Monitoring Bioeconomy

3 DECEMBER 2024

Monitoring the German Bioeconomy – Summary

STATUS, PERFORMANCE, TRENDS AND IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT

Bioeconomy Monitoring Report 2024

Monitoring the German Bioeconomy – Summary: Status, performance, trends and implications for sustainable development

This report was organized and prepared based on key outputs of the research project SYMOBIO 2.0 (Consolidation of Systemic Monitoring and Modelling of the Bioeconomy), funded by BMBF, and implemented by nine partners across Germany. See also: symobio.de

It includes contributions stemming from the research project MoBi II (Development of a systematic bioeconomy monitoring — Consolidation Phase), funded by BMEL and carried out by Thünen Institute. See also: Thuenen.de

Publisher
Center for Environmental Systems Research (CESR), University of Kassel

Formatting and design: Renata Sas
Photos: Freepik, R. Sas (p. 2, 8, 20); © Adobe Stock: TheWaterMeloonProjec (p. 3), Cheetose (p. 10-biopharmaceutical production), Anna Puzatykh (p. 10-cleaning products), almeera (p. 19); M. Beck-O'Brien (p. 10-alternative meat)

Printers: dieUmweltDruckerei GmbH

Editors and lead authors
Meghan Beck-O'Brien and Stefan Bringezu, Center for Environmental Systems Research (CESR), University of Kassel

Contributing authors*
*Authors and their affiliations are further distinguished in each chapter related to their contributions. Here they are provided in alphabetical order.

Martin Banse, Johna Barrelet, Alberto Bezama, Matthias Bösch, Simone Brüning, Bernhard Bührlen, Ana Cabezas, Karl-Friedrich Cyffka, Ilze Dzene, Fernando Gordillo Vera, Hanna Helander, Jan Henke, Klaus Hennenberg, Roman Hinz, Susanne Iost, Matthias Jordan, David Kilian, Susanne Köppen, Ellen Kynast, Christian Lutz, Simon Pereira, Mirjam Pfeiffer, Phuntsho, Paola Pozo Inofuentes, Thomas Reiss, Saskia Reuschel, Sören Richter, Rüdiger Schaldach, Margarethe Scheffler, Anna Schomberg, Jan Schüngel, Jörg Schweinle, Daniela Thrän, Mengxi Wang, Holger Weimar, Kirsten Wiegmann, Jayan Wijesingha, Burkhard Wilske, Sven Wydra, Walther Zeug, Christina Zinke

Citation of summary*
Beck-O'Brien, M., Bringezu, S., Banse, M., Barrelet, J., Bezama, A., Bösch, B., Brüning, S., Bührlen, B., Cabezas, A., Cyffka, K.F., Dzene, Gordillo Vera, F., I., Helander, H., Henke, J., Hennenberg, K., Hinz, R., Inofuentes, P. P., Iost, S., Jordan, M., Kilian, D., Köppen, S., Kynast, E., Lutz, C., Pereira, S., Pfeiffer, M., Phuntsho, Pozo Inofuentes, P., Reiss, T., Reuschel, S., Richter, S., Schaldach, R., Scheffler, M., Schomberg, A., Schüngel, J., Schweinle, J., Thrän, D., Wang, M., Weimar, H., Wiegmann, K., Wijesingha, J., Wilske, B., Wydra, S., Zeug, W., Zinke, C. (2024). Monitoring the German Bioeconomy — Summary: Status, performance, trends and implications for sustainable development. Published by the Center for Environmental Systems Research (CESR), University of Kassel, Kassel, doi:10.17170/kobra-2024111510677

References and list of abbreviations
All references and abbreviations can be found in the full report, available at: www.monitoring-biooekonomie.de/en/ or also www.uni-kassel.de/ub/en/ (doi.org/10.17170/kobra-2024111510679)

Contact and further information: meghan.beck-obrien@uni-kassel.de

Table of contents

Introduction

This report presents indicators, trends and scenarios on the state and performance of the German bioeconomy. The aim is to identify the challenges and opportunities that policy makers need to know in order to effectively steer the transition towards a circular and more sustainable bioeconomy. This report is intended for a wide public audience (policy makers, researchers, NGOs, industry and civil society) and is designed to reach readers with different levels of pre-existing knowledge about the bioeconomy. In the long term, it should provide the basis for further developing a regular reporting of bioeconomy monitoring in Germany.

This summary provides a snapshot of key findings. The figures presented are simplified versions of the more detailed illustrations found in the main report. All references and abbreviations can be found in the long report, and extended method descriptions and supporting data, when appropriate, are available in the supplementary information published alongside the main report.

What is the bioeconomy?

The overarching aim of the bioeconomy is to combine economy and ecology to ensure a more sustainable use of resources.

The bioeconomy is seen as a way to reduce the consumption of fossil resources, ensure global food security, and promote local primary sectors (agriculture, forestry, fishing) as well as high-value manufacturing. It is defined in the German National Bioeconomy Strategy as: "The production, exploitation and use of biological resources, processes and systems to provide products, processes and services across all economic sectors within the framework of a future-oriented economy" (BMBF and BMEL 2020). The bioeconomy is thus a cross-cutting topic that includes all sectors where biomass is grown, harvested, produced, manufactured, consumed and re-used. Innovation is at the heart of the bioeconomy transition, and the overarching aim is to combine economy and ecology to ensure a more sustainable use of resources.

Key challenges: Navigating trade-offs to steer the bioeconomy

How the bioeconomy is implemented makes a large difference to whether overarching sustainability goals can be achieved. While the three dimensions of sustainability (environmental, economic and social) are core to the strategic goals, they do not always overlap in ideal 'win-win' outcomes. Compromise, recognition of limits and risk mitigation are necessary, in particular in light of long supply chains and already high levels of consumption in Germany overall compared to other parts of the world. For that reason, a systemic monitoring is needed to understand, manage and overcome challenges, in particular as regards identifying trade-offs between sustainability dimensions.

What does a 'sustainable bioeconomy' mean?

A sustainable bioeconomy contributes to the attainment of the Sustainable Development Goals (SDGs) as set out in United Nations' 2030 Agenda. It is climate neutral, supports circular use, keeps levels of consumption within ecological limits, and promotes the use of bio-based products in prosperous and competitive German markets characterised by social acceptance and economic viability. The sustainable bioeconomy drives Germany towards becoming a hub for high- and low-tech innovation, creating jobs and new opportunities. It is achieved by using biomass in a way that is efficient, sufficient, just and safe, as ultimately balance between sustainable supply and responsible consumption is core to achieving aims.

Sustainability in this report is linked to aims for a holistic bioeconomy transition. Core elements include climate-neutrality, circularity, and balance between consumption and sustainable supply.

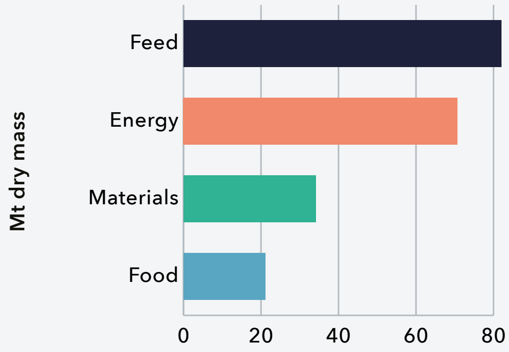
This vision of the bioeconomy is rooted in the principles expressed by the European and German political strategies. It depicts the type of bioeconomy understood as 'sustainable', and thus forms the basis for understanding monitoring needs. That said, the monitoring capacities connected to these concepts differ widely, with some aspects much more advanced than others. The needs for being able to better evaluate sustainability and improve monitoring tools, data and indicators are included throughout this report.

Biomass use

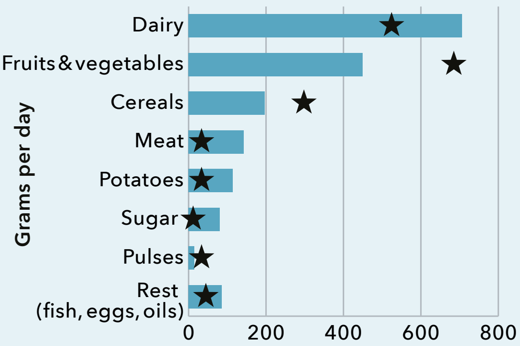
Over 200 million tonnes (t) dry mass of biomass from agriculture, forestry and fisheries were used by the German bioeconomy in 2020. This includes the re-use of residues, which were particular relevant for paper consumption and energetic use.

4 times as much biomass is used for feed (around 80 million t) than for food (21 million t). Of the food consumed, 7 Million tonnes is comprised of biomass from animal products.

Overview



Total biomass end uses in 2020, including residues



Average German diet (2022) compared to dietary recommendations (★)

Food

Meat consumption in Germany, at 143 grams (g) per day, is more than triple the amount recommended by German dietary guidelines (26–43 g per day). Although per capita meat consumption has been in steady decline since 2010 (falling around 0.8 kg per year), the rate of change is insufficient to reach recommended dietary guidelines in coming decades. If the trend would continue, Germany would first meet recommended levels in 2070.

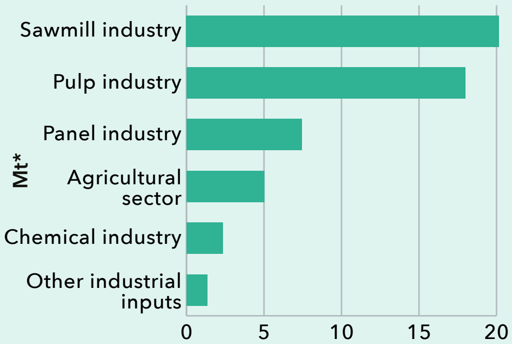
11 million t of food were reported as lost and wasted in Germany in 2020. The German Strategy for Food Waste Reduction aims to cut food waste quantities in both distribution and consumption in half by 2030.

The targeted monitoring of dietary patterns, e.g. as part of German National Nutrition Monitoring, focusing in particular on meat and milk intake, could help political priority-setting and complement the ongoing food waste monitoring.

Materials

54 million t dry mass (DM) were estimated as inputs to German processing industries for material use in 2020. Forest-based biomass comprises the largest share, in particular for sawmill and pulp processing, noting that some of these products were exported for final material consumption abroad. Around 3.3 million t DM of agricultural-based biomass were used for material processing in 2020, with the vast majority (73 %) used in the chemical sector. This sector is in particular expected to increase its use of biomass in the future.

The current use of biomass in the material sector seems to be undergoing a shift. An increased use in innovative material applications could increase the competition for non-food biomass. In comparison to the energy sector, the material use of biomass is generally more influenced by long-term strategies and less by regulatory frameworks and measures (such as quotas, exclusion of biomasses, price incentives or sustainability requirements).



Biomass use in material sectors in Germany, 2020

* Data depicts input mass used for processing biomass in German industries (some of which is later exported for material end use abroad). It is based on multiple sectoral reports and does not include conversion losses, causing deviations to the overview (which shows final end use amounts). For the agr. & chem. sectors, ingredient materials are included, whereas for forestry, dry mass is depicted.

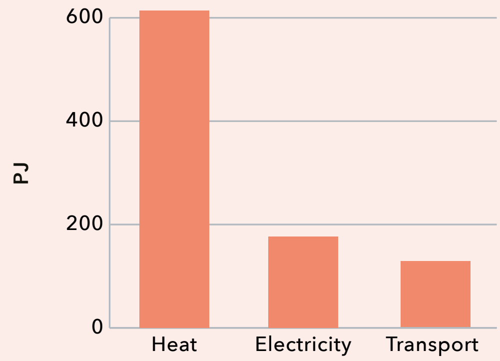
12%

of total energy supply in 2023 was supplied by biomass.

Energy

Biomass contributed a total of 919 petajoules (PJ) to German energy supply in 2023, or 12 % of total energy and 49 % of renewable energy provision. It was mostly used for heat, followed by electricity production and biofuels. The latter two sectors show decreasing absolute trends since 2020, and the relative contributions of biomass to overall renewable energy supply has been in decline since 2010 as alternatives (like wind and solar) grow in importance. The extent and further development of bioenergy use in the future will depend mainly on the regulatory framework.

While agricultural crops were the largest source of biomass inputs for bioenergy in Germany in 2020 (44 % in terms of tonnes dry mass), a significant shift towards the use of residues and wastes occurred from 2020 to 2022. Germany's policy goal of increasingly shifting the production of bioenergy towards residues and wastes is thus progressing in general.



Bioenergy use in 2023, in petajoules

Import dependencies for both conventional and advanced (based on wastes and residues) biofuels remained high in 2022, with more than 80 % originating outside Germany. Some of these import residues, such as palm oil mill effluent, entail fraud risks, and a cap could be considered for certain advanced feedstocks. The production infrastructure for using advanced biofuel streams in Germany is also not yet being built, potentially limiting the capacity to make full use of the mobilisable potential of waste and residues estimated for Germany.

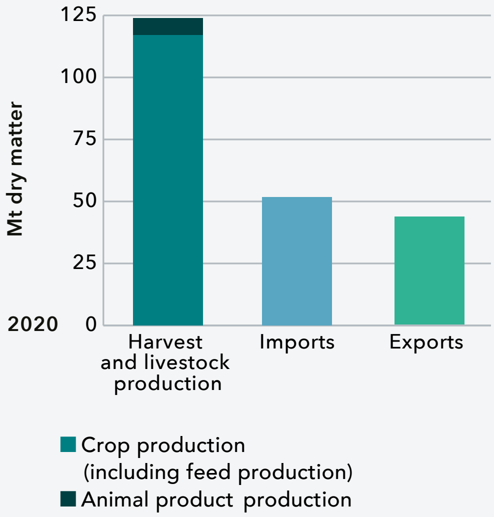
Modelling comparative scenarios for future biofuel use shows that GHG quota requirements do not yet promote the use of biofuels in areas or sub-sectors of the transport sector in which they could be cost optimally allocated according to a long-term energy optimisation scenario. Biofuels are currently mainly promoted in passenger road transport instead of in shipping and aviation.

Future bioenergy policy could try to integrate carbon capture, use and storage where possible (e.g. as in the German Carbon Management Strategy) in order to work towards counterbalancing unavoidable emissions.

Currently high import levels of advanced biofuels (80 % in 2022) need to be critically questioned in terms of energy independence and with regards to the progress on competitiveness of clean energy technologies.

Biomass flows

Agricultural biomass



Agricultural biomass is the most important form of biomass use in terms of quantity in the bioeconomy. While plant-based biomass production is subject to fluctuations, e.g. due to weather conditions, the amount of animal-based biomass produced, i.e. animal products such as meat, eggs, milk or skins and hides, has remained almost constant at around 7 million t over the last decade.

The production of plant-based biomass amounted to 117 million t in 2020, of which 67 million t and thus more than half (57 %) was comprised of roughage and biomass inedible for monogastric animals.

52 million t of biomass were imported and 43.5 million t were exported in 2020, making Germany a net importer of biomass overall.

Nearly 80 million t dry matter of agricultural biomass were used for feed for animal husbandry in 2020. 100 million t were used for non-feed purposes: energy (50 %), food (39 %), material use (7 %) and pet food (4 %).

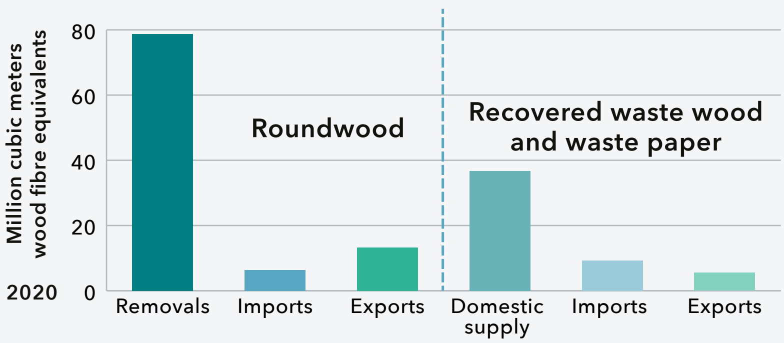
Forestry biomass

Removals of roundwood increased significantly, due to salvage fellings caused by drought and bark beetle infestations, in the 2020 reporting period. 79 million cubic meters of roundwood were removed from German forests in 2020. Net trade also shifted as a result of natural disasters in German forests, with Germany becoming a net exporter (of 7 million m^3 wood fibre equivalents (f)) in 2020, mainly due to changed trade of coniferous roundwood.

Most domestic used roundwood (56 %) is processed in sawmills, which mainly used coniferous wood (95 %). Roundwood is also used for the production of wood-based panels (7 %) and of wood pulp (7 %), with coniferous wood also dominating here. About 28 % of domestic roundwood consumption is used for energy, for which non-coniferous roundwood dominates.

Recovered materials of waste wood and waste paper comprised a significant share (37 million m^3(f) in 2020) of the domestic supply of wood fibres. Trade shows net imports of these of these raw materials of about 3.8 million m^3(f). Most of the recovered paper is processed and used for the manufacture of semi-finished paper and paperboard. Recovered waste wood is mostly utilised for energy and, to a lesser extent, for material use in the wood-based panels industry.

The final consumption of wood products in the various consumption sectors amounted to 37 million m^3(f). In total, Germany showed a net export of wood fibres of 14 million m^3(f) in 2020.

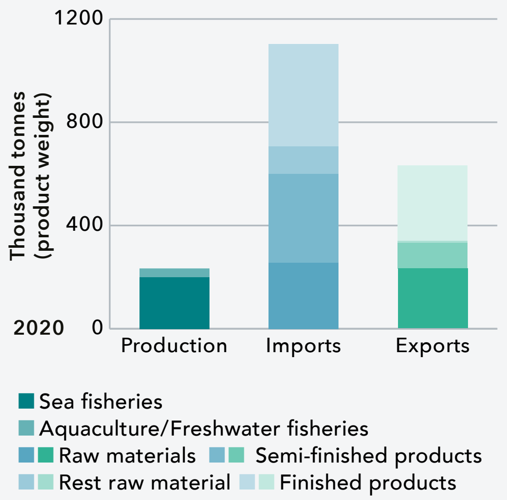


Aquatic biomass

Compared to 2015, German consumption of aquatic biomass increased by 11 % and production of aquatic biomass decreased by 11 %.

The decline in production was primarily due to reduced harvests from coastal fisheries — related to drastic quota reductions in the Baltic Sea — coupled with large fluctuations in the catch volumes of commercially vital brown shrimp. In contrast, high-seas fisheries have maintained stable catches while improving resource efficiency, e.g. by utilising by-products for fish oil and meal production at sea and reducing fleet capacities without lowering catch volumes. Stagnation in aquaculture production can be observed.

Around 230,000 t of aquatic biomass were produced in Germany in 2020. Around 86 % stemmed from sea fisheries, 12 % was a result of aquaculture production and 2 % from freshwater fisheries. Coastal fisheries in Germany are struggling to ensure their economic survival and would benefit from increased value added to their products by, e.g., regionalisation of the value chains and market establishment of under-utilised species.

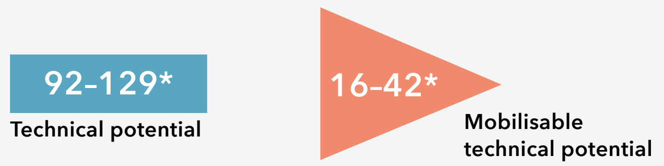


Note: Finished products includes fish meal and oil

Despite extensive fish processing activities, Germany is increasingly dependent on imports. The composition of imports changed between 2020 and 2015, toward less imports of raw materials and increased volumes of finished products. Overall, Germany's self-sufficiency rate has dropped from over 40 % in the 1980s to 17–20 % in the last decade.

Salmon was the most popular fish by consumers in Germany, with a market share of 19 % in 2020, and is almost exclusively imported. Detailed analysis of the material flows for salmon provided more precise information and helped identify gaps in the publicly available data to improve monitoring. Altogether, data on aquatic biomass flows is available, but presents considerable gaps and imprecisions that can only be compensated by surveys and/or assumptions.

Secondary biomass



* Million tonnes dry mass in 2020

The potential of secondary biomass (waste, by-products and residues) has slightly decreased rather than increased from 2015 to 2020. This sets the national potential of secondary biomass in contrast to the generally increasing demand for biogenic carbon sources including wastes, residues and by-products. However, there are still untapped potentials that need to be mobilised across the country, among them are the quota of (a) households connected to obligatory biowaste collection, and (b) the separate collection of spent cooking oils and fats.

31%

of technical potential stems from municipal waste and sewage sludge.

The 'technical potential' of total secondary biomass amounted to 91.7–128.9 million t of dry mass in 2020, of which 68–83 % were used. The largest share stems from municipal waste and sewage sludge (around 31 % of technical potential).

There were 15.7–41.9 million t of mobilisable technical potential in 2020. Six biomasses — deciduous forest (7 %), cattle slurry (12 %), cereal straw (15 %), solid cattle manure (14 %), wood residues of coniferous forests (16 %) and of green waste (20 %) — contributed 84 % to the mean mobilisable potential.

Reinforcing selective collection and utilisation of urban waste is needed across all regulatory levels. Co-design approaches when developing and improving circularity-focused systems, especially as regards the re-use of urban 'waste', could help create incentives for citizens to participate in re-use initiatives.

Cascades, co-production and circularity

In the recent literature, multiple methods to monitor resource efficiency by quantifying cascades, co-production and circularity have been tested and discussed. However, in practice, there is not one method applicable to all sectors, as data availability differs significantly.

While increased circularity of biomass use is at the core of political strategies, methods to monitor e.g. cascading use are still being tested in the scientific literature.

In the forestry and wood sector, data on flows of residues and recycled biomass are monitored via the wood resource monitoring, which is now conducted as a permanent task at Thünen Institute of Forestry. Based on this monitoring, data are available which can be considered also for further analyses on cascades, co-production and circularity within a bioeconomy monitoring.

In the food processing sector, increasing resource efficiency primarily involves the prevention of waste and the utilisation of industrial rest raw material for producing additional products. Official statistics on residues from food production are not publicly available. Approximations can be made based on expert knowledge from within the sector.

The cascading use principal generally prioritises material use before energy use. Future monitoring of the bioeconomy needs to better reflect these flows and their trends in order to identify potential opportunities, hot spots and trade-offs. Overarching monitoring of primary resource inputs can also indicate the extent to which cascading use, co-production and circularity contribute to total resource efficiency.

Socio-economic performance and innovation

Employment

2.7 – 2.9 million jobs in Germany

Decreasing trend

The bioeconomy comprised at least **7 % of total employment** in Germany. Nearly half of all bioeconomy employment in 2020 was in manufacturing. Unlike the rest of the economy, which as a whole saw a continuous increase in employment (of 8 % between 2010 and 2020), employment in the German bioeconomy decreased by around 11 % between 2010 and 2017. Trends beyond 2018 are difficult to estimate due to data gaps. The number of employees in agriculture, forestry and fisheries is slowly but steadily declining.

Gross value added

€ 134–150 billion

Fluctuating and rather steady since 2010

The bioeconomy comprised around **5 % of total gross value added in** Germany. Roughly half of this was generated by the manufacturing sector. In contrast to steady growth seen in the price-adjusted gross value added for Germany as a whole, the development of the German bioeconomy fluctuated (with 5 % growth between 2010 and 2017 and back to the same level in 2020 as in 2010). A gap in data availability since 2018 has disrupted the time series, making it difficult to monitor and draw conclusions on trends over the whole time period.

Innovative material use applications and markets

Bio-based plastics comprise a very small portion of total plastic production; globally they represent a share of around 1 %. For Germany, related bio-based value-added is estimated to be around € 1.1 billion and employment to be around 15,000 employees in 2021. While there is currently no large production plant for bio-based plastics in Germany, there is a significant presence of R&D institutes and SMEs active in this field, interested in, for example, developing 3rd generation bio-based plastics.

Biorefinery plant being built in Leuna, Germany by UPM. The biorefinery will use wood, in particular beechwood, to produce various industrial products and consumer goods, such as PET bottles, cleaning agents, and rubber.

Source: UPM Biochemicals GmbH

Bio-based chemicals account for an estimated 6 to 15 % of the chemical sector in Germany. Using the lower figure, value-added is estimated to be around € 3 billion with employment of around 25,000 employees in 2021. In the future, bio-based chemicals, next to the use of CO_2, are expected to gain a significant role in the de-fossilisation pathway of the chemical industry,

Textiles from cotton (comprising around one-fifth of global textile production) and man-made cellulosic fibers (with around 6 % of production) are the most common bio-based textiles used currently. Leather required more than 1.4 billion animals in 2021. For Germany, a value-added of around € 3 billion and employment of around 45,000 employees in 2021 are estimated. Germany is strong in applied research on textiles.

The use of 2D timber construction modules provides strong opportunities for the serial energetic refurbishment of e.g. apartment buildings in Germany.

© Photo from B&A Seriell GmbH

Modular timber construction is gaining importance in Germany, for example in the construction of new buildings (single or double family houses) and in the context of the densification of urban space, like the addition of storeys or the extension of existing buildings. The share of wood construction for new buildings increased from 4 % to almost 10 % between 1993 and 2021. Of all the wood used in construction, about one-third is used for new buildings and about two-thirds are used in modernisation and refurbishment of existing buildings.

State of technological innovation

Technology trends in Germany are characterised by a wide range of innovations with potential for both incremental (e.g. substitution with bio-based feedstocks) and disruptive (e.g. carbon capture and use (CCU), cultured meat, biotechnology in healthcare, microbiomes in agriculture) change. Maturity, up-scaling and performance reliability despite fluctuating feedstock quality are key challenges. Market incentives, e.g. for the material use of bio-based products, bio-based plastics, CCU or biosurfactants, are largely absent. While there has been some improvement, full price competitiveness for many of the assessed innovations is unlikely for the upcoming years. Regulations and consumer acceptance pose additional challenges.

Patent analysis shows that Germany has a relatively high degree — and increasing level — of specialisation in areas especially connected to machinery-related technology. Nevertheless, the US leads patenting in all technology-related areas, and China is strongly catching up and has surpassed the EU in some cases.

Altogether, Germany has a rather strong position for competitive innovation development in e.g. biopharmaceuticals, bio-based surfactants and CCU, due especially to Germany's rather strong pharmaceutical and chemical industries, which have to align to a green transition pathway in the upcoming decades.

Comparatively high*

Innovative wood products (44)
Agriculture 4.0 (55)
Bio-based surfactants (66)

Increasing since 2009

Comparatively low*

Biotechnology (– 47)
Biopharmaceuticals (– 55)
Plant breeding (– 59)
Microbiomes (– 71)

Decreasing since 2009

*Relative patent advantage index (2019 – 2022) for Germany

Innovation potentials

Meat alternatives

Meat alternatives are attracting wide interest and show significant growth (nearly tripling turnover in Germany between 2019 and 2023 to reach € 580 million). They currently make up around 1 % of total meat product markets in terms of economic value. In Germany there are some start-ups and also some leading players from the meat industry active in both plant-based meat alternatives and cultivated meat.

Biopharmaceuticals

There is a clear shift toward biopharmaceuticals in medicine. Most of 2028's top 10 drugs are expected to be biotechnology-based, and the sector is a significant and growing opportunity for employment in the processing sectors of the German bioeconomy (with around 50,000 employees in 2022).

Second generation bio-based surfactants

Germany leads production of bio-based surfactants in the EU and is in second place in global patent applications. Surfactants are used e.g. for household detergents. Bio-based surfactants represent a flagship product group and a success story in terms of market relevance for bio-based chemicals. Investments in 2nd generation biosurfactant technologies have intensified and a number of SMEs are dedicated to expanding the use of inputs, like food waste, to improve environmental performance.

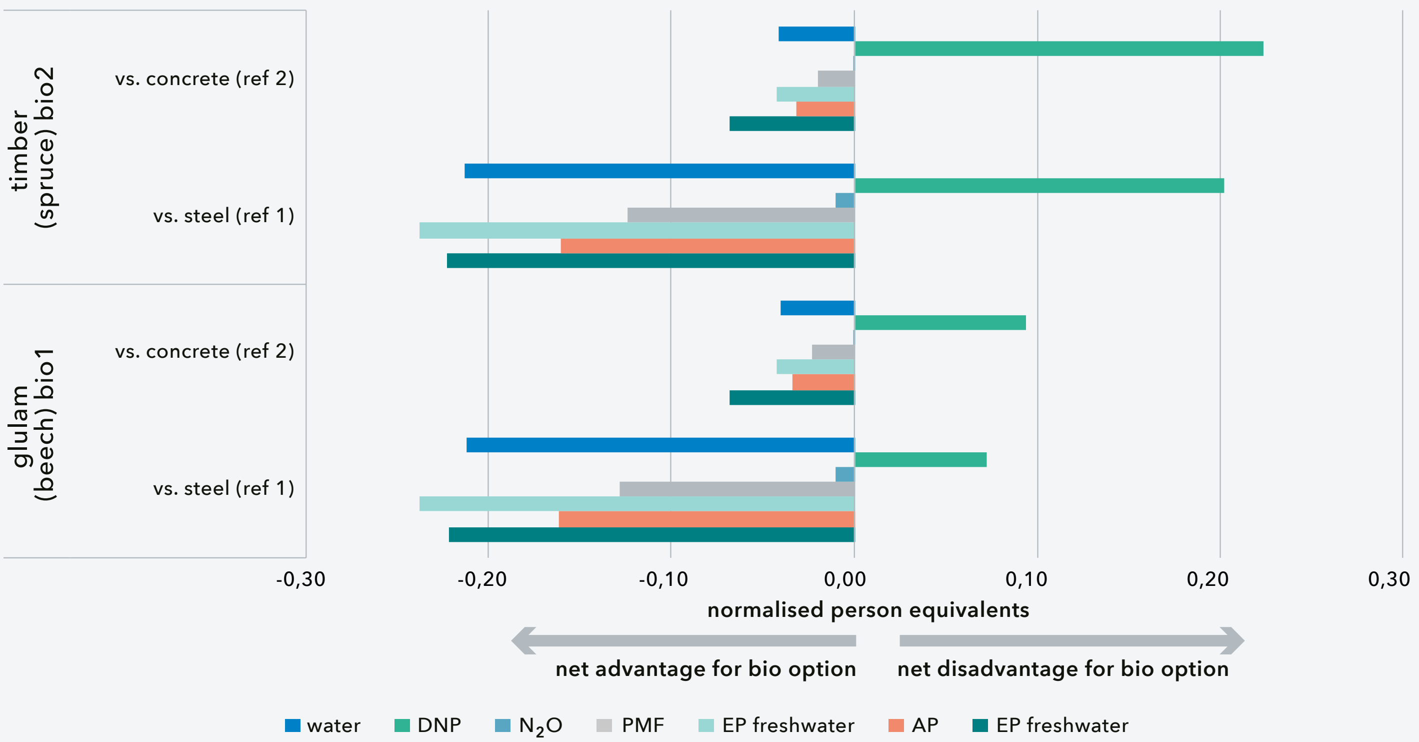
Environmental impacts

Biomass substitution effects

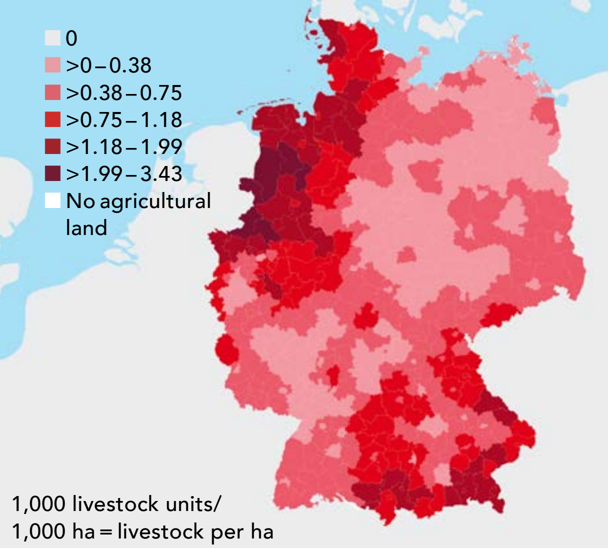
Life cycle analysis (LCA) shows potentially positive environmental benefits of substituting wood for concrete and steel as a load-bearing element in the construction sector, as well as CO_2-based ethylene for mineral naphtha in the chemical sector. Conventional textile production was found to have a highly negative environmental performance compared to alternatives, including e.g. CO_2-based fibre from carbon capture and use.

Robust analysis of substitution effects requires a blend of methodological approaches to take system wide impacts into account. For example, the scale of construction and level of demand for timber also play a role in overarching performance over time. How biogenic carbon is treated in GHG balances can significantly impact LCA results. This is particularly relevant for considerations of land use change. For example, increased harvest intensity, e.g. at scales that over-use forests for wood supply, can impact the capacity of the forest to act as a CO_2 sink in some cases. At the same time, promoting long-lived harvested wood products can also be a strategy to store carbon in the built environment. Against this background, the impacts of production and consumption need to be carefully balanced, using monitoring tools like LCA complemented by macro level analysis.

Normalised Life cycle impact assessment results for two biomass-based options (Glulam beech and timber spruce) balanced against two non-biomass options (steel and reinforced concrete, references) show that there could be positive environmental benefits of substitution for a load bearing element in the construction sector, but that these should only be promoted at a larger scale when system wide impacts to avoid problem shifting are taken into account and monitoring tools and regulatory boundaries are in place.



Note: Functional unit: beams for a hall roof spanning 10 meters; GWP: global warming potential; AP: acidification potential; EP Eutrophication potential; PMF: particulate matter formation; DNP: distance to nature potential. More information on the impact categories and definitions is in the supplementary information.



Livestock density at the regional level for the year 2020 depicts the importance of including indicators that can provide detailed information on spatial variation of impacts over time for a comprehensive and cross-scale bioeconomy monitoring.

Source: Thünen Atlas: Agricultural use (2020); Method: Gocht and Röder (2014)

Environmental impacts in Germany

The agricultural sector

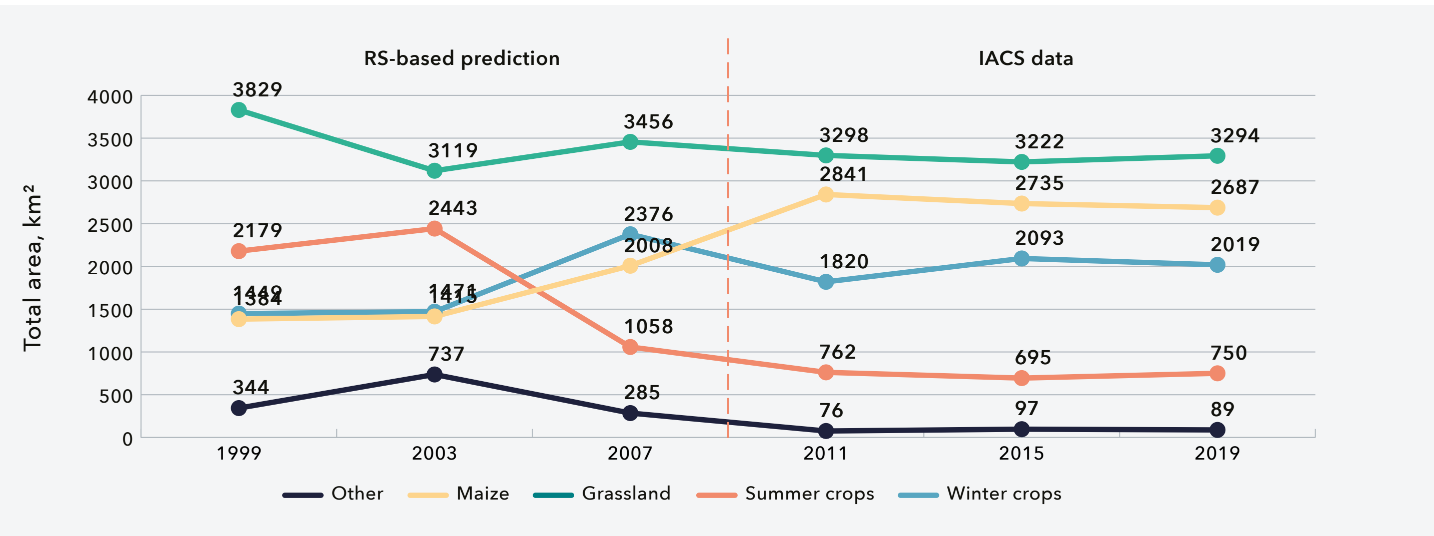
243 specific indicators addressing environmental sustainability were identified and narrowed to a core set of nearly 20 suitable indicators for monitoring the agricultural-environmental impacts of the German bioeconomy.

84 studies were reviewed to identify 18 models capable of modelling the identified core indicators for agriculture. However, only a very limited number of scenario results are available for Germany, and of those, most focus almost exclusively on GHG emissions. To develop a regular bioeconomy monitoring, inclusion of relevant bioeconomy issues, including coverage with spatial variation, in existing agricultural modelling frameworks is needed.

Case study: Land use change driven by increased biogas production

Weser-Ems is one of the most developed biogas production regions in Germany, with more than 800 agricultural biogas plants operating in the region. A case study using remote sensing techniques found that major land cover changes occurred in areas that overlap with high and medium biogas capacity zones, indicating a direct relationship between biogas production and agricultural land cover change. The case study demonstrates that remote sensing data can successfully be applied to overcome the lack of high-quality, spatially-explicit historical land use data and that it can be used to quantify landscape level changes, induced by e.g. biogas production.

Agricultural land cover changes in Weser-Ems showing that between 1999 and 2019 the area of maize cultivation increased by 94 %, while the areas of other summer crops and grasslands decreased by 66 % and 14 %.



Note: Values for years 1999-2007 were predicted based on remote sensing, while the values for years 2011–2019 were obtained based on IACS (Integrated Administration and Control System) data

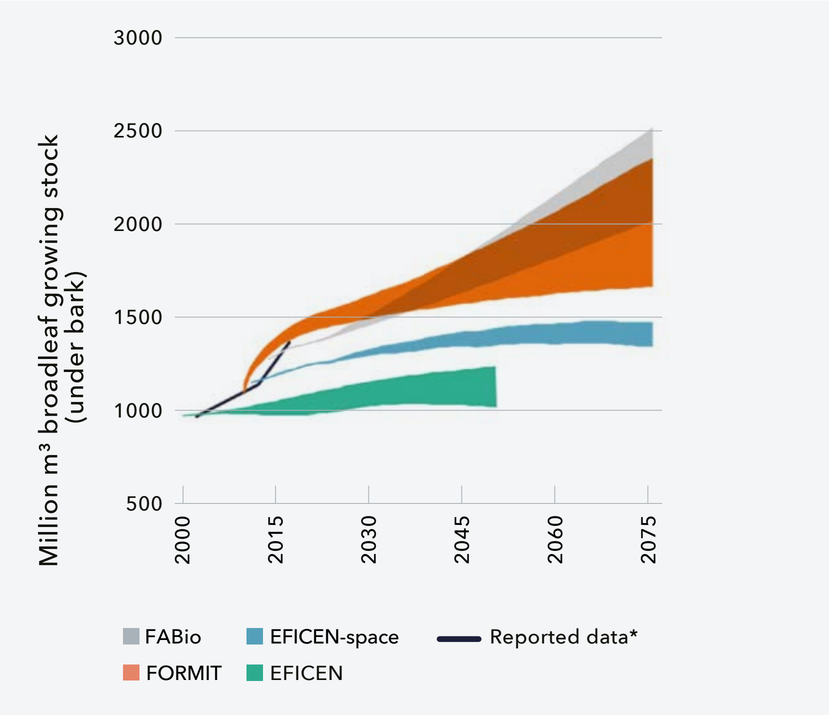
The forestry sector

Out of more than 70 surveyed models, 10 were identified as suitable for monitoring Germany's forestry sector at a national level. In other words, those 10 models can spatially cover all of Germany and at the same time provide all or at least a subset of the monitoring indicators identified as relevant for forests and forestry bioeconomy monitoring during expert exchange.

A dashboard of forest indicators was developed based on results of three basic scenarios in different studies, considering three different disturbance sensitivities. It was found that harvest scenarios reveal significant variations in wood extraction, emphasising the need for careful planning to balance supply, demand, and conservation efforts to maintain biodiversity and mitigate climate change impacts. Model results indicate that growing stocks of broadleaf trees will likely continue to contribute to CO_2 sequestration, but that coniferous stand's growing stocks are more vulnerable to natural disturbances.

Drought and bark beetle infestations strongly impacted the forestry sector in recent years. If high rates of forest disturbance continue, this could affect capacities to meet demands in the bioeconomy with wood from German forests, in particular in e.g. construction with a preference for coniferous wood. The occurrence of these natural disasters underscores the need to support a structural shift in the composition of German forests — toward higher levels of broadleaf species — as well as to support innovation for increasing the use of such species in German product markets.

Current forest bioeconomy monitoring models represent biomass and carbon indicators well, but have some shortcomings regarding comprehensive coverage of biodiversity, soil, and water indicators. Biodiversity indicators show positive trends across scenarios, but careful management is needed to optimise outcomes. Tentative results for forest soil carbon sequestration indicate that soils may approach saturation, with projected significant decreases in annual CO_2 sequestration by 2050.

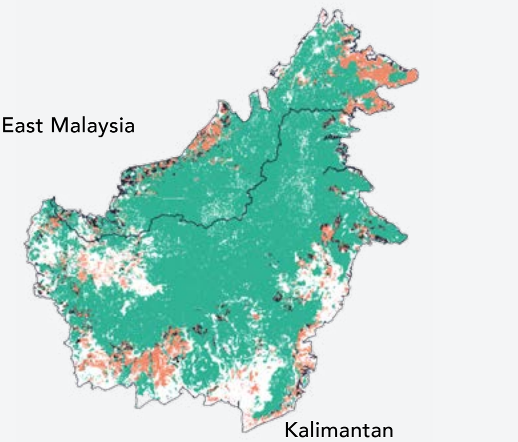


*Reported data: forest inventory (www.bwi.info)

FABio: Forestry and Agriculture Biomass Model; FORMIT: Forest management strategies to enhance the mitigation potential of European forests; EFISCEN: European Forest Information Scenario Model

Scenarios simulated for Germany's forests with four different forest growth models for different climate change and management assumptions reveal that projected pathways for broadleaf wood stock development differ considerably. A general conclusion is that the influence of the wood withdrawal and management regime on the development of broadleaf stocks can be as high or even higher than the influence of the prescribed climate / disturbance scenarios.

Environmental impacts abroad



The consolidated map shows the deforestation attributed to oil palm cultivation between 2015 and 2021 in specific regions of Indonesia and Malaysia. Indonesia and Malaysia produced over 83 % of the world's palm oil in 2022/2023.

Crop-driven deforestation and high value nature areas

Quantifying the extent to which crop production contributes to global deforestation provides a valuable context for understanding the role of the German bioeconomy within broader global trends. This insight helps to assess the associated risks and reveals how consumption patterns influence deforestation rates based on the sourcing of specific crops. To this end, remote sensing offers a significant advantage by delivering near real-time, up-to-date data on deforestation, surpassing conventional statistical methods in tracking changes in natural resources and environmental impacts.

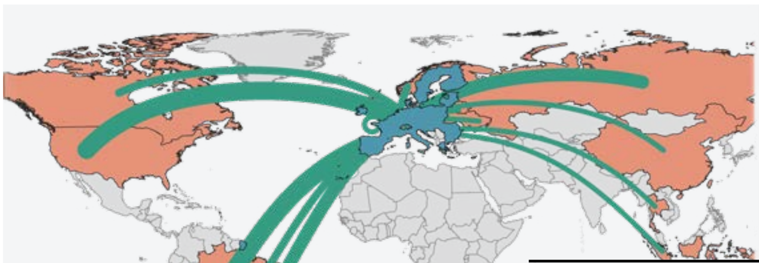
Crop-driven deforestation related to oil palm in both Indonesia and Malaysia as well as soybean and sugarcane in Brazil peaked in 2012 and, as a result of dedicated policy measures, has since been in decline. Mapping showed substantial overlap between soybean- and sugarcane-driven deforestation and high value nature areas, with e.g. high species diversity, in Brazil.

Further extending and operationalising the semi-automated remote sensing tool could support the development of more sustainable supply chains as well as the prioritisation of targeted conservation actions, in particular in places where the destruction of natural ecosystems overlaps with high value nature areas. Such monitoring provides insights into how shifts in consumption and trade patterns influence deforestation rates in specific regions, enabling more effective responses.

Tracing wood products

To better monitor the foreign impacts of production associated with the German bioeconomy, a novel approach combining a physical accounting model with a material flow life-cycle assessment approach was developed and used to trace the locations of origin of specific wood flows and their associated sustainability effects.

It was found that nearly 113 million m^3 fibre equivalents of wood contained in finished paper products were consumed in the EU-27 in 2018. Around 65 % originated domestically and 35 % originated from other countries (especially the US, Brazil and Uruguay). Germany was the largest consumer country in the EU (consuming 26 % of the total). To assess socio-economic and environmental impacts, a case study looked at employment, value added generation and global warming potential in Uruguay connected to the EU consumption of paper products, underlining that impacts of the bioeconomy are not confined to national borders.



Global distribution of international wood origin contained in finished paper products (FPP) in the EU

Bioeconomy footprints

Footprints include both the direct and indirect resources used to produce the products consumed in Germany. They are calculated based on a global trade model, and present a complementary perspective to the more detailed tracing of national physical flows.

Agricultural biomass footprint

The total agricultural biomass footprint in Germany was 341 million t in 2021. It has fallen by 24 % over the last two decades, mainly due to a decline in fodder crops and grazing as well as vegetables and fruit.

The most important agricultural products in terms of volume used were fodder crops and grazing (103 million t), straw (74 million t), sugar crops (34 million t), cereals (35 million t), and vegetables, fruits and nuts (54 million t).

Overall, 30 % of the agricultural biomass footprint in 2021 came from Germany, 21 % from the rest of the EU-27 and 4 % from the rest of Europe. The share stemming from the Middle East and Northern Africa in particular has risen, from 7 % in 2000 to 11 % in 2021. As regards crops, wheat, other cereals, sugar crops, vegetables, fodder crops and grazed biomass are predominantly sourced from Germany and the EU, while the majority of rice, tobacco, spices, nuts and fibres come from outside Europe.

In 2021 the per capita agricultural biomass footprint of consumption was 4.1 t per person. In comparison to the global average (3.1 t agricultural biomass per person), German total consumption is almost one-third higher. It is over double the suggested reference value (of 2 t of both agriculture and forestry biomass) for keeping global consumption levels within planetary boundaries.

tonnes per capita in 2021

Timber (industrial roundwood) footprint

Looking only at industrial use of timber — i.e. excluding fuel wood — a preliminary footprint was estimated for Germany of 62 million m^3 roundwood equivalents in 2021. Around 35 % came from Germany, 40 % from the rest of the EU-27 and 6 % from the rest of Europe. By tracking trends in consumption patterns as well as indirect flows connected to timber consumption, the timber footprint could contribute to monitoring Germany's contribution to pressures on global forests, as well as to grounding the discussion on how to best prioritise the consumption of forest-based wood in Germany. But to this end, the method and underlying database need improvement. In particular the shift to the GLORIA database has led to some challenges regarding sub-sectors, conversion values and domestic extraction after 2018.

cubic meters roundwood equivalents for industrial use per capita in 2021

Agricultural land footprint

In 2021, the total agricultural land footprint of the German bioeconomy was approximately 468 thousand km^2, of which around 40 % related to cropland and 60 % to grassland. In comparison, the total land coverage for agriculture in Germany was 166 thousand km^2. As such, the agricultural land footprint of consumption was 2.8 times higher than agricultural land use in 2021 in Germany.

The country with the largest total agricultural land use for German consumption in 2021 was Argentina (89.5 thousand km^2), followed by Germany itself (61 thousand km^2), the US (34.4 thousand km^2) and China (27 thousand km^2). The dominant land use that contributes to the footprint in Argentina, the US and China is grazing. Between 2000 and 2021 the land footprint decreased by almost 38 %, primarily driven by reductions in the footprint of fodder crops and grazing.

Around 68 % of used agricultural land was characterised by at least a medium risk for soil erosion, with 1.4 % located on high risk areas in 2021. As soil degradation is a critical problem for sustaining agricultural production systems, on-farm measures to improve soil quality and to minimise soil loss should be actively supported as part of sustainable supply chains.

thousand sqare meters per capita in 2021

The per capita German agricultural land footprint was 5,635 m² in 2021, of which around 2,200 m² were comprised of cropland. In comparison, the globally available cropland per person was 2,000 m² in 2021, making the German cropland footprint around 10 % higher. A global benchmark value for cropland use per person of 1,600 m² in 2050 has been suggested in the literature as safe and just (within planetary boundaries). Using this as a proxy reference value, the German cropland footprint in 2050 would just slightly surpass, by 1.25 %, the benchmark in the reference scenario (see below).

Climate footprint

tonnes CO_2 equivalents per capita in 2021

The climate footprint of the German bioeconomy was 152 million t of CO_2 equivalents in 2021, corresponding to 1.85 t CO_2 equivalents per capita. It has fallen by 35 % since the year 2000. While CO_2 emissions and N_2O emissions fell by 22 % and 18 % respectively, methane emissions have been reduced by 55 %.

Land use change related emissions were not included in the estimated footprint. If they were, the footprint would be higher. Preliminary results find that around 0.5 t of CO_2 equivalents per capita in 2021 were attributed to German consumption abroad linked to annualised land use change.

Germany's climate footprint was 76 % higher than the production-related bioeconomy GHG emissions in 2021. Overall, 33 % of the climate footprint in 2021 came from Germany, 22 % from the rest of the EU-27 and 3 % from the rest of Europe. Adjusting meat consumption and energy use are key reduction potentials.

The bioeconomy is regarded as a key lever for reducing the GHG emissions of the fossil energy system. At the same time, the bioeconomy also generates GHG emissions in proportions higher than their contribution to value added and employment: The bioeconomy comprises at least 5 % of total gross value added, 7 % of total employment and around 15 % of the total climate footprint. Although the climate footprint of the German bioeconomy is declining, careful attention to land use impacts is still needed, in particular to prevent counteracting substitution benefits.

Water footprint

cubic meters per capita in 2020

The total water requirement of the German bioeconomy was 37 km³ in 2020, of which around 8 % was for irrigation water withdrawals. The difference (34 km³) corresponds to the water that plants draw from the soil, i.e. rainwater. The cultivation of oil crops, followed by cereals, roots and tubers, and fruits were associated with the highest total water footprint in 2020.

The proportion of water consumed in Germany accounts for 14 % of the total water footprint. After Germany, the largest contributions came from the Ivory Coast, Brazil, Congo, Spain and Nigeria, each with around 5 %. Germany accounts for only 4 % of the irrigation water footprint, meaning that relatively more irrigation water (96 % compared to 86 % of total water requirements) is used abroad. Spain, the US, Turkey, Iran, India and Greece are the countries that irrigate the most for the German bioeconomy.

In 2020, 16 % of the total water footprint of the German bioeconomy was associated with regions that suffer from high water stress, led by the countries Iran, Egypt, Pakistan, Tunisia, Lybia and Syria. In the countries with high water stress, the median share of irrigation in the total water footprint was 53 %. Close monitoring is needed to ensure that global water stress is not exacerbated by the development of the German bioeconomy.

The contribution of the German bioeconomy to water pollution (e.g. through over-fertilization and pesticide use beyond environmental thresholds) requires greater attention and prioritisation, with the water quality footprint providing one tool to this end. In 2020, the total water volume needed to dilute the water pollution associated with agricultural production for the German bioeconomy was 4000 km³, which equals 90 times the volume of the Lake Constance.

Biodiversity footprint

As a new addition to more established environmental footprints, the biodiversity footprint exists as a prototype and its methodology and database are being further developed. It aims to capture biodiversity impacts of commodities in unprecedented detail, accounting for species-specific sensitivities and fine-scale exposures to land-use changes, and for effects of both land use expansion and intensification via ecosystem displacement and degradation. To this end, it assimilates comprehensive biodiversity and remote sensing data using advanced machine-learning approaches.

A case study found a 134 % increase in the biodiversity footprint of Germany's consumption of Brazilian soy from 1997–2007 to 2008–2018, despite a 55 % decrease in imports. This was mainly a result of the expansion of soy-production areas into biodiverse landscapes. The case study demonstrated that this type of analysis offers unique insights that complement monitoring of e.g. crop-driven deforestation and land footprints. The preliminary results underscore the key role of regional land-use dynamics (expansion, intensification, shifts) and biodiversity gradients and sensitivities, which can drive even greater footprint changes than mere changes in import and consumption volumes.

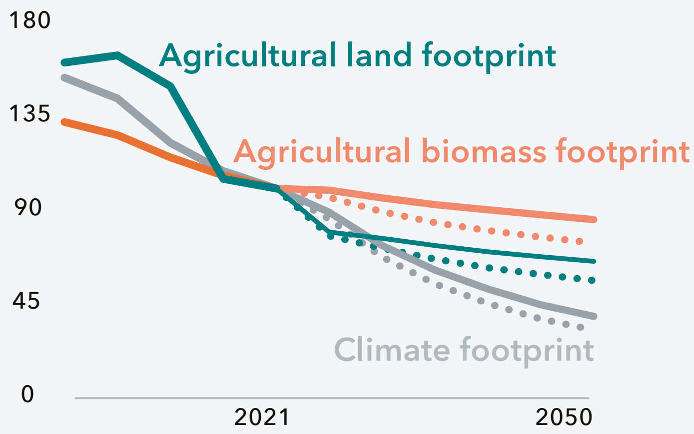
Scenarios and implications

Future footprint scenarios were modelled until 2050. The reference scenario is largely based on continuity with regard to the influencing variables that are important for the development of the bioeconomy in Germany, Europe and the world. Deviations from trend developments are taken into account when they are enshrined in law, as is the case with the energy transition in Germany and the EU (e.g. based on the Climate Protection Act and the Green Deal), so that e.g. the reference scenario aligns with climate targets.

Simple what-if scenario elements were used to showcase alternative pathways from the reference scenario. The aim was to explore key levers for change by isolating parameters in a comparative-static analysis that could contribute to (or harm) a sustainable transition. For example, the scenario 'dietary change' considers an enhanced dietary shift toward less meat and dairy, as aligned with dietary recommendations of the German Nutrition Society. The scenario 'organic farming' is to test the impact that 100 % organic farming in Germany by 2050 (linear increase until then) would have on the size of the land footprint.

The scenarios show a continued decline in the agricultural biomass, agricultural land and climate footprints. Reducing meat consumption is clearly one of the biggest levers to lower Germany's global land pressures. If per capita meat consumption were reduced to 300 grams per week in Germany, the agricultural biomass footprint would be 13 % lower, the agricultural land footprint 14 % lower and the climate footprint 17 % lower than in the reference scenario in 2050.

In the 100 % organic farming in Germany scenario, the agricultural land footprint in 2050 is 5.9 % higher than the reference. This is a result of the assumed lower crop yields. Potentially positive effects on soil carbon, biodiversity of agricultural systems and reduced application of mineral fertilizer were not accounted for in the analysis.



Solid line: Past trend and reference scenario

Dotted line: Dietary change scenario

Conclusions

Policy plays a pivotal role in how the bioeconomy is implemented. It is crucial for creating an enabling environment that fosters bio-based innovations. At the same time, measures targeting increased biomass use can have far-reaching impacts on landscapes and resources, both within Germany and abroad. This has been demonstrated in several cases, such as on the impacts of biogas production in the Weser Ems region of Germany and of soybean cultivation in Brazil. As Germany moves forward with the bioeconomy transition, it is essential to carefully weigh potential future impacts against stated objectives to ensure a holistic and sustainable bioeconomy transition. This balanced consideration is vital for developing a bioeconomy that aligns with broader sustainability goals and minimises unintended negative consequences. Five key messages are summarised here.

1. Base policies on a systemic perspective

Policy should not be based on a single indicator or aspect, but on a comprehensive perspective and cross-scale analysis, which usually requires a combination of methodological approaches, like those depicted in this report (material flows analysis, life cycle assessment, remote sensing, innovation analysis, stakeholder participation, scenario modelling, etc.). This is the only way to avoid problem shifting and spill-over effects. For example, monitoring substitution effects faces the challenge that it relies on assumptions that may not fully capture real-world complexities, in particular as regards the scaling-up of product innovations. In this case, it is particularly relevant to pay attention to the system boundaries and methodological limits when interpreting key findings for policy making. Along these lines, diverse and flexible strategies that can be adapted over time to reflect new circumstances are needed.

While bio-based resources are potentially regenerative, they are not unlimited. Synergies and trade-offs from a systemic perspective require careful consideration.

While bio-based resources are potentially regenerative, they are not unlimited. Therefore, synergies and trade-offs between different biomass use options requires careful consideration. This is particularly relevant for decisions between material versus energy use. New policy strategies aim to prioritise the material re-use of biomass in cascades, with energy recovery as the final stage. However, biomass access between competing end uses is currently not equal. In comparison to the energy sector, the material use of biomass is generally more influenced by long-term strategies and less by regulatory frameworks and measures (such as quotas and price incentives). A more level playing field is needed as a first step toward incentivising cascading use.

Policy should focus not only on improving sustainable biomass production, but also on monitoring and promoting the sustainable processing and consumption of biomass-based products. That includes their use, re-use and avoidance when relevant, through e.g. awareness raising as regards excess and sufficiency as well as incentivising business models that promote more efficient biomass use.

2. Remove barriers and invest in positive drivers

Invest in people. Provide training for skills development, support rural start-ups and foster social innovation.

Invest in education and skills development programmes to equip the German workforce, in particular in industry, with the necessary expertise in biotechnology, digitalization, and other bio-based and novel technologies needed to implement the future bioeconomy. Simultaneously, in light of declining employment in primary production sectors, provide support for rural development initiatives, such as fostering new creative business strategies (rural start-ups) related to bioeconomy goals. Promote a just transformation for affected communities by ensuring that the bioeconomy does not lead to precarious working conditions or intensify wage gaps.

Create incentives for private sector investment in product and process innovation focused on smart, strategic and sustainable biomass use. Revisit existing misleading regulations and develop supportive regulatory frameworks, including tax incentives and streamlined approval processes and regulations for bio-based products. However, make meeting sustainability criteria a prerequisite for funding to ensure responsible development. Avoid broad stroke measures that risk promoting overconsumption, instead favouring targeted approaches that encourage sustainable practices, accompanied by clear indicators to assess new value chains from the start.

Foster the development of business models and infrastructures for re-use through investments in research and development. This should encompass technical, cross-cutting, and social innovation. Ensure that the quality of materials such as textiles, paper, and wood-based products is suitable for the transition to a circular bioeconomy, facilitating their repeated use and recycling.

3. Raise public awareness and participation

Technological innovations can contribute significantly to sustainability, but they must be complemented by behavioural changes and strategic prioritisation in biomass use. Engaging the public in both monitoring and policy-making processes fosters a more inclusive and effective transition to a sustainable bioeconomy, ensuring that diverse voices, fields of knowledge, values, interests and perspectives are considered in the process.

Clarify to the general public that biological resources are overused in many places across the world. The agricultural land and agricultural biomass footprints, in particular, show that there is no sustainable capacity for increased total use of primary agricultural biomass in already high-consuming countries like Germany. Instead, inefficient and excessive use patterns must be adapted and the focus shifted to secondary biomass. To this end, promote the general message: “Biomass is limited. There is no ‘waste’, only secondary resources.” This shift in perspective can encourage more sustainable practices.

BOX 1. STAKEHOLDER PERCEPTIONS

Stakeholder participation helps to build a monitoring that is credible, transparent, and covers multiple perspectives. Stakeholder participation has been a part of the SYMOBIO project since 2017. Recent findings indicate that the perception of stakeholders as regards narratives versus implementation of the EU and German bioeconomy strategies differs widely, with an express desire towards a ‘socio-ecological transformation’, but a perception of the bioeconomy’s current performance as closer to ‘green capitalism’. Stakeholders have also identified monitoring gaps in the coverage and robustness of social indicators as compared to environmental and economic dimensions.

4. Establish a regular bioeconomy monitoring

So far, research projects in Germany, like SYMOBIO 2.0 and MoBi II, have assessed the tools, data, and indicators available for monitoring the bioeconomy from a systems perspective, focusing on further developing both analytical methods and underlying data. This knowledge now needs to be used and directed toward the development of a regular bioeconomy monitoring, ideally characterised by a robust, comprehensive and manageable set of indicators that is useful for diverse groups of stakeholders (society, politics, business and science).

BOX 2. THE BIOECONOMY MONITORING LANDSCAPE

Dedicated reporting initiatives, programs and activities monitor specific and varied aspects of the bioeconomy (from natural resource management to innovation activities and social change). While individually they do not provide a systemic overview of the bioeconomy transition, they can provide deep insights into detailed aspects, as well as potential overlaps, synergies and connection points for bioeconomy monitoring as a whole. To this end, over 100 specific monitoring systems across Germany, the EU and at a global level were reviewed. It was found, for instance, that the six environmental footprints presented in this report have thematic links to more than 60 reviewed monitoring initiatives with bioeconomy relevance, revealing the potential for the monitoring presented in this report to complement on-going activities. In general, a high level of overlap and strong coverage related to environmental impacts was found, whereas socio-economic factors, including aspects like consumption dynamics, were identified as underrepresented.

To this end, data and indicator gaps, e.g. in established statistics, must be addressed. For example, the wider availability of official statistical data, in particular for research purposes, is crucial. Currently, official statistics on e.g. residues from food production of aquatic biomass do not exist. Instead, monitoring relies on approximations based on expert knowledge. Statistical classifications should also be further developed and updated at regular intervals to better differentiate between bio-based and fossil-based sectors and products, and in both monetary units as well as physical quantities. Data is often available only at highly aggregated levels, which diminishes the capacity to account for smaller bio-based sectors or to monitor regional bioeconomy data. The continuity of methodological approaches in statistical reporting is also essential. The disruption in 2018 of the time series for both gross value added and employment shown in this report hinders the ability to derive policy-relevant implications regarding trends. The German Federal Statistical Office (Destatis) plays a fundamental role in this process and could benefit from increased support. This might also help to enhance the internationally comparable provision of resource footprint indicators (biomass, water, land).

To discuss and agree on a concise set of core metrics suitable for regular reporting, prioritisation and compromise is essential. Prioritisation requires broad stakeholder participation. Compromise may be necessary due to gaps between ideal indicators for bioeconomy monitoring and current monitoring capacities, which are in some cases under development and can only provide proxies at this time. The indicators provided in this report depict a potential core set of indicators on especially the status and environmental performance of the bioeconomy. Monitoring of socio-economic developments must be given more consideration overall.

5. Further support the development of modelling tools and monitoring capacities

Multiple novel monitoring approaches were presented in this report. There is a pressing need to continue to maintain, expand and adapt existing modelling and monitoring capacities to specifically address core issues related to the bioeconomy. While some loosely related indicators and models have already been developed, they are not necessarily designed to tackle bioeconomy-related monitoring questions effectively. To better support strategic decision-making, both an overview of bioeconomy performance and sufficiently detailed indicators are needed. To this end, it is essential to create fit-for-purpose indicators that align with the unique goals and needs of the bioeconomy. Key areas for actions include expanding analytical tools for monitoring e.g. biodiversity, establishing common standards for modelling, harmonising trade data and conversion factors, better incorporating land use change related impacts in greenhouse gas emission assessments, and further developing quantitative benchmarks on globally safe and just consumption levels for comparisons to footprints.

To better support strategic decision making, both an overview of bioeconomy performance and sufficiently detailed indicators are needed.

At the same time, it is crucial to reduce overlap and duplication in research efforts. By connecting bioeconomy monitoring to established and well-recognised monitoring systems, existing gaps in the monitoring landscape can be closed and understanding of interconnected topics is improved. At the state level, cross-boundary cooperation in Germany would also help to lever synergies between different regions.

Both types of analysis — improving new methods tailored to the bioeconomy and building links to established monitoring frameworks — should be further developed. This dual approach will facilitate a more comprehensive, concise and effective monitoring system that supports informed policy decisions in the bioeconomy sector.

Altogether, the trends and messages highlighted in this report have focused on the critical challenges ahead. This should not, however, detract from the big picture presented in this report: The bioeconomy is progressing, and it offers a whole range of sustainable development potential for Germany, e.g. in biotechnology. The prerequisite is that the use of biomass supports economic and social development within ecological limits. Our monitoring capacities are also continuosly advancing. Future efforts should focus on a smarter, more efficient and regenerative use of biomass. Monitoring of the German bioeconomy at the national level should continue to provide an overview of socio-economic and environmental performance from a systems perspective, and in the context of global sustainable development goals.

Find the main report and more information on bioeconomy monitoring at: www.monitoring-biooekonomie.de/en/

IMPRINT

This report was organized and prepared based on key outputs of the research project SYMOBIO 2.0 (Consolidation of Systemic Monitoring and Modelling of the Bioeconomy), funded by BMBF, and implemented by nine partners across Germany.

SPONSORED BY THE

Federal Ministry of Education and Research

It includes contributions stemming from the research project MoBi II (Development of a systematic bioeconomy monitoring—Consolidation Phase), funded by BMEL and carried out by Thünen Institute.

PUBLISHER

Center for Environmental Systems Research (CESR)
University of Kassel

3 December 2024