European Commission

The European Commission's Knowledge Centre for Bioeconomy

Future transitions for the Bioeconomy towards Sustainable Development and a Climate-Neutral Economy

Knowledge Synthesis Final Report

Knowledge Synthesis and Foresight

Work Package 1 - Network of Experts

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2020

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Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Fritsche, U., Brunori, G., Chiaramonti, D., Galanakis, C., Hellweg, S., Matthews, R. and Panoutsou, C., *Future transitions for the Bioeconomy towards Sustainable Development and a Climate-Neutral Economy - Knowledge Synthesis Final Report*, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-21518-9, doi:10.2760/667966, JRC121212.

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Abstract

The 2018 EU Bioeconomy Strategy aims to develop a circular, sustainable bioeconomy for Europe, strengthening the connection between economy, society, and environment. It addresses global challenges such as meeting the Sustainable Development Goals (SDGs) set by the United Nations and the climate objectives of the Paris Agreement.

A circular, sustainable bioeconomy can be a core instrument for the Green Deal in the post-COVID-19 era, making the EU more sustainable and competitive.

In this context, the EC (Joint Research Centre in collaboration with DG Research and Innovation) created an ad-hoc external Network of Experts (NoE) through individual contracts to contribute to the EC's Knowledge Centre for Bioeconomy with forward-looking analysis needed for exploring possible scenarios towards a sustainable, clean, and resource-efficient bioeconomy, with a focus on climate-neutrality and sustainable development. This first work package concerned knowledge synthesis and foresight.

The post-Brexit EU27 bioeconomy employs ≈17.5 million people (≈ 9% of its workforce) and generates € 1.5 trillion (≈ 10% of its GDP) when the tertiary bioeconomy sector (bio-based services) is included. To analyse, assess and monitor the bioeconomy's sustainability, interactions with fossil, mineral, renewable systems as well as bioeconomic contributions to ecosystem services are important, considering dynamic interlinkages and substitution effects. The bioeconomy is the only system providing food, feed, and ecosystem services, i.e. for those there is no substitute.

Sustainable, affordable, and secure biomass is available from EU sources in the medium- to longer-term, meeting demands for existing and emerging uses (e.g. bio-based material) by 2030. There is enough sustainable EU biomass to contribute to all sectors by 2030, and probably beyond, as well as to bring organic carbon back to soil.

To ensure sustainable supply, not only residues and wastes are relevant, but sustainably sourced agricultural and forestry feedstocks, and feedstocks from recovering and restoring marginal and degraded land. Options for managing land and forestry systems for biomass supply that lead to a better carbon balance depend on many factors and have biodiversity, other environmental and socioeconomic trade-offs, all needing consideration.

The bioeconomy includes sustainable food systems which can increase resilience.

For all of this, change is needed: The EU Bioeconomy Strategy intends a shift from the substitution logic towards circularity and sustainability. This requires governing the sustainability of the bioeconomy for which the SDGs are the normative framework. The challenge is to implement sustainability governance of the bioeconomy to safeguard against negative impacts while fostering positive options. The weak integration of sustainability governance of forests into EU policies and vis-à-vis non-EU countries is a hindrance to achieve the objectives of a circular, sustainable EU bioeconomy, which may be addressed in the upcoming new European Forest Strategy intended to promote the bioeconomy while respecting ecological principles favourable to biodiversity.

In preparing for a post-COVID-19 era, the bioeconomy should be a priority for the European economic recovery support: promoting short domestic sustainable bioeconomic supply chains brings resources back to the real economy, creates (rural) employment and favours CO_2-neutral development, e.g. through biorefineries and land-based Carbon (C) sequestration with respective agricultural and forestry investments.

The synopsis of all EU bioeconomy drivers and trends for 2030 and 2050 (assuming a successful implementation of a sustainable, circular EU bioeconomy, i.e. not for "business-as-usual") indicates that bioenergy would become less relevant, while biomaterials and ecosystem services will gain significantly, strengthening the EU competitiveness and creating employment.

Biomass for construction materials, fibre, food and feed, furniture, and textiles will grow, and use of innovative biomaterials such as bio-based chemicals, lubricants, and bio-based plastics which offer high value added per mass unit will increase.

Despite the impressive potential of wind and solar, biomass will provide grid balancing services, and help sectors difficult to be decarbonised through electricity (aviation, heavy duty and maritime transport, high-temperature industrial processes). There is a complementary role of bioenergy and electricity until 2050.

Yet, a sustainable bioeconomy is not the only possibility to shape the future, nor the only vision on how to make the world a better place. Over the last decades, several drivers (alternative food, non-biomass renewables, Power to Anything (PtX), socio-economic patterns) emerged which may become trends in the 2030 - 2050 horizons. These competing drivers could significantly affect opportunities for implementing the bioeconomy. Some of these drivers could be disruptive, but some are potentially synergistic to the bioeconomy.

The SDG framing for the bioeconomy requires integration. With the European Green Deal, important steps of integration are underway regarding various EU policies, especially biodiversity, circularity, climate change, food systems, forest protection and restoration, and renewable energy. The bioeconomy needs to be part of this integration, for which its inclusion in the EU post-COVID-19 recovery plan would be a critical step. In addition, domestic EU land use – especially in rural areas – and footprints implied outside of the EU need to be integrated, considering the multiple opportunities for rural livelihoods, employment and innovation, both within the EU and outside. Circularity requires integration in terms of recycling and re-use of residues & waste flows for which biorefineries are key, but as mentioned above, there is need for integrated governance as well.

The bioeconomy in Europe is not a single one – in Northern EU countries forestry dominates, while large proportions of the bioeconomy in the South West concern fibres, bio-based textiles and high-quality food. There is growing interest in the blue bioeconomy in Northern and Southern Europe. This diversity implies not a weakness but a strength: instead of focussing on e.g. corn (as the US), forest (Canada), palm oil (Indonesia), soy (Argentina) or sugarcane (Brazil), the diversified EU bioeconomy is more resilient to changes in feedstock supply, market dynamics and technology innovation.

The term transformation is used frequently throughout this report, building on the UN 2030 Agenda which calls for transformative change. The guiding principle of being transformative is acknowledging that trade-offs and possible synergies are subject to societal decision-making, not to a neoliberal economic logic alone. Market aspects are one component of decision-making, but not necessarily the dominant one. This requires to re-define the SDG framing of sustainability: Instead of linear box-by-box representation, the SDGs are ordered according to levels. The base is the biosphere which sustains society, which in turn is served by the economy. This is the fundament for deciding how to live within planetary boundaries and align the economy with societal needs, not vice versa. This is reflected in the Just transition concept of the European Green Deal.

Transformation also requires working with people in active roles, considering their capacities to think and speak about the transformation (future literacy). This is why social aspects are of high importance, for which a new term is suggested: **BioWEconomy.**

The 2018 EU Bioeconomy is a sound base to start from – its further development and implementation should aim at becoming a **BioWEconomy** and include respective targets.

Still, even such a bioeconomy will not make all of us secure, nor protect against all dangers. There is a large variety of risks mankind has to face, and most of these are interlinked so that a linear scale may be misleading (e.g. tipping points in the climate system).

A circular, sustainable, and transformative **BioWEconomy** can mitigate several of the severe and likely risks, especially food and water crises, climate change, migration, and social instability. A circular, sustainable, and transformative EU **BioWEconomy** could become a role model for transforming other parts of the economy as well, helping to make the world a better and safer place for all.

Finally, this report presents open questions relevant for further research: climate impacts of biomass, future-proof bioenergy systems, competing drivers, social factors, and sustainability governance.

Investing in research on these questions will improve the understanding and implementation of a circular, sustainable, and transformative **BioWEconomy,** not only in the EU, but globally through knowledge-sharing networks.

Executive Summary

Background

The updated EU Bioeconomy Strategy adopted in October 2018 aims to develop a sustainable bioeconomy for Europe, strengthening the connection between economy, society, and environment. It addresses global challenges such as meeting the Sustainable Development Goals (SDGs) set by the United Nations and the climate objectives of the Paris Agreement.

A circular, sustainable bioeconomy can be a core instrument for the Green Deal in the post-COVID-19 era, making the EU more sustainable and competitive.

Extensive knowledge and foresight capacities are needed to inform the direction of future research and innovation programmes and policy making, but also modelling needs to integrate all three sustainability dimensions to provide a thorough assessment. In this context, the European Commission (JRC in collaboration with DG RTD) created an ad-hoc external Network of Experts (NoE) through individual contracts to contribute to the European Commission's Knowledge Centre for Bioeconomy with forward-looking analysis needed for exploring possible scenarios towards a sustainable, clean, and resource-efficient bioeconomy, with a focus on climate-neutrality and sustainable development. This first work package aims to analyse current R&I measures and solutions and develop mid- to long-term scenarios for a bioeconomy that contributes to sustainable development and a climate-neutral economy.

What is the bioeconomy?

According to the EC definition, the bioeconomy covers all sectors and systems that rely on biological resources (plants, microorganisms, and derived biomass, including organic waste), their functions and principles, and related products and services. It includes and interlinks

- land and marine ecosystems and the services they provide,
- all primary production sectors that use and produce biological resources (forestry fisheries and aquaculture),
- and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy, and services.

The bioeconomy of the post-Brexit EU27 employs ≈17.5 million people (≈ 9% of its workforce), and generated ≈ € 614 billion of value added in 2017, representing ≈ 5% of its GDP. If estimates for the tertiary bioeconomy sector (bio-based services) are included, the size of the bioeconomy increases to € 1.5 trillion (≈ 10% of its GDP)

To analyse, assess and monitor the bioeconomy's sustainability, interactions with the fossil, mineral, and renewable systems as well as bioeconomy contributions to ecosystem services are important, considering dynamic interlinkages and substitution effects.

The bioeconomy is the only system providing food, feed, and ecosystem services, i.e. for those there is no substitute. More than 1/3 of the overall biomass input to the EU bioeconomy is imported from outside, so that international trade is relevant. Given the EU bioeconomy ambition to contribute to the SDGs, linkages with economies not only within the EU, but also outside need consideration.

Global sustainable biomass potentials

Biomass used for energy purposes (bioenergy) is the largest source of renewable energy, currently supplying ≈ 10% to global final energy. Today, modern bioenergy contributes to more than half of total renewable energy production and is about four times larger than the combined energy from photovoltaic and wind.

Many raised concerns about the sustainability of biomass use and future prospects, as humans appropriate already about 25% of all global biomass growth. To clarify future opportunities in terms of overall sustainable biomass potential for all possible uses and functions (food & feed, fibre, energy and fuels, materials as well as ecosystem services), a variety of studies derived an estimate for the sustainable potential by 2050 of ≈ 15% of global energy demand, with dominant contributions from Latin America and Africa.

However, most estimates do not represent the broader bioeconomic perspective (food & feed, energy and materials, ecosystem services etc.), so that further analysis is required.

Sustainable biomass potentials of the EU

Currently, annual biomass production in the EU27+UK land-based sectors is ≈ 1.5 billion tonnes of dry matter (t_{dm}), equivalent to ≈ 27 EJ, of which 2/3 come from agriculture and 1/3 from forestry. Not all grown biomass is used, as parts remain in fields and forests to maintain C sinks and other ecosystem services, but also because of missing incentives for mobilising unused residual biomass streams and lack of knowledge within the farming community about sustainable practices and new bio-based markets.

Various studies identified sustainable biomass potentials in the EU, considering resource efficiency, sustainability (incl. biodiversity, ecosystem services, GHG emissions, soil protection, water) and demand for non-energy uses, giving ≈ 500 Mt_{dm} of EU biomass (≈ 10 EJ) as sustainably available for all additional uses by 2030.

There is also potential to sustainably cultivate biomass on marginal and degraded land in the EU, which could contribute significantly to the overall domestic biomass potential.

Limits of the bioeconomy

In order to understand the potential and the limits of a sustainable bioeconomy, a re-evaluation of the value of potentials as core information for policy making on the bioeconomy is necessary. In fact, as business-as-usual is not an option and the next decades call for decarbonisation, the fossil system is not the benchmark anymore.

Expectations on bioeconomic contribution to sustainability have been scaled down somewhat in recent years, but the bioeconomy is still an important driver of economic growth, especially in terms of value-added, and employment, not only in the EU but in many countries. The bioeconomy also contributes to social and environmental improvements, if adequately governed. The food (price) crisis of 2007-2008 made clear that bioeconomy potential for sustainable growth is subject to planetary boundaries and socioeconomic constraints, especially food security concerns.

The bioeconomy is basically renewable, yet biophysical limits to growth apply, and distributional issues of e.g. income and land tenure indicate socioeconomic limitations, or at least inertia. Adding circularity to the bioeconomy can push the efficiency of biomass use and expand its value, but cannot promise endless cycling, given the 2nd Law of Thermodynamics, accumulation of toxics, and logistical problems.

The potential of a circular, sustainable bioeconomy in relation to growth is linked:

- to its capacity to increase the efficiency of the system,
- to reduce its environmental impact and restoring and enhancing ecosystem services,
- to geographically redistribute employment, growth and value added,
- to diversify local rural economies, and
- to at least partially compensate the decline of the fossil fuel-based economy.

Most of this has been taken up in the EU Bioeconomy Strategy, but if economic growth is to continue unchanged, even a circular bioeconomy cannot avoid a radical redesign of the economy.

A transformative bioeconomy

The SDGs, as the normative framing of the bioeconomy, require transformation (of agriculture, consumption patterns, energy and food systems, forestry...), and quantitative potentials measured in cost-supply curves over time and volumes are just helpful think pieces for the possible upper end of the transformation.

In the past, the driving force for the development of bioeconomy worldwide has been the societal transition towards circular and low carbon economies based on the potential to provide "green" alternatives to fossil-based production and consumption. The bioeconomy has wide sectoral coverage and the unique potential to link primary production at local level with multiple industrial processes and products under safe and sustainable operating boundaries, including ecosystem services.

Earlier decision-making on the bioeconomy was typically based on comparing bio-based value chains with those of fossil fuel origin. This narrative relied on assumptions and metrics mostly related to reducing GHGs and delivering low carbon solutions. The recent unprecedented crisis, however, brings to surface a much wider role that bioeconomy can have to diversify supplies for food, feed, and raw materials, contribute to circularity and climate neutrality whilst at the same time create employment and foster rural development. This view is basically taken up in the EU Bioeconomy Strategy, but a fresh perspective is needed considering the new framing conditions for sustainable development and operation of bio-based value chains to foster resilience and smooth transition to a circular post-COVID 19 economy within the framework of the European Green Deal, and the European Recovery Plan.

For this, the transformative logic asks for turning challenges for local economic resilience in crisis into opportunity for diversification through deploying the bioeconomy widely. The social component also requires careful revision: from the target to protect underdeveloped economies and low-income population towards employment and value-generation of bio-based value chains.

Then the bioeconomy could contribute to the post-COVID-19 recovery and avoid lock-in to traditional economic patterns. The 2018 EU Bioeconomy Strategy has started to reflect that, and further development especially regarding transformation is needed: setting clear targets for 2030 and 2050, establishing sustainability governance for implementation, and improve on inclusiveness. A circular, sustainable bioeconomy has excellent fit to this transformative approach, can create opportunities in agriculture, fishery, forestry and waste sectors and deliver more biomass than produced and used today while increasing carbon sinks, sustainably manage land-based and marine ecosystems and foster employment and value generation in rural areas.

Bioenergy within the bioeconomy

A sustainable bioeconomy will necessarily incorporate bioenergy as a key component, necessary not only for decarbonisation (with a particular focus on transport, the most difficult sector to intervene) but also as a mean to support economic development. Well-designed bioenergy chains will reduce imports, increase EU energy security and storage, and stimulate local economies at community level.

Bioenergy is part of the bioeconomy as it can also valorise side and residual streams from high-value feedstocks used for bio-based products. Biorefining will contribute to substitute fossil components with bio-based sustainable ones, as bio-fertilisers, bio-nutrients, bio-amendments, and other bio-based materials co-generated with biofuels and bioenergy.

Shifting from linear thinking to a circular approach will leverage on sustainable bioenergy chains to increase resilience of food/feed chains, improving efficiency in land use. The adoption of negative emission technologies such as BECCS and the recovery of land affected by climate change are means to further increase the availability of sustainable feedstocks while at the same time supporting more organic, circular and less fossil-dependent agriculture delivering food, feed and energy.

Bioeconomy and trade

Special attention must be paid to sustainable supply chain management of biomass. The EU imports a large fraction of biomass by weight, and the share of environmental and socio-economic impacts caused abroad for European consumption is even higher. Almost half of the land-related biodiversity-loss impacts for the consumption of biomass-based products within the EU occur outside of Europe (particularly through imported food products, and wood). Animal products are majorly contributing to biomass-related climate change impacts.

While the EU relies heavily on foreign workforce for producing imported agricultural goods, the value added created in the countries of origin is comparatively small.

Prospective studies show that this trend of burden shifting (outsourcing) is likely to even increase in the future. Sustainable supply chains are key for a sustainable bioeconomy.

A transformative sustainable bioeconomy must include adjusting the trade system, considering the socioeconomic limitations discussed previously. To allow for a circular, sustainable, and transformative bioeconomy governed by the SDG framing, the same framing should govern the WTO, and its subsequent laws and rulemaking.

From monitoring to governance

As part of the EU Bioeconomy Action Plan, the EC is developing a monitoring system and modelling tools to inform about and evaluate such trade-offs, both ex-post and ex-ante.

The challenge remains to move beyond monitoring and develop multi-level governance approaches for the EU, and in the global context.

Agriculture and food

Agriculture (including aquaculture) is a fundamental component of the EU bioeconomy, with a high relevance for biodiversity, rural employment, farmer's income, GHG emissions, land use and pesticides application as well as nitrogen and phosphorous loads. A core concept of a green CAP reform is agroecology which offers potential for climate change adaptation, and for transforming the EU food system while providing biodiversity benefits and rural employment and income, as indicated by the new EC *Farm-to-Fork Strategy*.

Yet, the food system causes the majority of impacts on animal welfare, biodiversity, land, and water. If unmitigated, these impacts could go up by 50–90% until 2050 due to growth in population and changing diets driven by increased income.

Transformative food systems address how biomass for food and feed is produced, processed, and consumed. Cornerstones of such developments are innovation and productivity (as already supported by the EU), but also changing the views on food systems is important.

As its first priority, a sustainable bioeconomy needs to avoid, prevent, and reduce food losses (FL) and food wastes (FW). This needs collaborative and concerted efforts, redistributing surplus food, and valorising surplus that cannot be used to feed people into animal feed and high value products. The SDG 12.3 goal of halving FW is a feasible target for the food service sector and realistic also for households.

Regarding circularity, unavoidable food processing by-products, residues, and food waste can be turned into bio-based feed and nutraceuticals using e.g. small-scale biorefineries, either by primary producers alone or in cooperative business models.

A sustainable bioeconomy is linked to sustainable diets. An increasing number of studies on the sustainability impact of different diets recognise that plant-based diets are beneficial for the environment, but some raise concerns about the magnitude of the impact, and affordability. Diets that include higher amounts of fruits, vegetables, and plant-based sources of protein as well as lower consumption of alcoholic beverages, soft drinks and meat are considered both more sustainable and healthier.

The increase of alternative protein sources could also increase the resilience of food systems regarding the COVID-19 and future pandemic crises. However, the sustainability of very novel alternative protein sources is yet questionable (e.g. lab-grown meat), and reductions in GHG emissions could be obtained without entirely excluding (but decreasing) meat products from diets.

Current trends in food waste research centre around consumer and household behaviour which is a reliable indicator that the reduction in food waste is tightly connected to sustainable food consumption and SDG 12.

All related actors (e.g., companies, governments, and consumers) need to take actions to reduce FW and change dietary patterns to more healthy approaches (e.g., less meat, more nuts, vegetables, whole grains, and fruits) to end food overconsumption, eliminate malnutrition, and ultimately improve health.

A sustainable bioeconomy can turn food processing by-products, residues, and food waste into bio-based nutraceuticals and other added-value products (e.g., biopolymers, bioceramics, packaging materials, bio-based textiles, coatings and composites, bioenergy) helping processors, retailers, and consumers to reduce FW.

Alternative pathways compete with the bioeconomy

A sustainable bioeconomy is not the only possibility to shape the future, nor the only vision on how to make the world a better place. Over the last decades, several drivers (alternative food, non-biomass renewables, PtX, ecosystem services, socio-economic patterns) emerged which may become trends in the 2030 - 2050 horizons. These competing drivers could significantly affect opportunities for implementing the bioeconomy. Some of these drivers could be disruptive, but some are potentially synergistic to the bioeconomy.

Drivers and trends of the bioeconomy

This report provides a synopsis of all EU bioeconomy drivers and trends for the normative assumption of a successful implementation of the sustainable, circular EU bioeconomy, not for a "business-as-usual" development.

This analysis indicates that bioenergy would become less relevant until 2050, while biomaterials and ecosystem services will gain significantly, strengthening the EU competitiveness and creating employment.

Biomass for construction materials, fibre, food and feed, furniture and textiles will grow, especially innovative biomaterials such as bio-based chemicals, lubricants, and bio-based plastics which offer high value added per mass unit.

Despite the impressive potential of wind and solar, biomass will provide grid balancing services, and help sectors difficult to be decarbonised through electricity, e.g. aviation, heavy duty and maritime transport, and high-temperature industrial processes. There is a complementary role of bioenergy and electricity until 2050.

Beyond drivers and trends: shaping the next generation Europe

The SDG framing for the bioeconomy requires integration. With the European Green Deal, important steps of integration are underway regarding various EU policies, especially biodiversity, circularity, climate change, food systems, forest protection and restoration, and renewable energy. The bioeconomy needs to be part of this integration, for which including it in the EU post-COVID-19 recovery plan would be a critical step.

Furthermore, integration is needed in terms of moving beyond co-existence and competition between the bioeconomy and the broader economic system. Market interaction for food & feed, fibre, chemicals, energy etc. is currently driven by prices, with few policy interventions (quota systems, taxation etc.). The COVID-19 pandemic indicated that societal priorities such as health and resilience need to be seen as necessary co-drivers of market interactions (including trade), and the Paris Agreement implies that competition between the non-renewable economy and the renewable one (including the bioeconomy) needs to integrate at least a strong carbon signal.

In addition, domestic EU land use – especially in rural areas – and the footprints implied outside of the EU need to be integrated as well: A sustainable circular bioeconomy must be implemented with a view of the multiple opportunities for rural livelihoods, employment and innovation – both within the EU and outside.

Circularity requires integration in terms of recycling and re-use of residues & waste flows for which biorefineries are key – but as mentioned above, there is need for integrated governance as well: The SDGs call for "breaking down the silos" of current political systems governing the bioeconomy in many different and segmented institutions and policy areas. Using the integration lens, a screening of policies with regard to their integration across governance levels indicated that for many policies, the EU has rather strong governance instruments (Directives…) to align externally, and with Member States. There is one exception from this finding, though: the forest sector is lacking integration on the EU level (and global/internationally) while national governance is quite elaborate and strong but rather unaligned with the EU Bioeconomy Strategy. The upcoming new EU Forest Strategy intends to integrate the bioeconomy and might close this gap – it needs to be seen how suitable arrangements with Member States and with actors outside the EU will be found.

A circular sustainable European bioeconomy must deliver on the integration challenges as well – with the EU Green Deal, at least some steps in this direction are taken.

The bioeconomy can be a core instrument for the Green Deal in the post-COVID-19 era, making the EU more sustainable and competitive. For this, the change from a substitutive to a transformative bioeconomy needs to be expressed stronger to avoid lock-in and contribute to delivering on the SDG ambition of transformation. The 2018 EU Bioeconomy Strategy has, compared to its 2012 predecessor, evolved in this direction, but clear targets and an adequate governance approach are still needed.

Bioeconomic diversity

The bioeconomy in Europe is not a single one – in Northern EU countries forestry dominates, while a large proportion of the bioeconomy in the South West concern fibres, bio-based textiles, and high-quality food. There is also growing interest in the blue bioeconomy in Northern and Southern Europe.

This diversity implies not a weakness but a strength: Instead of focussing on e.g. corn (as the US), forest (Canada), palm oil (Indonesia), soy (Argentina) or sugarcane (Brazil), the diversified EU bioeconomy is more resilient to changes in feedstock supply, market dynamics and technology innovation.

This diversity within Europe is reflected in the various national and regional bioeconomy strategies, with a similar diversity being observed globally. European strategies must consider the position of future domestic bioeconomies in international markets for both food and non-food products, as those affect the sustainability of bio-based products and industries, the affordability of food, and potential implications for national land-use choices.

Outside Europe, the bioeconomy landscape is even more diverse than in the EU, as some overview reports and examples from several countries indicate. In engaging in discourse over the future bioeconomy, Europe can learn from others.

Transformation ahead

The term transformation is used frequently throughout this report, building on the 2030 Agenda which calls for transformative change. Transformation is understood as the process to shift from a certain pathway towards a more sustainable one.

The guiding principle of being transformative is to acknowledge that various trade-offs and possible synergies are subject to societal decision making, not to neoliberal economic logic alone - market aspects are one component of decision making, but not necessarily the dominant one.

This requires to re-define the SDG framing of sustainability: Instead of the planar box-by-box representation, the new logic orders the SDGs by levels. The base is the biosphere which sustains society, which in turn is served by the economy.

This is the fundament for deciding how to live within planetary boundaries and align the economy with societal needs, not vice versa. This is reflected in the Just transition concept of the European Green Deal.

Transformation requires working with people in active roles, considering their capacities to think and speak about the transformation (future literacy). In that, social aspects are of high importance, for which a new term is proposed: **BioWEconomy.**

No future without risks

A circular, sustainable, and transformative **BioWEconomy** makes change towards more resilient and future-proof economic systems possible. Still, even such a bioeconomy will not make all of us secure, nor protect against all dangers. There is a large variety of risks mankind – and Europeans – has to face, and most of them are interlinked so that a linear scale may be misleading (e.g. tipping points in the climate system).

A circular, sustainable, and transformative **BioWEconomy** can mitigate several of the severe and likely risks, especially food and water crises, climate change, migration, and social instability.

The improved governance of a circular, sustainable, and transformative **BioWEconomy** could become a role model for transforming other parts of the economy as well, helping to make the world a better – and safer – place for all.

In that regard, foresight processes can help to explore possible futures, identifying respective narratives and possible pathways, and inform policy makers and society about options to choose from.

Open research issues

The final section of this report collects core questions relevant for further research concerning a circular, sustainable, and transformative **BioWEconomy** to inform the direction of the upcoming Horizon Europe Research and Innovation Framework Programme, and respective work under the Green Deal. These open questions concern

- Climate impacts of biomass
- Integrated modelling
- Future-proof bioenergy systems
- Competing drivers
- Social factors
- Sustainability governance

Investing in research on these questions will improve the understanding and implementation of a circular, sustainable, and transformative **BioWEconomy** not only in the EU, but globally through knowledge-sharing networks.

The EC should increase its invitations and support for non-EU researchers, especially from Africa, Asia, Latin America and the Caribbean to engage in more joint projects and respective capacity development, as in the view of the SDGs, all countries are developing.

Europe would benefit from enhanced collaboration with its partners in moving jointly towards a better world for all for which research and innovation are key.

1 Background

The updated EU Bioeconomy Strategy adopted in October 2018 aims to develop a sustainable bioeconomy for Europe, strengthening the connection between economy, society, and environment (EC 2018). It addresses global challenges such as meeting the Sustainable Development Goals (SDGs) set by the United Nations (UN 2015) and the climate objectives of the Paris Agreement.

Extensive knowledge and foresight capacities are needed to inform the direction of future research and innovation (R&I) programmes and policy making, but also modelling needs to integrate all three sustainability dimensions to provide a thorough assessment.

In this context, the European Commission (JRC in collaboration with DG RTD) created an ad-hoc external Network of Experts (NoE) to contribute to the European Commission's Knowledge Centre for Bioeconomy with forward-looking analysis needed for exploring possible scenarios towards a sustainable, clean, and resource-efficient bioeconomy, with a focus on climate-neutrality and sustainable development. This (first) work package aims to analyse current R&I measures and solutions and develop mid- to long-term scenarios for a bioeconomy that contributes to sustainable development and a climate-neutral economy. The analysis addresses the questions:

1. How sustainable are current biomass supplies and can more biomass than is produced and used today, be sustainably sourced (either internally or from third countries) while fulfilling the need to increase carbon sinks and sustainably manage land-based and marine ecosystems to secure the long-term provision of ecosystem services?
2. How can the development of the bioeconomy foster climate change adaptation and mitigation and, in particular, how can negative emissions approaches related to the bioeconomy be optimised (e.g. BECCS versus bio-based material use, versus wood buildings, versus afforestation)?
3. What dietary changes would have a positive impact on climate and on the economic, social, and environmental sustainability of food systems as well as consumer and planetary health?
4. How can sustainable, affordable, and secure bioenergy be delivered where needed in the longer term, while meeting biomass demand for other existing and emerging uses (e.g. bio-based material)?
5. As a key activity in a circular bioeconomy, how can the design and implementation of strategies that limit food losses and waste along the entire supply chain, contribute to developing sustainable and resilient food systems?

For these questions, the experts prepared thorough reviews of state-of-the-art literature and projects[1].

Based on the reviews and further work of the authors, this synthesis paper aggregates key findings from all review papers as an input to a foresight exercise on a sustainable European bioeconomy to 2050.

- It informs about what the EU bioeconomy is (Section 1.1),
- its "size" (Section 1.2) as well as its scope and system boundaries (Section 2),
- discusses cross-cutting issues of a sustainable circular bioeconomy (Section 3),
- summarises key drivers and trends (Section 4) and
- presents perspectives for a circular sustainable transformative EU bioeconomy (Section 5) and remarks on research questions (Section 6).

In addition, several Appendices to the report provide details on specific issues.

[1] For a list of these synthesis papers and authors see **Annex 1**.

1.1 What is the EU bioeconomy?

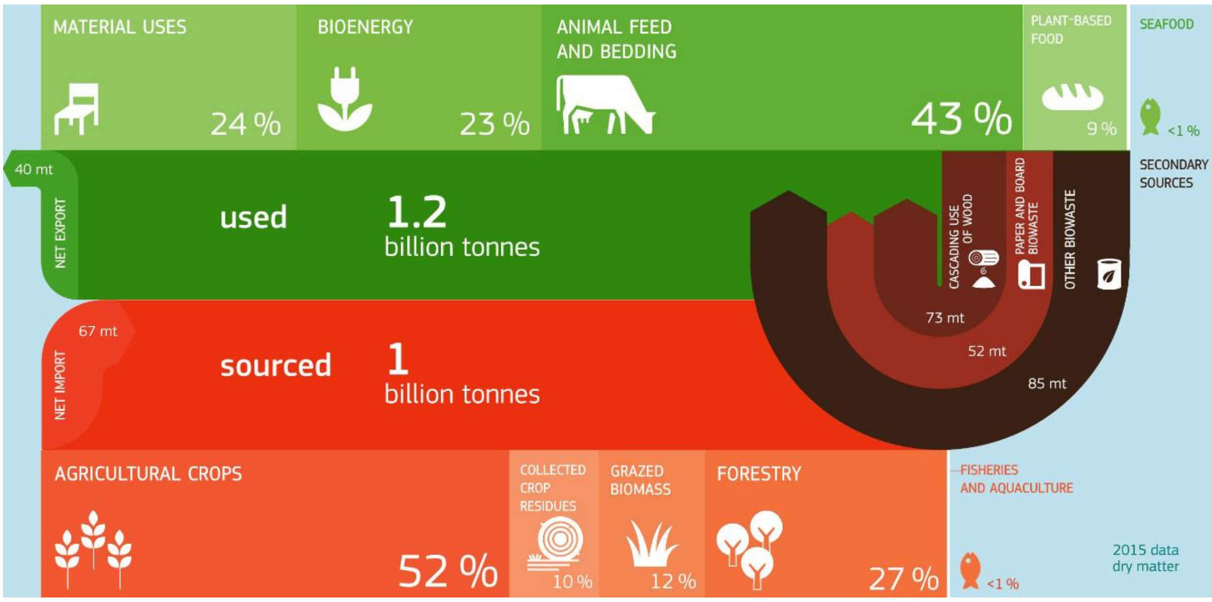
The European definition of a circular and sustainable bioeconomy is as follows[2]:

"It covers all sectors and systems that rely on biological resources (plants, microorganisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks

- land and marine ecosystems and the services they provide
- all primary production sectors that use and produce biological resources (forestry fisheries and aquaculture)
- and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services." (EC 2018)[3]

The respective biomass flows[4] are shown in Figure 1.

Figure 1 Aggregated biomass flows of the EU27+UK bioeconomy



Source: JRC https://ec.europa.eu/knowledge4policy/sites/know4pol/files/20190925_jrc_biomass_ri_days_final_pubsy_0.pdf

1.2 The economic dimension of the EU bioeconomy

The bioeconomy of the post-Brexit EU27 employed ≈17.5 million people (≈ 9% of its workforce), and generated ≈ € 614 billion of value added in 2017, representing ≈ 5% of its GDP (Ronzon et al. 2020).

These values exclude estimates for the tertiary bioeconomy sector, i.e. bio-based services, which significantly increase the overall size of the bioeconomy by ≈ € 872 billion to a total of nearly € 1.5 trillion (JRC 2020a).

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2 Note that several EU Member States as well as other countries and international organisation use different definitions of the bioeconomy. The full definition of the bioeconomy is given in EC (2018).

3 Note that biomedicines and health biotechnology are excluded.

4 Note that the EU bioeconomy definition also includes non-material ecosystem services, and the (partially non-material) services in the tertiary sector. Thus, the figure does not represent the full EU bioeconomy.

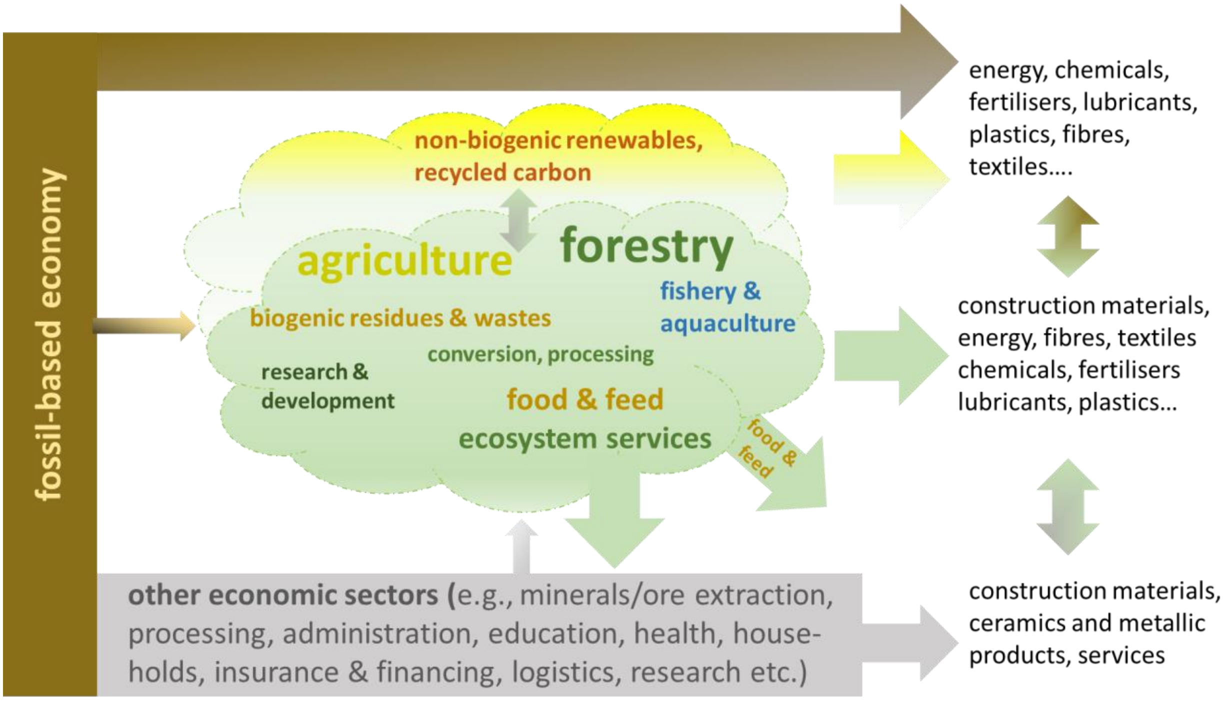
2 Scope of the bioeconomy and system boundaries

Before addressing the bioeconomy in more detail (Sections 3 and 4), its overall scope and system boundaries are discussed briefly in the following sub-sections.

2.1 The bioeconomy as part of the wider economy

To analyse, assess and monitor the bioeconomy's sustainability, interactions with the fossil, mineral, and renewable economies, and bioeconomy contributions to ecosystem services are important, all considering dynamic interlinkages and substitution effects[5].

Figure 2 Simplified system boundaries of the bioeconomy



Source: *own compilation; yellow- and green-shaded clouds represent renewable economy, green-shaded cloud represents bioeconomy (as part of renewable economy); right side represents outputs to society (products and services); arrows = outputs; double-arrows = substitution potentials*

The simplification in the system boundaries shown above concern the temporal (change over time), and spatial (trade flows across borders) dynamics.

Note that as of now, the bioeconomy is the only system providing food, feed, and ecosystem services, i.e. for those there is no substitute[6].

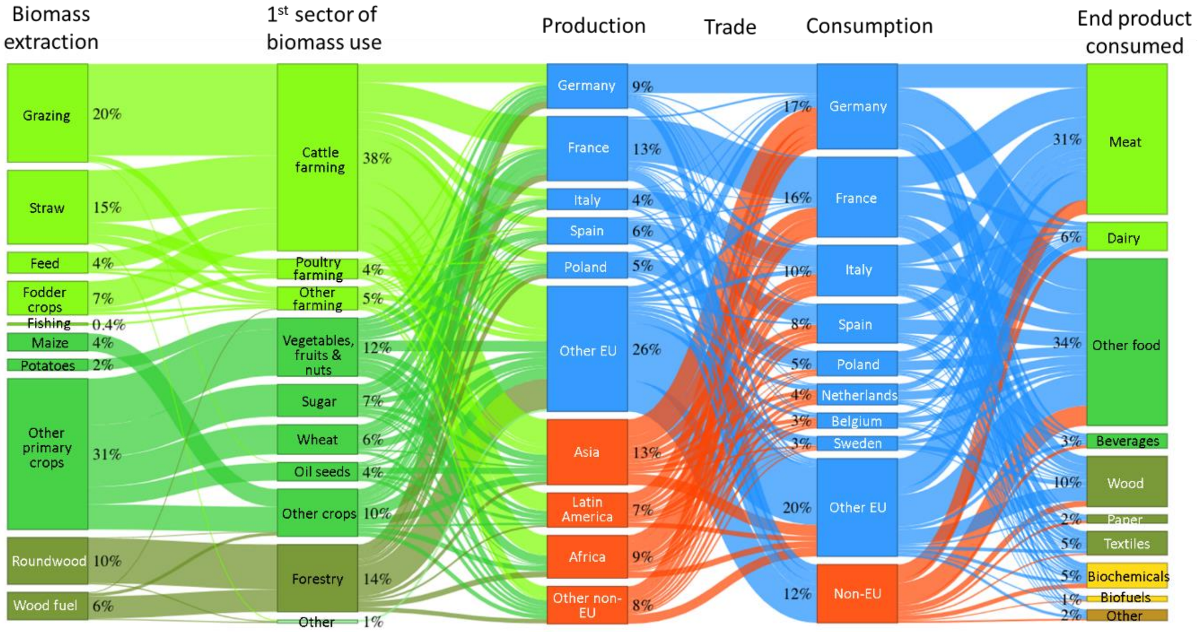
2.2 The international dimension of the bioeconomy

In addition to the temporal bioeconomy dynamics, there is the spatial dimension to be considered, as indicated in the following figure.

[5] For simplicity, the spatial and temporal dimensions are not shown in Figure 2. A "real" representation of the overall bioeconomy within the broader economy, the respective temporal dynamics and geographical extension would require two more dimensions, i.e. Figure 2 would have to be a hypercube. A four-dimensional structure cannot be meaningfully scaled down to a two-dimensional figure for this text.

[6] For potential future alternatives see Sections 0 and 6.4.

Figure 3 Flows of domestic and imported biomass for EU-27 consumption in 2015



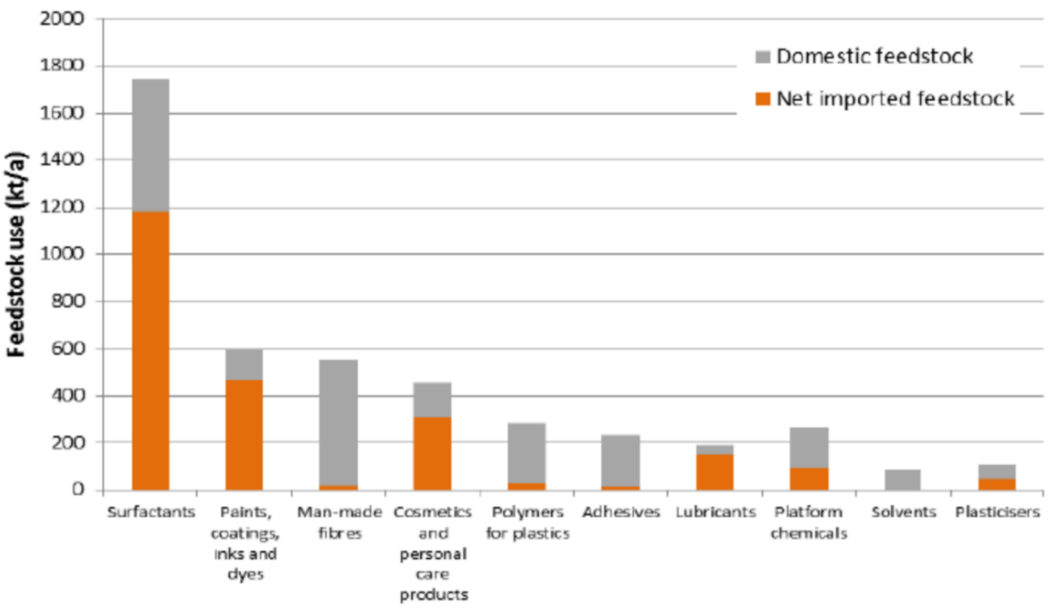
Source: *own elaboration supported by L. Cabernard based on methods from Cabernard, Pfister & Hellweg (2019); data from Exiobase v3.4 (https://www.exiobase.eu); shares based on* ***wet matter***

More than 1/3 of the overall biomass input to the EU bioeconomy is imported from outside, so that international trade is relevant (Section 3.5).

Note that Figure 3 includes data on indirect imports and exports, and shares are based on wet biomass. These are significant differences compared to JRC data (Figure 1) which are based on dry matter. Thus, data in Figure 3 cannot be directly compared with data in Figure 1.

For the growing bioeconomy segment of bio-based chemicals, JRC (2019a) estimated current domestic and imported feedstocks, and found that the overall import dependency of this segment of the EU bioeconomy is in the order of 50%, with higher shares for products quantitatively relevant in total EU consumption, as depicted in Figure 4.

Figure 4 Domestic and imported feedstocks for bio-based chemicals in the EU27+UK



Source: JRC (2019a)

Given the EU bioeconomy ambition to contribute to the SDGs, linkages with economies not only within the EU, but also outside, need consideration (Rijnhout et al. 2019).

"The EU bioeconomy strategy thus has to be simultaneously implemented in, by and with Europe:

In Europe means that bio-based products need to be produced, processed, consumed and reused sustainably (sustainable consumption and production) (…);

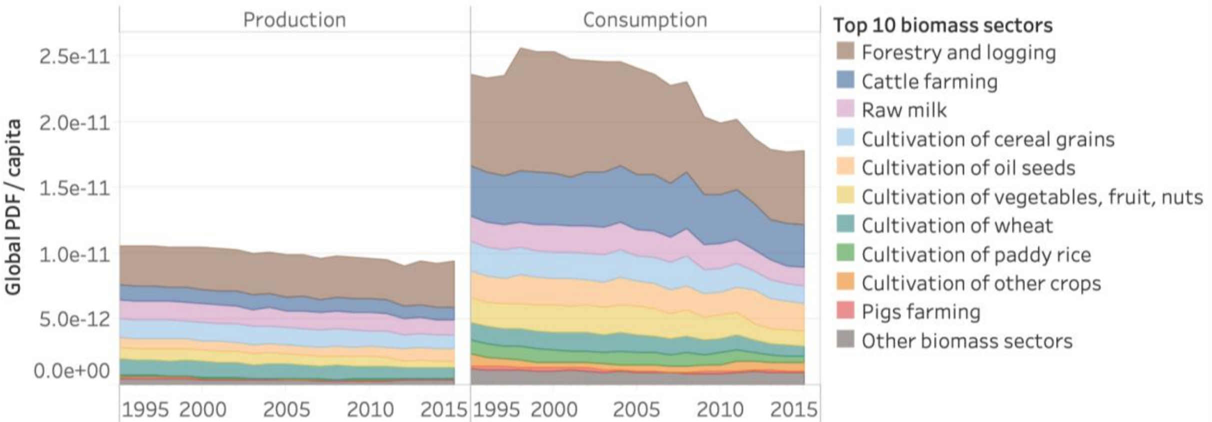
By Europe means sustainable sourcing of bioresources and fair international supply chains of biobased products (…);

With Europe refers to north-south (-south) partnerships, e.g. through development cooperation, capacity building, sharing of knowledge & technologies, technological/social/institutional innovations (e.g. sustainable agricultural intensification), green investments, trade agreements, fair benefit sharing and other mechanisms in which the different partners' respective strengths and comparative advantages are combined." (Hoff et al. 2018, p.5)

A recent analysis of bioeconomy developments to 2050 indicated trade-offs between sustainability in the EU and other regions (Philippidis et al. 2020). The following two figures illustrate this for land-use related biodiversity loss (Figure 5) and employment effects (Figure 6).

In each figure, the left side represents impacts of EU production in the EU alone while the right side shows impacts of EU consumption, including impacts outside of the EU through imports.

Figure 5 Domestic and total land-use related biodiversity loss implied by the EU biomass production, consumption, and imports (excluding land use by households)



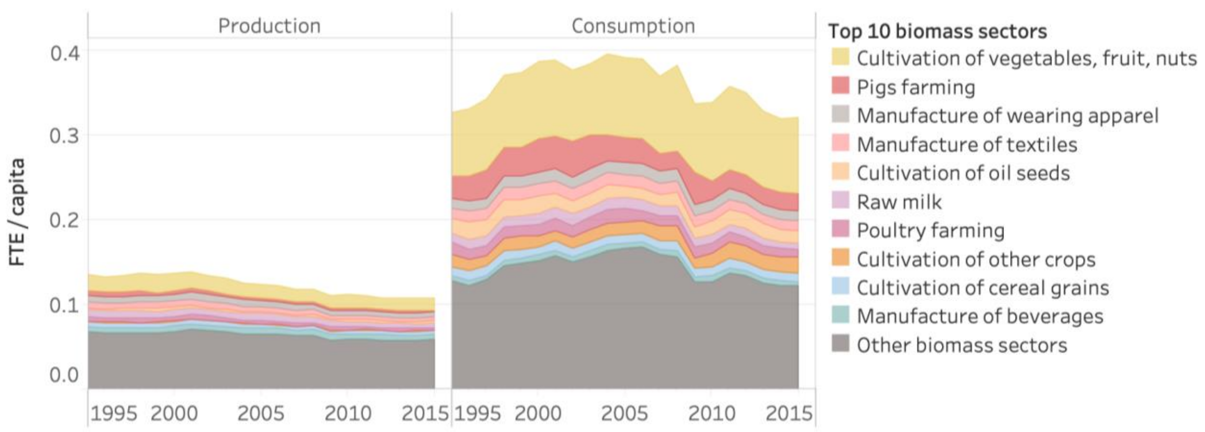
Source: *own elaboration supported by L. Cabernard based on methods from Cabernard, Pfister & Hellweg (2019); data from Exiobase v3.4 (https://www.exiobase.eu); PDF = potentially disappeared fraction of species; note that In Exiobase, land use data show a decreasing trend (particularly after 2011), while other studies show an increasing trend (Di Fulvio et al. 2019)*

The potential biodiversity loss related to the EU biomass production and consumption (incl. imports) is dominated by forest and logging activities, cattle farming, raw milk, and the cultivation of oil seeds. Most impacts are caused outside the EU due to imports, particularly for cattle farming and oil seeds cultivation[7].

[7] For similar finding with a focus on biodiversity and trade see Bellora et al. (2020).

With regard to socioeconomic impacts, the employment effects (Figure 6) show a similar pattern: they are dominated by the cultivation of vegetables, fruit, and nuts, and by pig farming, and they mainly occur outside of the EU, i.e. through imports.

Figure 6 Domestic and total employment implied by the EU biomass production, consumption, and imports



Source: *own elaboration supported by L. Cabernard based on methods from Cabernard, Pfister & Hellweg (2019); data from Exiobase v3.4 (https://www.exiobase.eu); FTE = full-time equivalent*

These global linkages are taken up in more detail in Section 3.5 (Trade).

2.3 Circularity: flows and natural capital

Besides becoming sustainable (Sections 3.1 and 4.1), the EU bioeconomy intends to be circular[8] (EC 2018), an ambition built on the EC Action Plan for the Circular Economy (EC 2015b). Many bioeconomy outputs are already cycled back into the bioeconomy (e.g. food wastes, paper…), as indicated in Figure 2.

Circularity includes also natural capital[9], an addition to the other three capitals: manufactured (or man-made), human, and social (EEA 2018b). Natural capital comprises those ecosystems and abiotic assets of the planet that provide people with exploitable resources, e.g. solar radiation, fossil fuels and minerals, and that generate a flow of benefits via ecosystem services, e.g. food, climate regulation and recreation.

The EC circularity ambition is not just conceptual, however: the EU Green Deal (Section 4.2.1) aims to implement regulatory instruments as well[10].

It should be noted also that circularity is not a unique characteristic of the bioeconomy, as fossil and mineral systems could and should – in principle and to varying degrees – become more circular as well, as EC (2015b) and EC (2020c) indicate.

8 For a critical reflection on the concept see Korhonen et al. (2018) and Corona et al. (2019); OECD (2019c) discusses challenges and business applicability, and Moreau et al. (2017) the social and institutional dimensions.

9 This term was first proposed by Pearce, Markandya & Barbier (1989), and later refined by Pearce & Barbier (2000) and Barbier & Markandya (2013).

10 The EC "*…will consider the introduction of mandatory requirements to increase the sustainability not only of goods, but also of services. The possibility to introduce requirements linked to environmental and social aspects along the value chain, from production through use to end of life, will also be carefully assessed, including in the context of WTO rules*" (EC 2020c, p. 4-5).

3 Cross-cutting issues

A sustainable bioeconomy requires governing the sustainability of the bioeconomy, for which the SDGs could be the normative framework[11]. The following considers this framing for selected cross-cutting issues defined in previous work (see Annex 1), i.e. biomass potentials, climate impacts, and food systems. This report adds socioeconomic aspects and international trade to reflect further bioeconomy-SDG links.

3.1 Sustainable biomass potentials

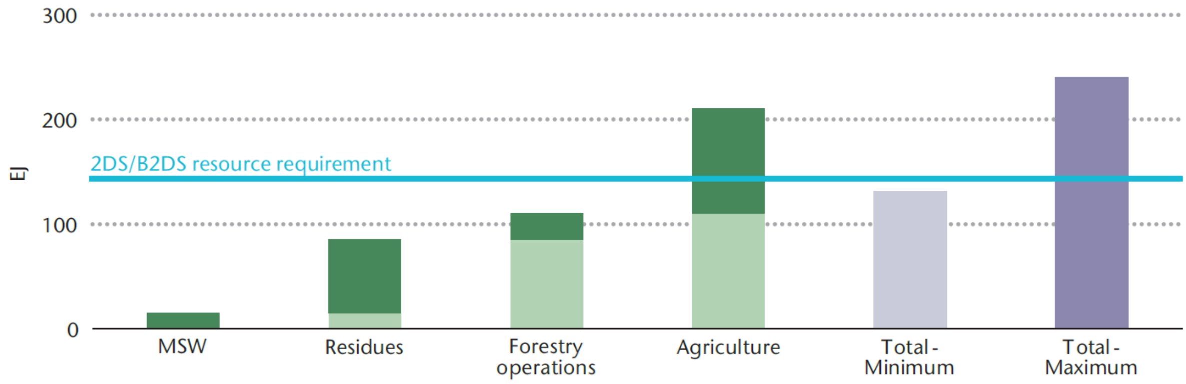
3.1.1 The global view

Biomass used for energy purposes (bioenergy) is the largest source of renewable energy, currently contributing ≈ 10% (56 EJ) to global final energy supply (IEA 2019; IEA et al. 2020)[12]. Today, modern bioenergy contributes to more than half of total renewable energy production and is about four times larger than the combined energy from PV and wind (IRENA 2020a).

Beyond the current global situation, many have raised concerns about the sustainability of biomass use and future prospects (e.g. Reid, Ali & Field 2020), as humans appropriate already about 25% of all global biomass growth, and this "predation" may rise to 30% by 2050 (Jenkins et al. 2020).

To clarify future opportunities in terms of overall sustainable biomass potential for all possible uses and functions (food & feed, fibre, energy and fuels, materials as well as ecosystem services), IEA (2017) analysed a variety of studies, and derived a global estimate for 2050 and beyond (Figure 7).[13]

Figure 7 Global sustainable biomass potentials



Source: IEA (2017); MSW = municipal solid wastes; 2DS = 2 °C scenario; B2DS = below 2 °C scenario; lightly green-shared bars indicate lower limits of potential, dark green bars upper limits

Analysis by Wu et al. (2019) indicated that including not only environmental safeguards but also social transformation policies may actually increase the sustainable global potential by 2050 to ≈ 190 EJ, with dominant contributions from Latin America (90 EJ) and Africa (55 EJ), and overall production cost below 5 US$/GJ. This estimated increase results from dietary changes, increased crop yields, and optimisation of land use.

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11 EUBA (2019); Fritsche & Rösch (2020); Humpenöder et al. (2018); JRC (2018c + 2019b); Philippidis et al. (2020); Ronzon & Sanjuán (2020).

12 More than 50% of that is still used for "traditional" inefficient heating and cooking especially in developing countries (IEA et al. 2020), but this amount is expected to decline over the next decades (IRENA 2020a).

13 For a discussion of sustainable global biomass potentials see Chiaramonti (2020). It should be noted that the IEA (2017) potentials include possible contributions from rehabilitating marginal and degraded lands (Kulišic et al. 2019), which are substantial in many countries (Fritsche et al. 2017).

However, most estimates do not represent the bioeconomic view (ecosystem services, food & feed, energy, materials, etc.), so that further analysis (e.g., Beuchelt & Nassl 2019) is required.

3.1.2 EU potentials

Currently, the average annual biomass produced in the EU27+UK land-based sectors is ≈1466 Mt_{dm}, (≈27 EJ)[14] with 956 Mt_{dm} from agriculture, 510 Mt_{dm} from forestry and 119 Mt_{dm} grazed by animals on pasture (JRC 2018a).

Not all grown biomass is harvested and used, mostly as parts should remain in fields and forests to maintain Carbon sinks and other ecosystem services, but also because of missing incentives for mobilising unused residual biomass streams and lack of knowledge within the farming community about sustainable practices and new bio-based markets.

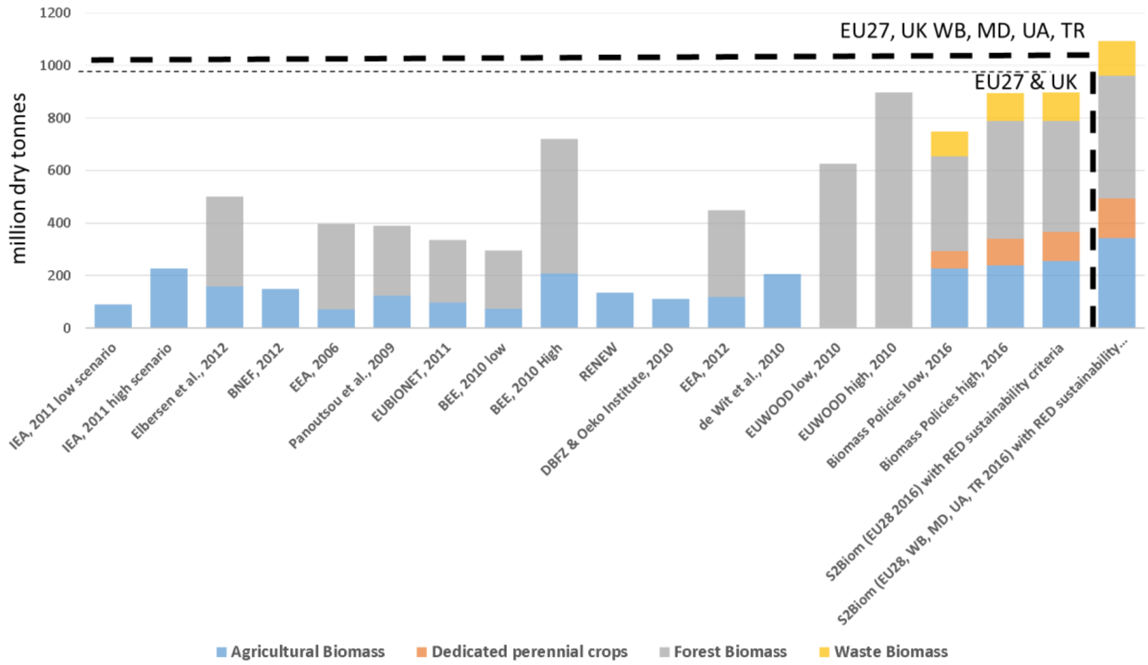
JRC (2018a) estimated biomass production from fisheries and aquaculture as ≈1.5 Mt_{dm}.

Various studies[15] identified sustainable biomass potentials in the EU, considering resource efficiency, sustainability (incl. biodiversity, ecosystem services, GHG emissions, soil protection) and demand for non-energy uses, giving a resource baseline of ≈ 750 Mt_{dm} (≈14 EJ) of biomass for 2030. This excludes all currently known non-energy uses but includes energy and fuel use estimated as ≈250 Mt_{dm} (240 Mt_{dm} forest biomass + 10 Mt_{dm} agricultural residues, mainly for heat and power).

These figures imply that a net total baseline of 500 Mt_{dm} (≈10 EJ) of EU biomass can be sustainably available for all additional uses by 2030.

There is also potential to sustainably cultivate biomass on marginal and degraded land in the EU which could contribute significantly to the overall domestic biomass potential[16].

Figure 8 EU27+UK sustainable biomass potentials as estimated during the last decade through various initiatives



Source: Panoutsou et al. (2016)

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[14] Conversion factor used: 1 Mt_{DM} = 0.019 EJ (Chiaramonti 2020).

[15] See Panoutsou & Brunori (2020) for an in-depth discussion.

[16] Several studies underline such potentials, e.g., Cossel et al. (2019), Englund et al. (2020), Pancaldi & Trindade (2020), and http://magic-h2020.eu - all consider sustainability safeguards.

A recent analysis of EU biomass potentials for energy (Manley et al. 2020) indicated a demand of 7 - 12 EJ by 2030, and ≈10 EJ by 2050, compared to domestic potentials[17] of 10 - 25 EJ by 2030, and 10 - 20 EJ by 2050.

Box 1 Aquatic biomass: Algae

Both micro-algae and macro-algae are considered as a potential feedstock for biofuel production in the overall biorefinery concept (Box 8 and Bose et al. 2020), mainly because of their low land and water requirements as compared to crop-based biomass. Theoretical calculations show attractive potential for future algae-based biofuels, with high productivity per unit land area, but cost reduction and scale-up are critical challenges (JRC 2019d). Also, aquatic biomass is a relevant source of food today, and even more so in the future (Box 5).

The advantages of algae as biofuel feedstock are multifold (Anto et al. 2020). Tolerance of algae to harsh conditions makes them a good choice for biofuel production and algae have the ability to mitigate CO_2 (Liu et al. 2017; Schenk et al. 2008). Algae can grow almost in all types of water (fresh water, seawater, even in industrial waste waters, see Collotta et al. 2018).

Considering the growth and oil content, the growth rate of algae is approximately 20–30 times faster than food yielding crops and the oil content of algae is around 30 times more than the conventional 1st and 2nd generation feedstocks (Ullah et al. 2015). The algae remnants after oil extraction can be used as fertilisers or as fish feed in fish and oyster farms. Research shows that microalgae biodiesels (Chen et al. 2015) exhibit higher yields (158 vs. 60–100 t of macroalgae, see Christi 2007), and are easier to convert due to their low carbohydrate content (Jin et al. 2013).

However, large scale microalgal lipid production is not yet economically viable (JRC 2015; Murphy et al. 2015) and several technological and economic obstacles must be overcome before starting on industrial scale biodiesel production (Menegazzo & Fonseca 2019).

A great challenge is the choice of an effective strategy for biomass recovery and lipid extraction since the scheduling of these processes can be critical, requiring the development of an energetically favourable, environmentally friendly and economically viable process (Christi 2007; Halim, Danquah & Webley 2012).

Besides biofuels, algae have high importance for the EU as they are used for a larger number of applications including feed and fertilisers, cosmetics, food additives (proteins), pharmaceuticals, etc. As mentioned in the EC Farm to Fork Strategy: "The Commission will set out well-targeted support for the algae industry, as algae should become an important source of alternative protein for a sustainable food system and global food security". (EC 2020b)

In addition to domestic EU biomass potentials, there are opportunities for imports of non-food/feed biomass, especially in the form of pellets, biomethane, and advanced biofuels[18] which often appear more cost competitive with domestic production (Visser, Hoefnagels & Junginger 2020). Nevertheless, imports would not foster development (employment, income…) in Europe, and – in the absence of an effective sustainability governance – could imply sustainability risks in regions from which biomass would be imported.

In that regard, and with a view to SDG 8 (sustainable growth, employment), SDG 10 (reduce inequality), SDG 13 (climate change mitigation), SDG 15 (life on land) and SDG 17 (partnerships), sustainability governance (Sections 4.1 and 6.6) is of key relevance and will have to balance the interests of the EU and its international partners.

For this, the explicit analysis of trade-offs and exploration of synergies for a sustainable EU bioeconomy within the broader international context is crucial[19].

[17] Manley et al. (2020) provide data for the biomass potential in energy terms [EJ] – to compare with mass-based potentials, an average conversion factor of 17.5 GJ/t_{dm} can be applied, giving a range of 570 – 1,100 Mt_{dm} which well fits the 750 Mt_{dm} resource baseline indicated before.

[18] See for a discussion Fingerman et al. (2019), Junginger et al. (2019), Mai-Moulin et al. (2019), Pelkmans et al. (2019) and the results of the EU BioTrade 2020 plus project https://www.biotrade2020plus.eu/ .

[19] See Heimann (2019); JRC (2018c); Mai-Moulin (2020); Philippidis et al. (2019 and 2020); Ronzon & Sanjuán (2020).

3.2 Climate impacts: mitigation and adaptation

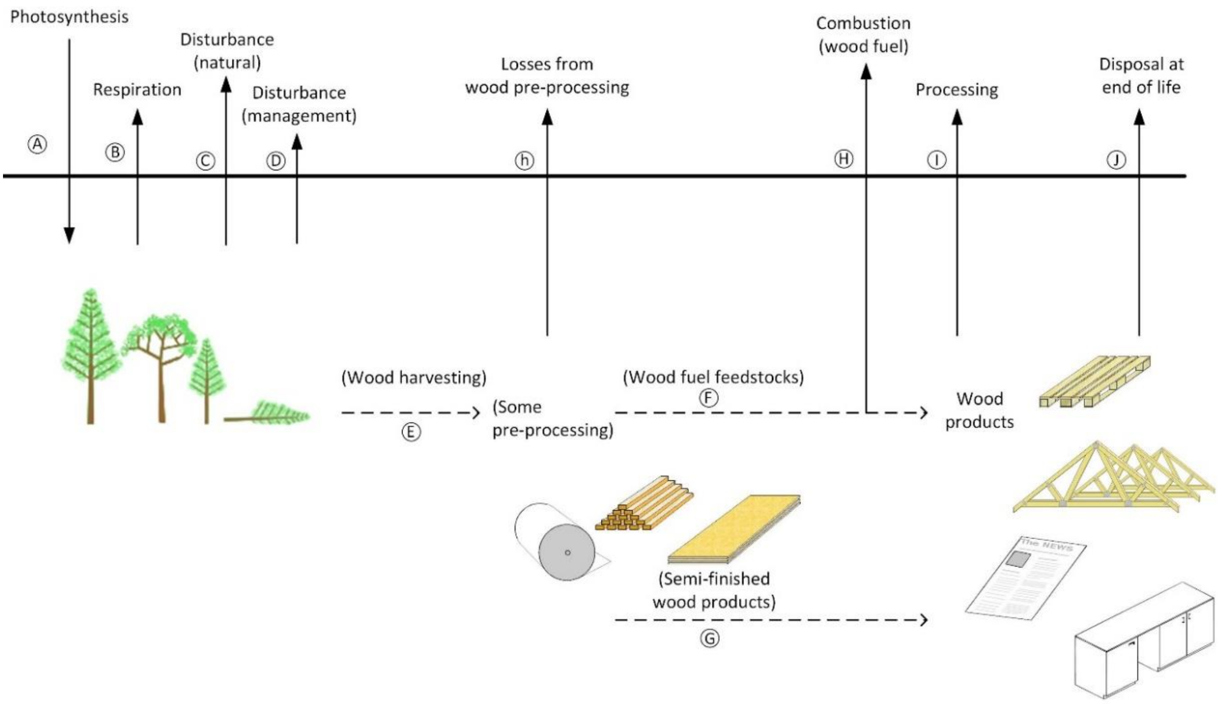
A key cross-cutting consideration for a sustainable EU bioeconomy is climate change mitigation and adaptation (EC 2018), especially achieving the objectives of the European Green Deal (EC 2019a+b) and of the Paris Agreement.

The overall balance of all the carbon flows associated with vegetation and harvested products consists of the combined flows of carbon between the atmosphere, vegetation and products (illustrated in Figure 9 for the case of forests and wood products) by the arrows crossing the black system boundary line. Expressed as an equation that is:

Overall carbon sink/source = A – B – C – D – h – H – I – J (Equation 1)

where the positive contribution (A, sink) indicates an atmospheric transfer to vegetation and negative contributions indicate transfers to the atmosphere (sources, or emissions).

Figure 9 Simplified carbon flows associated with forests and wood products



Source: *Matthews (2020); the net carbon sink/source consists of the combined flows of carbon between vegetation, biomass products and the atmosphere indicated by the solid arrows crossing the black system boundary line. Other transfers of carbon (dashed lines) are also considered implicitly.*

The resource of carbon constituted by forest biomass makes contrasting contributions in terms of climate change mitigation:

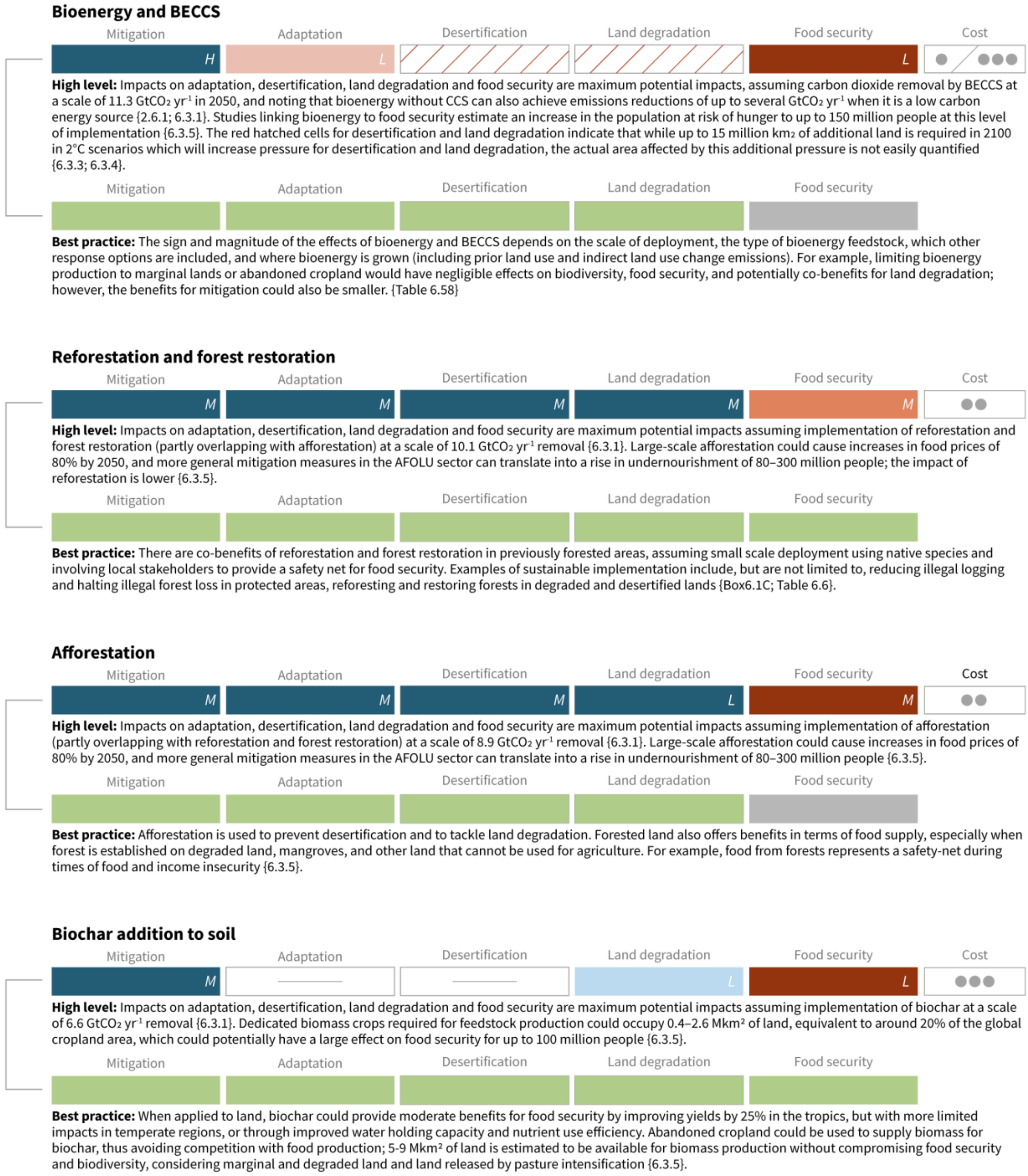
a) The C stocks in vegetation biomass, litter and soil represent a natural reservoir of C sequestered from the atmosphere. In principle, forests could be "managed" to retain carbon stocks and as carbon sinks.

b) Biomass can be harvested and used for a range of products (e.g. energy, transport fuels, bioplastics, construction materials, paper etc.), some of which also represent a C reservoir and can be used to substitute for generally GHG-intensive non-biomass materials and energy sources. Although the lifetimes of products are temporary, some are long-lived, suggesting that the reservoir of carbon in products could also be "managed" to retain carbon stocks and as carbon sinks.

c) Wood products can also be used to substitute for generally GHG-intensive non-biomass materials and energy sources. In situations where bioenergy derived from wood biomass can be regarded as having low GHG emissions, combination with CCS could contribute towards negative emissions (Box 2).

Which option implies a better C balance depends on many factors and has biodiversity, other environmental and socioeconomic trade-offs needing consideration. IPCC (2019) addressed climate change mitigation options related to biomass and land (Figure 10).

Figure 10 IPCC comparison of biomass-based climate change mitigation options



Source: IPCC (2019); For each option, the first row shows implications for global implementation at scales delivering CO_2 removals of more than 3 Gt CO_2/yr. Red hatched cells indicate increasing pressure but unquantified impact. 2[nd] rows show qualitative estimates of impact if implemented using best practices in appropriately managed landscapes that allow for efficient and sustainable resource use and supported by appropriate governance mechanisms. In these qualitative assessments, green indicates a positive impact, grey indicates a neutral interaction.

Box 2 Bioenergy with Carbon Capture and Storage (BECCS): a game changer?

Current national and international policies to achieve the Paris Agreement– i.e. to stay well below 2 °C global temperature increase by the end of this century – are not sufficient (UNEP 2019). This implies that global GHG emissions may "overshoot" the emission trajectories needed to achieve a 1.5 or at least a well below 2 °C target, and there will be residual GHG emissions from e.g. agriculture. Thus, a need to compensate excessive emissions by taking CO_2 out of the atmosphere ("negative" emissions) could arise by 2050 at the latest (IPCC 2018), i.e. it would not be enough to achieve a carbon-neutral global energy system, but to deploy "negative" emission technologies.

Here, bioenergy could play a key role: when bioenergy combustion is combined with carbon capture and storage (CCS), it becomes bioenergy with CCS (BECCS), which could result in negative GHG emissions, as vegetation – including cultivated energy crops - removes CO_2 from the atmosphere. The biomass is then converted to energy (e.g., biofuels, electricity, heat) and CO_2 released during biomass combustion is captured and stored. BECCS is technically feasible – but is it sustainable?

IEA (2017) strongly argued BECCS is needed to stay below 2 °C, and that to achieve the required increase in bioenergy supply and use, an appropriate approach to sustainability governance is needed. Yet, the scale of BECCS and the respective biomass supply have raised concerns: key potential negative trade-offs are biodiversity loss from large-scale monocultures, related land tenure problems, and water availability. IPCC (2019) identified such trade-offs and linked them to the scale of bioenergy (and other mitigation options, see Figure 10) deployment, and options such as biochar and pyro-CCS need consideration as well[20].

Given that even sustainable bioenergy is a limited resource, priority should be given to a circular and mainly residue- and waste-based bioenergy. Seen from this perspective, BECCS would "only" be a safeguarding strategy – but quite an important one.

Box 3 Agricultural adaptation and resilience

Contributions to direct GHG emissions from agriculture are estimated to account for 10% to 15% of total anthropogenic GHG emissions and 48% of global non-CO_2 anthropogenic GHG emissions (Vermeulen, Campbell & Ingram 2012; Tubiello et al. 2015). These emissions are mainly in the form of methane, mostly from animal production; nitrous oxide, mostly from fertilisers on arable land; and CO_2 mostly from soil C changes and energy use (IPCC 2019). A major challenge for agricultural production is to facilitate economic and social recovery which will however be in line with a more productive but still ecological agriculture (Section 4.3.1).

Bioeconomy however offers unique opportunities for agriculture to diversify supplies for food, feed and raw materials, contribute to circularity and climate neutrality whilst, at the same time, create employment and foster rural development. While climate change poses multiple risks to different elements of the agricultural systems and negatively affects food security, biomass production under sustainable agroecology can offer a strong systemic response to climate change-related challenges[21].

Biomass production can be integrated into landscapes, especially through conservation agriculture, cover cropping, rotational cropping, agroforestry, use of biochar, and restoration of degraded land, and biomass conversion is integrated into food/feed/fibre/energy systems through biorefining (Bradford et al. 2016). The cultivation of more resilient and resistant crops adapted to changing climate conditions (e.g. recurrent droughts, water scarcity etc.), namely in the most affected areas such as the Mediterranean basin, is also very important (EEA 2019).

[20] For a brief discussion and respective references see Matthews (2020).

[21] https://enb.iisd.org/climate/agroecology/ .

Conservation agriculture[22] *is any method of soil cultivation that leaves the previous year's crop residue (such as corn stalks or wheat stubble) on fields before and after planting the next crop to reduce soil erosion and runoff, as well as to gain other benefits such as carbon sequestration. Switching from conventional to conservation tillage, including no-till and minimum-till, could decrease carbon oxidation and CO_2 emissions from soil as well as increase carbon sequestration (Lal & Kimble 1997; Lal 2004; Lange et al. 2015).*

Cover cropping: when two or more crops are grown in a year on the same land, the system is referred to as double cropping or multiple cropping (or sequential cropping). This practice consists of growing crops in sequence within a crop year (in one growing season one crop is being sown after the harvest of the other) and offers positive C balance as compared to soil being left bare.

Rotational cropping is the practice of growing a series of different types of crops in the same area in sequential seasons. Crop rotation gives various nutrients to the soil and also helps to reduce erosion. Rotating crops helps to improve soil stability by alternating between crops with deep roots and those with shallow roots. Pests are also deterred by eliminating their food source on a regular basis. Rotational cropping can decrease carbon oxidation and increase aggregate stability and the concentration of soil carbon (Blair & Crocker 2000).

Agroforestry involves the tending of livestock or growing of food crops on land that also grows trees for timber, firewood, or other wood products. It includes shelter belts and riparian zones/buffer strips with woody species and can offer broader benefits for climate adaptation to animal stock (e.g. shading in warm climates). The standing stock of carbon above ground is usually greater than the equivalent land use without trees, and planting trees may also increase soil carbon sequestration (Brahma et al. 2018; Feliciano et al. 2018; Shi et al. 2018).

Biochar production and addition to agricultural soils could be a very good way to reduce demand for fertilisers (cutting dependency, costs and pollution), sequester carbon and enable relatively cheap and lasting amelioration of degraded land and sustainable and improved agriculture (Barrow 2012; Chiaramonti & Panoutsou 2019).

Restoration of degraded land (through erosion control, organic amendments, nutrient amendments, cultivation of perennial crops, etc.). A large proportion of agricultural land has been degraded by excessive disturbance, erosion, organic matter loss, salinization, acidification, and other processes that curtail productivity. Often, carbon stocks in these soils can be partly restored by practices that reclaim productivity, including: re-vegetation (e.g. planting grasses); improving fertility by nutrient amendments; applying organic substrates such as manures, biosolids, and composts; reducing tillage and retaining crop residues and conserving water. Feng et al. (2018) describe how growing biomass crops on marginal land, especially perennial grasses such as switchgrass and Miscanthus, is expected to benefit the environment by increasing carbon sequestration (Lal 2006) and reducing nonpoint source pollution comparing with those from crop land (Feng et al. 2018; Gessesse, Bewket & Bräuning 2015).

Box 4 Forestry adaptation and resilience

Forest management in the context of mitigating climate change must also be able to adapt or be resilient to environmental change[23]*. Cohen-Shacham et al. (2019) have compared a number of approaches (sometimes collectively referred to as "nature-based solutions"). However, there appears to be a lack of a coherent distinction between practical measures and the policy frameworks to support them. Relevant measures include forest protection, restoration, diversification, and reduced-impact management.*

22 https://www.climatetechwiki.org/technology/conservation-tillage .

23 Note that for the adaptation of forests in the EU, in contrast to agriculture, rather long implementation periods must be considered: Europe's temperate forests require several decades for (re-)growth, while for the Northern boreal forests this takes up to several centuries. Furthermore, annual growth is subject to various factors with high variation, so that the adaptation success can be determined only over a long time, and the "signal-to-noise-ratio" as a quality measure will be rather low. Given these circumstances, field-based experiments may deliver only little evidence within the time horizon of 2030-2050, and if positive results are gained, they would be subject to longer-term implementation.

Forest protection may be required from natural and/or human threats, including fires, storms, pests, diseases, grazing animals, invasive species, unsustainable logging, or deforestation. Differing threats can hamper the transfer of strategies from one region to another. Where threats from human activity dominate, both ecological and social aspects must be considered. Nabuurs et al. (2009) stress that adaptation strategies need to work on both local and landscape scale.

*Forest and landscape restoration is "*the process of reversing the degradation of soils, agricultural areas, forests, and watersheds thereby regaining their ecological functionality*" (Besseau et al. 2018). Restoration can involve increasing the number and variety of tree species in gardens, farms, fields, and forests, or allowing natural regeneration of overgrazed, polluted or otherwise overused ecosystems.*

Three forest restoration measures may be identified:

1. *"Mosaic restoration" of deforested and degraded land – where forests and trees are combined with agriculture, waterways, protected areas, and settlements on a landscape scale*
2. *Large-scale restoration (afforestation/reforestation) may have relevance in some areas*
3. *Trees can also be introduced at lower densities in croplands and densely populated areas.*

Stanturf et al. (2014) provide a detailed review of forest restoration measures. Restoring forests can offer many benefits, including climate mitigation and adaptation, biodiversity conservation, support for other ecosystem services, local livelihoods, and well-being as well as economic gains. Challenges to forest restoration include a shortage of tree stock for planting, lack of practical guidelines and tools, including on site species matching, and aligning restoration activities with the needs and expectations of affected communities.

Forest diversification aims to increase the complexity of forest areas. Forest management options include conversion from even-aged stands and clearfelling to "continuous-cover forestry" (CCF), i.e. continuous thinning to develop a more complex, two- or multi-storey canopy structure. This can also include more diverse mixtures of tree species in stands. Whilst it can make management more complex and costly, it can increase resilience, e.g. to fires, pests and diseases and to climate change (Stokes & Kerr 2009). CCF management should not be confused with more narrowly defined practices such as "close-to-nature" forestry, which emphasise small-scale forest management interventions, reliance on natural regeneration rather than planting and avoiding the use of "exotic" (introduced) tree species where possible (O'Hara 2016).

Diversification can include the assisted migration of tree species to locations where growing conditions may become more favourable in the future (e.g. Dumroese et al. 2015). Locally-sourced tree species are sometimes considered best able to adapt to changes in the local environment[24], however some consider the introduction of exotic species as a necessary part of forest adaptation and they already form a significant part of forests in some European countries and can play an important role in supporting forest industries.

Reduced-impact forest management can also include improvements to existing forestry practices, for example reduced use of fertilisers and herbicides and managing the use of harvesting machinery to minimize damage to forest soils (e.g. Salmivaara 2020).

Relevant existing policies in the EU include the Natura 2000 network (EC 2020g), aiming to protect valuable and threatened species and habitats. Whilst the network includes protected nature reserves, the general approach is "people working with nature rather than against it" for both ecological and economic sustainability. Natura 2000 is being built upon as part of the EU Biodiversity Strategy for 2030 (EC 2020a) which also includes an EU Nature Restoration Plan (actions to restore degraded ecosystems), and measures to strengthen governance, track progress and secure finance from public and business sources. The Strategy also addresses measures to tackle the global biodiversity challenge, offering leadership in taking forward the UN Convention on Biological Diversity (UN 1992).

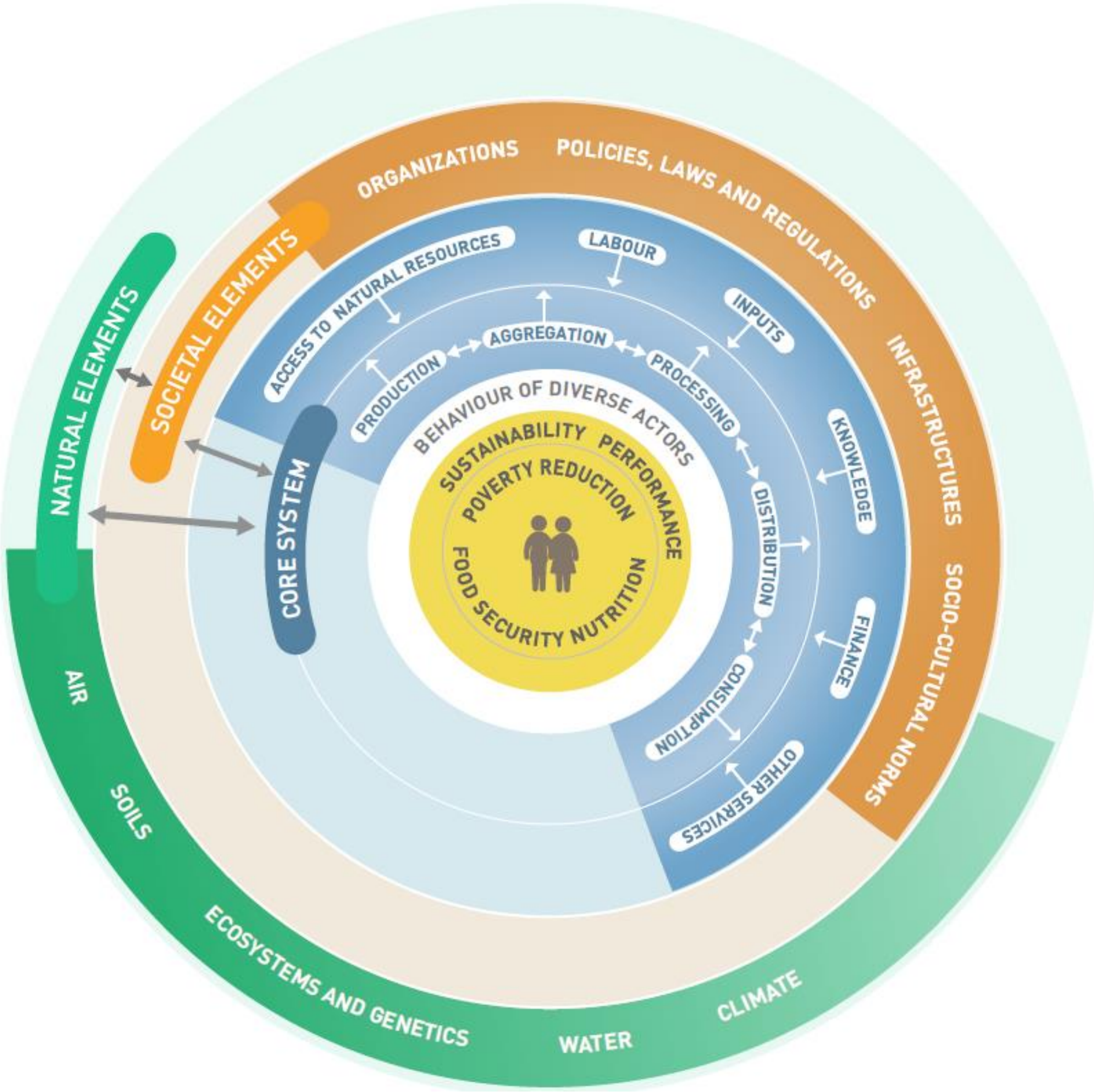
[24] One possible approach to creating resilience in terms of genetic diversity and local species adapted to changing climate conditions could involve supporting "natural regeneration" occurring in full-protection forest areas, which could potentially provide some results within a few decades.

The EU has also produced a Blueprint for a new Strategy on Adaptation to Climate Change (EU 2020h) aiming to work with existing EU Strategies and promote adaptation measures.

3.3 Food systems

Before discussing drivers and trends for food, feed and diets (Section 4.3), an integrated view of agriculture, fishery, forestry as well as processing of food/feed and ultimately nutrition, and end-of-life, is necessary to reflect on the linkages[25]. This is the food system[26] perspective, as shown in the following figure.

Figure 11 The concept of food systems



Source: FAO (2018)

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25 Again, the food system view must also consider the spatial dimension (e.g. Laroche et al. 2020), especially trade (Section 3.5).

26 Food systems "*encompass the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture, forestry or fisheries, and parts of the broader economic, societal and natural environments in which they are embedded. The food system is composed of sub-systems (e.g. farming system, waste management system, input supply system, etc.) and interacts with other key systems (e.g. energy system, trade system, health system, etc.). Therefore, a structural change in the food system might originate from a change in another system; for example, a policy promoting more biofuel in the energy system will have a significant impact on the food system. A sustainable food system is a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised*". (FAO 2018, p. 1)

The conceptual framework of food systems was given by HLPE (2017).

Food and feed comprise the largest consumers of biomass, dominate many environmental impacts such as biodiversity loss (IPBES 2019) and contribute to climate change (IPCC 2019).

Bahar et al. (2020) and Gerten et al. (2020) demonstrated that feeding ten billion people while staying within planetary boundaries is possible. As often highlighted, food security depends first and foremost on access to food and its utilisation. To achieve food security, significant improvements in the global food system, and forest/land governance are needed.

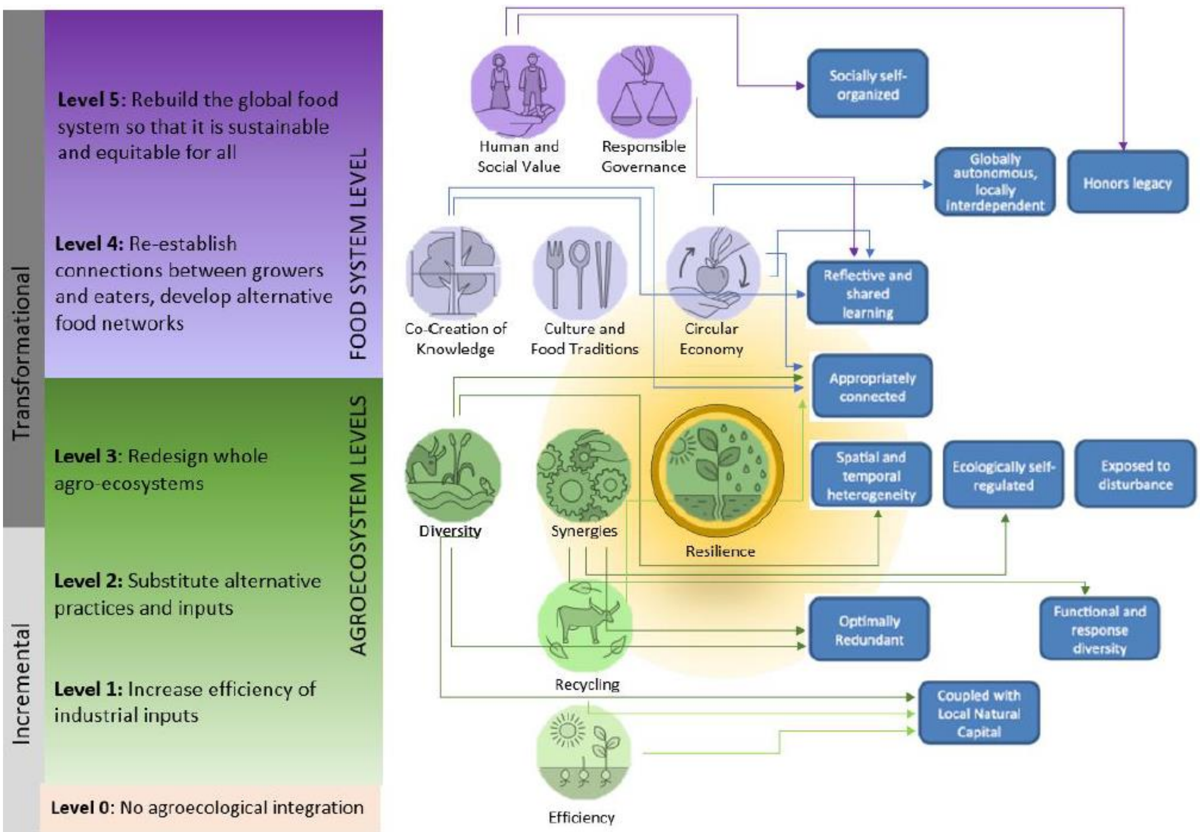
Transformative food systems address how biomass for food and feed is produced, processed and consumed (Galanakis 2020b).

Cornerstones of such developments are innovation (Herrero et al. 2020) and productivity (DeBoe 2020), and the EC already supports a wide range of respective R&I activities (EC 2016). Instigating attitudinal change is also crucial with respect to issues like food loss reduction, and adding value to food processing by-products, as a recent review of 50 years of literature on "how to feed the world" has indicated (Tamburino et al. 2020). IFPRI (2020) calls in its latest Global Food Policy Report on governments and stakeholders to build inclusive food systems, and Hadjikakou et al. (2019) provided tools for assessing food system sustainability.

IPES-Food (2015 and 2016) provide clear pathways towards sustainable food systems, especially the need to shift from industrial agriculture to diversified agroecological systems (Section 4.3.1), i.e. a transformation.

Similarly, UNEP-IRP (2016) uses the food system view to underpin the need for an agricultural transformation and Darmaunt et al. (2020) build on HLPE (2017) and FAO (2018) to clarify the levels of food system transformation (Figure 12).

Figure 12 Levels of food system transformation



Source: Darmaun et al. (2020)

Such a degree of high-level recognition and support for better governance and a food system transformation is also manifest in SAPEA (2020) which calls for an EU sustainable food system, and in the recent EC *Farm-to-Fork Strategy* (EC 2020b). In this context, the EC Scientific Advice Mechanism (SAM) food systems report (EC 2020m) promotes recognition of food as an actual common good, and not just as a commodity/consumer good.

Important for the bioeconomy is that the food system view enables to better understand both opportunities and policy challenges associated with sustainable food systems (OECD 2019a): A sustainable bioeconomy avoids and reduces food losses and wastes. Regarding circularity, unavoidable food processing by-products, residues, and food waste can be turned into feed and nutraceuticals using e.g. small-scale biorefineries (Box 8), either by primary producers alone or in cooperative business models. This provides new perspectives for farmers and rural areas and could not only reduce GHG emissions but also improve carbon, nitrogen and phosphorous cycling (and thus, circularity), and overall land-use efficiency.

3.4 Socioeconomic limits of a sustainable bioeconomy

Expectations on bioeconomic contribution to sustainability were scaled down somewhat in recent years, but the bioeconomy is still an important driver of economic growth, especially in terms of value-added, and employment, not only in the EU but in many countries. The bioeconomy also contributes to social and environmental improvements, if adequately governed.

Since the 1970s until the 2000s, Western governments had to deal with low agricultural commodity prices and surplus production, and saw the bioeconomy as a win-win solution: Giving support to farmers, sustaining an innovative industry, phasing out fossil fuels, and avoiding WTO trouble with agricultural subsidies. The food (price) crisis of 2007-2008 made clear that bioeconomy potential for economic growth is subject to planetary boundaries and socioeconomic constraints, especially food security concerns[27].

The bioeconomy is basically renewable (Figure 2), yet biophysical limits to growth apply, and distributional issues of e.g. income and land tenure indicate socioeconomic limitations, or at least inertia[28]. Adding circularity to the bioeconomy[29] can push the efficiency of biomass use and expand its value, but does not allow endless cycling, given the 2nd Law of Thermodynamics, accumulation of toxics, and logistical problems.

In other words, the bioeconomy potential in relation to economic growth is linked to

- its capacity to increase the efficiency of the system,
- reducing its environmental impact, restoring and enhancing ecosystem services,
- geographically redistributing employment, growth and value added by diversifying rural economies, and
- at least partially compensating the decline of the fossil-based economy.

Most of this has been taken up in the EU Bioeconomy Strategy (EC 2018), but if economic growth is to continue unchanged, even a circular bioeconomy cannot avoid a radical redesign of the economy (Göpel 2016).

For this, the bioeconomy must shift from the substitution paradigm of replacing fossil resources with biomass towards becoming transformative[30], i.e. acknowledging planetary boundaries (as the EU Bioeconomy Strategy does) and enabling economic and societal change, as called for by the SDGs (Section 5.4). Then the bioeconomy could contribute to post-COVID-19 recovery (Section 5.3) and avoid lock-in to traditional economic patterns.

27 FAO (2019b); Candel & Biesbroek (2018); Aubert, Brun & Treyer (2016); GEF-STAP (2016); IAASTD (2008).

28 Muscat et al. (2019); Henry et al. (2018); Borras Jr., Saturnino et al. (2020) and see Section 6.

29 See e.g. EC (2020c+d) EEA (2018a+b); Giampietro (2019); Stegmann, Londo & Junginger (2020); Zabaniotou (2018).

30 See Annex 2 for details; some considerations are given in Section 5.4.

"It always seems impossible until it's done." (Nelson Mandela)

3.5 Trade

The EU bioeconomy is part of international trade, as indicated in Figures 3-6, and subject to trade law and rules under the World Trade Organisation (WTO), but the EU has also bi- and multilateral trade agreements with many countries and regions. Trade is common for feed and food, rising for biofuels and pellets (Proskurina et al. 2019; Thrän et al. 2019), and established for various biochemical and biomaterial feedstocks (Figure 4). Yet:

"Trade today is not sustainable. (...) The reason behind is that production and consumption patterns do not reflect the true costs to society". (Schmieg 2018)

A recent analysis for the European Parliament argued in the same direction:

"Trade also impacts global biodiversity, for instance through the 'virtual' water, land, and deforestation contained in EU imports. Economic theory shows that trade with countries that fail to protect a renewable resource can be detrimental for all. Protecting global biodiversity calls for a variety of instruments, at the EU border as well as in the provisions of preferential agreements. The EU already includes biodiversity-related non-trade provisions in trade agreements, but these provisions are not legally binding and hardly effective". (Bellora et al. 2020)

UNEP-IRP (2019) details the brief analysis of trade impacts of EU consumption (Section 2.2), underlining that imports can have detrimental effects on exporting countries. Thus, a circular, sustainable, and transformative bioeconomy needs adjusting the trade system, considering the socioeconomic limitations (Section 3.4). In that regard, it is paramount to understand the SDGs as above the WTO, i.e. as superior. Governments negotiated the SDGs, they also negotiated how the WTO works, and under what rules:

"The WTO was created as a flexible institution that would evolve in parallel to the needs of the modern economy." (FoE 2020, p. 12)

To allow for a circular, sustainable, and transformative bioeconomy governed by the SDG, the same framing should govern the WTO, and its subsequent laws, and rulemaking (EP 2018; Kettunen et al. 2020). To transform the WTO accordingly is a major political challenge under current international political conditions and will surely not be implemented before 2030, as previous WTO reform processes indicate. Some actors, including the EU, show willingness to initiate such a process, and the EU Green Deal (Section 4.2) as well as the Circular Economy Action Plan (EC 2020c) can be read in that direction[31]. The WTO itself reported:

"WTO members have shown growing interest in discussing circular economy approaches and to deepen their understanding of how trade policies can support them. The focal point for policy dialogue on these issues has been the WTO Committee on Trade and Environment or CTE, which is open to all WTO members." (WTO 2020, item 3.5)

Until a WTO transformation is achieved, the EU can start implementing the SDG framing in its own bi-and multilateral trade agreements (EP 2018; Kettunen et al. 2020) and open the path for fair trade, and partnerships. Given the recent COVID-19 pandemic and its severe impact on global trade and disruption of highly integrated value chains,

"…it is very likely that productive processes will be redesigned after the pandemic. The decision to involve additional economies in a value chain will no longer depend solely on the estimation of profitability." (Oliveira et al. 2020)

[31] The Annex to the Circular Economy Action Plan states that the EU will take action on "*Mainstreaming circular economy objectives in **free trade agreements**, in other **bilateral, regional and multilateral** processes and agreements, and in **EU external policy funding instruments*** (EC 2020k, p.3).

Such redesign should improve the resilience of EU trade systems, and critically reflect costs of imports. Given the climate ambition expressed in the EU Green Deal (Section 4.2), the foreseen border adjustment tax could account for the GHG emissions embodied in trade, which should be seen as an option to harmonise EU trade policies on biofuels, feed/food, biochemical feedstocks, and the EU forest policy.

4 Key drivers and trends

This section briefly discusses key drivers and trends for a sustainable and circular EU bioeconomy[32].

4.1 SDGs: a framework for sustainability governance of the bioeconomy

To deliver on a sustainable EU bioeconomy, not only goals are needed but means of implementation (capacity building, financing, governance). The EU and all Member States signed up to the SDGs in 2015, and the Commission is committed to their implementation (EC 2019d). The EU Bioeconomy Strategy refers to the SDGs several times and acknowledges that the bioeconomy:

"(…) is essential to most of the Sustainable Development Goals." (EC 2018, p. 2)

Yet, both qualitative (Heimann 2019) and quantitative research (JRC 2019b, Philippidis et al. 2020; Ronzon & Sanjuán 2020) concerning impacts of the bioeconomy on the SDGs shows that the bioeconomy is not per se sustainable: there are significant trade-offs to be considered. A tentative assessment of relevant linkages between the bioeconomy and SDGs is given in Table 1.

Table 1 Qualitative assessment of bioeconomy linkages to relevant SDGs

SDG	Assessment of impacts	
	Positive	**Negative**
2. Zero hunger	Changed land management activities such as remediation of soil quality through incorporation of more organic matter in soil (as part of climate change mitigation measures) could improve crop yields. Restoring land of low quality to agricultural productivity increases available land for food/ feed and bioeconomy.	Expansion of non-food/feed biomass crops and forests could compete for land needed for food production. Increased use of crop residues in bio-based value chains could lead to diversion from other uses (e.g. animal feed) or lower organic matter inputs to soil (productivity impacts, GHG emissions).
6. Clean water and sanitation	Changed land management (e.g. perennial instead of annual crops, better soil management, more diverse landscapes of crops and forests) could reduce nutrient and sediment runoff into aquatic systems. Wastewater use for non-food cropping can improve sanitation, increase crop yields and ability to grow on low quality land.	More intensive use of land for agricultural biomass production, increased use of fertilizers (e.g. for biomass crops), and increased forest harvesting (e.g. for GHG emissions displacement) could increase nutrient and sediment runoff into aquatic systems.
7. Affordable and clean energy	Increased biomass production and local use for energy could increase energy security for local communities. In traditional electricity systems, power from biomass offers baseload. Dispatchable bioenergy (biogas, biomethane) contributes to flexibility in electricity systems with high shares of fluctuating renewable generation.	Restricted access to forest resources (as part of measures to conserve forest carbon stocks) could limit the utilisation of forest biomass as a bioenergy source. Cultivation of monoculture plantations can pose risks to biodiversity and other ecosystem services.

[32] This section deals with specific drivers for the EU bioeconomy, as identified by expert judgement of the authors. For a broader review of drivers such as GDP, population etc. see Bisoffi (2019) and for megatrends Sitra (2020) and https://ec.europa.eu/knowledge4policy/foresight_en.

SDG	Assessment of impacts	
	Positive	**Negative**
8. Decent work and economic growth	More diverse land use could provide better opportunities for income generation and wider range of job roles and skills. New business models will be introduced, offering farmers and foresters important roles in supplying non-food biomass.	Local or regional over-reliance on biomass production could reduce economic resilience. Child labour and insecure land tenure when cultivating biomass can have negative social impacts.
12. Responsible consumption and production	Increased biomass recycling and incineration of biomass with energy recovery could reduce waste and increase the supply of renewable products.	See SDG 2 comments. Increased use of some waste wood residues could redirect supplies from manufacture of composite wood products, increasing GHG emissions.
13. Climate action	More biomass use could increase C sequestered in biomaterials and mitigate GHG emissions from fossil energy when bioenergy emissions are low (Box 6); BECCS for "negative" emissions (Box 2). Restoring forests and landscapes and improving agricultural land use can sustain C stocks/sinks and addresses ecosystem adaptation/resilience. Restoration of unused, abandoned and degraded land and low intensity crop management could increase soil C.	More intensive use of land for agricultural and/or forest biomass production; increased use of fertilisers could lead to reduced soil C stocks and increased GHG emissions. Utilisation of biomass resources may increase GHG emissions due to land use and soil C changes.
14. Life below water	Not determined due to current minor relevance for the EU – but large regional differences (Section 5.2), and rising interest for the blue bioeconomy, and of increasing future relevance. For a brief discussion of algae see Box 1 and for aquaculture Box 5.	
15. Life on land	Reduced intensity of biomass crop management and conservation of forest areas could support ecosystem restoration and safeguard biodiversity. Restoration of unused, abandoned and degraded land will increase opportunities for raw material supply and rural development. Increased economic value for crops and forests (either as biomass sources or valued C reserves) could give incentives for protection of agricultural land and forests. Better managing undermanaged forests improves habitat provision in some situations.	Greater pressure on agricultural land and forests from demand for food and bioenergy/materials could lead to over-exploitation and degradation of ecosystems and possibly ecosystem loss. Cultivating non-food crops with unsustainable practices will increase soil compaction and reduce soil organic C. Increased removal of agricultural and forestry biomass residues could lead to loss of soil nutrients and structure with negative effects on crop and forest productivity.

Source: Adapted from Matthews (2020)

Thus, the challenge is to implement sustainability governance for the bioeconomy which safeguards against negative impacts while fostering positive options (Niestroy et al. 2020). Governance is also an SDG accelerator (OECD 2019d).

As part of the EU Bioeconomy Strategy, the EC is developing a monitoring system (JRC 2020b and 2020d; Robert et al. 2020) and modelling tools to inform about and evaluate such trade-offs, both ex-post and ex-ante (JRC 2019b)[33].

The challenge remains to move beyond monitoring and develop multi-level governance approaches for the EU[34], and in the global context[35].

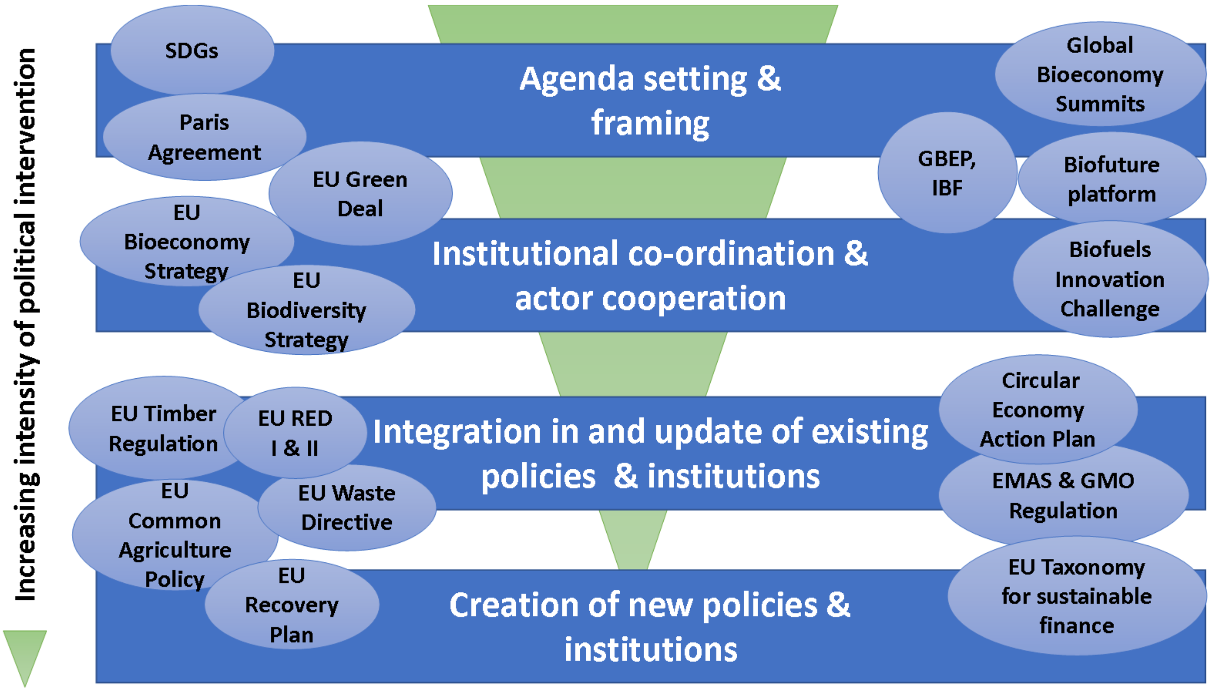
The SDGs and the European Green Deal (Section 4.2) have 2030 as a time horizon for implementation, while sustainability issues such as climate change, decarbonisation and resource efficiency typically aim at longer time frames such as 2050 or 2100.

In that regard, the SDGs and the European Green Deal are relevant stimuli for the longer-term development of a sustainable bioeconomy, and developing post-2030 goals and targets should be part of the overall EU bioeconomy governance.

On the other hand, implementation of the SDGs and the European Green Deal both face the problem of shorter time perspectives and preferences of market actors. For those, sustainability governance of the bioeconomy may best be expressed through near-term means of implementation such as the EU Taxonomy (TEG 2020) and financial schemes of e.g. the EIB, i.e. adding conditionality of monetary support in terms of sustainability.

Governing the sustainability of the (EU) bioeconomy should be seen as a process which ranges from agenda setting and framing to the creation and implementation of new policies, and possibly respective institutions (Figure 13).

Figure 13 EU-focussed governance processes related to the bioeconomy



Source: Iriarte, van Dam & Fritsche (2020)

33 Note that Work Package 2 of the Network of Experts is addressing the specific bioeconomy modelling challenges and opportunities.

34 See e.g. COR (2019), Moosmann et al. (2020) and Ugarte et al. (2020).

35 It should be noted that for the latter, an international governance framework is (yet) missing (Fritsche & Rösch 2020). Intergovernmental partnerships such as the GBEP (www.globalbioenergy.org) and the Biofuture Platform (www.biofutureplatform.org) as well as the Global Bioeconomy Summits (https://gbs2020.net), the International Bioeconomy Forum and the International Sustainable Bioeconomy Working Group initiated by FAO have potency to create such a framework (Pelkmans, Berndes & Fritsche 2019), and research activities such as https://www.sei.org/projects-and-tools/projects/sei-initiative-bioeconomy/ and https://strive-bioecon.de/ as well as ongoing work of IEA Bioenergy Task 45 may support respective developments.

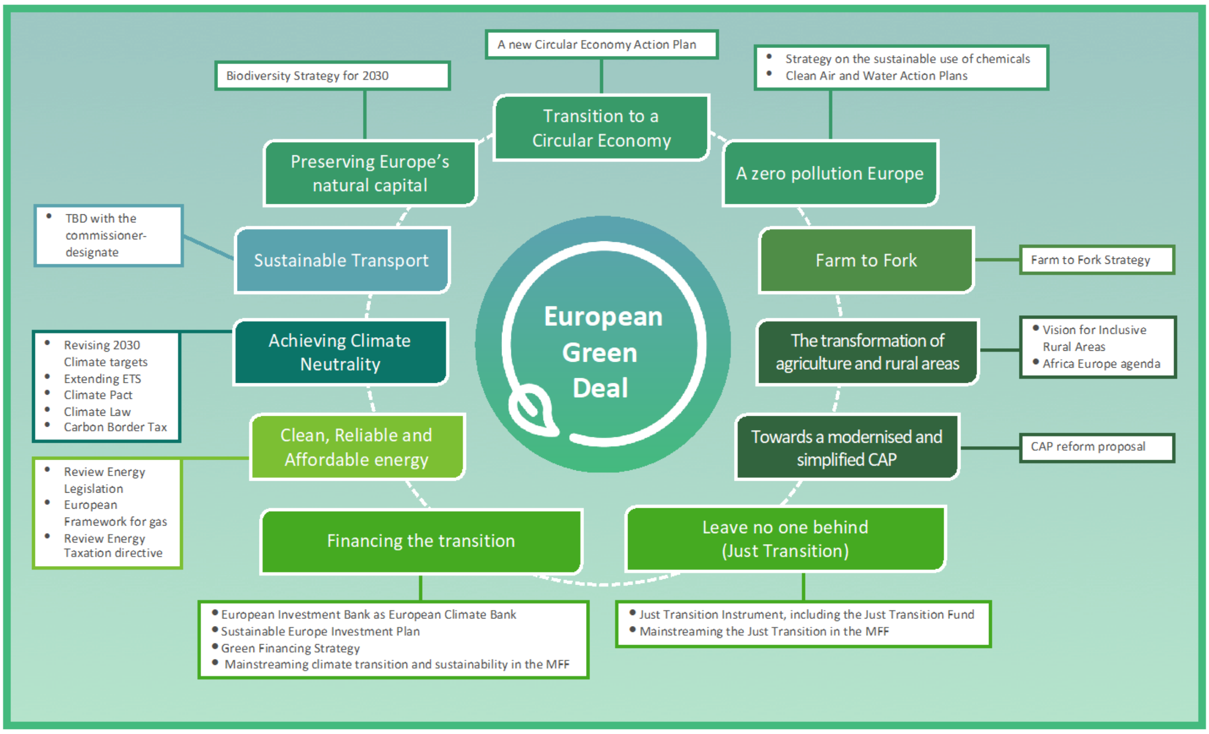
4.2 The European Green Deal and the Recovery Plan

Comparatively new drivers for a sustainable EU bioeconomy are the European Green Deal (EC 2019a) and the EU Recovery Plan "Next generation Europe" (EC 2020i and 2020j).

4.2.1 The European Green Deal

The following figure depicts the key components of the European Green Deal.

Figure 14 The European Green Deal



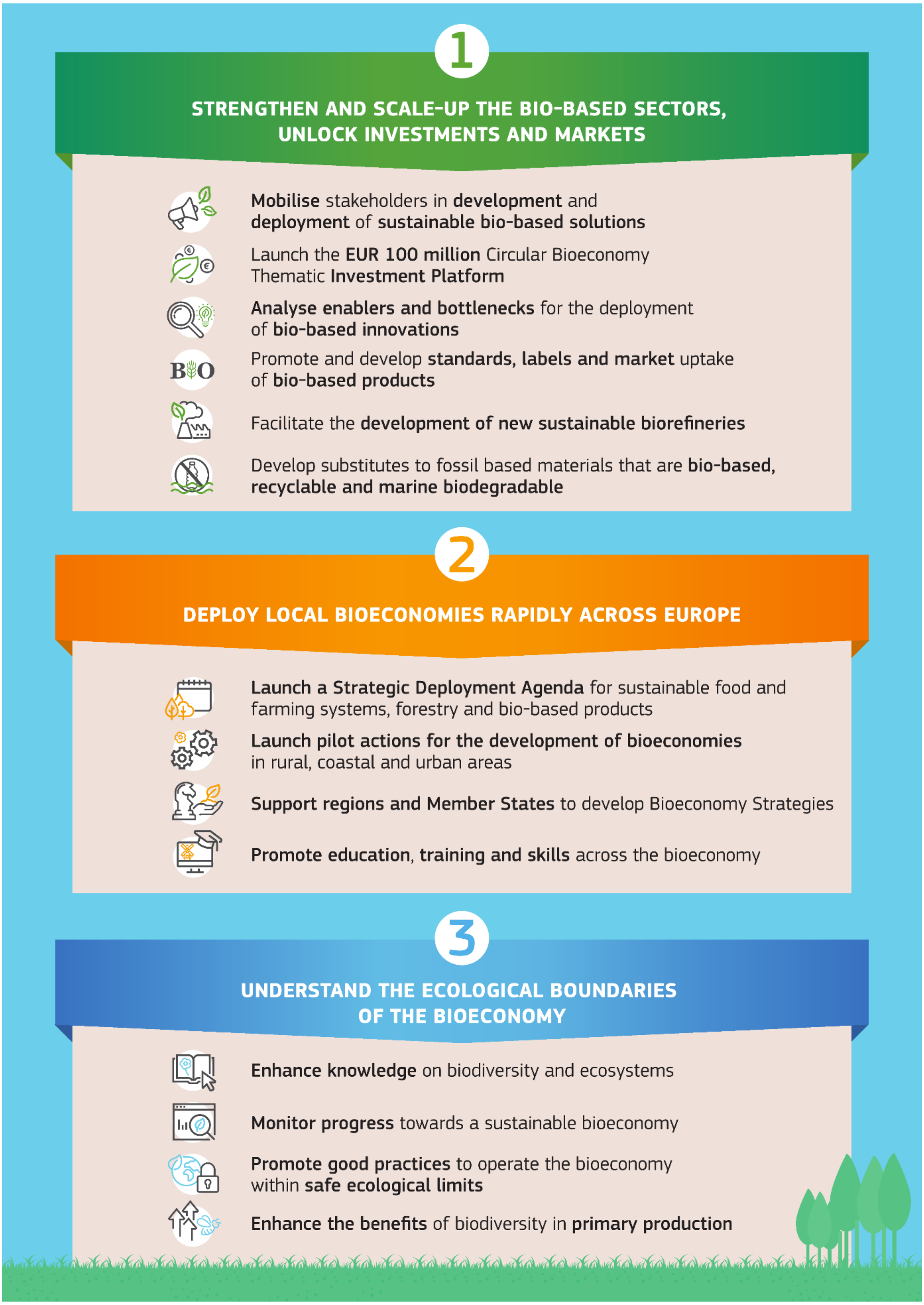
Source: *https://twitter.com/TimmermansEU/status/1181653669399400448?s=20*

The mix of incentives, regulation and strategy aims to deliver a more coherent policy framework to implement a sustainable European economy, including the bioeconomy.

The EU Bioeconomy Strategy Action Plan (EC 2018) contains some elements which were taken up by the European Green Deal, but the action plan is more focused (Balzi 2019), as indicated in Figure 15.

Similar to the Green Deal, the action plan aims at implementation within Europe, provides investment opportunities, is inclusive regarding Member States and stakeholders, and reflects on the ecological boundaries of the bioeconomy.

Figure 15 Key actions of the Bioeconomy Strategy Action Plan



Source: EC (2018)

The European Green Deal is an opportunity to integrate a variety of policies and strategies. The new EU *Biodiversity Strategy* (EC 2020a), the *Farm-to-Fork Strategy* (EC 2020b) and the EU *Circular Economy Action Plan* (EC 2020c and 2020d) as well as the New Industrial Strategy (EC 2020e) give positive indication that the EC is indeed delivering on that opportunity.

Furthermore, the *European Green Deal Investment Plan* (EC 2020f) is a core component of the means of implementation for the bioeconomy, and the Green Deal fulfils and concretises some of the strategic considerations of the Bioeconomy Action Plan.

The upcoming new EU *Forest Strategy* and measures to support deforestation-free value chains allows to deepen the drive towards sustainability and to provide at least some additional components of the sustainability governance for the bioeconomy, including the international dimension (Section 6.6).

Complementary to the European Green Deal, the EC priority for "A Stronger Europe in the world" is of crucial importance to strengthen the EU's role as a global leader while ensuring the highest standards of climate, environmental and labour protection.

As a driver towards sustainable bioeconomy, two policy areas are particularly relevant within this Commission priority:

1. The policy on international cooperation and development, including the comprehensive Strategy with Africa and the EU-Africa partnerships to work particularly on the green transition and energy access, and on sustainable growth and jobs; and
2. The trade policy, in particular seeking an open trade without sacrificing Europe's standards and achieving a balanced and progressive trade policy to harness globalisation.

Both are intended to unlock Africa's potential to make rapid progress towards a green and circular economy including sustainable energy and food systems – in other words: towards sustainable circular bioeconomy (or better in plural: bioeconomies, see Section 5.2).

As within Europe, smaller-scale biorefineries using grassy feedstocks as well as food residues and wastes to provide food, feed, fertilisers and other chemicals, materials and energy (Box 8) are important for Africa as well, especially in Sub-Saharan Africa (Callo-Concha et al. 2020), but there are many other nature-based solutions[36].

Sustainability governance has been mentioned already as a driver (Section 4.1) and is an important research issue as well (Section 6.6), to which collaboration with African partners could strongly contribute:

"*Most importantly, resolving the issue of Africa's green transformation through the biomass sector hinges on good governance*." (Okoh, Mailumo & Iganga 2018, p. 75)

The upcoming development of the African bridge part of the Green Deal may have a positive dynamic in that regard, and a collaborative approach in the sense of SDG17 (partnerships) would be appropriate to support this drive.

Thus, in considering future work on the bioeconomy foresight, not only modelling should include Africa, but also the development of storylines and narratives should consider this driver.

In that, co-creation and collaboration should be the guiding principles to include African partners in the foresight process, at least at a later stage.

The preparation for such an inclusive endeavour should start now, though[37]. The upcoming Global Bioeconomy Summit 2020, in which the EC and several of the authors of this report contribute, offers a key opportunity to start building such a partnership.

[36] See e.g. Cohen-Shacham et al. (2019); Palahí et al. (2020); Sachs et al. (2019).

[37] There are research activities which could contribute to such an outreach – see previous footnote 35.

"If you want to go fast, go alone. If you want to go far, go together." (African proverb)

4.2.2 The European Recovery Plan

The EU Recovery Plan with a financial volume of €1.85 trillion (EC 2020i and 2020j) is unprecedented, as the EC wrote:

*"Europe is in a unique position to be able to invest in a sustainable recovery and future. This investment will be a **common good for our shared future** and will show the true and tangible value of being part of the Union."* (EC 2020i. p.3)

The €1.85 trillion, compared to the total EU27 GDP of ≈ €14 trillion and the expected GDP loss from the COVID-19 pandemic of ≈€ 1 trillion in 2020 alone (EC 2020j), does not seem to be excessive.

Given the bioeconomy's EU-wide GDP share of more than 10% (Section 11) and its high importance for (underdeveloped) rural areas, it will have to be a critical part of building back better (OECD 2020b).

4.3 Food and Feed

Globally, the food system[38] contributes up to 50% of anthropogenic GHG emissions if all factors are considered (25-30% for direct effects only).

Furthermore, it causes the majority of impacts on animal welfare, biodiversity, land, and water. If unmitigated, these impacts could go up by 50–90% until 2050, due to growth in population and changing diets driven by increased income (Galanakis 2020a).

As food and feed are deeply rooted in societies, cultural aspects need consideration in food systems (Section 3.3), which is also part of the open research issues (Section 6.5).

4.3.1 Agriculture: towards agroecology

Agriculture is a fundamental component of the EU bioeconomy, and the EU Common Agricultural Policy (CAP) a key lever for improving its sustainability. Agriculture has a high relevance for biodiversity, rural employment, farmer's income, GHG emissions, land use and pesticides application as well as nitrogen and phosphorous loads.

A special report by the European Court of Auditors found that the CAP has not halted biodiversity decline on European farmland (ECA 2020).

With its new *Biodiversity Strategy* and *Farm-to-Fork Strategy*, the EC has taken up some of the considerations for a future sustainable food system, as depicted in Section 3.3, and a recent EC staff analysis of links between the CAP reform and the Green Deal clearly states:

"The new 'eco-schemes' will offer a major stream of funding to boost sustainable practices, such as precision agriculture, agro-ecology (including organic farming), carbon farming and agro-forestry." (EC 2020l)

A core concept of a "green" CAP reform is agroecology which also offers potential for climate change adaptation (EC 2020h; Darmaun et al. 2020; HLPE 2019, and Box 3).

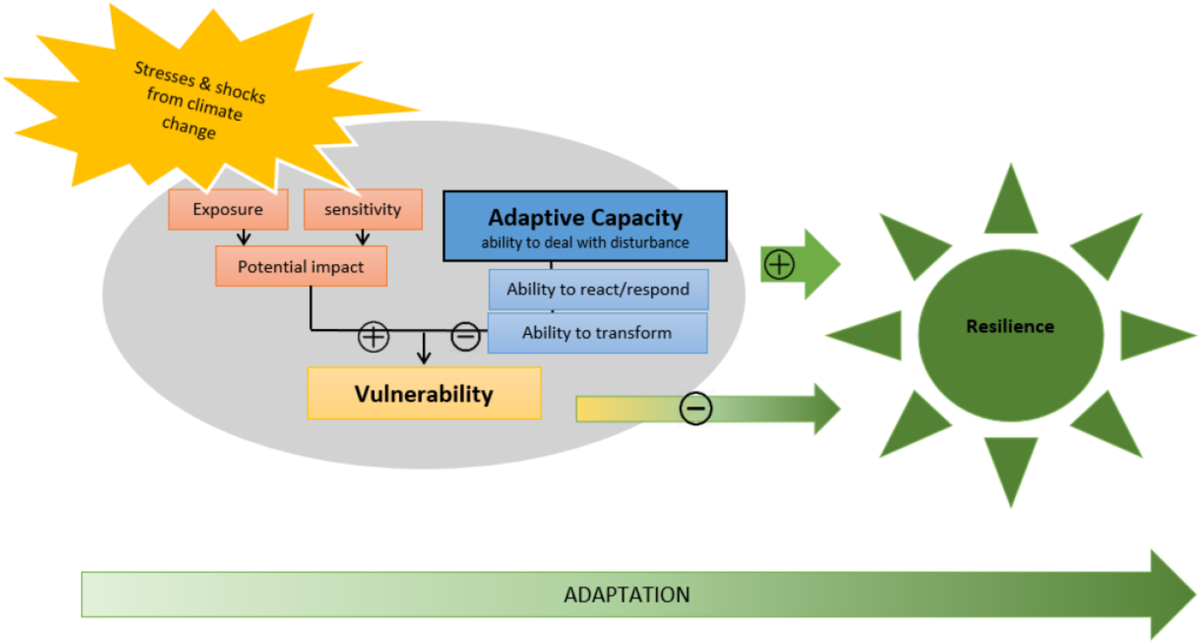
As EFBCP & IDDRI (2016b) and IDDRI (2019) showed, agroecology has a huge potential to transform the EU food system while providing biodiversity benefits and rural employment and income, as indicated by the new EC *Farm-to-Fork Strategy*. There is a variety of agroecological initiatives already operating in the EU (EFBCP & IDDRI 2016a).

DeBoe (2020) found that agricultural policies impact significantly on agricultural sustainability performance, not only in Europe.

[38] This section provides a summary of Galanakis (2020a) and Beretta & Hellweg (2020).

As agroecology is increasingly discussed internationally, its potential for improved resilience becomes more relevant in the post-COVID-19 era (Figure 16).

Figure 16 Agroecology as a key concept to deliver on adaptation and resilience



Source: Darmaun et al. (2020

4.3.2 Diets

An increasing number of studies on the sustainability impact of different diets recognise that plant-based diets are beneficial for the environment, but some raise concerns about the magnitude of the impact, and affordability. Diets that include higher amounts of fruits, vegetables, and plant-based sources of protein as well as lower consumption of alcoholic beverages, soft drinks and meat are considered both more sustainable and healthier (Galanakis 2020a).

Decreasing excessive portion sizes and the cost of healthy foods, improving access to food, and increasing diversity of diets are among the main drivers of healthy diets. Such a dietary shift will allow staying within planetary boundaries, as many studies indicated[39]. To establish sustainable diets, various measures are available, e.g., modified labelling, taxing unhealthy products, education on behavioural changes and health benefits (Galanakis 2020a).

Europe has seen a slight reduction in meat consumption over the last years along with increased demand for vegetarian food and number of vegetarians. However, per capita consumption is among the highest in the world, though with differences between Member States (Galanakis 2020a).

Dietary shift to a more balanced proportion between animal- and plant-based proteins and fats is considered necessary to reach sustainability (Willett et al 2019; Tilman & Clark 2014; EC 2020b). The increase of alternative protein sources could also increase the resilience of food systems regarding the COVID-19 and future pandemic crises (Galanakis 2020a and 2020b). It must be noted that the sustainability of novel alternative protein sources (e.g. lab-grown meat) is yet questionable, and reductions in

[39] See e.g. Gerten et al. (2020); GPAFSN (2016); Henry et al. (2018); IPES-Food (2015 + 2018) IPCC (2019); OECD (2019a + 2020s+b). What is yet missing is an integrated view on healthiness, cost environ-mental impacts, and whether consumers will change their eating behaviours accordingly, as there are cultural limitations and individual inertia.

GHG emissions could be obtained without entirely excluding (but decreasing) meat products from diets.

Current trends in food waste (FW) research centre around consumer and household behaviour which is a reliable indicator that the reduction in food waste is tightly connected to sustainable food consumption and SDG 12. All related actors (e.g., companies, governments, and consumers) need to take actions to reduce food waste and change dietary patterns to more healthy approaches (e.g., less meat consumption, higher consumption of nuts, vegetables, whole grains, and fruits) to end food overconsumption, eliminate malnutrition, and ultimately improve health (IIASA & SDSN 2019).

A sustainable bioeconomy can turn food processing by-products, residues, and food waste into bio-based nutraceuticals and other added-value products (e.g., biopolymers, bioceramics, packaging materials, bio-based textiles, coatings and composites, bioenergy) helping processors, retailers, and consumers to reduce food waste.

Box 5 The future role of aquaculture

Aquatic biomass is comprised of fisheries and aquaculture (both fish and aquatic plants), including algae. According to FAO (2019a), global fish production was 171 Mt of fish in 2016, with 91 Mt of wild fisheries and 11 Mt of inland capture. Aquaculture represents 53% of global fish production. Total captures have been relatively steady since 1990. The share of aquaculture in total production grew since 1990 to 47%, and it is forecasted that soon the amount of fish produced by aquaculture will overcome captures.

FAO (2019a) estimates sustainable fish stocks[40] decreased from 90% in 1974 to 67% in 2015. With regard to utilization, Benè et al. (2016) estimated that of a total of 173 Mt, 131 Mt of fish go to direct human food and about 23 Mt for animal feed and other non-food uses. Given the situation of natural stocks, there is no room for increase of fish captures in the medium-term. To the contrary, reducing overfishing is the highest priority (FAO 2020a).

Aquaculture: a valid alternative?

Aquaculture has grown steadily (FAO 2020b), with China being the biggest producer (62% of global production). It has an ecological footprint lower than pork and chicken, and there is broad scope for technological innovation (WRI 2019).

Areas of innovation could be breeding and genetics, alternative sources of feed, disease control, water recirculation and pollution control. FAO foresees a growth to more than 100 Mt by 2050 (FAO 2019). However, there are several concerns about the sustainability of aquaculture growth.

The most relevant concern is its dependence on wild fish captures: as fish eat fish, growth of aquaculture may imply a tension on destination of wild stocks. Herbivore fish now comprise 80%, but as carnivore fish (salmon, shrimp, and other finfish) are also those preferred by wealthy consumers, growth in demand may generate tensions. A second concern relates to land and water: aquaculture uses about 2% of global available water (WRI 2019). Yet, aquaculture is seen as a fundamental building block of a sustainable global food system and offers many opportunities for improving its sustainability performance (Lengyel 2020).

Among the areas of innovation in this field, integrated multitrophic aquaculture systems introduce the cascading approach to aquaculture by co-cultivation of species with different trophic levels (Buck et al. 2018; Troell et al. 2009) and emerge as a promising model.

Algae

Production of algae includes macroalgae harvested from wild stocks or produced in aquaculture systems, and microalgae cultivated in open or closed systems.

[40] Amount of captures lower than the level necessary to stock reproduction.

According to JRC (2019d), production of macro algae was 32.67 Mt in 2016, global production is mainly based on aquaculture cultivation (97% in 2016). Europe, including Norway and Iceland, contributes marginally to global production (less than 1%), and most of production is harvested from wild stocks. EU production plants of algae biomass are located in 15 Member States. According to the EU Blue Economy report (EC 2019c), the EU algae sector has an annual turnover of €1.5 billion. Algae are used for a variety of high-value commercial products (e.g. cosmetics, nutra/pharmaceuticals) as well as biomaterials and energy, in addition to food, feed and fertilisers.

Yet, even the currently limited EU contribution to global algae production has reduced the biological potential by harvesting of wild stocks in Europe.

Stressors such as global warming, decline in water quality and introducing non-native species put the sector's sustainability at further risk.

4.3.3 Food losses and wastes

Food losses and wastes (FLW) account for 25-33% of today's total food production. Food waste (FW) quantities arising at household level are higher than in any other stage of food value chains, and environmental impacts caused from FW at household level are larger than for FLW at the previous stages of food value chains (Beretta & Hellweg 2020).

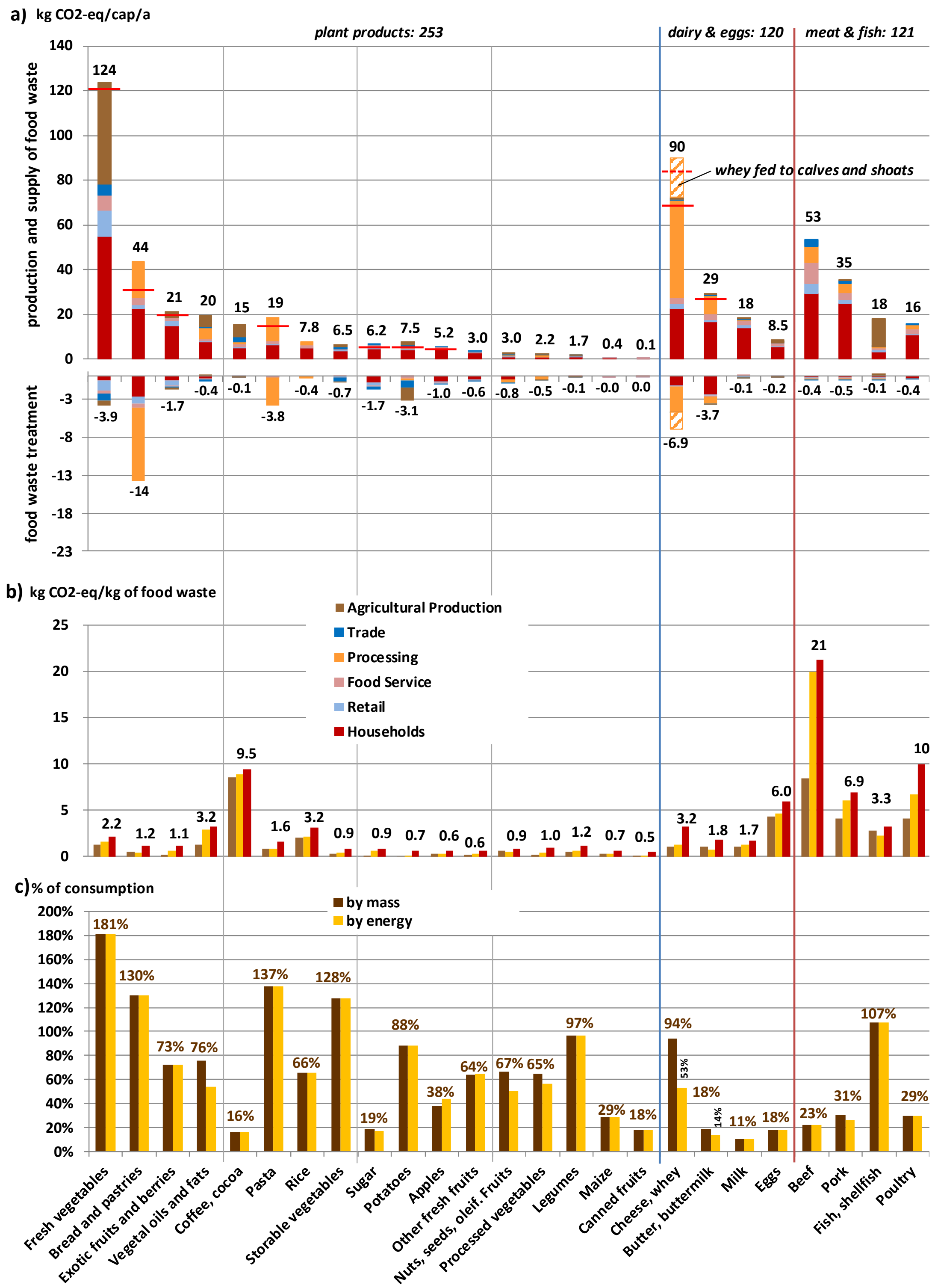
The synopsis of potential GHG emission savings from reductions of FW indicates a broad range of findings. Yet, a hierarchy of food types ranked according to the amount of FLW and according to the environmental impacts can be derived (Figure 17).

If FLW prevention strategies are implemented and scaled up to the entire sector, SDG 12.3 goal of halving FW is a realistic target for the food service sector (Beretta & Hellweg 2020). For this, collaborative and concerted efforts are required, focusing on preventing food surplus and waste being generated in the first place, redistributing surplus food, and valorising surplus unfit to feed people through animal feed and high value products.

The net environmental benefits from FLW treatment are less than 10% of the impacts from production and supply of the wasted food (Beretta & Hellweg 2020). Thus, avoiding food waste should be a first-line priority.

Since FLW are largely caused at the intersection between different actors of the food value chain, it is important to adopt a food systems perspective including all sectors of the food value chain (Section 3.3).

Figure 17 Food waste hierarchy according to various criteria



Source: *Beretta et al. (2017)*

a) Total GHG emissions (GWP 100) per person and year caused by production and supply of food that is wasted at various stages of the food value chain (positive values) and GHG savings from FW treatment (negative values)

b) GHG emissions per kg of FW from production, supply, and treatment of food, including credits for FW treatment

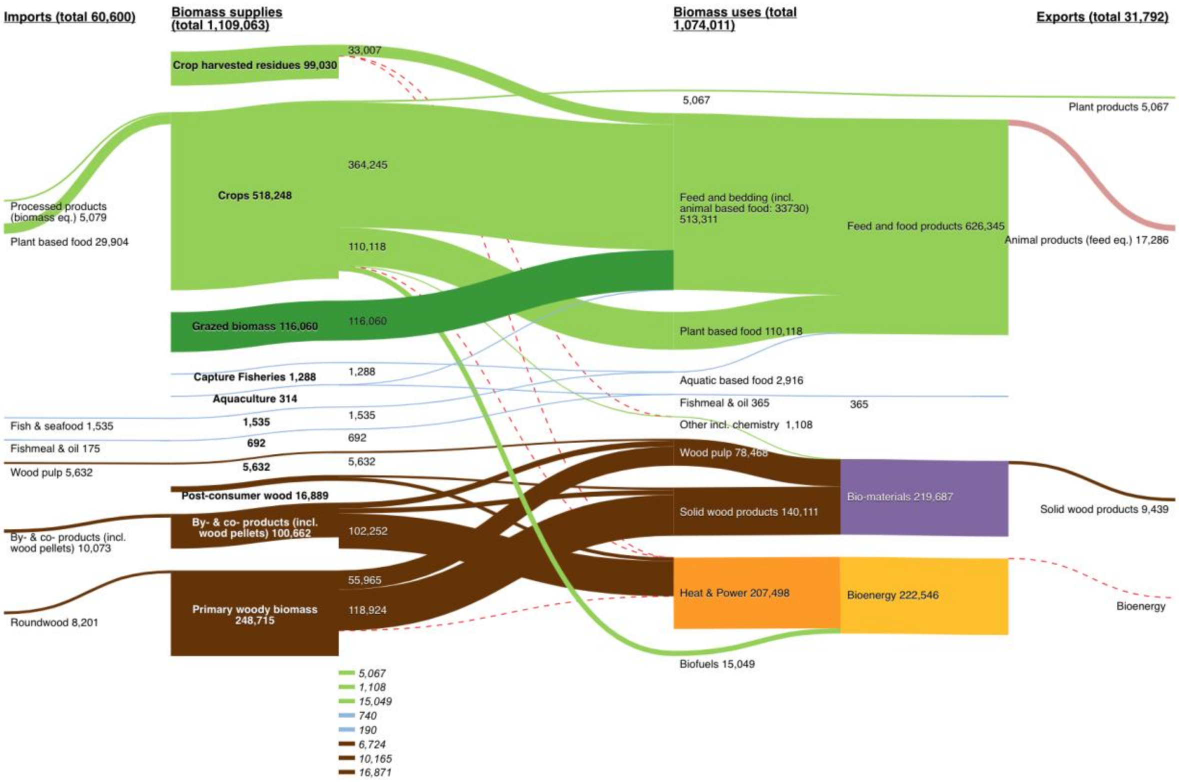
c) Relative FW amounts compared to final consumption (=100%) by mass and energy.

All underlying data refers to Swiss food consumption and FLW.

4.4 Bioenergy and biomaterials

Building on Section 3.1, this section presents key drivers and trends for bioenergy and biomaterials as components of the EU bioeconomy. Figure 18 indicates that the biomass flows to EU use of energy and materials (except food/feed) are relatively low.

Figure 18 Sectoral biomass shares in the EU27+UK



Source: *JRC (2018) https://ec.europa.eu/knowledge4policy/visualisation/biomass-flows_en; data in kt$_{dm}$*
Please note: Supply and use figures might not match due to estimation errors, stock changes, waste and/or loss of biomass or differences in the data sources used. Known data gaps are shown as dotted red lines. Gaps derive from missing or incorrectly reported data, data not assigned to a specific category or data that cannot be estimated.

Which are the potential drivers to increase those shares?

4.4.1 Biomaterials

Beside the traditional use of biomass for construction materials, fibre, furniture and textiles, modern biomaterials need consideration, especially bio-based chemicals, lubricants, and plastics.

The use of biomass feedstocks in petrochemistry is at an embryonic stage: In 2015, the EU27+UK petrochemical industry used 84 Mt of fossil feedstocks and 1.2 Mt of dry matter (Mt$_{dm}$) of biomass for bio-based chemicals (Duscha et al. 2019). The latter is equal to a 0.1% share of all biomass used within the EU27+UK, but with a 50% rising trend from 2010[41]. Yet in the last years, investments in alternative chemical feedstock start-ups have faced a decreasing trend.

At the EU27+UK level, the GHG-neutral EU2050 scenario projects 77 MtOE of biomass use in the chemical sector as feedstock by 2050, with an 80% share of total feedstock uses (Duscha et al. 2019).

[41] https://ec.europa.eu/knowledge4policy/publication/food-feed-fibres-fuels-enough-biomass-sustainable-bioeconomy_en

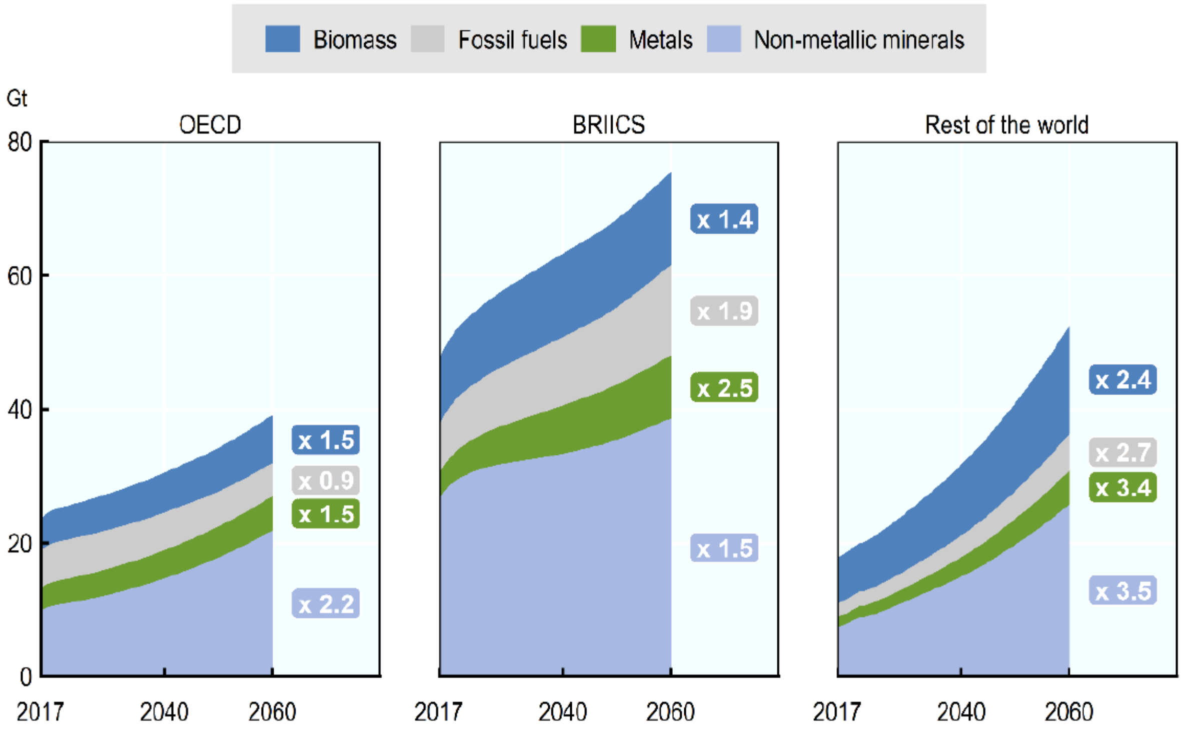
The 4th SCAR foresight exercise (EC 2015a) estimated a growth for biomass demand in the EU27+UK chemical sector from 59 Mt in 2011 to 500-1,000 Mt in 2050. This projection is based on a compound annual growth rate of 3.5% in the whole sector and on an increasing share of biomass use. SCAR identified several challenges that can be expected during this transition period, in particular the transport costs of biomass and/or low biomass availability that biorefineries (Box 8) would face.

Moreover, when biomass is co-processed in the petrochemical industry, some issues linked to the intrinsic variation of biogenic physical-chemical characteristics could emerge. A possible scenario where biomass is transformed into platform chemicals is addressed, indicating a disadvantage in the partial utilisation of biomass (mainly C and H, ≈ 20-50% of total biomass). However, this depends on the biorefinery configurations and how these will develop.

The synthesis of IEA and EC scenarios clearly indicate that future demands for bio-based feedstocks for the chemical industry will rise significantly, possibly taking up to 50% of the global sustainable biomass potential by 2050.

This is reflected in a recent projection: future material use up to 2060 will rise in all countries despite increased recycling and resource efficiency gains, and biomaterials have a high growth potential (Figure 19)[42].

Figure 19 Future projected role of biomass in global material use



Source: OECD (2019b); data given in Gt; BRIICS = Brazil, Russia, India, Indonesia, China, and South Africa

With a bioeconomic view, fertiliser production and use of digestates play a relevant role for future biomass use, and the "traditional" use of woody materials is currently modernised (see Box 6).

[42] For an alternative view on future biomass and fossil resource developments see Asada et al. (2020).

Box 6 Wood for materials

An estimated 12% of annual harvested wood volume is produced from EU forests (534 out of 4 344 million m^3 [Mm^3] over bark in 2017)[43]. Reported consumption of wood in the EU approximately equals production, although there is significant trade between Member States and externally. Around 75% of EU wood production supplies the wood industries (principally sawmills, panel mills and paper mills), with 25% used as wood fuel[44]. This is in contrast to global wood production where wood fuel makes more than half of total harvest, often going for inefficient "traditional" uses for domestic heating and cooking. The main products of EU wood industries are based on sawn timber, composite wood-based panels and paper and cardboard. The utilisation of wood biomass in the forest and wood processing sectors is complicated, with many exchanges of biomass between industries and in some cases significant use of recycled wood (e.g. EASAC 2017; Matthews et al. 2014). Within this system, statistics indicate that the consumption of wood for energy has increased in the last two decades. This may reflect improved reporting of fuelwood use but is also the result of polices encouraging the use of bio-energy. Whilst the relatively high value of sawn wood generally ensures that better-quality wood goes to sawn timber and structural products, there may be competition for lower quality wood to feed the energy, panel and paper industries.

The increased use of wood in buildings has been highlighted as offering significant benefits (Churkina et al. 2020; Geng et al. 2017; Johnston & Radeloff 2019). Climate change mitigation is identified as a key function of longer-lived wood products, through their physical retention of sequestered carbon. More generally, wood products are frequently promoted as involving low GHG emissions for their manufacture, so offering potential to substitute for more GHG-intensive materials (Leskinen et al. 2018).

To the conventional uses of wood must be added growing interest in the use of wood biomass as a material and feedstock for the manufacture of a wide range of innovative products[45]. Many areas of innovation will place wood at the centre of a circular, resource-efficient bioeconomy, including use of underutilised resources such as small roundwood, minor species and recycled wood. The trend for more timber in construction is due partly to its suitability for modern methods of offsite premanufacture. Laminated wood (e.g. cross-laminated timber) is high profile, and thanks to developments in processing there are many engineered and modified wood products, including boards, with enhanced performance, particularly for durability and moisture movement, such as acetylation, resin impregnation, and novel coatings. Growing interest in adhesive free methods, and modification by heat, densification, or natural chemicals, will reduce the resource footprint and improve circularity.

Burning for energy is the obvious end-of-life use, but pyrolysis and biochar present a wealth of alternatives, from facades to soil improvers, filters, fuels, and industrial feedstocks. The biorefinery concept (Box 8) extends a long-standing practice in the pulp and paper industry to produce an even wider variety of useful co-products for other sectors, including pharma-ceuticals, chemicals and food. High value speciality substances can be obtained from natural extractives, and the basic wood components (lignin, hemicellulose, and cellulose) provide a basis for new fabric fibres, bioplastics and other advanced materials.

Whilst wood can be a low-emissions and renewable resource, forests have a finite capacity to supply wood renewably. A significant expansion in requirements for woody biomass in the EU will be challenging to meet entirely through domestic production. A very large increase in harvesting in EU forests will lead to negative impacts on forest carbon stocks and the forest carbon sink (as defined earlier in Equation 1 and Figure 9) and potentially in the longer term, could undermine efforts to meet climate change mitigation targets.

The EU Regulation on LULUCF (EU 2013) enables Member States to identify future levels of wood harvesting while avoiding net GHG emissions increases (or reduced sinks) in forests[46].

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43 Estimates based on FAO data and conversion factors reported in Forest Research (2019), excluding UK wood production.

44 It is likely that fuelwood harvesting is not fully reported in statistics for some Member States, e.g., harvesting of fuelwood for domestic "own" consumption by private landowners is not always reported.

45 Relevant reviews and overviews are given in Ormondroyd, Spear & Curling (2015), Berglund & Burgert (2018), Jiang et al. (2018), Jones et al. (2019), Blanchet & Breton (2020) and Fernandez & Dritsas (2020).

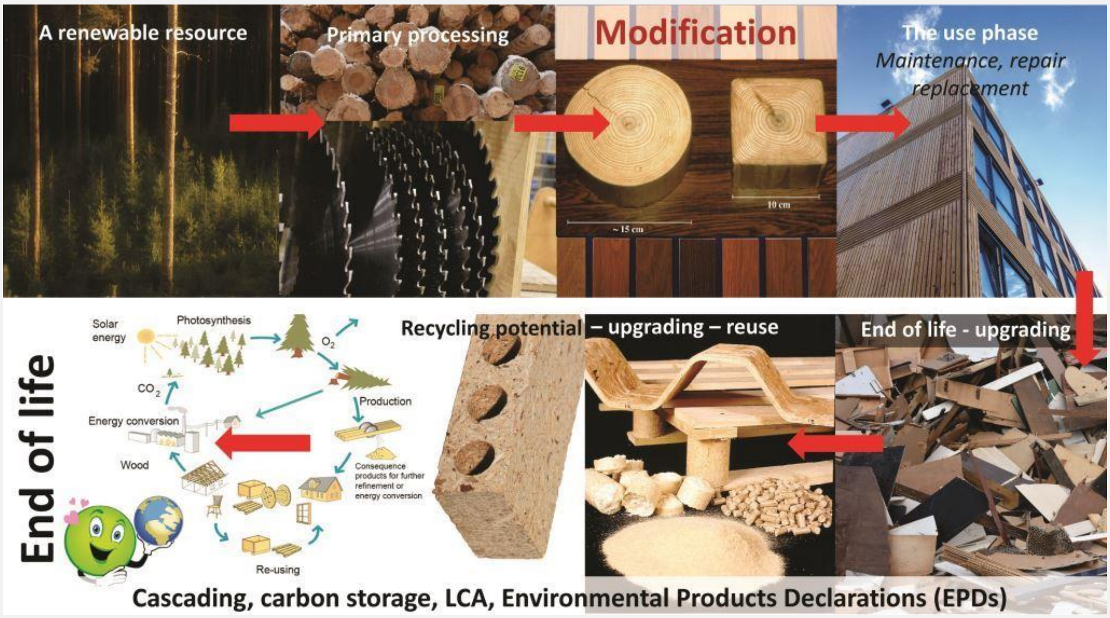
46 It must be stressed that the LULUCF Regulation does not require Member States to keep forest manage-ment (and harvesting) within the limits implied and so avoid accounted emissions, only to ensure that net emissions are accounted for when forest management (harvesting) is intensified compared with historical

Nabuurs, Arets & Schelhaas (2018) have estimated that annual wood production in the EU must not rise above 560 Mm^3 in 2050, if accounted net emissions from forests in the EU (under the LULUCF Regulation) are to be avoided. They further estimated that wood production would be limited to 493 Mm^3 in 2050 if Member States are to avoid situations in which harvesting in forests exceeds the rate of growth[47], albeit temporarily. This analysis does not consider potential wider impacts on the ecosystem services provided by forests, including biodiversity.

The development of a role for wood biomass in a bioeconomy thus appears to be a highly constrained optimisation problem, in terms of the use of wood biomass resources and the associated forest management practices, if wider climate change and sustainability goals are to be met. Climate-Smart Forestry (Verkerk et al. 2020) has been proposed as an approach to managing forests, which involves variously conservation of forest carbon stocks or harvesting for timber and biomass supply, or some combination of both activities, recognising local circumstances and the objective of climate change mitigation. Management strategies are also linked to efforts towards forest protection, restoration and diversification, so as to support the adaptation and resilience of forests to climate change and the maintenance of other ecosystem services alongside climate change mitigation (Box 3).

In terms of the effective use of wood resources, matching the supply of wood biomass types to the best applications (from the perspective of impacts on GHG emissions) could be considered. Biomass cascading has been suggested for efficient wood utilisation which involves prioritising the use of wood for the manufacture of longer-lived and structural products, preferring the use of wood industry residues (e.g. chips and sawdust) for material products (including innovative new wood-based products), ensuring effective re-use, repurposing and recycling of wood at end of use and eventual combustion for energy generation on disposal or as a by-product of materials production. Jones et al. (2019) highlight that the approach involves considering "the whole [wood biomass] value chain", from forest management, through wood processing, decisions about the use of wood products in service, the treatment of wood at end of life, second/third-life uses and ultimately incineration with energy recovery (Figure 20).

Figure 20 Illustration of integrated wood supply, modification, use and cascading



Source: Jones et al. (2019)

Whilst such opportunities for utilising wood biomass resources in conjunction with sustainable forest management offer considerable potential, their realisation is likely to involve challenging changes to infrastructure in the forest and wood processing sectors (Kunttu et al. 2020).

levels, leading to an effect on the forest sink. However, Kallio et al. (2018) argued that the LULUCF Regulation implicitly sets such constraints on forest management, as Member States seek to avoid accounted emissions for forest land.

47 Strictly, this is not a requirement of the LULUCF Regulation.

4.4.2 Bioenergy

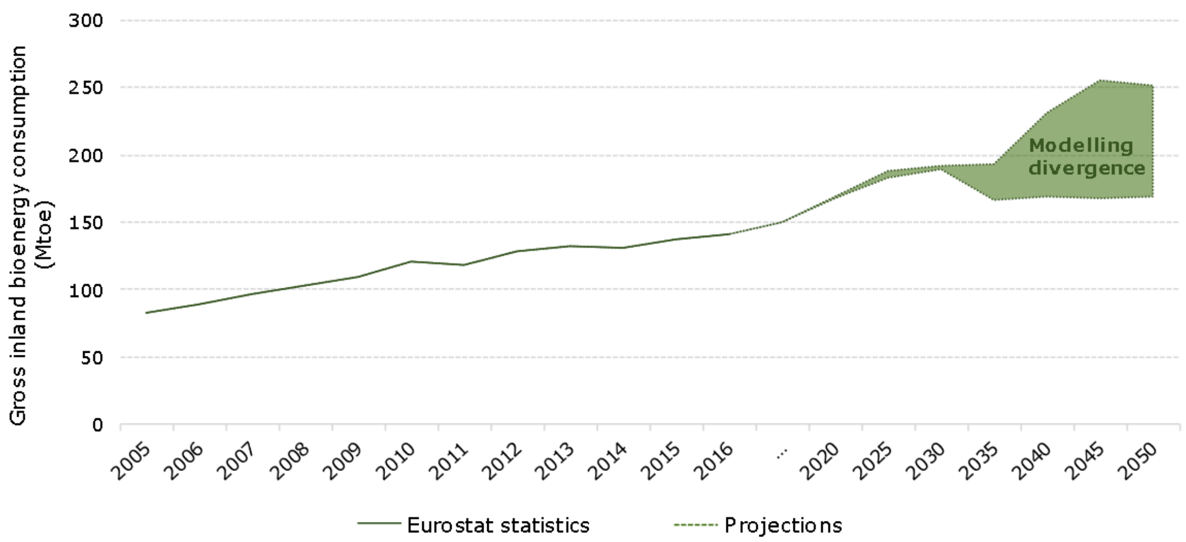
Bioenergy is part of the bioeconomy, as defined in the EU Bioeconomy Strategy: valorising side and residual streams from high-value feedstocks used for bio-based products should be seen as precious sources for the energy sector, as the non-energy parts of the bioeconomy employ high-value feedstock, while collected waste streams are used for bioenergy at the end of the useful lifetime of biomaterials (circularity and cascading).

The wide deployment of sustainable agricultural and cropping system (Section 4.3.1), the adoption of BECCS (Box 2) and the recovery of land marginalized by climate change, are all means to further increase the availability of sustainable feedstocks supporting at the same time more organic, circular and less fossil-dependent agriculture (Section 3.1), delivering food, feed and energy.

The demand for bioenergy in the EU27+UK (in 2017: 144 MtOE ≈ 6 EJ) is projected by some to rise beyond today's use, with a range of 169 to 737 MtOE (i.e. ≈ 7 to 31 EJ in 2050), and increasing flexible bioenergy for balancing the electricity system, as despite the impressive potential of wind and solar (Ruiz et al. 2019), grid balancing services are needed. This not only applies to electricity networks but to the whole energy system in which biomass can play a key role for energy storage.

Biofuels for transport are seen with large uncertainty similar to biomass use as feedstock for chemicals. Recent analysis narrowed the range of longer-term projections (Figure 21).

Figure 21 EU27+UK bioenergy scenarios



Source: JRC (2019c)

Some sectors, namely those more difficult to be decarbonised through electricity, will need to be prioritised: heavy duty, aviation and maritime. The IEA foresees a complementary role of biofuels and electricity in transport until 2050.

A non-technical factor complicating projections of long-term bioenergy demand is its dependence on policies related to climate, energy, transport, agriculture, environment, labour, infrastructure, and of course bioeconomy.

Reduction in EU energy dependence and energy system/grid balancing are seen as very relevant drivers in the future for the sector.

"Facts do not cease to exist because they are ignored." (Aldous Huxley)

4.5 Potentially competing drivers

A sustainable bioeconomy is not the only possibility to shape the future, nor the only vision on how to make the world a better place. Over the last decades, several competing drivers[48] emerged which may become trends in the 2030-2050 horizons, and could significantly affect opportunities for implementing the bioeconomy, mostly disruptive, but potentially also synergistic:

- As regards food, hydroponics, lab food ("artificial meat")[49] and "print-on-demand" of simple food from protein slurries are such drivers. "Hi-tech" urban and vertical agriculture using automated systems, controlled feeds and environments imply higher standardisation of diets, and may diminish the role of land, and landscapes.
- In the energy sector, non-biomass renewables (especially for electricity), "Power-to-anything" (PtX) and "green" hydrogen (H_2) are prominent drivers (Christensen 2020; Gielen 2020; Gielen, Castellanos & Crone 2020; Olsson & Bailis 2019). Batteries and PtX could stabilise grids facing high shares of variable solar and wind generation. Improved electric heat pumps and direct heating for zero-energy buildings could replace woody fuels as well as biomethane, both in small-scale boilers, and in district heat/cogeneration systems. The role of biofuels may be diminished through battery-electric or H_2/fuel cell drives, PtX and electrification of long-distance transport (trains, hyperloops etc.). The key factors for competitiveness are cost and infrastructure, considering technology learning, and increasing CO_2 prices (Malins 2020).
- In the material system, PtX also plays a role e.g. through Power-to-Carbon Compounds (PtCC), as well as light-weight carbon fibres, improved ceramics, nanocomposites and other nanomaterials. Furthermore, recycled carbon (atmospheric, biogenic, fossil or mineral) could be a radically new building block for materials through carbon capture, use or storage (CCUS) in combination with PtX/H_2.
- Concerning ecosystem services, intensification of agriculture (through digitisation, drones, GMOs, synthetic biology etc.) could significantly affect biodiversity and soils, and CCUS may become an alternative to soil C sequestration. The impacts of virtualisation ("2nd nature") on recreation may be profound, especially if health risks and cost associated with travel become more relevant.
- The socioeconomic system could be affected regarding employment through digitisation and robotics ("internet of things"), food security through longer and standardised supply chains (which are subject to common-mode failures) delivering more prefabricated and standardized foods, and health may be affected through increased exposure to nanoparticles. More balanced trade and domestic production might be affected by increased global competition, as innovators and investors may prefer non-EU countries (e.g., Brazil, China).

This list is neither comprehensive nor exhaustive: unexpected innovation or developments ("black swans") might add more drivers or reduce one or more of the ones indicated above.

With regard to foresight, the storylines and narratives for future sustainable bioeconomies should at least reflect on those competing drivers to improve robustness, and possibly integrating at least some of them (e.g. H_2-boosted advanced biofuels; biogenic C in PtX and CCUS; biomethane/H_2 mixes).

48 The respective open research questions are presented in Section 6.4.

49 The even more radical approach of "e-food" is conceptualised by Mishra et al. (2020).

4.6 Summary of all drivers and trends

The following table provides a synopsis of all EU bioeconomy drivers and trends for the normative assumption of a successful implementation of the sustainable, circular EU bioeconomy, not for a "business-as-usual" development.

Table 2 Synopsis of drivers, trends and counter-drivers for the EU bioeconomy

↑	strongly positive
↗	positive
→	neutral
↘	negative
↓	strongly negative

Driver	Trends 2030	Trends 2050	Key enabling factor(s)	Competing driver(s)
Role of the bioeconomy in sustainable food system (demand & supply) - EU Bioeconomy Strategy objective 1: Ensuring food and nutrition security				
Agroecology	↗	↑	food price, agricultural subsidies/carbon price	Hydroponics, lab food
Healthy diets	↗	↗	Acceptance of dietary changes	Print-on-demand
Reduce food loss & waste	↘	→	Prevention, re-use	More standardised food
Role of the bioeconomy in decarbonised energy system (markets/sectors) - EU Bioeconomy Strategy objective 3: Reducing dependence on non-renewable, unsustainable resources & objective 4: Mitigating and adapting to climate change				
Electricity, incl. CHP	→	↘	Cost	Non-bio renewables, PtX/H_2
Heat	↘	↓	Cost	Electricity, PtX/H_2
Transport	↗	→	Cost	Electricity, PtX/H_2
Circular renewable material system (markets/sectors) - EU Bioeconomy Strategy objective 3: Reducing dependence on non-renewable & objective 4: Mitigating and adapting to climate change				
Chemicals, fibres, plastics etc.	↗	↗	Cost	PtX, CCUS
Construction materials	↗	↑	Building codes (quota), price	Ceramics, nanocomposites
Fertilisers	↗	↑	Price (incl. carbon price)	PtX
Ecosystem services (relevant for EU bioeconomy) - EU Bioeconomy Strategy objective 2: Managing natural resources sustainably & objective 4: Mitigating and adapting to climate change				
Biodiversity	→	↗	Agroecology	Intensification
C sequestration	↗	↗	Carbon price	CCS, CCU
Socioeconomic system (EU level) - EU Bioeconomy Strategy objective 5: Strengthening European competitiveness and creating jobs				
Domestic employment	→	↗	Border adjustment tax	Digitisation, trade
Food security	↗	↑	Price, income	Longer supply chains
Health	→	↗	Governance	Nanoparticles exposure
Resilience	↗	↑	Agroecology, diets	?
International trade	→	↘	Border adjustment tax; transform WTO & bi/multi-lateral trade agreements to SDGs	Global competition

Source: own elaboration; PtX = Power-to-anything (chemicals, gases, liquids, proteins, solid compounds…); CHP = combined heat & power (cogeneration, incl. cooling) CCUS = carbon capture, use or storage; ? = unknown
Qualifiers for trends from experts' judgement; scope: EU only – global effects not included

5 Perspectives for a circular, sustainable, and transformative European bioeconomy

5.1 Towards integration

It has been mentioned in Section 4.1 that the SDG framing for the bioeconomy requires integration. With the European Green Deal (Section 4.2.1), relevant steps of integration are underway for key EU policies, especially biodiversity, circularity, climate change, food systems, forests' protection and restoration, and renewable energy.

The EU circular, sustainable, and transformative bioeconomy needs to be part of this integration – especially, the inclusion of the bioeconomy in the EU post-COVID-19 recovery plan (Section 4.2.2) would be a critical step[50].

Furthermore, integration is needed in terms of moving beyond co-existence and competition between bioeconomy and the broader economic system (Figure 2). Yet, the interaction food & feed, fibre, chemicals, energy etc. is currently driven by markets and prices, with few policy interventions (quota systems, taxation etc.). The COVID-19 pandemic indicated that societal priorities such as health and resilience need to be seen as necessary co-drivers of market interactions[51] (including trade, Section 3.5), and the Paris Agreement implies that competition between the non-renewable economic sub-system and the renewable sub-system, including the bioeconomy, needs to integrate at least a strong carbon signal.

Box 7 SDG values?

As a perspective, establishing "SDG value" of products as outputs of a transformative bioeconomy instead of the traditional economic value seems worth considering. "SDG value" would be composites of e.g. biodiversity, carbon, circularity, employment, income, health, materials, resilience - and energy. Starting with a carbon price component and then consecutively adding more aspects e.g. in the EU Taxonomy, public procurement and preferential trade systems could be an evolutionary governance approach for this.

The SDG value concept would also allow to integrate and valorise multiple benefits without relying on "monetisation" and could help agroecology, biorefineries, and carbon farming to gain better and broader market access. To what extent this concept would need e.g. certification or labelling to be effectively communicated within B2B supply chains and to customers should be an issue of future research.

Domestic EU land use – especially in rural areas – and the footprint outside of the EU need integration as well, with a view of the multiple opportunities for rural livelihoods, employment and innovation – both within the EU and outside.

The rural development policies are a crucial component to be integrated into the implementation, as recognised in the EU 2018 Bioeconomy Strategy (EC 2018a). But this will not just happen: recent research and exchange between many EU regions (ENRD 2019a-e) indicated that capacity building and networking, market development beyond mere economic (international) competition, and research and implementation must be part of the transformative bioeconomy.

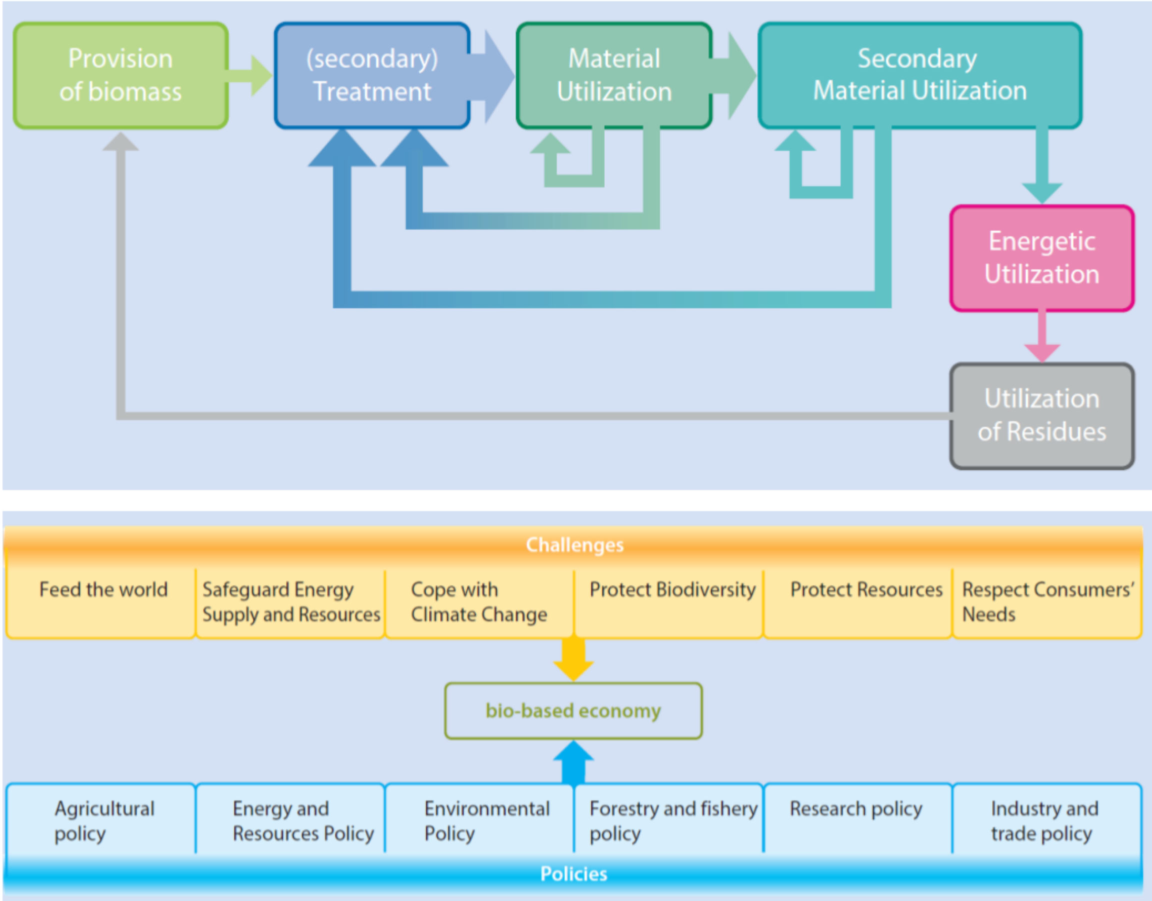
Circularity requires integration in terms of recycling and re-use of residues & waste flows for which biorefineries (Box 8) are key, but as mentioned above, integrated governance is need as well (Figure 22): the SDGs call for "breaking down the silos" of current

[50] Note that in the EU Recovery Plan, the circular economy and renewable energies are mentioned, **but not** the bioeconomy. The upcoming Global Bioeconomy Summit 2020 could provide a forum to discuss respective integration options with international partners, with the EU Green Deal as a concept for others to consider.

[51] A circular, sustainable bioeconomy can provide basic needs (such as food, energy) without compromising climate change mitigation – and GDP growth is not the best measure of human wellbeing (see e.g., OECD 2020c; Steinberger, Lamb & Sakai 2020).

political systems governing the bioeconomy in different segmented institutions and policy areas.

Figure 22 The integration challenge of the bioeconomy: technologies and policies



Source: Fritsche & Rösch (2020)

Box 8 Cross-sectoral integration: biorefining

Biorefineries[52] are a fundamental building block of a circular bioeconomy (Carus & Dammer 2018; Ubando, Felix & Chen 2020), and have received attention since the mid-1990ies, with several EU-funded projects and BBI-JU activities. Yet, EU biorefinery activities are dominated by large-scale projects to achieve cost-effectiveness and high efficiencies. This ignores massive infrastructure requirements and potential path dependencies, and is, at least in the longer-term, not supportive of a transformative bioeconomy. It can play its role in a transition period, though. There are promising alternative routes for biorefining which seem more compatible with rural development, resilience, and system efficiency:

Grasses and herbaceous perennials such as Miscanthus are excellent protein producers on par with e.g. soybean due to much higher total biomass production (Bentsen & Møller 2017). Smaller-scale green biorefineries operating on these feedstocks to extract protein prior to energy conversion lose only a limited amount of the bioenergy potential and provide fertilisers and fibres as well. More than 80% of the proteins present in the feedstock can ideally be extracted chemically or mechanically.

Food wastes can be an important feedstock for smaller-scale biorefineries, improving the circularity of the bioeconomy (Dahiya et al. 2018; Mohan et al. 2016a, 2016b and 2019).

52 Defined here as "*the sustainable processing of biomass into a portfolio of marketable bio-based products, which could include co-production of food and feed, algae, wood and woody biomass- based materials, products and bioenergy*" (Michels 2020). Various definitions exist (http://task42.ieabioenergy.com), and FNR et al. (2020) currently updates data on existing and planned EU biorefinery projects.

"New" feedstocks such as algae (Bose et al. 2020) or fungi (Meyer et al. 2020) could provide more options for cascading, and may be better integrated with aquaculture (Box 5).

All these biorefineries operate on smaller scales, valorise local and regional biomass and provide higher employment than large-scale biorefineries which were often adapted from fossil refineries.

A screening of EU policies with regard to their integration across governance levels by the authors (Table 3) indicates that for many policies, the EU has strong governance instruments (Directives…) to align its policies within the EU (Member States), and with actors outside of the EU.

There is one exception from this finding, though: The forest sector is lacking integration and "strength" on the EU (and global/internationally) while national governance is elaborate and strong, as shown in Table 3.

Table 3 Horizontal and vertical integration challenges for selected policies related to the bioeconomy

Policy theme	Global/International	EU (outwards)	EU (internal)	National
Resources/wastes	UNEP 10YP SCP	(Waste & Plastic Directives)	Waste & Plastics Directives	various
	UNEP IRP	?	EPD	various
	G7/20 RessEff			various
		?	Bioeconomy Strategy	various
		?	Circular Economy Strategy	various
Environment	Paris Agreement	ETS	ETS	NECPs
	UN FCCC			various
	UN CBD	?	2030 Biodiversity Strategy	Nature protection laws
	UN Water	?	Water Directive	various
	UN CCD	?	?	Land conservation strategies
Energy	IFC, World Bank etc.	(RED)	RED	Energy/bioenergy policies
	UN SE4All	?	EPD	FIT, various
		?	Gas Directive	various
		TEN	Internal market, competition	Market design, grid access etc.
Finance	UNEP FI	?	Taxonomy	various
	UN Compact	?	?	various
Agriculture	WTO	bi-/multilateral Trade Agreements	CAP	CAP implementation; domestic incentives
Forestry	UN-REDD	TR/FLEGT	Forest Strategy	Forest certification & carbon offsetting
	UNFF	(Forest Strategy)		Deforestation laws
	Forest certification			Planting/restocking
				Publicly-owned forests
				Forestry standards/codes

Legend	Regulatory (comprehensive)	Incentives	Voluntary
	Regulatory (partial)	Strategic/aspirational	

Source: own elaboration; UNEP 10YP SCP = United Nations 10-year programme on sustainable consumption and production; UNEP IRP = United Nations International Resource Panel; EPD = Environmental Product Declaration; ? = unknown; ETS = Emission Trading System; NECPs = National Energy and Climate Plans; UN FCCC = United Nations Framework Convention on Climate Change; UN CBD = United Nations Convention on Biological Diversity; UN CCD = United Nations Convention to Combat Desertification; IFC = International Finance Corporation; RED = Renewable Energy Directive; UN SE4All = United Nations Sustainable Energy for All; FIT = feed-in tariffs; TEN = Trans-European Networks; UNEP FI = United Nations Finance Initiative; CAP = common agriculture policy; UN-REDD = United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation; TR/FLEGT = Timber Regulation/Forest Law Enforcement, Governance and Trade; UNFF = United Nations Forum on Forests

The upcoming new EU Forest Strategy intends to integrate the bioeconomy (EC 2020a), which may close this gap. It needs to be seen how suitable arrangements with Member States and actors outside of the EU will be found.

A circular sustainable European bioeconomy must deliver on the integration challenges as well – with the European Green Deal (Section 4.2), key steps in this direction have been taken.

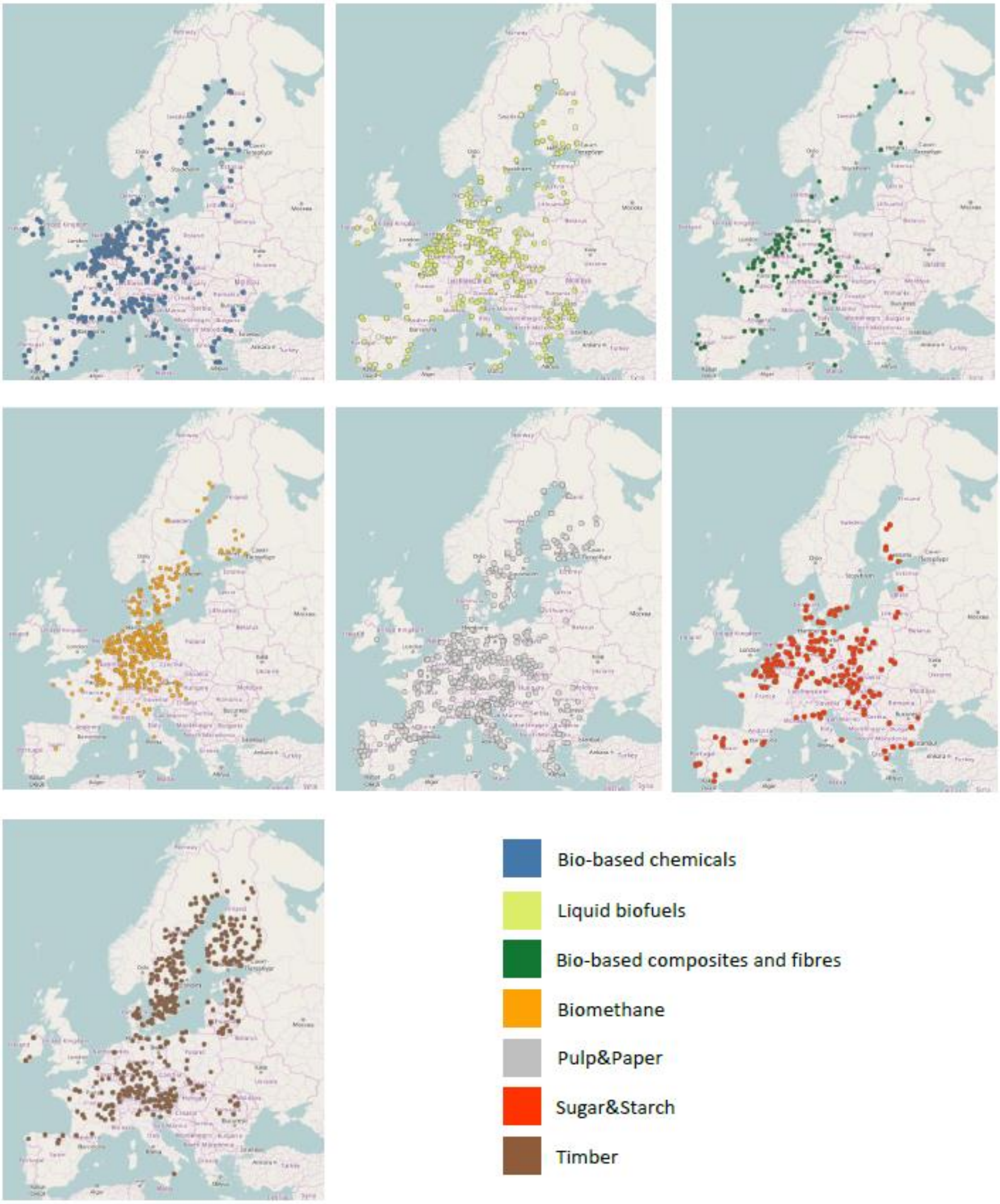
"If you want truly to understand something, try to change it." (Kurt Lewin)

5.2 Diversity of the bioeconomies (intra-EU and globally)

The bioeconomy in Europe is not a single one: in Northern EU countries (e.g., Estonia, Finland, Latvia, Sweden) forestry dominates, while a large proportion of the bioeconomy in Italy, Portugal, and Spain concern fibres, bio-based textiles, and high-quality food.

Denmark, France, and The Netherlands have large agricultural segments but increase also biochemical production. More biorefineries operate in Belgium, France, Germany, Italy, and the Netherlands (JRC 2020c). There is also growing interest in the blue bioeconomy in Northern and Southern Europe (EC 2019c).

Figure 23 Disaggregation of the EU bio-based industry (including biorefineries) per type of bio-based production



Source: *JRC (2020c);* [*https://ec.europa.eu/knowledge4policy/visualisation/bio-based-industry-eu_en*](https://ec.europa.eu/knowledge4policy/visualisation/bio-based-industry-eu_en)

This diversity implies not a weakness but a strength: Instead of focussing on e.g. corn (as the US), forest (Canada), palm oil (Indonesia), soy (Argentina) or sugarcane (Brazil), the diversified EU bioeconomy is more resilient to changes in feedstock supply, market dynamics and technology innovation.

The diversity within Europe is reflected in the various national and regional bioeconomy strategies, with a similar diversity being observed globally.

European strategies must consider the position of future domestic bioeconomies in international markets for both food and non-food products, as they may affect the sustainability of bio-based products and industries, the affordability of food, and potential implications for national land-use choices (JRC 2019b; Philippidis et al. 2020).

As regards outside Europe, the bioeconomy landscape is even more diverse than in the EU, as some overview reports and examples from several countries indicate (FAO 2019; GBS 2018; Motola et al. 2018).

- In Africa, the bioeconomy is often developed with a rural development perspective, considers residues and wastes, and expectations concern improved employment, income, and security of supply (Callo-Concha et al. 2020; Poku, Birner & Gupta 2018)[53]. Countries such as Namibia and South Africa have priorities for high-value biomass conversion and high-value products, though.
- In Asia, the variety of bioeconomies is high as well (see e.g. for India: Mohan et al. 2018; for Thailand: Fielding & Aung 2018; Tanticharoen 2018).
- In Latin America, a recent UN-ECLAC report provided an overview of bioeconomy developments (Rodríguez & Aramendis 2019; see also earlier work by Sasson & Malpica 2018)[54].
- In Russia, Osmakova, Kirpichnikova & Popov (2018) give some insights, but clearly, the bioeconomy is not (yet?) a major policy issue.
- In North America, Canada is quite active, considering its immense forest resource as a strategic option, while in the US, the competing view of a "circular carbon economy" prevails on the Federal level. On the State level, though, a broad variety of approaches exist.

"Those who are willing find ways. Those who are unwilling find excuses." (Albert Camus)

[53] The Eastern African Community recently started its own Regional Bioeconomy Portal, see https://bioeconomy.easteco.org/knowledge-base/# .

[54] See also for Bolivia: Canales et al. (2020); for Brazil: Lap et al. (2019).

5.3 Build back better: a healthy planet for healthy people and prosperity

Build back better: this term was coined in 2006 in the aftermath of the 2004 Asian tsunami, incorporated into the priorities of the Sendai Framework for Disaster Risk Reduction (UNODRR 2015), and taken up in the post-COVID-19 discussion:

"As the health crisis gradually abates in some countries, attention is now turning to preparing stimulus measures for triggering economic recovery (…) that "builds back better", i.e. not only getting economies and livelihoods back on their feet quickly, but also safeguarding prosperity for the longer term." (OECD 2020b, p.3)

As Dubois (2020) indicates, linking energy, food security and health can help face the COVID-19 pandemic. Similarly, IPES-Food (2020) and OECD (2020a) refer to agroecology as a potential solution for improving the resilience of the food systems.

Palahí et al. (2020) call for "*investing in nature to transform the post COVID-19 economy*" and develop an Action Plan to create a circular bioeconomy devoted to sustainable wellbeing. Already in 2014, the EU wrote:

"*In 2050, we live well, within the planet's ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a global safe and sustainable society*". (EU 2014, p. 176)

From panic buying, food shortages, and price spikes, to other social and economic impacts, as well as food loss and food waste issues, the COVID-19 crisis has shown that our food systems are fragile and need to be redesigned to increase food security (Galanakis 2020).

Over the next decades, global population growth and urbanisation are expected to continue, which might increase pandemic outbreak frequency, and climate change will become more intense.

Thus, the transformations of our societies towards sustainable development and a climate-neutral economy require resilient food systems. This includes contingency plans and adapting fast to extreme events, as well as ensuring that future crises will minimally affect the food chain and most vulnerable people (Galanakis et al. 2020).

Similar policy considerations can be found in the OECD's initial views on COVID-19 and agriculture/food OECD (2020a). Yet, as de Paula (2020) argues, there are some COVID-19 consequences promoting planetary health, and IEA (2020a+b) indicates potential positive effects for the global energy system, with unclear longer-term impacts.

All this also means: moving beyond the EU 2018 Bioeconomy Strategy. In preparing for post-COVID-19, the bioeconomy should be a priority in the EU Recovery Plan (Section 4.2). Circularity, decarbonisation and economic recovery can be synergistic: promoting short domestic sustainable bioeconomic supply chains brings resources back into the real economy, creates (rural) employment and favours CO_2-neutral development, e.g. through biorefineries and land-based C sequestration with respective agricultural and forestry investments.

Moreover, the bioeconomy with its emphasis on ecosystem services can support a process of economic dematerialisation by decoupling human well-being from material and energy consumption (Steinberger, Lamb & Sakai 2020).

The bioeconomy can be a core instrument for the Green Deal in the post-COVID-19 era, making the EU more sustainable and competitive. For this, the change from a substitutive to a transformative bioeconomy - as sought by the European Bioeconomy Strategy (Section 3.4) - is necessary to avoid lock-in and contribute to delivering on the SDG ambition of transformation. The EU Bioeconomy Strategy (EC 2018) is, compared to its 2012 predecessor (EC 2012), evolving in this direction, but clear targets for 2030 and 2050, and an adequate governance approach are required.

The heading of this sub-section names people, planet and prosperity – but not profits. This is on purpose: The transformative bioeconomy serves economic goals, as required by the SDGs, but profit representing "the" economy should be transformed into a socially inclusive and planetary-boundary-proof balance of private interests and broader economic considerations of commons[55].

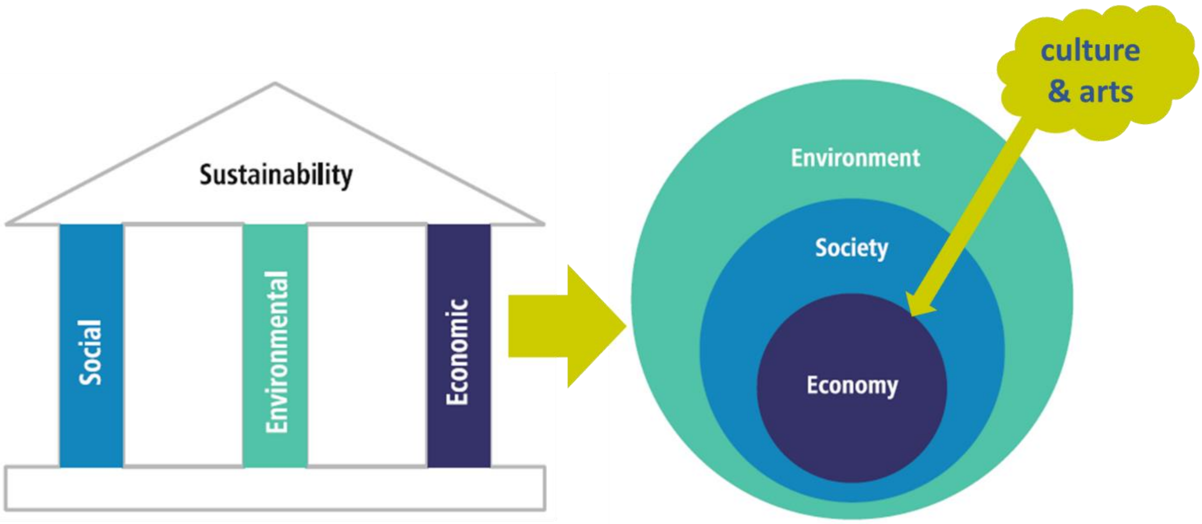
5.4 Beyond business-as-usual: transformation

The term transformation is used frequently throughout this synthesis paper, building on the 2030 Agenda which calls for transformative change (UN 2015)[56]. Transformation is understood as the process to shift from a certain pathway towards a more sustainable one:

"A more resilient economy depends on a shift to sustainable practices." (OECD 2020b, p. 3)

The guiding principle of being transformative is to acknowledge that various trade-offs and possible synergies are subject to societal decision-making, not to a neoliberal economic logic alone. Market aspects will be one component of decision-making, but possibly not the dominant one. Thus, it seems reasonable to re-define the traditional "pillar" concept of sustainability to an embedded systems view (Figure 24).

Figure 24 Sustainability: from pillars to embedded systems



Source: *own elaboration based on Göpel (2016) and Fritsche & Eppler (2018); for a brief discussion on the role of culture & arts in the sustainability see* ***Annex 4***

This re-definition also concerns how the SDGs are structured: instead of the typical planar box-by-box representation, the new logic calls for ordering the SDGs according to levels. The base is the biosphere which underpins society, which in turn embeds the economy (Figure 25).

This is the base for discussing how to live within planetary boundaries and align the economy with societal needs, not vice versa.

This is reflected in the Just Transition concept of the European Green Deal.

55 "*The crisis has shown that governments can and must intervene to correct market failures and realign economic activities for the public good. It is now imperative to ensure that food businesses internalize the negative socio-economic and environmental costs they engender*." (IPES-Food 2020, p.1).

56 Interestingly, the H2020 EKLIPSE project drafted an expert report which explicitly calls for "Transformative Change" in the context of the Post-2020 Global Biodiversity Framework (Bulkeley et al. 2020).

Figure 25 Transforming the SDGs: from flat plane to wedding cake

Source: own elaboration based on UN (2015) and Rockström & Sukhdev (2016)

A sustainable bioeconomy needs to acknowledge that:

"Achieving the SDGs requires deep, directed system transformations that must be carefully designed involving all sectors in society. Market forces alone will not achieve the SDGs. Instead directed transformations are needed to develop the technologies, promote the public and private investments, and ensure adequate governance mechanisms needed to achieve the time-bound goals." (OECD & SDSN 2019, p. 3)

The EU Bioeconomy Strategy (EC 2018) refers to the new "wedding cake" logic of sustainability, but the consequences of this concept need to be considered further.
Transformation requires working with people in active roles which means considering their capacities to think and speak about the transformation (future literacy, see Göpel 2016). This is why social aspects (Sections 3.4 and 6.5) are of high importance, for which a new term is proposed (Figure 26): **BioWEconomy**[57].

Figure 26 A circular, sustainable, and transformative ***BioWEconomy***

Source: own elaboration based on EC (2018); note that there is no typo in the title nor in the figure: The capital ***WE*** *is meant to indicate that the* ***BioWEconomy*** *is an issue for* ***all of us***

[57] For a more detailed discussion of this term see Annex 3.

5.5 No future without risks

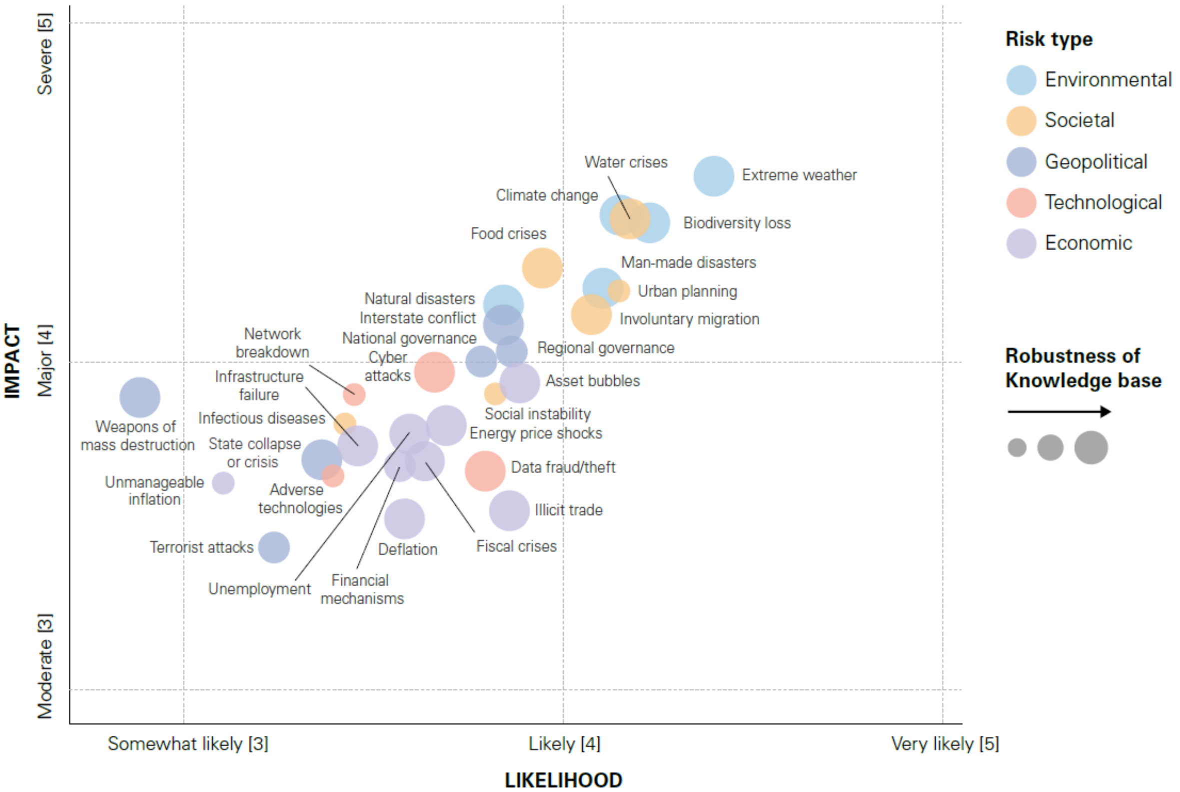
A circular, sustainable, and transformative **BioWEconomy** makes change towards more resilient and future-proof economic systems possible. Still, it must be acknowledged that even such a bioeconomy – and a future transformed sustainable general economy – will not make all of us secure, nor protect against all dangers.

There is a large variety of risks mankind – and Europeans – have to face, and most of them are interlinked so that a linear scale may be misleading (e.g. tipping points in the climate system).

A circular, sustainable and transformative **BioWEconomy** can mitigate several of the severe and likely risks (Figure 27)[58], especially food and water crises, climate change, migration, and social instability.

The improved governance of a circular, sustainable, and transformative **BioWEconomy** could become a role model for transforming other parts of the economy as well, helping to make the world a better – and safer – place for all.

Figure 27 Impact versus likelihood of key risk types



Source: Future Earth (2020)

In that regard, foresight processes can help to explore possible futures, identifying respective narratives and possible pathways, and inform policy makers and society about options to choose from.

We hope that this report is a small contribution to that process.

58 This figure is consistent with the "Long-Term Risk Outlook" data given by WEF (2020).

6 Open research issues

This final section collects core questions which are deemed relevant for further research concerning a circular, sustainable, and transformative **BioWEconomy** to inform the direction of the upcoming Horizon Europe research and innovation Framework Programme, and respective work under the Green Deal.

6.1 Climate impacts

Climate impacts of biomass and land use are researched since the 1980ies, but respective impacts of the bioeconomy are considered only since the early 2000s.

As a consequence, integrating the bioeconomy into the global climate discussion, and especially into the Integrated Assessment Models used in the IPCC, still needs much work.

- The monitoring of agricultural, fishery (including aquaculture) and forestry activities in the context of actions aimed at supporting a bioeconomy and climate change mitigation (incl. national GHG inventories) requires elaboration, with the aim of enabling the verification of the intended impacts of practices on carbon sequestration and GHG emissions (reductions).
- Further analysis is needed to manage risks in terms of impacts on GHG emissions and other ecosystem services associated with some agricultural, fishery (including aquaculture) and forestry practices and the consumption of certain biomass sources with the aim of bioeconomy development and climate change mitigation.

There is a rather limited scientific understanding yet of possible future development pathways of a sustainable bioeconomy that consider climate change mitigation (and adaptation) objectives. Some exploratory work has been carried out, but full integration e.g. in the IPCC modelling framework is yet missing.

Integration of the dynamics and interaction between e.g. sustainable provision of bioeconomy feedstocks, related land-based sink effects, carbon storage in bio-based products and their "after-life" use (cascading, circularity) and displacement effects both in energy and material systems is needed.

Furthermore, warming implications of albedo changes are relevant for the bioeconomy (Huang et al. 2020; Sieber et al. 2020) and should be explored further.

6.2 Integrated modelling

This report is not specifically looking into modelling issues[59], yet the significant role of Integrated Assessment Models predominantly in climate policies cannot be ignored, and an adequate overall representation of the bioeconomy is yet to be achieved.

The "bridging" between input-output tables (IOT) and computable general equilibrium models (CGE) with life-cycle and material flow analysis (LCA, MFA) is rudimentary, and further research is needed on that (Soest et al. 2019).

6.3 Future-proof bioenergy systems within a circular, sustainable, and transformative bioeconomy

Following the argumentation in Section 0 and the trends identified up to 2050 (Section 0), the conventional bioenergy pathways are under threat, especially in the electricity and heat sectors which dominate current EU biomass use (Section 4.4.2).

[59] Work Package 2 of the Network of Experts just started its work on the specific bioeconomy modelling challenges and opportunities.

Research is needed on the integrative functions of bioenergy in stabilising future electricity systems massively relying on variable renewable sources (solar, wind). Here, the role of biomethane requires more research, especially on potential hybrid options with green H_2.

For bioheat, a transformation from low-efficient small-scale direct burning towards biomass use in hard-to-decarbonise industry sectors (e.g. base chemicals, cement, and metallurgic processes such as steelmaking) seems inevitable. In this, the role of syngas and again biomethane needs further exploration. Similarly, integration of (advanced) biofuels into sustainable transport systems, e.g. fuel-cell drives, should be researched, and the possible roles of alternative biorefinery concepts (Box 8) need closer investigation.

The expected overarching role of carbon in the future implies to consider a change in the overall value of biomass: instead of its heating value, its value in terms of carbon mitigation, sequestration and circular use value (Box 7) should be investigated.

The EC just launched the European Clean Hydrogen Alliance and Hydrogen Strategy under the German Council Presidency (EC 2020a), and its recent Biodiversity Strategy calls for re-considering the role of biomass, especially in the energy system (EC 2020b). Research outcomes to underpin such consideration are required in the near-term.

6.4 Competing drivers

As indicated in Section 0, there are many options to shape the future in non-biomass patterns, especially through renewables for electricity/PtX/H_2, and alternative approaches to food and materials.

The promise of such options is far-reaching (Box 9).

Box 9 A contrasting vision: the Era of Abundance ("post-scarcity")

The longer-term emergence of a fully decarbonised global energy system based mainly on solar (with biomass, wind and hydropower as derivatives), together with nano-level technologies and non-local communication and control (digitisation) bring forward a vision of a "post-scarcity" world: Renewable electricity and hydrogen, coupled with recycled C, could provide most material and service demands for everyone.

With solar influx in the order of 10,000 times current global energy demand, even full recycling of composites, metals and minerals from seawater and waste streams would not "deplete" the resource base, and there would be "spare" energy to even decompose toxins. In this vision, planetary boundaries are a limitation of thought, not of (bio)physics. Disruptive technological innovations operating on carbon-free and low operating cost renewable electricity(IRENA 2020a+b) would create a new era of abundance.

Instead of fossil or biogenic resources, rare metals and minerals, PtX would enable us to move away from nature-linked bio-based systems for food and materials, providing input to molecular manufacturing and on-demand 3D printing, with synthetic biology taking care of natural "constraints". This clearly would revolutionise logistics, supply chains and waste treatment, and may evolve into a post-scarcity economy.

*Some elements of this vision might be integrated into the bioeconomy, but the overall logic is surely a stark contrast to nature-based solutions favoured in a circular, sustainable, and transformative **BioWEconomy**.*

6.5 Social factors

In Section 3.4 of this report, the socioeconomic bottlenecks of a circular and sustainable bioeconomy were briefly mentioned.

For better understanding of this crucial issue, far more research is needed, as well as capacity building to overcome knowledge gaps.

Transdisciplinary research, as carried out in e.g., Finland, Germany, The Netherlands, and Switzerland, should be encouraged also at the EU level, with a profound and active role of non-science actors from civil society, e.g. (but not limited to) citizen science to support participatory monitoring of the EU bioeconomy.

In that, the integration of health issues into the social dynamics of actors, as well as social "resistance" to and acceptance of transformative changes, are clear priorities for bioeconomic research.

Under the SDG framing, bioeconomy research must also address the potency of culture & arts in communication, participation, and implementation of a circular, sustainable, and transformative EU **BioWEconomy**.

This includes a humanisation of the abstract term bioeconomy through e.g., Bio cities, as proposed by the former German Bioeconomy Council, and active roles for culture and arts in transdisciplinary research, as currently tested within the German Federal Ministry for Research's Bioeconomy Year (2020-2021).

6.6 Sustainability governance

The cross-sectoral and transboundary nature of the bioeconomy (Section 2) with local and regional diversity (Section 5.2) is matched by the multi-dimensional and multi-level concept of sustainability, and the combination of both is clearly a complex challenge which - so far – the EU has not yet taken up constructively (Moosmann et al. 2020).

Proposals from the Horizon2020 project STAR-ProBio concerning potential co-regulation of the EU (Ugarte et al. 2020) as well as outcomes of other research projects[60] should be reflected in future research and could contribute to this.

6.7 Collaborative research: a global partnership

Investing in research on the questions identified will improve understanding and implementability of a circular, sustainable, and transformative **BioWEconomy**, not only in the EU, but globally through knowledge-sharing networks.

The EC should increase its invitations to and support for non-EU researchers especially from Africa, Asia, Latin America and the Caribbean to engage in more joint projects and respective capacity development, as in the view of the SDGs, all countries are developing.

Europe would benefit from enhanced collaboration with its partners in moving jointly towards a better world for all for which research and innovation are key.

[60] See footnote 35.

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List of abbreviations and definitions

AFOLU	Agriculture, Forestry and other Land Use
BAU	Business As Usual
BECCS	Bioenergy with Carbon Capture and Storage
C	carbon
CAP	Common Agricultural Policy
CCS	carbon capture and storage
CCUS	carbon capture, use or storage
CHP	Combined Heat and Power Plant
EC	European Commission
ECA	European Court of Auditors
EEA	European Environment Agency
EFI	European Forest Institute
EJ	ExaJoule
EPD	Environmental Product Declaration
ETS	Emission Trading System
EU	European Union
EU27	27 Member States comprising the EU since the departure of the UK on 31 January 2020
FAO	Food and Agriculture Organisation of the United Nations
FIT	feed-in tariffs
FL	Food losses
FLEGT	Forest Law Enforcement, Governance and Trade
FLW	Food losses and wastes
FW	Food wastes
GBEP	Global Biomass Partnership
GDP	Gross domestic product
GHG	Greenhouse Gas emissions
H_2	hydrogen
IAM	Integrated Assessment Models
IEA	International Energy Agency
IFC	International Finance Corporation
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
(i)LUC	(indirect) Land Use Change
IINAS	International Institute for Sustainability Analysis and Strategy
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	European Commission’s Joint Research Institute
LULUCF	Land Use, Land Use Change and Forestry
mio.	million
MS	EU Member State
Mt	Million tonnes
Mt_{dm}	Million tonnes dry mass
MtOE	Million tonnes of oil equivalent

NECPs	National Energy and Climate Plans
NGO	Non-Governmental Organisation
OECD	Organisation for Economic Co-operation and Development
PtX	Power-to-anything (gases, liquids…)
PV	photovoltaics
RED	Renewable Energy Directive
RTD	European Commission's Research and Innovation Directorate-General
SCAR	Standing Committee on Agricultural Research
SDG	Sustainable Development Goals
SDSN	Sustainable Development Solutions Network
SEI	Stockholm Environment Institute
TEN	Trans-European Networks
TR	Timber Regulation
UK	United Kingdom
UN	United Nations
UN CBD	United Nations Convention on Biological Diversity
UN CCD	United Nations Convention to Combat Desertification
UN FCCC	United Nations Framework Convention on Climate Change
UNEP 10YP SCP	United Nations 10-year programme on sustainable consumption and production
UNEP FI	United Nations Finance Initiative
UNEP IRP	United Nations International Resource Panel
UNFF	United Nations Forum on Forests
UN-REDD	United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation
UN SE4All	United Nations Sustainable Energy for All
US	United States of America
WBCSD	World Business Council for Sustainable Development
WEF	World Economic Forum
WRI	World Resources Institute
WWF	World Wide Fund for Nature
WTO	World Trade Organisation

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ANNEXES

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ANNEX 1: List of D1 Reports prepared by the Network of Experts Work Package 1

The following reports synthesise results from a thorough review of state-of-the-art literature and projects carried out by the NoE authors and were edited by Uwe R. Fritsche, Coordinator of the NoE, work package 1.

They represent the Deliverable 1 (D1) of this work package, each addressing a specific question (Q1 – Q5) and were used as a basis for the joint analysis of the present report:

- Panoutsou, Calliope & Brunori, Gianluca (2020) Sustainability of current and future biomass supplies (Report Q1). London & Pisa
- Matthews, Robert (2020) Contribution of the bioeconomy to climate change adaptation and mitigation (Report Q2). Farnham
- Galanakis, Charis (2020) Impact of dietary changes on sustainability of food systems and on planetary health (Report Q3). Vienna
- Chiaramonti, David (2020) Sustainability of bioenergy supply, considering biomass demand for other uses (Report Q4). Florence & Turin
- Beretta, Claudio & Hellweg, Stefanie (2020) Design and implementation of strategies limiting food losses and waste to contribute to a sustainable and circular economy (Report Q5). Zurich

These reports are available from the EC Knowledge Centre Bioeconomy: email EC-Bioeconomy-KC@ec.europa.eu

ANNEX 2: On Transformation

Definitions of transformation

Oxford Dictionary

- A marked change in form, nature, or appearance
- A sudden dramatic change of scenery on stage
- A metamorphosis during the life cycle of an animal

Wiktionary

- The act of transforming or the state of being transformed.
- A marked change in appearance or character, especially one for the better.

The sources of transformation

Already during World War II, Karl Polanyi published "The Great Transformation: The Political and Economic Origins of Our Time" (Polanyi 1944). More than 60 years later, the report "World in Transition – A Social Contract for Sustainability" followed up on this, underlining the need for radical change, and change in cultural practices (WBGU 2011).

This was re-confirmed in 2015 by the UN Agenda 2030 which also calls for "*system change*" and "*transforming the way we live*" (UN 2015), and a recent informal group in the European Commission issued a call for "*unprecedented change NOW*" (EUS4C 2019).

There are many examples for transformative change related to the bioeconomy:

- From degraded land to providing biomass and ecosystem services, especially carbon sequestration, restoration of land, and improved water retention;
- From waste streams to feedstocks for energy, food/feed, and materials;
- From transcontinental fossil energy pipelines to networks for distributed renewable (and biogenic) gases;
- From the traditional indicator logic to participatory approaches (proxies and practices), and transparency;
- From lab science to citizen science.

There are also transformations in the socioeconomic systems, e.g., in food systems (Steiner et al. 2020), in financing and marketing concepts (Göpel 2016), and – last not least – in science (Bai et al. 2019; DRIFT & Ecologic 2016; Ramirez et al. 2019; Shrivastava et al. 2020; Wittmayer et al. 2018).

A transformative bioeconomy aims at changing the system of provision and consumption and considers new market actors as well as new economic concepts of creating value (commoning, sharing etc., see Göpel 2016 and Söderholm 2020).

ANNEX 3: On the term BioWEconomy

In 2018, the book "*WEconomy*" was published in the US (Kielburger, Branson & Kielburger 2018). In the same year, two Germans published a manifesto entitled "*Economy to Weconomy*" (Marx & Stegfellner 2018), expanding the individualistic US approach to a more societal and economic view.

Much in parallel, Tim Jackson opened the Centre for the Understanding of Sustainable Prosperity (CUSP)[61] in the UK, the Donuts Economic Lab started operating[62], Maja Göpel published *The Great Mindshift*[63], and the Wellbeing Economy Alliance was formed[64].

Inspired by these developments, the insertion of the "**WE**" into the bioeconomy to form the term **BioWEconomy** is already a - small - transformation.

At crossroads

The e-world paradigm – i.e. the electrification of everything (see Section 0) – is strong:

Source: own elaboration based on EC (2018)

It promises fully artificial cities (arcologies), allowing to "give back" the rural to nature. "e-meat" would get rid of animals, and free large track of land previously needed for animal feed.

Such an electric world could contribute to SDGs as well, assuming massive technology improvement and innovation - but might miss e.g.

- biodiversity improvements via sustainable land management;
- carbon sequestration in soils, restoring degraded land;
- rural development & employment.

In contrast, the bioeconomy could be a versatile integrator, with a new narrative under a new paradigm. But for this, transformation is needed to a circular, sustainable **BioWEconomy** which includes, stimulates and supports transforming agriculture, fishery, forestry and waste management (Table 4).

61 https://www.cusp.ac.uk
62 http://www.doughnuteconomics.org/
63 http://greatmindshift.org/
64 https://wellbeingeconomy.org/

Table 4 Comparison of the "classic" bioeconomy and the BioWEconomy

Issues	**"Classic" Bioeconomy**	**BioWEconomy**
Sustainability	GHG mitigation	Wellbeing*
	Substitution of non-renewable resources	Transformation
Agricultural logic	Intensification	Agroecology & ecosystem services
Business logic	Linear, private profit, economy of scale, producer-customer	Circularity, societal value, industrial symbiosis & networks, prosumers
Innovation logic	Technical/engineering	Biological and technical, social & economic
Spatial patterns	Large scale	Regional clusters

*Source: own elaboration; *= healthy people, planet, and prosperity (see Section 5.3)*

A **BioWEconomy** could drive system changes (transformations) in the economy itself towards sustainability, as its agents are producers, consumers, and prosumers - all of us.

Pathfinding, and exploration

- The **BioWEconomy** reaches out to new sociocultural actors (collaborative/sharing economy, commoning), and explores innovation not only in technologies but also in business modes, and social practices.
- Culture & arts are not just means of communication, but integrated elements of the **BioWEconomy**, both in terms of (societal and economic) service provision, and means of transformation.
- The **BioWEconomy** favours nature-based solutions & fair international trade**.** It will take many experiments, explorations, and critical reviews to get there.

Going together

- Governing a sustainable bioeconomy requires collaborative, multilevel approaches and new indicators.
- Creating trust needs transparent supply chains, collaborative approaches, and participatory verification ("citizen science").

Providing guidance

- Financing institutions need sustainability checks for bioeconomy investments – certification is not enough**.** Sustainability has to become conditional for finance (EU Taxonomy, Green Deal, recovery packages etc.), and participatory crowd sourcing will allow the **WE** approach to inclusively sponsor bottom-up projects.
- The **BioWEconomy** needs targets for 2030 and 2050 to guide the transformation. **WE** will engage in co-creating the targets, considering global views.

ANNEX 4: On culture and arts

In Figure 24, the role of culture and arts as an in between society and economy was highlighted, and the **BioWEconomy** sees socioeconomic practices as important components of its value generation, though less in terms of GDP, more in societal value.

Cultural practices are as old as humanity, and arts are a specific expression of such practices.

With changes in societies over millennia, increasing (economic) wealth and rising neoliberal concepts of how we live and interact, the market became a determining factor of cultural practices, and arts. This concerns not only mass and new "social" media, but how museums work, how cultural practices are valued, and how products of art are marketed.

On the other hand, culture and art were never as free, multifaceted, and accessible before.

Cultural diversity is becoming a market value, and cultural resources such as fashion, food, music, sports, and stories (e.g. Manga comics, telenovelas, Bollywood movies) increasingly escape earlier restrictions in terms of control by clans, monarchs, nations, oligarchs and potentates, religions, etc. to become available for globalised customers seeking newness.

With the Summer of '69 and the "flower power revolution", with post-colonial opening of many countries, and with improved media and internet access, and digitisation, cultural practices – including art – are continuously transformed.

The trend of 3D printing (no more "originals") and the re-emerging of manufacture and crafts as counter-trends, increased digitisation and virtualisation as part of the COVID-19 driven lockdown and the experience of cultural absence or meagre ersatz of the "real" thing (concerts, sport events etc.) will have influence on how cultural practices and art will develop further.

Meanwhile, artists such as Olafur Eliasson question the relation of mankind and nature[65], Emma Hislop explores links between microbiomes in our bellies and circular economy concepts[66], Kristiane Kegelmann combines food art and entrepreneurship[67], Banksy inserts art into everyday life using subversive graffiti[68], Donna Haraway coined the term Chthulucene[69] and Bruno Latour calls for Landing on Earth[70]. These few examples indicate a fertile ground to link up with an inclusive **BioWEconomy** which could benefit from exposure to non-technical and post-modern views and practices.

This is needed, as humanising the term bioeconomy is not done by adding the "**WE**". It could be a good start to reach out to artists and re-define nature-based cultural practices (e.g. cooking, education, gardening, health care, walks etc.) as components of the **BioWEconomy** which create societal value for all.

The inclusion of traditional knowledge embedded in e.g. in agricultural practices of seed selection (as in Iran), adaptive climate architecture (as in Northern Africa), nature-based long-wearing fabrics and materials ((as in e.g. Latin America and Asia) might enrich the **BioWEconomy** further: it's worth a try.

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65 https://olafureliasson.net
66 https://opentongue.cargo.site/AiR-2020
67 www.kristianekegelmann.com
68 http://www.artbanksy.com/
69 https://www.dukeupress.edu/staying-with-the-trouble
70 https://zkm.de/en/exhibition/2020/05/critical-zones

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KJ-01-20-542-EN-N

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Publications Office
of the European Union

doi:10.2760/667966

ISBN 978-92-76-21518-9