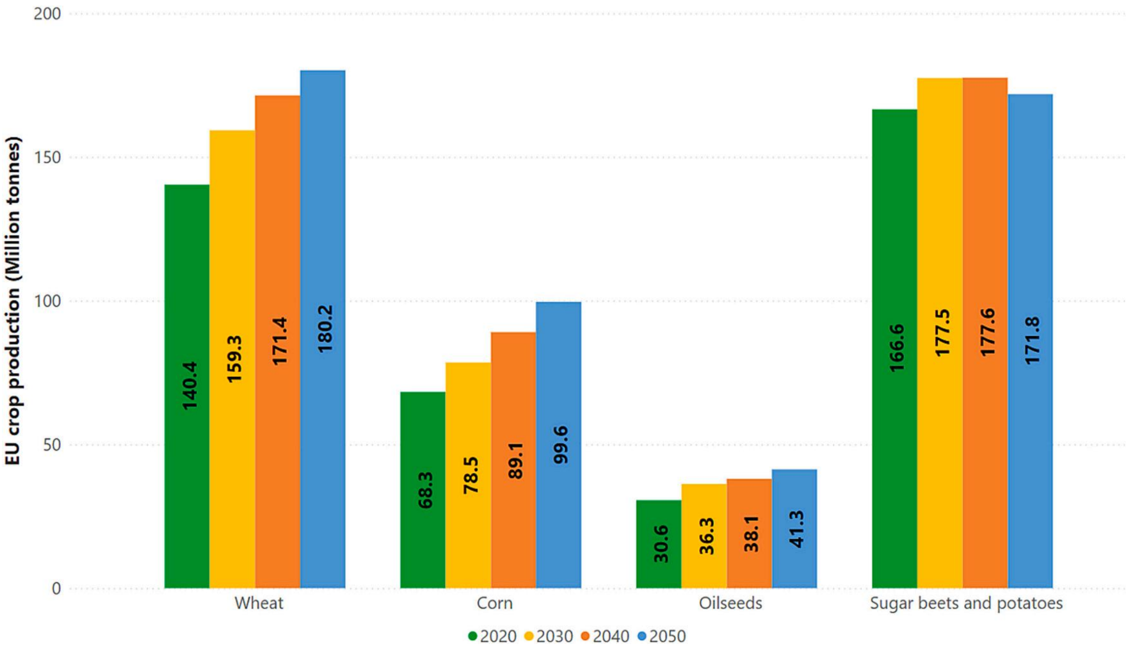

Fig. 3. BRS EU crop production trends from 2020 to 2050.

by-product animal feeds is greatly reduced, with the result that pastureland demand rises compared with the BRS. This result is not surprising given the significant allocation of agricultural biomass to feed uses (see Section 4.3.1). In BER, to support the shift toward non-food feedstock in advanced generation liquid biofuels and solid biofuels, by 2050 dedicated EU energy crop land demand rises to 0.141 million hectares (vs 0.132 mha in BRS) (not shown).

4.2.2. *Roundwood production from forests*

In the BRS, roundwood production is estimated to decrease by 3% between 2020 and 2050 (Fig. 5), due to a moderate fall in the potential availability of wood from EU forests (−5% between 2020 and 2050, not shown). In contrast, due to assumed measures that enhance production and improve supply in the GIA, HIH and BER scenarios (see Table A1 in the SOM document), the potential availability of wood from forests is estimated to increase by 10% between 2020 and 2050 (Verkerk et al., 2018). Driven by increased demand for wood products, by 2050, roundwood production is estimated to increase by 7%, 12% and 14% in GIA, HIH and BER, respectively, compared to the BRS.

A key indicator for the sustainable management of forests is the ratio between fellings and increment (forest utilisation rate) on forest available for wood supply. In BRS and GIA, the FUR (Fig. 6) decreases slightly from 84% in 2020 to 83% in 2050. The utilisation rate increases to 87% and 89% by 2050 in the HIH and BER scenarios, respectively. In all three alternative scenarios, the increment rates are estimated to slightly increase (not shown) as a result of improved tree breeding material during forest regeneration. However, felling levels increase, which explains why the rate remains the same in the GIA scenario, whilst increasing in

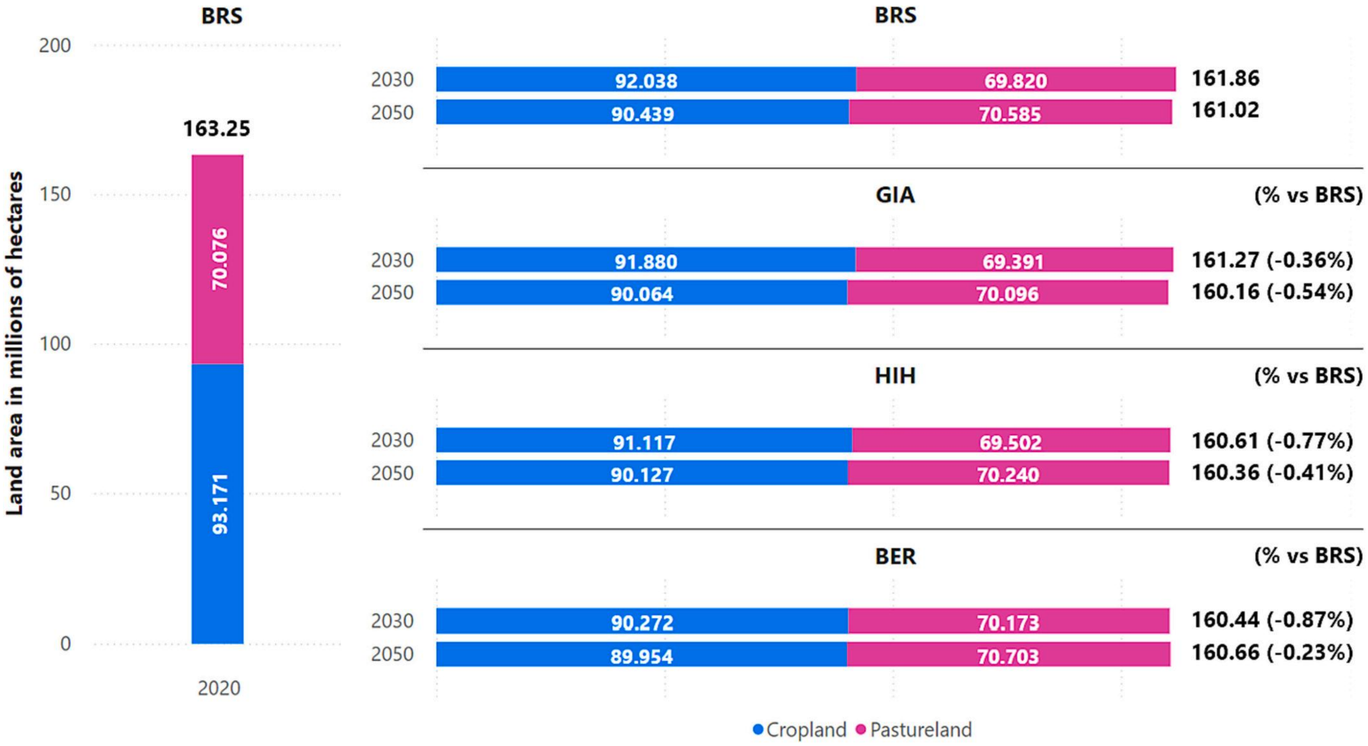

Fig. 4. Agricultural land use trends by scenarios from 2020 to 2050.

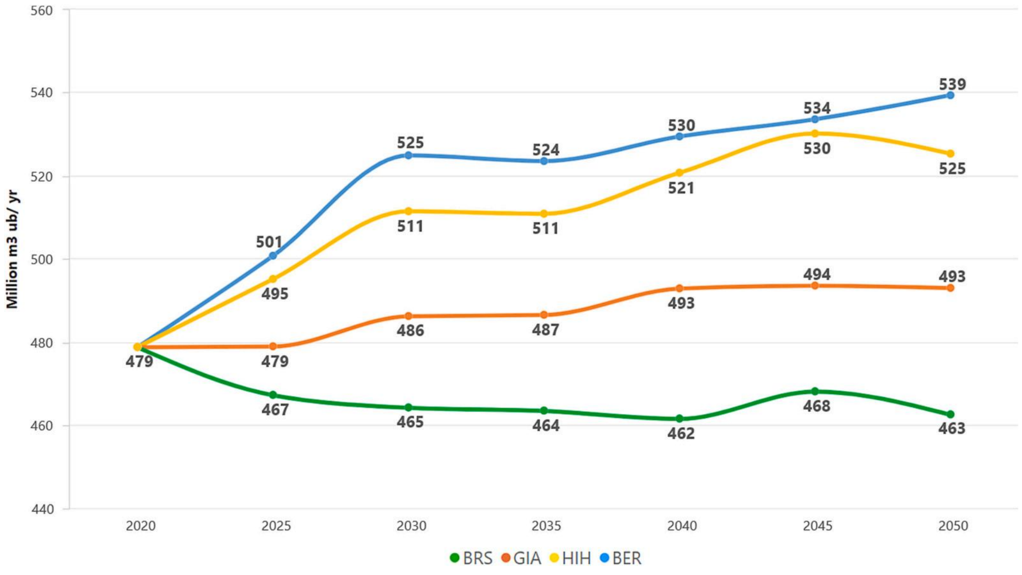

Fig. 5. Development of EU27 roundwood production by scenario from 2020 to 2050. Results are given as averages for 5-year timesteps.

HIH and BER. Overall, ambitious targets for biomass usage in industry will likely entail an intensification of forest management. If such targets are restricted to the EU, results indicate that the impacts on EU forests may be limited when combined with improved management practices. If this development were to happen globally, however, or in combination with increased biomass demands for bioenergy, the impacts could represent a substantial intensification.

4.3. Reducing dependence on non-renewable unsustainable resources

4.3.1. Use of agricultural biomass

Over the thirty-year period from 2020, the total available EU agricultural crop biomass measured in million tonnes of dry matter (dm), increases by 12% in the BRS (Fig. 7). Almost half (48%) is dedicated to feed across all time periods. The share going to food declines slightly from 24% (2020) to 21% (2050), with a concurrent rise in the share used for materials and energy – rising from 28% (2020) to 29% (2050). Comparing with BRS, by 2050, food and feed uses decline by close to eight million tonnes due to the halving of household food waste. On top of this, policies implemented in BER aim to use resources more efficiently by substituting first-generation biomass in the energy market (including fuels) with agricultural residues/by-products. Compared with BRS in 2050, this combination of policies frees up approximately 19 million dm tonnes of crop biomass.

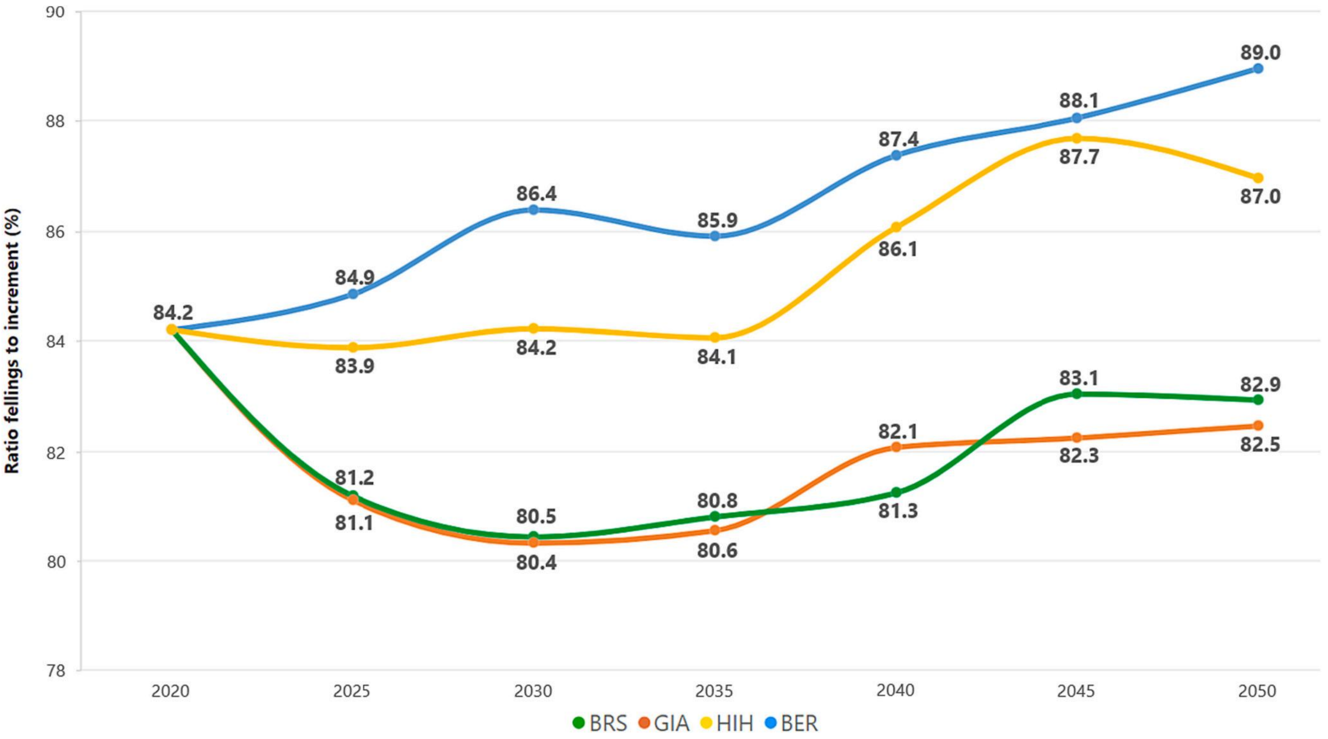

Fig. 6. Forest utilisation rates by scenario from 2020 to 2050. Results are given as 5-year timestep averages.

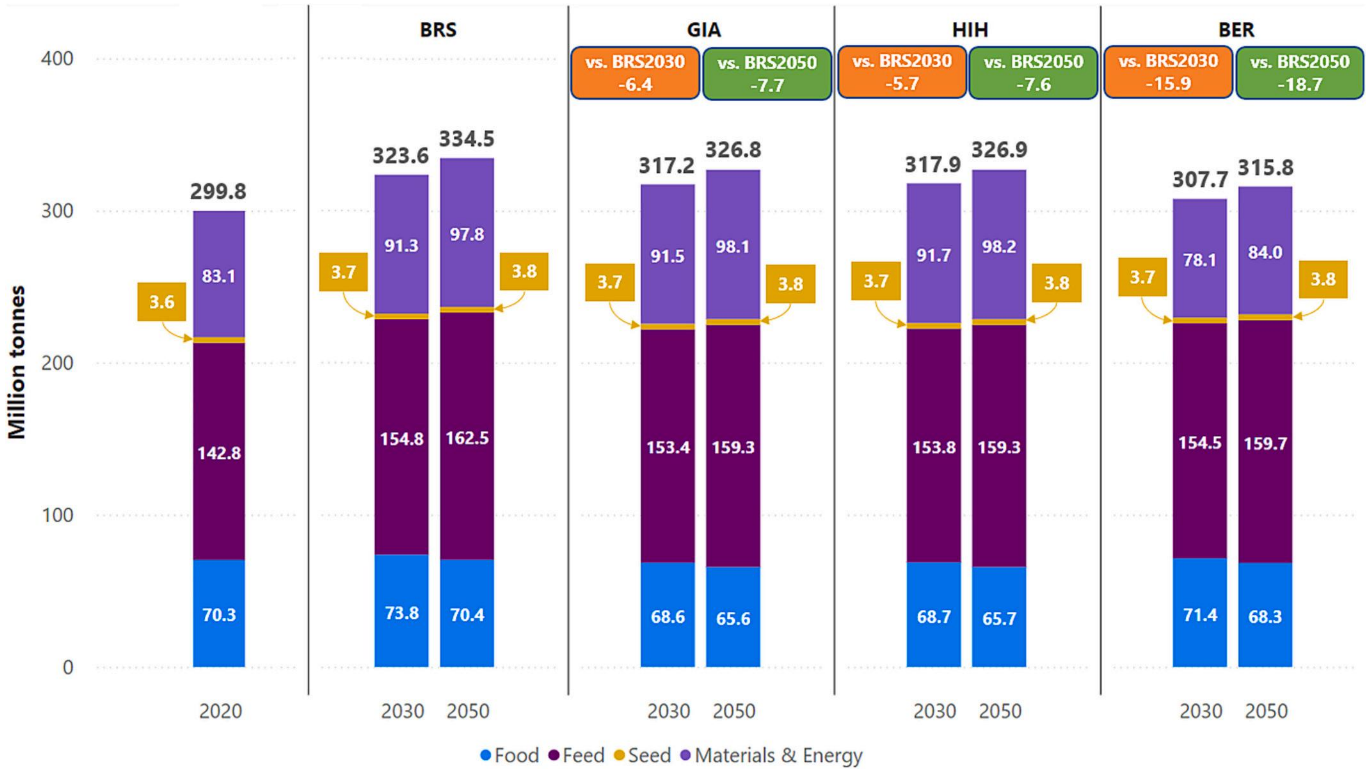

Fig. 7. Uses of agricultural biomass by scenarios from 2020 to 2050.

4.3.2. *Wood-based product market trends*

Fig. 8 shows the development of wood and wood fibre availability from the forest industry for materials in the EU region in the BRS and alternative scenarios. In the BRS, EU annual industrial roundwood production remains stable at approximately 380 million m^3 between 2020 and 2050, whilst a 7% rise in recycled paper and a doubling in sawmilling wood residues by 2050, is expected. As a result, in the BRS, there is an 8.6% increase in available wood and recycled paper biomass for materials. Compared to the BRS, the alternative scenarios exhibit higher growth, where by 2050, EU wood and recycled paper biomass

Fig. 8. EU27 woody biomass availability for materials - Roundwood equivalent (RWE).

growth is higher by 6.1% (GIA), 10.5% (HIH) and 8.0% (BER). Indeed, in HIH, rising worldwide requirements for (woody) biomass, lead to an almost tripling of EU sawmilling residues (from 42.3 to 114.1 million m^3/yr) over the thirty-year period. The growth in EU woody biomass and recycled paper growth for materials in BER is slightly below that of HIH due to higher competition with woody biomass for energy (not shown).

The apportioning of available woody biomass for materials between mechanical- (i.e., sawn-wood and wood-based panels) and chemical- (paper and paperboards, man-made cellulosic fibers (MMCF), chemical and dissolving pulp) forest related industries is shown in Fig. 9. In the BRS, from 2020 to 2050, production rises by 7.0% from 606 million m^3/yr to 649 million m^3/yr, with rises in both mechanical and chemical forestry industry production. With strong projected growth in EU internal demand (not shown), particularly for mechanical forestry products, by 2050 the EU net trade balance (i.e., internal production less demand) in the BRS deteriorates from 100 million m^3/yr in 2020, to 88 million m^3/yr in 2050.

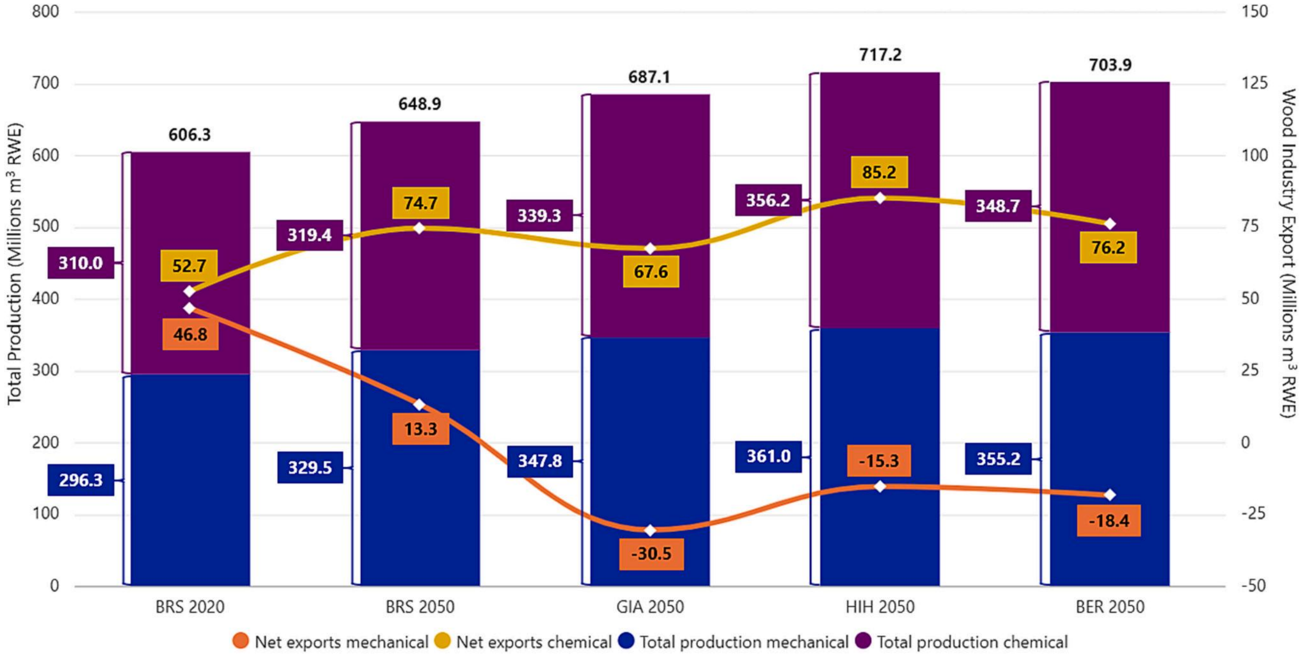

Fig. 9. EU mechanical and chemical wood industry production and net exports in Roundwood Equivalent (RWE).

In GIA, HIH and BER, strong demand for mechanical material products (i.e., rising sawn-wood demand for construction (based on Churkina et al., 2020) and from chemical material products (i.e., 10% of plastic packaging substituted by paper packaging; from a small base, a tripling in the share of MMCF in textiles) drives up EU27 internal production in both categories. Compared with the BRS, total forest-based industry production for GIA, HIH and BER rises to 687 million m^3/yr, 717 million m^3/yr and 704 million m^3/yr, respectively. By 2050, the net EU trade balance for mechanical forestry products becomes negative (i. e., rising import leakage) especially in GIA, and to a lesser extent in HIH and BER, which drives the reduction of the EU net forestry industry trade surplus.

4.3.3. EU27 bio-based chemicals

Fig. 10 provides an overview of the BRS market developments (production, domestic use and net trade) for bio-based chemicals driven by steady rises in total (bio- plus fossil) chemical production due to assumed economic growth and demographic projections. The bio-based share of chemical production increases due to the technologically driven declining wedge in production costs and consumer price ratios in bio-based products (vis-à-vis fossil substitutes).

In the spirit of GIA, HIH and BER, the implemented green premium,[7] which reflects the additional price consumers pay for bio-based products versus conventional products, further drives down the cost disadvantage ratio of bio-based goods versus their fossil equivalents. Thus, by 2050 compared with the BRS, EU27 bio-based chemical production increases 8.7 million tonnes (11.1%), 8.8 million tonnes (11.2%) and 9.7 million tonnes (12.4%) in GIA, HIH and BER, respectively (not shown).

In the absence of any consumer price incentives for bio-based products in GIA and HIH, final demand for bio-based chemicals rises only slightly (0.5 million tonnes), although with the increase in production noted above, by 2050 the net-trade balance of bio-based chemicals in both scenarios improves 8.2 and 8.3 million tonnes (39%) in GIA and HIH, respectively (not shown). In BER, bio-based chemicals become more price competitive with additional fossil fuel price and carbon tax increases. By 2050, this stimulates an additional internal demand of 9 million tonnes compared with the BRS (not shown).

A reduced dependence on fossil inputs is also exhibited by examining the bio-based share of chemicals (not shown), indicating a more rapid relative growth of bio-based (vs fossil based) chemicals. In the BRS, the 2020 bio-based share is 16%, increasing to 19% by 2050. In GIA and HIH the bio-based share of chemicals rises to 21% by 2050 (+37% compared to 2020), whilst the assumed rises in fossil prices in BER, push this corresponding share slightly up to 22% (+39% compared to 2020).

4.4. Mitigating and adapting to climate change

4.4.1. Greenhouse gas emissions and removals

The BRS reveals a moderate declining trend in net EU GHG emissions from 3232 $MtCO_2e$ in 2020 to 2390 MtCO2e by 2050. This is mostly due to the assumed degree of energy market decarbonisation in the BRS. Primary agricultural emissions are dominated by non-CO_2 emissions, whilst services (which includes sewerage collection and treatment) and waste (which includes collection of green, glass, plastic and other waste, their incineration, landfilling and recycling) are estimated to generate significant methane emissions.

Comparing with the BRS (Fig. 11), total emissions in GIA and HIH change very little. The halving of food waste reduces agricultural and food emissions, although under the assumption of fixed savings rates, EU consumers purchase more non-food products, which (ceteris paribus) promote higher direct energy emissions by households as well as rising non-food activity driven emissions. The effect of rising emissions is, however, partly counterbalanced by reduced fossil inputs into industrial processes through bio-based substitution, particularly in bio-based chemicals (see also Section 4.3.3).

In GIA, by 2050 the forest sink is estimated to develop similarly as for the BRS due to relatively stable harvest levels (see Fig. 5) and assumed measures to enhance forest productivity. In HIH and BER, however, the sink declines faster than BRS due to rising roundwood demand and production. Indeed, in HIH and BER, the sink is estimated to decline by 13% and 21%, respectively, compared to the development in the BRS. For total emissions in BER, higher carbon taxes reduce the intensity of emissions in energy and process activities, whilst an accompanying contraction in EU macroeconomic activity (see Section 4.5.1) further curtails EU emissions.

4.4.2. Final demand driven emissions footprints

Fig. 12 shows EU food, bioenergy and bio-based industrial product final demand driven emissions footprints (i.e., per capita). The footprints represent embedded emissions along the supply chains for said biobased product classifications, measured in kgCO2e per capita per year (kgCO2e/pc/year). Under the assumption of cleaner energy markets, as assumed in BRS, emissions footprint intensity declines in final purchases of biobased food and bio-industrial goods.

In GIA and HIH, the halving of EU and global household food waste further reduces emissions footprints. On final food purchases, by 2050 the emissions footprint (Fig. 13) falls 91 and 101 kgCO2e/pc/year, respectively, compared with the BRS. For bio-based industry and energy footprints, slightly rises reflect greater embedded quantities of upstream feedstock related emissions due to the promotion of biomass and biotechnology uptake. In BER, policy induced reductions in EU emissions reduce the emissions footprints compared with the BRS. For example, EU food consumer emissions footprints witness sliding reductions of 153 and 641 kgCO2e/pc/year compared with the BRS in 2030 and 2050, respectively.

4.5. Strengthening European competitiveness and creating jobs

4.5.1. EU GDP and bioeconomy production trends

Comparing with the BRS, the EU macroeconomic impact from GIA and HIH, is negligible. In BER, however, additional climate policy reduces relative EU real GDP by −1.729% by 2050 (not shown). Fig. 14 reveals the BRS production trends for 2030 and 2050 compared to 2020. The headline figure is that the EU bioeconomy grows by 29%. This is due to the sluggish growth of the agri-food sector, whilst forest sector production remains relatively stable. Despite a stagnation in conventional liquid biofuels, total (i.e., solid plus liquid) bio-energy production rises 40% and bio-based industrial growth rises 31% over the thirty-year period. In both cases, higher than average bioeconomy growth performance is stimulated by the additional drivers of rising fossil fuel prices and carbon taxes on higher emitting activities.

Comparing with the BRS in 2030 and 2050, EU bioeconomy production is expected to grow less quickly in all three alternative scenarios. This is largely motivated by the halving of household food waste, which reduces demand for agri-food supply.[8] Concurrently, increased public support for biomass and biotechnology promotes not only bio-based industry, but also the upstream forestry sector. In HIH, due to the global push toward bio-based industry support, there is even greater reliance on woody biomass from EU forests (see also Fig. 5). In BER, the

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[7] There is evidence (Morone et al., 2021), that supports consumer proclivities toward a higher willingness to pay for bio-based products.

[8] In the case of food services, it is assumed that restaurants and bars do not adjust the size of portions served to consumers. Thus, with household nutritive needs served by the subsequent home consumption of restaurant ‘leftovers bags’ (“doggie bags”) and the general reduction in wasted calories, there are fewer ‘eat-out’ visits by consumers, on average. This is, of course, a stylised and sustainably responsible representation of consumer behaviour.

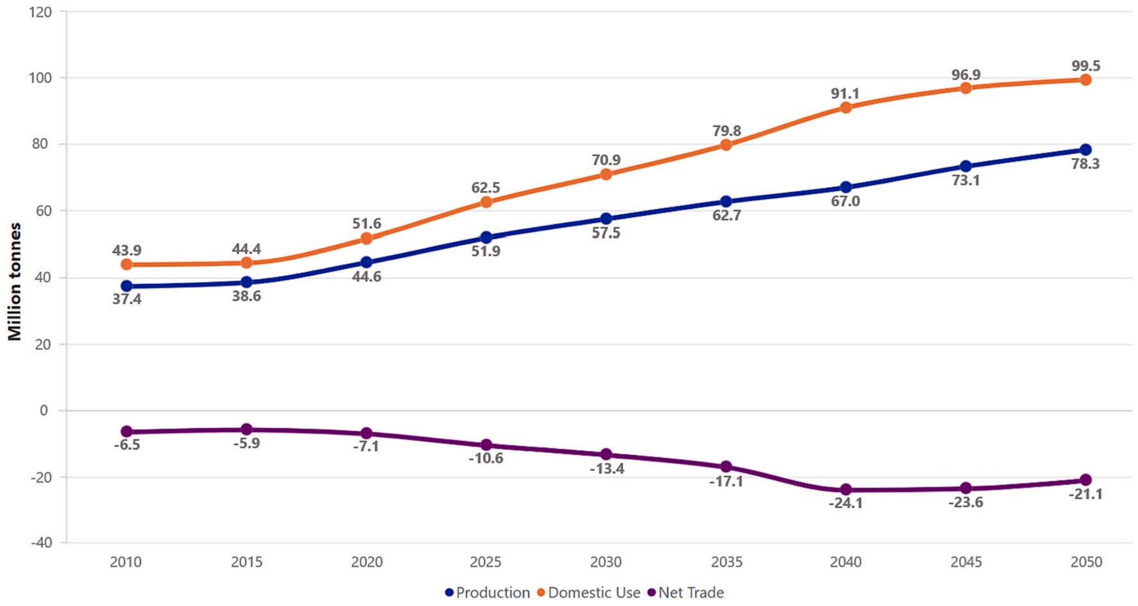


Fig. 10. BRS EU bio-based chemicals market from 2020 to 2050.

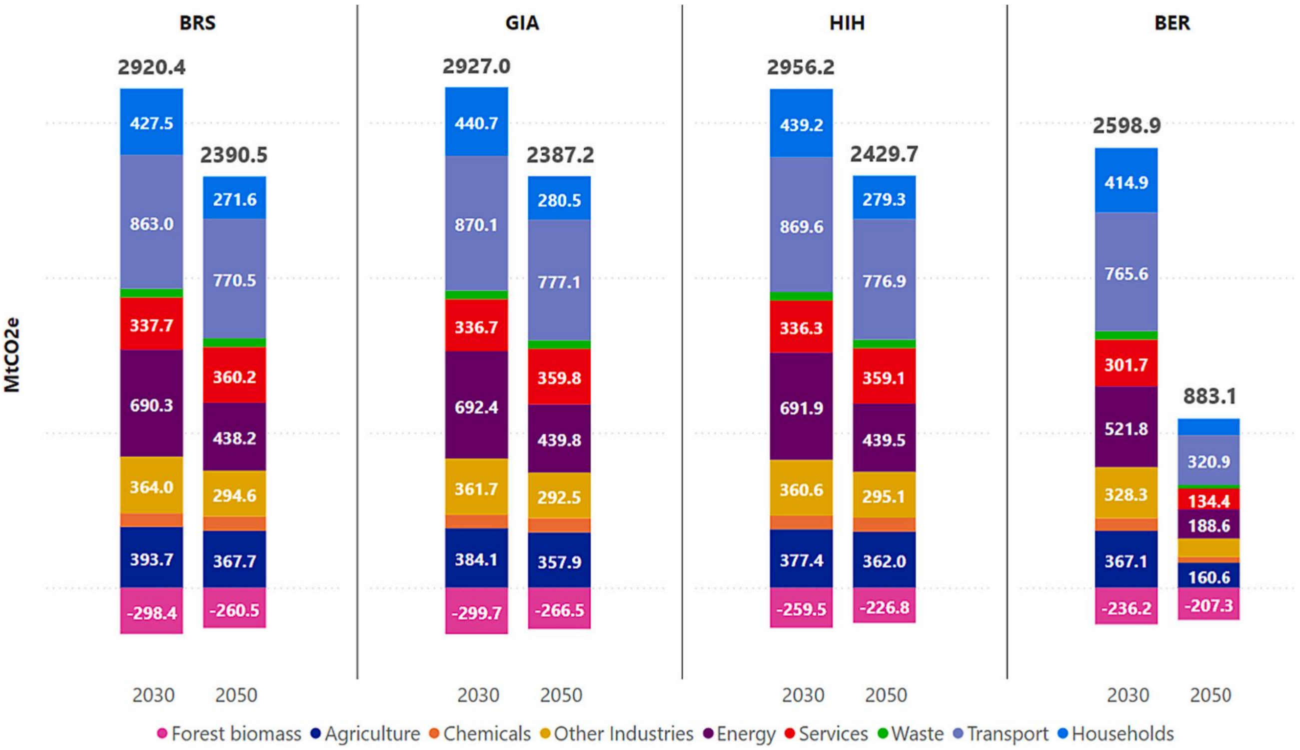


Fig. 11. Direct GHG emissions and removals by scenarios in 2030 and 2050 ($MtCO_2e$ / yr).

relative contraction in bioeconomy output is stronger than in GIS and HIH, partly due to the macroeconomic contraction, but also owing to the withdrawal of support for conventional biofuels.

4.5.2. *Employment*

In the BRS EU primary agricultural employment falls from 7.097 million persons in 2020 (not shown) to 4.876 million by 2050 (Fig. 15). This is largely due to rising (labour saving) productivity and sluggish rises in demand (static per capita food demand). In the collective of EU bio-based industry (textiles, wood, paper/packaging and chemicals), employment is estimated at 3.115 million in 2020 (not shown), which declines to 2.832 million by 2050 (Fig. 15). Given the trends in the 'large' bioeconomy sectors (agriculture, food and bio-based industry), there is a fall in EU bioeconomy employment from 21.518 million in 2020 (not shown), to 18.399 million in 2050 (Fig. 15).

Comparing with the BRS, EU bioeconomy employment trends follow those for output (Section 4.5.1). By 2050, total EU bioeconomy employment falls by 0.931 million jobs, 0.947 million jobs and 0.941 million jobs, in GIA, HIH and BER, respectively. In contrast, a steady promotion of biomass and biotechnology uptake improves relative employment prospects for bio-based industry in all scenarios compared with the BRS.

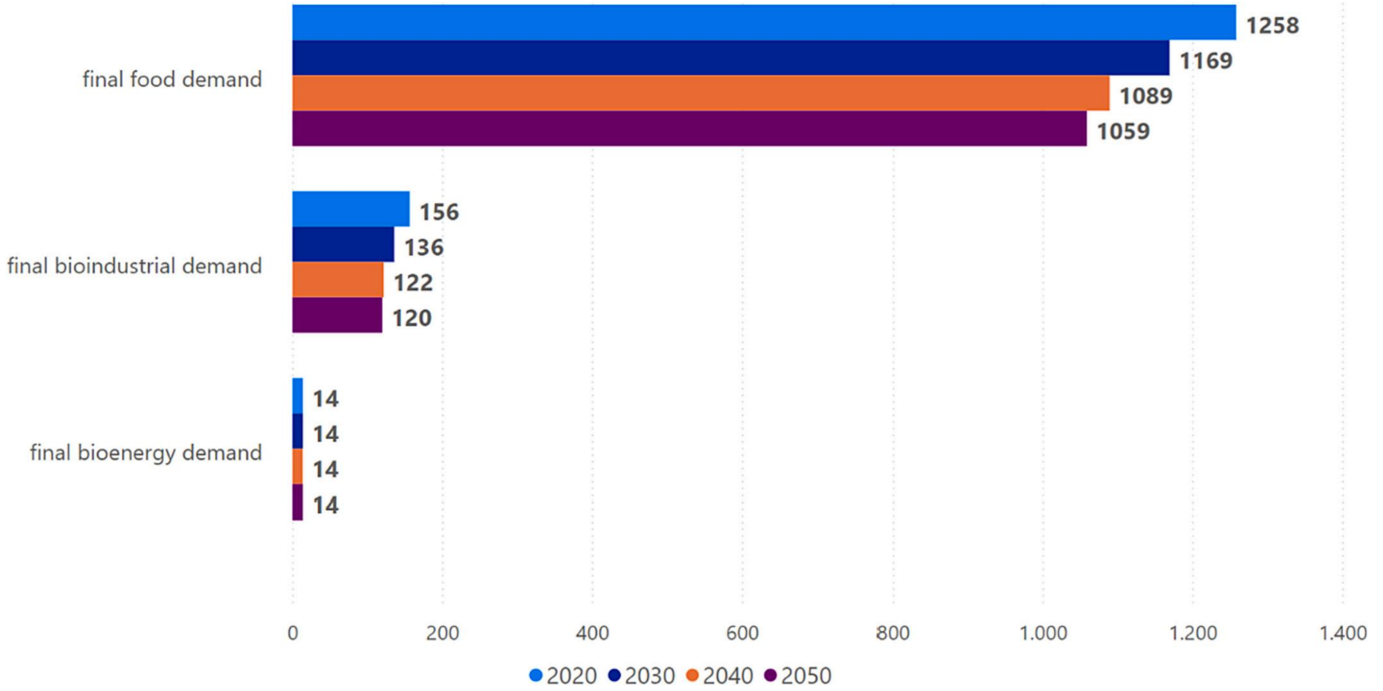


Fig. 12. BRS final demand driven emissions footprints (KgCO2e/pc/year).

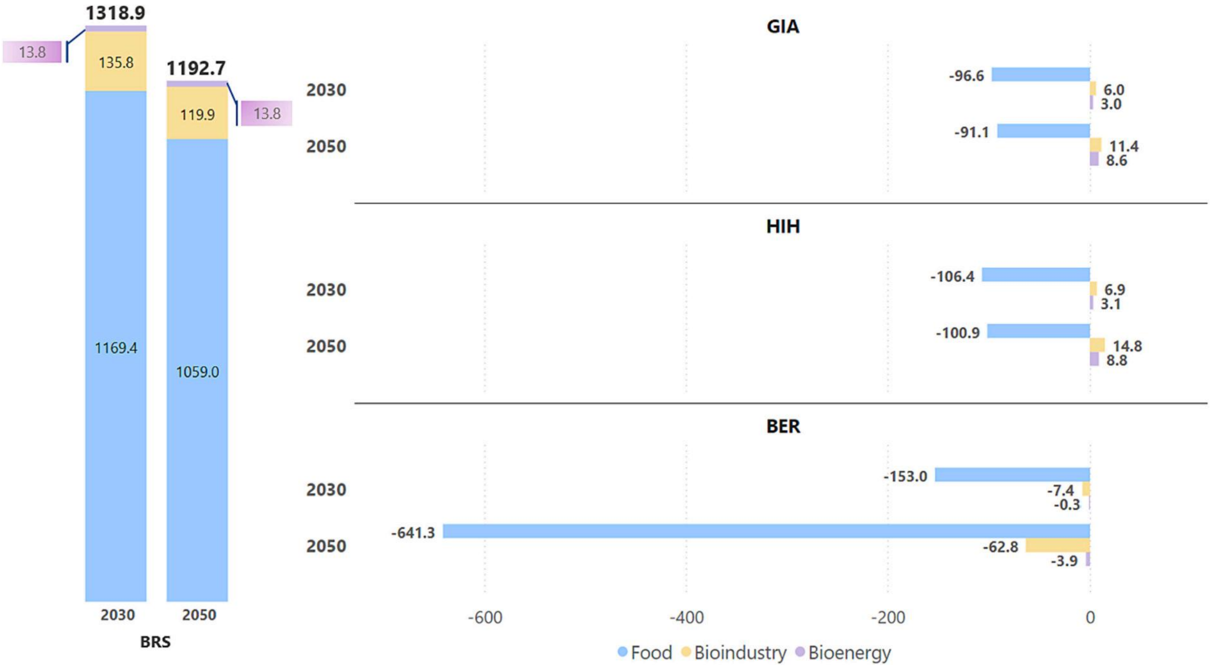


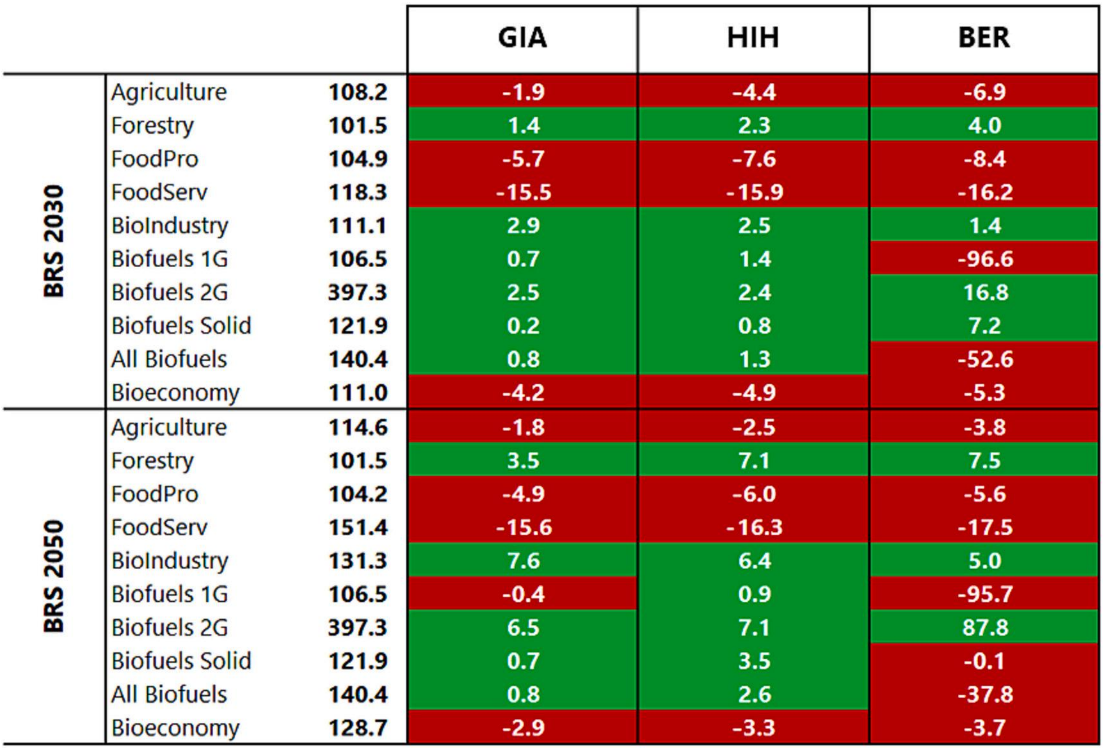
Fig. 13. Per capita emissions footprints by scenarios in 2030 and 2050 (kgCO2e/pc/year).

5. Discussion

5.1. Bioeconomy development

The modelling results, as summarized in Fig. 16, provide an overview of the medium- to long-run prospects, synergies and trade-offs for the EU bioeconomy through the prism of the EU's five bioeconomy objectives until 2050. As the BRS reveals, unlocking the potential of the bioeconomy through bio-based industrial growth requires more than market driven forces. To narrow the cost-disadvantage of bio-industrial processes to their fossil counterparts, an additional policy push is needed. Moreover, with a view to reducing EU emissions, our simulation results indicate that the substitution of fossil inputs with bio-based alternatives, especially if implemented globally, would not produce tangible reductions. In part, this is due to rising emissions from agricultural biomass production and reduced carbon storage in forests, a finding that is consistent with Escobar and Britz (2021).

On the issue of sustainable biomass availability and use, our results indicate that increased global demand in the HIH and BER scenarios can result in a substantial intensification of forest land use, as manifested by increased EU harvest levels and increased forest utilisation rates (Figs. 5 and 6). This intensification is accompanied by an estimated reduction of



			GIA	HIH	BER
BRS 2030	Agriculture	108.2	-1.9	-4.4	-6.9
	Forestry	101.5	1.4	2.3	4.0
	FoodPro	104.9	-5.7	-7.6	-8.4
	FoodServ	118.3	-15.5	-15.9	-16.2
	BioIndustry	111.1	2.9	2.5	1.4
	Biofuels 1G	106.5	0.7	1.4	-96.6
	Biofuels 2G	397.3	2.5	2.4	16.8
	Biofuels Solid	121.9	0.2	0.8	7.2
	All Biofuels	140.4	0.8	1.3	-52.6
	Bioeconomy	111.0	-4.2	-4.9	-5.3
BRS 2050	Agriculture	114.6	-1.8	-2.5	-3.8
	Forestry	101.5	3.5	7.1	7.5
	FoodPro	104.2	-4.9	-6.0	-5.6
	FoodServ	151.4	-15.6	-16.3	-17.5
	BioIndustry	131.3	7.6	6.4	5.0
	Biofuels 1G	106.5	-0.4	0.9	-95.7
	Biofuels 2G	397.3	6.5	7.1	87.8
	Biofuels Solid	121.9	0.7	3.5	-0.1
	All Biofuels	140.4	0.8	2.6	-37.8
	Bioeconomy	128.7	-2.9	-3.3	-3.7

Fig. 14. EU bio-based production trends in 2030 and 2050 (2020=100) for BRS and percentage deviation for the three alternative scenarios.

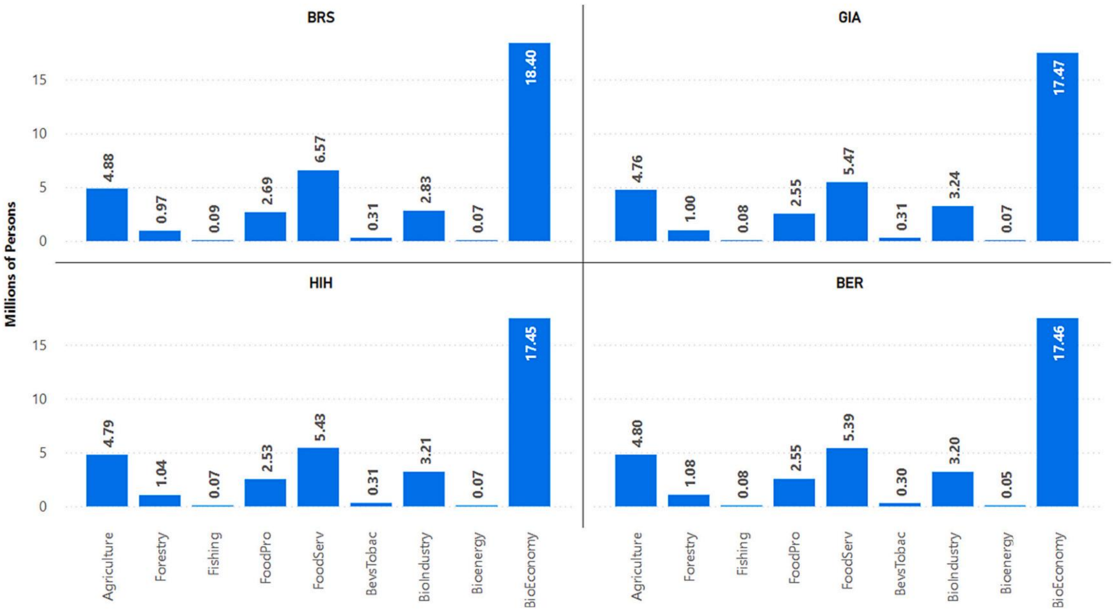


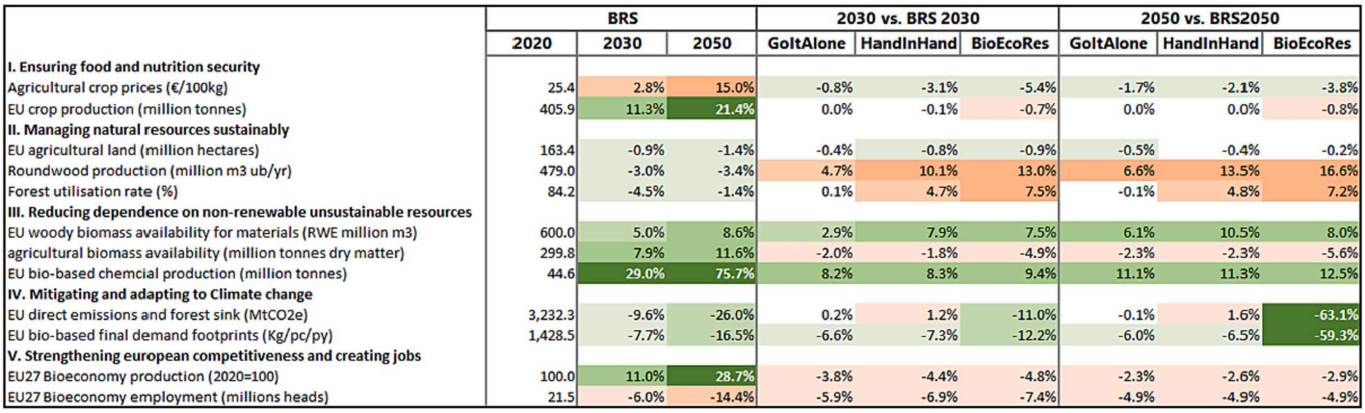
Fig. 15. EU bioeconomy employment by scenarios in 2050.

Notes: Satellite data for EU27 bio-based activity employment numbers are based on Eurostat data for 2020, except in the case of bio-based industry and energy where starting figures are taken for 2019 (latest available year) from the Joint Research Centre EU bioeconomy monitoring system.

Eurostat data by activity: https://ec.europa.eu/eurostat/databrowser/view/LFSA_EGAN22D_custom_7771226/default/table?lang=en

JRC Bioeconomy Monitoring System Dashboard: https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system-dashboards_en

CO_2 removals by European forests and only a small reduction in emissions in the HIH scenario (Fig. 11). This can in part be explained by the stronger demand for wood and wood-based products outside the EU and that a substantial part of the additional EU harvest (in HIH and BER) will be destined to satisfy wood biomass demand outside the EU, and therefore not result in emission reductions within the EU. Moreover, it is unclear whether increased wood production to substitute fossil-based alternatives will provide net climate benefits. This is because reductions in the forest carbon sink may counterbalance enhanced carbon storage in products and avoided emissions, although this depends on, inter alia, for what purposes wood is used (UN and FAO, 2021; Nepal et al., 2022; Jonsson et al., 2021). Our results indicate possible supply limits of wood from EU forests after 2040 (see Section 4.3.2). Therefore, if the bioeconomy is to support the mitigation of climate change, one



	BRS			2030 vs. BRS 2030			2050 vs. BRS2050		
	2020	2030	2050	GoItAlone	HandInHand	BioEcoRes	GoItAlone	HandInHand	BioEcoRes
I. Ensuring food and nutrition security									
Agricultural crop prices (€/100kg)	25.4	2.8%	15.0%	-0.8%	-3.1%	-5.4%	-1.7%	-2.1%	-3.8%
EU crop production (million tonnes)	405.9	11.3%	21.4%	0.0%	-0.1%	-0.7%	0.0%	0.0%	-0.8%
II. Managing natural resources sustainably									
EU agricultural land (million hectares)	163.4	-0.9%	-1.4%	-0.4%	-0.8%	-0.9%	-0.5%	-0.4%	-0.2%
Roundwood production (million m3 ub/yr)	479.0	-3.0%	-3.4%	4.7%	10.1%	13.0%	6.6%	13.5%	16.6%
Forest utilisation rate (%)	84.2	-4.5%	-1.4%	0.1%	4.7%	7.5%	-0.1%	4.8%	7.2%
III. Reducing dependence on non-renewable unsustainable resources									
EU woody biomass availability for materials (RWE million m3)	600.0	5.0%	8.6%	2.9%	7.9%	7.5%	6.1%	10.5%	8.0%
agricultural biomass availability (million tonnes dry matter)	299.8	7.9%	11.6%	-2.0%	-1.8%	-4.9%	-2.3%	-2.3%	-5.6%
EU bio-based chemcial production (million tonnes)	44.6	29.0%	75.7%	8.2%	8.3%	9.4%	11.1%	11.3%	12.5%
IV. Mitigating and adapting to Climate change									
EU direct emissions and forest sink (MtCO2e)	3,232.3	-9.6%	-26.0%	0.2%	1.2%	-11.0%	-0.1%	1.6%	-63.1%
EU bio-based final demand footprints (Kg/pc/py)	1,428.5	-7.7%	-16.5%	-6.6%	-7.3%	-12.2%	-6.0%	-6.5%	-59.3%
V. Strengthening european competitiveness and creating jobs									
EU27 Bioeconomy production (2020=100)	100.0	11.0%	28.7%	-3.8%	-4.4%	-4.8%	-2.3%	-2.6%	-2.9%
EU27 Bioeconomy employment (millions heads)	21.5	-6.0%	-14.4%	-5.9%	-6.9%	-7.4%	-4.9%	-4.9%	-4.9%

Fig. 16. A summary of EU27 bioeconomy indicator outcomes for the five pillars of the BioEconomy Strategy.
Note: From the perspective of each pillar, stronger tones of green (orange) indicate more ‘desirable’ (less ‘desirable’) outcomes.

must be selective and prioritise biomass uses that lead to the largest net emission reductions (see also Verkerk et al., 2022) and provide other (environmental) benefits.

Altogether, our findings (Section 4.4.1) suggest that improved environmental performance from bio-industrial policy requires policies that target ‘sustainable’ (i.e., non-food) biomass feedstock. For example, publicly led actions to encourage non-food biomass usage could follow previous policies adopted for advancing biofuels, such as the use of tax credits on specific types of biomass usage (De Gorter and Just, 2009). Thus, whilst the aforementioned market tensions for woody biomass can be expected, other non-food biomass types such as high energy crops and improved harvesting of crop residues and waste streams (circularity) offer clear avenues for reducing upstream emissions from more traditional (i.e., food) sources of biomass. Other evidence (BER scenario) further shows that matching publicly supported green investments in bio-based industry (particularly chemicals) with climate policy (i.e., carbon taxes), produces a win-win combination of further accelerated bio-based competitiveness and EU industry emissions reductions.

Our study also finds that for a successful bioeconomy transition, biomass conserving efforts will be needed. In the EU, this point is all the more pertinent as the Farm to Fork strategy (EC, 2020) (not modelled here) advocates a model of lower intensity farming, resulting in lower crop (biomass) yields and greater extensification of land management practises. Evidence here (Section 4.1.2) shows that the elimination of support for EU conventional biofuels could free up to 14 million tonnes of biomass dry matter for usage in bio- material applications (consistent with the cascading biomass principle discussed in the introduction). In the absence of any further assumptions regarding red meat demand, a trade-off identified here is that the resulting fall in the production of biofuel animal feed by-products, could increase demand pressure for pastureland.

A further biomass saving initiative considered here, is the halving of household food waste. This measure offers clear synergies with food nutrition security in the form of cheaper crops and improvements in EU self-sufficiency. Household food waste reductions also provide further benefits for natural resource management and climate change objectives. Indeed, as estimated in our study, halving food waste frees up approximately eight million tonnes of crop biomass dry matter and reduces direct emissions from the agri-food sector and EU emissions footprints on food demands (i.e., reduced leakage).

For the dimension of competitiveness and job creation there is, however, a trade-off between the two drivers of bio-industrial policy and consumer engagement. Despite bio-industrial policy driven growth, the halving of food waste reduces EU agri-food, and consequently EU bioeconomy production and employment. To arrest this eventuality, requires retraining schemes for displaced bio-activity workers, particularly in rural areas where depopulation in some member states is already an acute problem. Initiatives such as the proposal to make 2023 the European Year of Skills (EC, 2022d) move in this direction by promoting upskilling and reskilling opportunities.

Finally, the driver of research and development investment is essential for a transformative bio-based industrial revolution of competitive growth, employment and reduced fossil dependence of European industry. As noted in Section 3.2, with ‘learning-by-doing’ in nascent biotechnologies, a degree of biomass saving is anticipated in the medium term (captured here), although the limit of this technical improvement (calibrated to assumed rates of return) remains open to speculation and represents an avenue of further research.

5.2. Innovation and limits of bioeconomy modelling

This study applied a bioeconomy model toolbox consisting of five models (see Section 3.1 and A1 of the SOM). These models were improved and linked to address key gaps in bioeconomy modelling (for an overview of such gaps, see Verkerk et al., 2021a). In the following, we describe these innovations to bioeconomy modelling, but also identify avenues for further development.

A key innovation on previous bioeconomy modelling endeavours, is the construction of the bottoms-up BioMAT model with the focus on the bio-based chemical industry. By distinguishing between 8 types of biomass feedstocks for production of materials, especially biochemicals (Sturm et al., 2023), BioMAT enables the establishment of linkages with other models covering only specific types of biological resources and/or specific types of material use. In the present exercise, some links between BioMAT and AGMEMOD, EFI-GTM were explored (see Section A3 in the SOM document), although further work is needed to refine them and to broaden the overlap.

Another key innovation is the extension of EFI-GTM to include emerging wood-based products. This inclusion follows the growing interest in products that have a lower negative impact to the environment and that represent solutions to problems caused by the extensive use of non-renewable materials and the dependence on fossil sources (Hurmekoski et al., 2018; Hassegawa et al., 2022a, b). More specifically, EFI-GTM has been extended to include man-made cellulosic fibers and to consider engineered wood-products (cross-laminated timber and glulam). Including these products is challenging due to limited data availability on such emerging product categories, especially with regards to engineered wood products. Moreover, the model was improved to better capture recent trends in markets of existing wood-based products such as packaging (case materials, cardboard), newsprint and graphic paper and solid wood products (sawnwood, wood-based panels). Chemicals and energy products are other product categories, and a more detailed link with BioMAT and energy models could be explored.

In this study, EFI-GTM was linked with EFISCEN. Through this linkage, EFISCEN provided information on the maximum harvest level, but this link does not address elasticities for modelling the supply curves. Moreover, this link enables insights in resource availability from European forests but excludes similar detail for forests outside Europe. Instead, EFI-GTM's internal productivity rules were used. Finally, this approach excluded the consideration of climate change impacts on forests and wood availability. Further developments of this linkage could focus on a more dynamic link with a global forest resource model, and which considers climate change impacts.

Advances in the MAGNET model relate to the split of bio-based chemical, pharmaceutical and plastic activities in the data. Moreover, in the modelling the treatment of publicly funded bio-industrial investment in MAGNET is financed (by taxpayers) rather than the standard overly optimistic characterisation of "manna from heaven" (Pyka et al., 2022, pp5). But further work is required here. For example, with the availability of data on ringfenced funds under the auspices of the Green Deal and (post-COVID) 'Recovery and Resilience Plan' (EC, 2021), recent modelling enhancements in green investments (Smeets-Kriskova et al., 2023) provide greater behavioural insights on the allocation of said funding in response to relative rates of return between competing bio-based activities and the resulting impacts on the degree of bio-industrial capitalisation over time. A connected issue is the substitutability between fossil technologies and bio-based alternatives, which determine the sensitivity of bio-industry uptake (particularly nascent chemicals) in response to changing competitive conditions (for example, owing to public support instruments, different assumed rises in fossil prices or carbon taxes). Further econometric insight and/or sensitivity analysis of this key behavioural 'elasticity' parameter should also be further explored.

An attempt to represent the role of consumers in the bioeconomy transition process is seen as an advancement in the current modelling exercise. But further effort should be focused on internalising the costs (as well as the benefits) of reducing household waste (not modelled here). Any behavioural transition will incur a time cost in terms increased food purchase planning and preparation time, as well as publicly funded measures (e.g., legislation for legally binding targets on food waste reductions (EC, 2022e), educational programmes) and targeted market (i.e., tax) incentives to achieve desired reductions. Recent work by Bartelings and Philippidis (2023) examines some of these propositions, whilst making important breakthroughs in capturing the circularity of collection and treatment of waste streams for bio-based energy and material activities.

In summary, our approach addressed some of the important gaps in bioeconomy modelling. However, looking to future bioeconomy modelling, Pyka et al. (2022) emphasise the key processes of technological change or innovation, comprehensive representations of circularity, plausible behavioural representations of food waste and dietary behaviour, climate policy and the quantification of biodiversity measures of performance. In some areas, for example circularity (Bartelings and Philippidis, 2023) and green investments (Smeets-Kriskova et al., 2023), initial advancements are already underway. Elsewhere, the challenge of monetarising nature-based ecosystem services (e.g., water quality, crop pollination) modelling the potential (negative) feedback on human wellbeing (Chaplin-Kramer et al., 2019), remains a hitherto unexplored avenue of research.

6. Conclusions

This study developed an integrated modelling toolbox of four established bioeconomy-focused models and a newly constructed model for the bio-based chemicals sector. With different sectoral focus and through a series of model links, the key aims were to (i) internalise comprehensive coverage of biomass feedstock types and (ii) project forward-looking market prospects across a series of scenarios for EU food-, feed-, energy-, and more innovatively, material applications. The current analysis confines itself to examining potential pathways to 2050, consistent with current policy mechanisms and strategy documents.

Under 'Business-as-usual' trends for biomass usage and consumer attitudes, simulation results suggest rises in productivity that (i) keep food security in check (albeit with slight crop price rises), (ii) reduce agricultural land requirements and (iii) allow for greater agricultural biomass usage in materials and energy. Roundwood production and utilisation rates in the BRS are estimated to remain relatively stable. The assumed decarbonisation of energy markets in the BRS, leads to gentle falls in EU direct emissions and consumer footprints for bio-based products. From 2020 to 2050, bioeconomy employment declines by approximately 3.1 million persons. Moreover, despite assumed gradual rises in fossil fuel prices, and in the absence of additional policies, EU bio-based industry production growth is broadly similar to the EU bioeconomy average. When examining the incremental impacts of alternative scenarios, model simulations until 2050 indicate that the promotion of biomass for industry reduces fossil dependence, although if enacted globally, may result in a substantial increase in biomass demand. Moreover, a bio-based industry transformation contingent, at least in part, on woody and agricultural biomass feedstocks, will not achieve important reductions in emissions. To safeguard sustainable usage of food crop and woody biomass, consideration must be given to the responsible targeting of alternative sources of 'sustainable' biomass, which in tandem with carbon taxes, can be expected to accelerate the switch to biotechnologies and reduce EU industry emissions. From a bioeconomy employment perspective, these measures must be supported by retraining programmes in rural areas. Finally, in addition to a strict adherence to the principle of circularity in biomass usage, a socially responsible change in consumption behaviour represents an essential strategy for easing (agricultural) biomass market tensions.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108156.

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