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Bioeconomy national strategies in the G20 and OECD countries: Sharing experiences and comparing existing policies

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ABSTRACT

This manuscript addresses the existing governance tools and monitoring systems for implementing a sustainable and regenerative Bioeconomy in the OECD member states and G20. It takes inspiration from the outcomes of an international workshop entitled "Bioeconomy in the G20 and OECD countries: sharing and comparing the existing national strategies and policies for co-designing more effective bioeconomy governance mechanisms and monitoring systems" co-organized by the Italian Presidency of G20 environment 2021, the National Bioeconomy Coordination Board of the National Committee of Biosafety, Biotechnology and Life Sciences of the Italian Presidency of Council of Ministers and the OECD Working Party on Bio-, Nano- and Converging Technologies. The workshop aimed to share virtuous experiences, identify challenges and co-design more robust governance tools and more comprehensive monitoring systems. The manuscript outlines the current situation regarding governance and monitoring, so as to identify relevant issues and areas for further research and policy action.

1. Introduction

The world has realized that building a sustainable bioeconomy can boost economic growth within environmental policy goals. At least 50 nations (Fig. 1) have put in place national tailored bioeconomy strategies or have policies that are steering towards a sustainable bioeconomy (El-Chichakli et al., 2016). For bioeconomy policy makers, the future is complex and multi-faceted. As the first generation of bioeconomy policies comes to a close, the vision of a bioeconomy pitched against societal grand challenges clearly needs better national and international policies and governance to succeed (OECD 2018).

The pervasiveness of national bioeconomy strategies (Fig. 1) manifests the increasing worldwide commitment to the green transition, i.e., drastically reducing greenhouse gas (GHG) emissions, replacing fossil carbon with renewable resources, and regenerating the environment, its biodiversity and ecosystems (Anon 2023). While the fundamental justification for public intervention in the bioeconomy is improved sustainability (Marvik and Philp, 2020), there is a need to agree on informative and practical measurement tools and indicators as a basis for policy development and for an effective and responsible implementation of the bioeconomy in the different territories, countries and continents. One of the earliest strategies was the US bioeconomy blueprint of 2012 (US White House 2012), which maintained the link between economic activity and biotechnologies. Since then, the links to major economic sectors have been reinforced while the emphasis on biotechnologies has decreased (Bell et al., 2021; National Academies of Sciences, Engineering, and Medicine 2020).

There is no internationally accepted definition of 'bioeconomy', and different definitions have often arisen in response to the priorities of an individual country (Frisvold et al., 2021). Most EU member states (MS) have adopted the definition proposed in the EU bioeconomy strategy (European Commission 2022). Since the bioeconomy is meant to stimulate international trade, a lack of an agreed international definition means that measuring and monitoring the bioeconomy cannot be carried out on an internationally comparable basis. Moreover, there is wide agreement that sustainability encompasses the three pillars of

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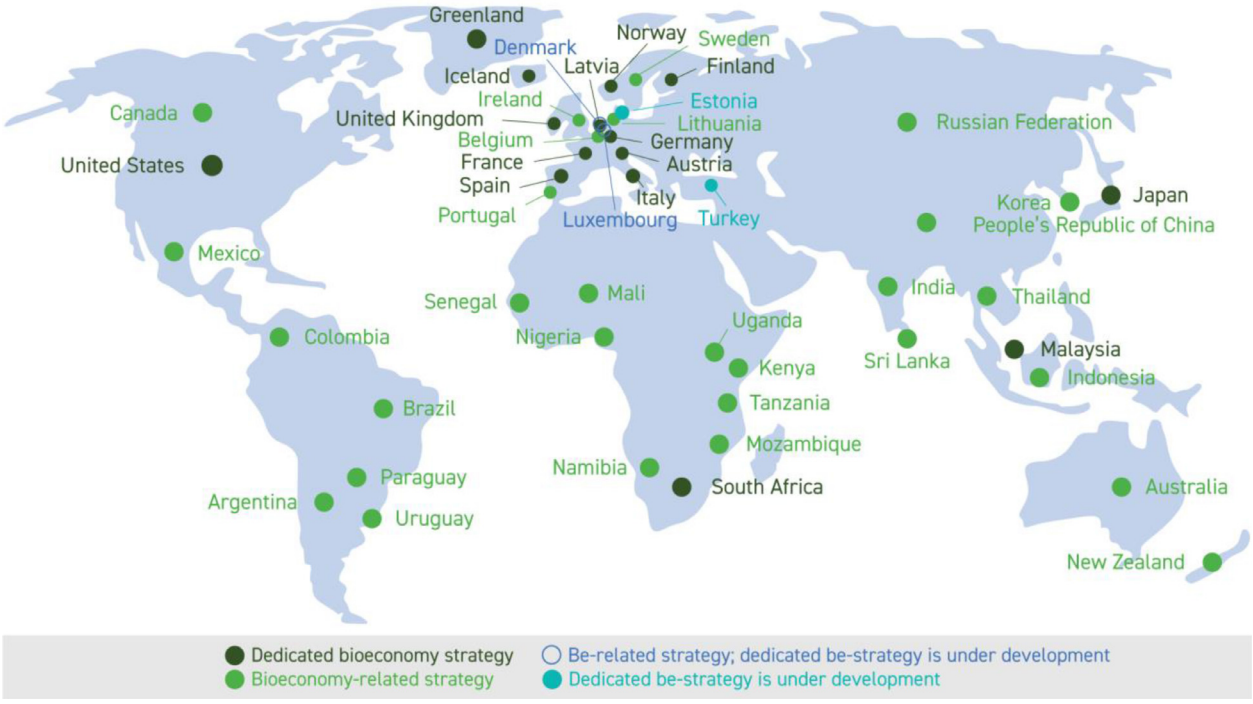

Fig. 1. National bioeconomy strategies and related policy instruments. Source: OECD (2018). Meeting policy challenges for a sustainable bioeconomy. OECD Publishing, Paris. ISBN 978–92–64–29,233–8.

economic, environmental and social aspects. This further complicates sustainability assessment. For instance, there are no internationally agreed tools or indicators to measure biomass sustainability (van Dam and Junginger, 2011; Böhringer and Jochem, 2007; Bruckner et al., 2015; Arru et al., 2022; Velasco-Mu˜noz et al., 2021; Dumitru and Wendling, 2021; Aggestam and Giurca, 2022) and social issues such as workers' rights and land rights are difficult to measure (Shawki, 2016).

Not only has the bioeconomy concept diversified, but several G20 and OECD countries have revised, or are revising, their bioeconomy strategies. In Europe, they are aligned in terms of sectors and priorities and there is significant association of the bioeconomy with the circular economy (Stegmann et al., 2020). Furthermore, bioeconomy has also the capacity to regenerate the environment, coastal, rural and abandoned lands as well as former industrial sites. Therefore an inescapable conclusion is that sustainability and environmental regeneration will be a major goal of governance for the bioeconomy of the future. But with continuing debate about how to measure and monitor sustainability, it is timely for an OECD event organized in the frame of a G20 environment chaired by a Ministry for the Ecological Transition to revisit the topic and identify a way forward for OECD economies. The National Bioeconomy Coordination Board of the National Committee of Biosafety, Biotechnology and Life Sciences of the Italian Presidency of Council of Ministers in Rome held a workshop to highlight recent developments in bioeconomy strategies and ask some key questions of the governance of the bioeconomy. All G20 and OECD countries with a dedicated bioeconomy strategy in place or ready to be adopted were invited to contribute to the event, which was designed as two panel sessions. The detailed programme is reported on the Supplementary Materials and further information is available at the dedicated web site (Anon 2022). The workshop aimed to share virtuous experiences and identify challenges. It is hoped that this could lead to future work to co-design more robust governance tools and more comprehensive monitoring systems across countries such that international harmonization might be approachable.

The present paper attempts to set out progress in monitoring the bioeconomy internationally, with particular reference to OECD member states, then takes a more nuanced look at what is happening within the European Union. Concrete progress towards a methodology for monitoring at the international level has been made at the United Nations Food and Agriculture Organization, and this deserves specific attention as it seems to point to the way that the private sector may operate in future. But the bioeconomy will increasingly need to adjust to the needs of net-zero carbon by 2050. Thus the final section considers how the bioeconomy relates to carbon management and the extension to other forms of renewable carbon which take pressure off land and biomass – it is not possible to replace fossil production completely with biomass (Kircher, 2022). The use of such forms of carbon as flue gases, solid municipal waste and in the longer term atmospheric carbon (Carus et al., 2020) will alleviate biomass supply issues while bringing greater political visibility to the bioeconomy.

2. Bioeconomy strategies and monitoring progress: the contribution of different OECD countries

The workshop was organized in two panels: "Bioeconomy strategies in the different OECD countries: comparison of their objectives, priorities, governance and implementation guidelines" and "Targets and monitoring tools: towards a common framework to monitor progress in the bioeconomy". Experts from G20 and OECD countries with a national bioeconomy strategy in place or under elaboration were designated by their national delegates and contributed to the two web panels mentioned and according to the programme in the supplementary material. Their contributions are summarized in the sections below, along with comments and some key statements of the representatives of OECD, European Commission, FAO and the hosting G20 Italian Presidency. The first panel session examined the essential elements of the existing bioeconomy strategies relating to governance through three questions.

1 Which sectors comprise your national bioeconomy (i.e., agriculture, livestock, aquaculture, fisheries, forestry, food industry, industrial biotechnology and biorefineries – plus the use of products in the pharmaceutical, cosmetic, chemical, textile, energy industries, municipal biowaste and wastewater valorization, composting, etc.) and the reasons for their selection.

2 How is the strategy on bioeconomy in your country implemented? Did your country develop an Implementation Action Plan following the Bioeconomy Strategy definition?
3 What are the missing policies, current needs and opportunities for your national bioeconomy?

The Bioeconomy of the EU MSs with a national strategy comprises sectors and economic activities that have been selected in line with the EU bioeconomy strategy. However, the relevance of the quoted sectors depends on the individual country, and the sectors' impacts on the respective economy, ecosystems and industrial context. Some countries are focusing more on agriculture, others on forestry, others on marine resources; some others are providing a special emphasis to the key enabling role of biotechnologies. Looking beyond the EU borders, Brazil, Japan, United States and South Africa included health, life sciences, medical diagnostics, therapeutics and precision medicines amongst the enabling pillars of their national bioeconomy, while Norway gives emphasis to the reduction of climate emissions and more effective use of renewable bioresources.

Details of the sectors that characterise the bioeconomies of the different OECD countries involved in the workshop are available in Table S1 of Supplementary Material.

The second panel session attempted to identify the gaps and opportunities in policy to ensure this sustainable future, again addressing three questions

1 Objectives versus indicators: Taking into account the context of your national bioeconomy, what indicators (economical, environmental and social) are you using and would be appropriate for the corresponding monitoring?
2 Managing complexity and interlinks: How did your country tackle the challenge of accessing statistical sources of high quality, homogeneous and aggregated data for monitoring and assessing the impact of the national bioeconomy strategy?
3 What kind of cooperation is needed/recommended between countries and actors active in this field, such as the Food and Agriculture Organization (FAO), the JRC Knowledge Centre for Bioeconomy of the European Commission, in order to reach consistent and comparable country assessment and results?

The inputs provided by the speakers during their presentations or in the discussion session, are summarized in the following paragraphs. The aim was to offer a picture which, far from being exhaustive, is nonetheless significant because it was traced on the basis of a lively discussion between the representatives of the participating states, rather than on desk analysis.

Concerning the monitoring of national bioeconomies, many of the countries with a national strategy (i.e., Italy, Austria, Norway) or similar national policy statements (i.e., Ireland), are working at the definition of the most suitable indicators and data to use. The general intention is to implement different databases and use the therein mapped measures to show the public the level of achievement of the strategic objectives of the bioeconomy strategies. The point is that the bioeconomy relies on several sectors and that each sector draws on a wide range of data and measures to monitor and evaluate its performance and sustainability. The most envisioned indicators are the availability of primary feedstock, the output from economic sectors considered part of the bioeconomy, and a number of sustainability indicators, including economic (e.g., employment, private investments in new bioeconomy value chains), social (e.g., well-being), and environmental (e.g., accounting of natural capital and ecosystem services such as carbon sequestration, reduction of GHG emissions).

There are risks associated with countries developing their own bioeconomy strategies in isolation. They tend to emphasise what is important for their own country (Bracco et al., 2018), and this is often contributions to GDP, turnover and employment in the sectors of most direct concern to them. On the other hand a clear objective of the bioeconomy in an international sense is environmental sustainability: national bioeconomy strategies overwhelmingly discuss sustainability (Bell et al., 2021) but as long as there is confusion as to what sustainability is and how to measure it, its deployment will be hindered.

As climate change policy has evolved, there has been a sharp focus on emissions reduction in sustainability, which should help increase the visibility of the bioeconomy. If other aspects of sustainability are crowded out of policy conversations, this creates a potential for unintended consequences that later may need to be reversed (OECD 2023). This has been termed "sustainability tunnel vision". For example, overreliance on biomass for bioenergy purposes could result in deforestation, and exacerbate negative externalities for biodiversity (Anon 2023), and even stimulate criminal illegal logging. Land use and land use change is a major, if not the major, source of sustainability trade-offs: efforts to maximise one benefit of land nearly always reduce other benefits (Meyfroidt et al., 2022). If not apparent at the national level, this is an essential reason for international dialogues such as this workshop.

The debate gave voice to the efforts of nine different countries towards the implementation of monitoring systems capable of assessing environmental and socio-economic progress specifically attributable to the bioeconomy. Representatives from Austria, Canada, Finland, Germany, Ireland, Italy, Japan, South Africa, the United States reported on the reasons that led to the identification of databases and the selection of performance indicators that can be used for the monitoring process, which, in some cases, have not been fully implemented. For instance, Italy relies on EU key performance indicators (KPIs) on national supply and demand sides (Anon 2022) as reported in Table 1. Most indicators refer to Eurostat and national data and allow for the implementation of benchmarking analysis while others are based on the studies of Lier (Lier et al., 2018) and Egenolf (Egenolf and Bringezu, 2019) and on the results of the BERST project consortium (Anon 2022, 2022).

Finland is monitoring bioeconomy at sectoral level annually using selected indicators through the LUKE Institute (Anon 2022). Environmental and social indicators are now part of the broader national sustainability programme and SDGs. Germany is adopting a collaborative and joint monitoring approach developed by several German federal ministries (Research, Agriculture, Economic Affairs). The monitoring comprises material flows of resources from the agrarian, forestry and fishery sectors, but also data on residuals and waste streams. It includes more than 60 economic indicators and five footprints of the German bioeconomy (agrarian and forest land use, material use of wood, water use, GHG balance), which were modelled. Data, indicators and models are under refinement with the intent of expanding the monitoring scope by further aspects like biodiversity.

The Canadian forest bioeconomy is monitored through several processes. The Montreal Process is a framework of criteria and indicators to report progress towards achieving sustainable forest ecosystem management. Also, every year the State of Canada's Forests Report provides information on trends, statistics and stories related to sustainable forest management in Canada to ensure forests remain healthy for future generations.

South Africa is measuring the contribution of the bioeconomy to the GDP and the focus of much of government attention is on how the strategy assists in developing household food security, reducing the impacts of the disease burden, encouraging entrepreneurial opportunities and relevant skills development, together with the establishment of an enabling system of innovation. A broader macroeconomic monitoring system is under development, and it will rely on innovation input measures, innovation output measures, and more economic measures including economic growth, employment, investment and export measures.

The US Bioeconomy Initiative Implementation Framework tracks key indicators (economic, environmental, and social) while board member agencies complete an annual or biennial evaluation, leveraging resources such as EPA reports and RFS databases (USDA's various databases, statistical services, and market reports; DOE's biomass assessments). The US Administration priorities include a requirement to reach net-zero emissions by 2050 and indicators measuring bioeconomy

Table 1
Key performance indicators at national and regional level reported in the Italian Bioeconomy strategy.

Criterion	Indicators
Biomass availability	Agricultural biomass production (kg/capita) – import of agricultural biomass
	Blue biomass production (kg/capita) – import of blue biomass
	Forestry biomass production (kg/capita) – import of forestry biomass
	Waste biomass production, including OFMSW (kg/capita) – import of waste biomass
Productive structure	Firms in total bioeconomy sectors (% of total firms)
	Firms in bioeconomy sub-sectors (% of total firms)
	Innovation start-ups in total bioeconomy sectors (% of total innovation start-ups)
	Innovation start-ups in bioeconomy sub-sectors (% of total innovation start-ups)
Employment structure	Employment in total bioeconomy sectors (% of total employment)
	Employment in bioeconomy sub-sectors (% of total employment)
Human capacity	R&D Employment in total bioeconomy sectors (% of total employment)
	R&D Employment in bioeconomy sub-sectors (% of total employment)
	University courses in bioeconomy sectors (% of total university courses)
	Research institutes in bioeconomy sectors (% of total research institutes)
Innovation	IPRs (patents, trademarks, design) applications in total bioeconomy sectors (number of applications per 1000 population)
	IPRs (patents, trademarks, design) applications in bioeconomy sub-sectors (number of applications per 1000 population)
Investment	Private R&D expenditure (Index (EU=1])
	Public R&D expenditure (Index [EU=1])
Demographics	Population growth (% year)
	Population 15–65 years (% of total population)
	GDP (PPP) (Index [EU=1])
Markets	Turnover of total bioeconomy sectors
	Turnover of bioeconomy sub-sectors
	Value-added of total bioeconomy sectors
	Value-added of bioeconomy sub-sectors
	Exports of total bioeconomy sectors related goods (% of total exports)
	Exports of bioeconomy sub-sectors related goods (% of total exports)
	Imports of total bioeconomy sectors related goods (% of total exports)
	Imports of bioeconomy sub-sectors related goods (% of total exports)

progress toward emissions targets are also considered together with indicators on environmental justice to ensuring that the bioeconomy benefits all US citizens including traditionally underserved communities (Carlson, 2016; Executive Office of the President of the United States 2017).

Most countries recognise that monitoring and assessing national bioeconomy strategies is hampered by a general problem of data gaps and quality homogeneity, especially at the most disaggregated data levels. Although sectoral data are available, many bioeconomy actions are cross-cutting and the proposed measures are not able to distinguish how they interact with each other or the overall effect on implementation across the whole bioeconomy implementation. At the same time, disaggregation of the bioeconomic shares counted by international, EU and national agencies in terms of value-added and employment remains an important task. Amongst priorities, there is the need to develop tailored codes to distinguish between bio-based and non-bio-based products.

The US Office of Management and Budget (OMB) has recently accepted recommendations with respect to bio-based products manufacturing and renewable chemicals manufacturing, including the decision to "continue research and outreach in this important emerging area" (Carlson, 2016; Executive Office of the President of the United States 2017; Federal Register 2021). Similarly, Ronzon et al. (2020) described the challenges in estimating 'bio-based shares' for sectors which only partially belong to the bioeconomy, as reported in the European NACE (Nomenclature Statistique des Activités Économiques dans la Communauté Européenne) classification. Difficulties are also encountered for properly classifying people working in biorefineries, where they are currently considered workers providing different types of services.

In addition, monitoring mechanisms often fail to detect early-stage companies, start-ups and spin-outs, hence neglecting their key role in biotechnology development. Finally, monitoring tools are subjected to an evolutionary process, also in terms of data availability, that has to meet the change of public awareness and assessment priorities. Thus, several EU countries but also Canada and the US rely on the engagement of relevant national stakeholders for assessing data requirements and for conducting periodic revisions of programmes to evaluate impacts and future needs. At the same time, ad-hoc working groups, including different ministerial and regional representatives and national statistics offices, are active in some EU countries for monitoring and assessing purposes and they are often connected to the JRC (Joint Research Centre) of the EU Commission and EU networks and projects (e.g. Biomonitor; https://biomonitor.eu/).

An interesting initiative is represented by the Biopreferred Program of the US Department of Agriculture (USDA), which helps to ensure that the federal government prioritises purchasing of bio-based materials for federal procurement and monitors the impact of that programme on the US bioeconomy. The USDA tracks developments in the US bioeconomy with a report entitled "Indicators of the U.S. Biobased Economy" which details developments bioenergy jobs, revenues, and bio-based products (USDA 2018).

This second panel session of the workshop capitalised on the information and analysis provided by the country representatives. The conclusions called for more intensive cooperation between countries and actors active in this field (e.g. FAO, JRC Bioeconomy Observatory) in order to achieve a coherent assessment of the bioeconomy.

A more effective coordination between relevant institutions and stakeholders is essential to achieve the goal of recognising some common key indicators to evaluate the sustainability of the bioeconomy in a comparable manner in the different countries (Bugge et al., 2016; German Bioeconomy Council 2022; Stark et al., 2022). EU countries are already moving towards this objective *via* the European Bioeconomy Policy Forum and the actions formulated therein. In this context, all EU MS work together with the JRC to develop suitable indicators, applicable in a wider context. In that respect, Canada completed work as part of the International Bioeconomy Forum to overlay bioeconomy indicators with the UN SDGs to understand the linkages between the bioeconomy and the SDGs.

However, it is necessary to underline that bioeconomy potential and needs vary from country to country and even at regional level. Therefore, over-centralized, assessment practices and oversimplified data representations might jeopardise the validity of monitoring procedures. The workshop gathered the final auspices of the participants, amongst them South Africa and US asking for a far greater cooperation across the globe, possibly led by organizations such as the FAO. The cooperation will enable the identification of some common indicators for bioeconomy assessment at international level while other more specific indicators must be developed for constructing effective comparative analysis of bioeconomic developments at the global level. To ensure some agreement on the most suitable indicators, how specific parameters should be measured and ultimately how results can be compared (over time, regions, sectors) and interpreted, it would be useful to establish a network between bioeconomy monitoring groups, as well as stakeholders in the industry. Furthermore, the data should be available to anyone free of charge (open data access). The advances in digitalization, sensors, artificial intelligence (AI) and analytical tools relying on satellites

pave the way for the collection of reliable data and effective site-specific monitoring. At the same time these innovations allow for a drastic reduction of the reporting load for companies, forest owners and farmers. As new technologies are implemented and different priorities of sustainability come more into focus, the involvement of data collectors and statistic institutions becomes increasingly crucial for the establishment of consistent data codes and for the identification of new emerging needs in terms of data or monitoring practices. A comprehensive monitoring framework for the bioeconomy should thus address economic, environmental and social dimensions of sustainability and should be based on a set of indicators that were selected in a participatory process to provide information on the condition, performance and trajectory of the bioeconomy as a whole and at different levels. This will in turn support the preparation and evaluation of the bioeconomy related policies/legislations/instruments and will enable better coordination and cooperation at different policy levels, including regional and local scales. Thus, the impact of the monitoring framework may be an improved and consistent basis for better policy decisions at different policy levels.

3. The bioeconomy in The European Union: the position and the actions of the European Commission

The bioeconomy is a cornerstone of the European economy. The EU bioeconomy strategy was updated in 2018 (European Commission 2018) to place sustainability and circularity at its heart. For the update, the bioeconomy covers all sectors and systems that rely on renewable biological resources; it includes and interlinks land and marine ecosystems and the services they provide (Lange et al., 2021).

Looking at individual member states, there are currently ten EU member states with dedicated bioeconomy strategies and seven that are in the process of developing theirs. As highlighted in the progress report (European Commission 2022) published by the European Commission in July 2022, “since 2018, there have been several developments at national level: Austria, the Netherlands and Portugal have developed a (new) national strategy while Croatia, Czechia, Poland and Slovakia (supported by the BIOEAST initiative) as well as Sweden, started the process of developing one. Furthermore, Germany, Ireland, Italy and Finland, have updated their existing strategies or action plans and Finland, France and Spain are currently updating their existing national strategies or action plans.” Furthermore, 28 EU regions have in place their own dedicated bioeconomy strategies and 69 other EU regions are in the process or have already adopted strategies in which the bioeconomy is one of the key elements. (European Commission 2022; Haarich and Kirchmayr-Novak, 2022) Within the European scenario, Norway and the UK also have a dedicated bioeconomy strategy.

There are currently three large macro-regional bioeconomy initiatives in Europe, involving governmental authorities (Mubareka et al., 2023): BIOEAST - Central-Eastern European Initiative for Knowledge-based Agriculture, Aquaculture and Forestry in the Bioeconomy; Nordic bioeconomy; Bioeconomy in the Baltic Sea Region. Moreover, the European Territorial Cooperation Programmes – Interreg - played an important role in developing four additional macro-regional initiatives: Danube Region (DanubeBioValNet); AlpLinkBioEco, Linking BioBased Industry Value Chains Across the Alpine Region; BIO-ECOnomy Research Driven Innovation for the Adriatic-Ionian Region (Bioeco-RDI-ADRION); Bio-Innovation Support for Entrepreneurs throughout NWE regions (BioBase4SME).

The EU Bioeconomy Strategy and Action Plan takes a system-wide approach. It proposes more than research and innovation to strengthen the bio-based sectors and unlock investments. To deploy bioeconomies across Europe, policy must span the sectors and address tradeoffs (ecological boundaries) and co-benefits. It must deliver its benefits for rural areas in particular. To achieve this, it has a set of 14 well-defined actions, including a monitoring system. The further deployment of bioeconomy strategies and policies within the EU is supported through two key mechanisms. First, the European Bioeconomy Policy Forum is a knowledge exchange and policy dialogue forum for EU member states. It has five objectives, enabled by a dual structure: a strategic/political level high level group, and an operational/working level expert level group. The five objectives are:

1 Support networking and interaction between member states.
2 Enhance cooperation and best practice exchange.
3 Shape a concrete agenda of joint actions.
4 Increase the visibility/potential of the bioeconomy.
5 Enable policy feedback and analysis.

Second, the Bioeconomy Policy Support Facility was formed, with the objective to support the member states in the development of their own dedicated national bioeconomy strategy/action plans. Concerning governance, the facility took the form of a Mutual Learning Exercise with the aim of identifying and sharing best practice by 19 member states. The process was steered by independent experts and workshops were held addressing specific objectives (e.g., encouraging interministerial cooperation and stakeholder engagement, funding of bioeconomy development). A final report containing ten key policy messages and recommendations for the development of national (or regional) sustainable and circular bioeconomies has been published (Anon 2022). On the larger arena, the European Commission proposes transformation of the EU economy and society to meet climate ambitions through the European Green Deal. The European Commission sees a knowledge-based, sustainable and circular bioeconomy as a model for green growth. The JRC is the European Commission’s science and knowledge service. The EC’s Knowledge Centre for Bioeconomy, managed by the JRC, and the EU Bioeconomy Monitoring System are key tools for the deployment of a sustainable EU Bioeconomy (Sanchez-Jerez et al., 2023; Anon 2022, 2022, Kilsedar et al., 2021). A robust knowledge base and a fit-for-purpose monitoring system are crucial elements for adaptive and effective governance (Mubareka et al., 2023). The JRC approach to bioeconomy monitoring considers the constant evolution of the entire value chain and it is object of a constant updating activity (Kilsedar et al., 2023; Giuntoli et al., 2023). The system consists of ten steps to monitoring and evaluation (Fig. 2), with the selection, collection and compilation of indicators at its core, along with selection of reference values for each indicator (Anon 2022; Kilsedar et al., 2021).

The EU Bioeconomy Monitoring System addresses the need for a comprehensive monitoring system by establishing a mechanism to measure the progress of the EU bioeconomy towards the five strategic objectives it tackles (see Supplementary Material for details). It defines and implements a comprehensive monitoring framework for the EU bioeconomy, which covers environmental, social and economic dimensions of sustainability and relates to the overarching Sustainable Development Goals (SDGs) context.

As commented in a recent JRC publication, the monitoring of progress towards sustainability objectives still presents several indicator gaps, in particular on the full set of climate change adaptation indicators. Nevertheless, the existing indicators in agriculture and LULUCF (Land use, land use change and forestry), already show negative trends. Emissions from agriculture increased from 2012 levels and trends in the LULUCF are even more worrisome, with the sink effect reduced since 2013. The Water Exploitation Index, an indicator showing the balance between water demand and abstractions vs. water availability, appears particularly critical for water-stressed regions such as the Mediterranean (Mubareka et al., 2023).

4. The FAO initiative “Towards sustainable bioeconomy guidelines (SBG)”

Through support provided by the German government, FAO has been working on the project ‘Towards sustainable bioeconomy guidelines’ (De Santi, 2021) to help countries develop coherent sustainable and circular bioeconomy strategies, programmes and action plans. As part of

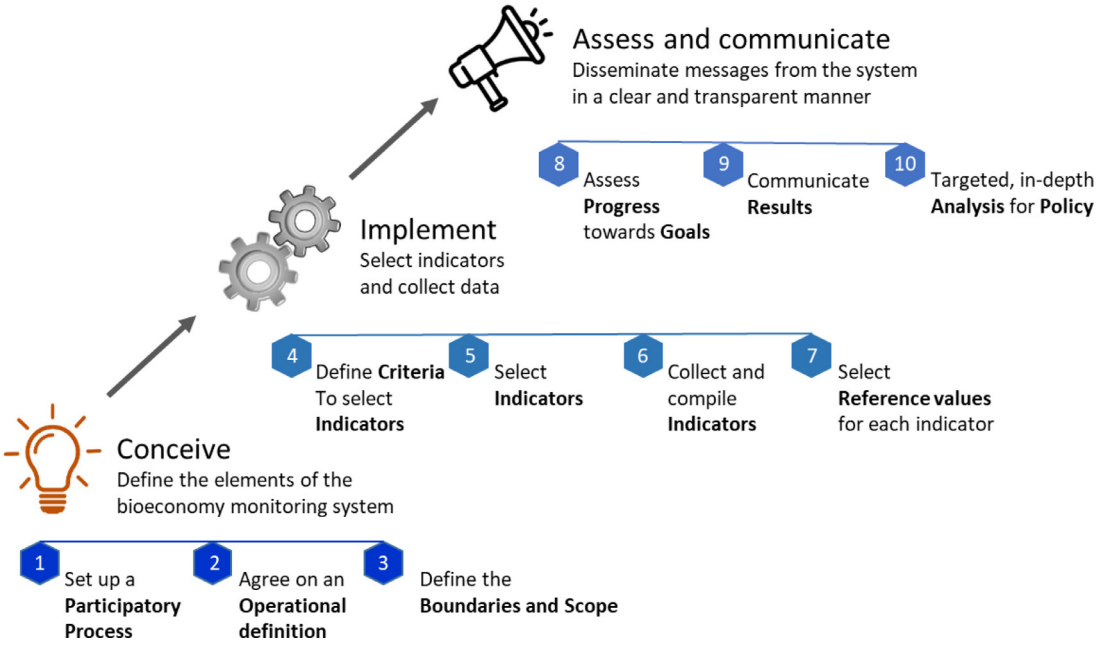

Fig. 2. Ten steps to monitoring and evaluation of the bioeconomy. Adapted from (De Santi, 2021).

this project, in 2016, an International Sustainable Bioeconomy Working Group, led by FAO, was established to foster knowledge-exchange on sustainable and circular bioeconomy between countries and regions, but also between science, policy and the private sector.

The International Sustainable Bioeconomy Working Group has already achieved a number of concrete results. First, Working Group members have agreed on a set of principles and criteria that serve as guidelines to mainstream sustainability in bioeconomy strategies. These 10 principles and 24 criteria cover the economic, environmental and social dimensions of sustainability, but also include governance as a fourth pillar. Second, Working Group members have stressed the need for comprehensive metrics and data for monitoring systems to measure the development of the bioeconomy and its contributions to the SDGs. Third, the International Sustainable Bioeconomy Working Group has stressed the need for bioeconomy initiatives to be linked more closely with other international policy processes, such as multilateral environmental agreements, including the Paris Agreement on climate change and the Aichi biodiversity targets.

5. The transition towards carbon neutrality: the OECD BNCT foresight study

An overarching question is how industry can be supplied with carbon feedstocks when the use of fossil carbon is discontinued. The concept of carbon management aims to provide a holistic view on carbon as a limited resource by broadening the perspectives of the bioeconomy to include reuse and recycling of carbon present in the bio- and technosphere (Carus et al., 2020) as well as direct use of atmospheric CO_2 as a future industrial feedstock. Finally, carbon capture and sequestration activities are also part of carbon management.

Even with the strongest intention to foster greater future sustainability and resilience, it is entirely foreseeable that the increasing use of biomass for food, materials, and chemicals, could lead to overexploitation of natural resources. Limited resources could then lead to competition for land between bioenergy (climate action) and food crops (food security) or between the bio-based production and the preservation of biodiversity and natural ecosystems. This raises a series of critical questions. How much land should be made available for human activities and when land appears to be a limited resource, how should it best be used, e.g. for food, feed, energy, or industrial products?

Meanwhile, it has become clear from various lines of evidence that biological resources alone cannot replace fossil resources as feedstocks for the future. Aviation fuel consumption in the EU was 62.8 million tonnes in 2018. Using sunflower oil as an aviation biofuel would require 60% of EU arable land (Anon 2022). Polymer production in Europe is of a similar volume (64 million tonnes in 2019). Global plastics demand could continue growing to about one billion tonnes by 2050 (Carus et al., 2020), while the entry of plastic waste to the marine environment is already out of control and growing as a threat to ocean health (Eriksen et al., 2023). Even with 60% recycling (mechanical and chemical), this implies a fossil replacement of about 400 million tonnes (McKinsey 2018). As alluded to above, the heart of the issue is competition for land, and the international community will need to confront the inevitable trade-offs. Thus, biomass must also be accompanied by other sources of renewable carbon, and completing the analysis will require policies to maximise the recycling of carbon, to create the renewable carbon paradigm (Carus et al., 2020; Anon 2022).

Carbon management strategies, which consider all available non-geological sources of carbon, provide a holistic mechanism to plan for the efficient supply and use of carbon, putting the carbon in its various forms to best use (Fig. 3). Carbon management strategies would bring together new tools to boost bioproduction (e.g., biotechnology), measures for resource efficiency (e.g., precision farming and cascading use of materials) and the circular economy (Marvik, 2021). Importantly, carbon management policies must also account for energy aspects (Huang et al., 2021) i.e., include the (renewable) energy needed to collect, concentrate, upgrade or recycle the various carbon resources.

In the context of carbon management, more work is required to better understand the constraints on land and water use in bioproduction and the energy consumption in carbon recycling (Hernandez and Cullen, 2019) or industrial capturing of atmospheric CO_2 (Chen et al., 2023). Even with appropriate indicators in place, it should be realized that a key challenge in addressing these issues and tradeoffs in policy making, is that it requires value-based assessment and prioritizing qualitatively different entities such as CO_2 footprint, food security, economic development and biodiversity. This is enshrined in the concept of "carbon tunnel vision" (Deivanayagam and Osborne, 2023).

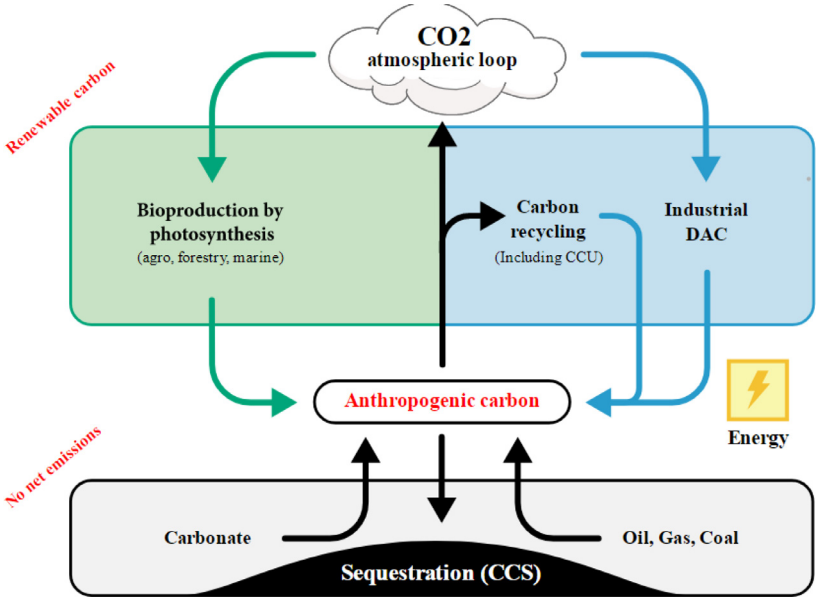

Fig. 3. Carbon management: a more complete narrative. DAC: Direct Air Capture. Source (Marvik, 2021), (Marvik O.J., 2021).

Thus, when limited availability of bioresources lead to sustainability tradeoffs, a logical step would be to expand the reference system to include all alternative carbon sources. From this perspective, the bioeconomy is a significant but fully integrated part of a comprehensive renewable carbon economy, while carbon management offers a new overarching framework for constructive discussions between all stakeholders in carbon-dependant value chains.

6. Conclusions: research and policy implications

There are important open-ended issues that are germane to the outcomes of the workshop that require further research and policy action. Given that it is unlikely that a unifying definition of bioeconomy is achieved in the near future, there will be a growing need to demonstrate to governments the economic returns of further investing in the concept. The factors that thwart such an analysis come back to the fundamental question about how economic activity and sustainability are measured. The difficulties in measuring economic activity (Carlson, 2016; European Commission 2008) have been alluded to, and the wide scope of economic sectors further complicates this measurement. An encouraging development has been that, for the 2022 revision, the US Office of Management and Budget (OMB) has accepted recommendations with respect to bio-based products manufacturing and renewable chemicals manufacturing, including the decision to "*continue research and outreach in this important emerging area*" (Federal Register 2021). Whilst not definitive, this is clearly a step in the right direction. If brought to the attention of policy makers in other countries, this might bring the impetus needed to fill serious gaps in data on economic activity.

Likewise, 'sustainability as a mode of governance' might be moving in the right direction, but political pressure will still be needed. In practical terms, harmonization of sustainability measurement may not be possible, but harmonization of the methodology for both the public and private sector seems possible. What is indicated is the need for an international public-private partnership that can decide on the key indicators that are within reach of gathering data. For example, Alviar et al., (2021) proposed five indicators to estimate the contribution of the bioeconomy to value added, employment, and GHG emissions in Colombia by an input–output analysis. The extent to which such national approaches can be harmonized internationally deserves research and policy attention.

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Supplementary materials

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