BIOENERGY, BIOGAS AND BIOFUELS:

Research and innovation gaps in the EU

EERA
European Energy Research Alliance
BIOENERGY

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Executive summary

EERA Bioenergy is the European Alliance for excellent research in sustainable bioenergy. The main European universities, research alliances, technology centres, scientific agencies, institutes and associations involved in R&D&I in bioenergy and bioeconomy are part of EERA Bioenergy, which currently comprises 46 members. Its main focus is addressing the challenges of the European energy and environmental policies from a research and innovation perspective and promoting international cooperation to accelerate the SET-Plan priorities.

This document 'Bioenergy, biogas and biofuels: Research and innovation gaps in the EU' was drafted in the first semester of 2024 and published on 25th June 2024 in the framework of the EUBCE. It's an update of the EERA Bioenergy Strategic Research and Innovation Agenda published in spring 2019 to respond to the current momentum the energy landscape is going through.

The COVID-19 pandemic -initiated in Europe at the beginning of 2020- and the Ukraine invasion -started in February 2022 and is still ongoing- changed substantially the European energy policy landscape. Fit for 55 was launched with the ambition to decrease emissions by 55% in 2030 (on a 1990 basis) and RePowerEu (which put forward a Biomethane Action Plan), ReFuelEU Aviation and FuelEU Maritime initiatives seek to increase significantly the local production and use of renewable energy, gases, and fuels to strengthen Europe's energy autonomy. Some of the current policies have concrete targets for bioenergy, biogas, and biofuels and their implementation in Europe. While bioenergy, biogas, and biofuels contribute to the phase-out of fossil fuels and the defossilisation of the EU economy, the EU Commission also points out that they must be used sustainably[1].

Given the described policy scenario the energy and climate goals in the region and the current status of bioenergy in Europe, EERA Bioenergy has identified several key issues that require a stronger research focus for the achievement of these goals. This paper summarises some of the main bioenergy-related topics in Europe in need of further research and provides recommendations regarding the way forward for European bioenergy, biogas, and biofuels R&D&I. This also includes suggestions for topics not currently included in European R&D&I funding schemes targeting bioenergy, biogas, and biofuels research and innovation, e.g. Horizon Europe, Innovation Fund, etc. which can be relevant to include in future calls.

The main takeaways for the reader are the following:

- Bioenergy (power, heat, fuels) will always be an integral and inescapable part of optimised biomass valorisation strategies, either being the main product in so called bioenergy/biofuel-based biorefineries or being secondary product(s) in so called bioproducts/biochemicals/biomaterials-based biorefineries.
- Defossilisation means that more biobased carbon is needed. Too often the focus is on maximizing carbon yield and the option of CO_2 sequestration or biochar utilization as a means towards negative emissions is forgotten. This important aspect of bioenergy needs to be stronger emphasized.
- When developing bioenergy/biofuel systems it shouldn't be forgotten that materials and energy go hand in hand. In the ongoing effort to develop the bioenergy/biofuels sector, the synergies with biobased product creation from biomass should be addressed much more, from low TRL to deployment.
- To meet future biomass demands required in the various sectors of the European Circular Bio(based) Economy (Biocircularity), both European non-food crops and aquatic feedstocks, and agro, process and post-consumer residues should be used circularly and sustainably. Also, huge amounts of sustainably sourced non-European biomass feedstocks should be made available to further fill up future European market demands and ensure security of supply. Further development of so-called biocommodities and a global biocommodities market will be the key success factor for making available the right amounts of right quality biomass feedstocks at the right place and acceptable costs.
- The emergence of a biofuels industry often involves significant technological changes and **economic effects** stretching beyond the sector itself, which can be estimated using CGE[2] models; such models are also well suited for studying the effects of policy interventions/support and can simulate the market dynamics of biofuels.
- Regarding bioenergy **environmental impacts**, access to company data will increase the credibility of LCA[3] studies; proper upscaling of the product system is required to ensure that environmental assessments reflect commercial-scale conditions; moreover, LCAs should also consider the effects of future technological changes in the value chains associated with or supporting the advanced fuels production.
- Public knowledge and **awareness of bioenergy in Europe** is low, as compared to other renewables. Some of the main concerns within the populations are related to water resource scarcity and competition with existing food supply and price. Enhancing social acceptance and engagement will lay the foundations for increasing the market share of bioenergy/biofuel production systems.

For EERA Bioenergy, as an Alliance for Excellent Research, it's of utmost importance to define strategic areas of research and the key research questions that need further research efforts, in each of its Sub-Programmes.

Advances in the development of technologies and processes of bioenergy, biofuels, and biogas will bring direct benefits to the European policy context. Sustainable deployment of this sector will contribute to the spread and consolidation of the bioeconomy in all the European regions, which has implications above the energy and environmental concerns.

It can induce significant benefits in both, the primary and secondary sectors and the demographic challenge.
The main R&D&I gaps in the fields of bioenergy, biogas, and biofuels (as well bio-based products) that should be addressed to significantly contribute to reaching the ambitious climate EU goals and gain strategic sovereignty (industrial capacity / local energy resources) are listed below and have been described along the document:

[1] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en#:~:text=Bioenergy%20contributes%20to%20the%20phase,increased%20climate%20and%20biodiversity%20ambition.
[2] Computable general equilibrium models
[3] Life Cicle Assesment studies

Sub-Programme 1: Sustainable production of biomass.

- Biomass commodities.
- Mobilisation of feedstock.
  - Feedstock availability.
  - Feedstock Logistics and Supply Chain Management.
  - Building Integrated Biomass Supply Chains.
  - Community and Stakeholder Engagement.
  - Market Development and Incentive Mechanisms.
  - Techno-Economic Analysis.
  - Continues Improvement and Innovation.
- Innovative cropping systems.
- Safety issues for biomass storage.

Sub-Programme 2: Thermochemical platform.

- Ramp up the deployment of advanced biofuels.
- Thermochemical bio-refineries.
- Flexibility to increase the resilience of the overall energy system.
- Next-generation biomass pellets via mild thermochemical conversion of biomass.

Sub-Programme 3: Biochemical platform.

- Next-generation biorefineries for the treatment and transformation of lignocellulosic biomass in integrated schemes via cascade-type processes.
- Quality and price of the obtained bio-based products.
- Development of new fermentation routes.
- Optimise the pretreatments and operating conditions of the anaerobic digestion.

Sub-Programme 4: Stationary bioenergy.

- Optimisation of energy performance and emissions.
- Utilising existing combustion infrastructure.
- Innovation oxy-combustion in stationary bioenergy for CO_2 capture.

Sub-Programme 5: Sustainability/techno-economic analysis and public acceptance of bioenergy.

- Socio-economic impacts at community/household level and societal engagement.
  - The use of CGE models to understand macro-economic implications of bioenergy.
  - Further economic modelling approaches.
  - Bioenergy in Europe: societal engagement and governance.
- Environmental sustainability.
  - LCA for bioenergy.
  - Sustainability criteria in the revised RED.
  - Phasing out of first-generation biofuels worldwide and switching to advanced biofuels based on lignocellulose.
  - Environmental impacts: hydrogen and/or CO_2.

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Introduction and paper overview

EERA Bioenergy and motivation for the position paper

EERA Bioenergy[4] is the European Alliance for excellent research in sustainable bioenergy, addressing the challenges of the European energy and environmental policies from a research and innovation perspective and promoting international cooperation to accelerate the SET-Plan priorities. The main European universities, research alliances, technology centres, scientific agencies, institutes and associations involved in R&D&I in bioenergy and bioeconomy are part of EERA Bioenergy, which currently comprises 46 members.

EERA Bioenergy is structured into 5 Sub-Programmes (SP's), or areas of research focus, namely:

- Sub-Programme 1: Sustainable production of biomass.
- Sub-Programme 2: Thermochemical platform.
- Sub-Programme 3: Biochemical platform.
- Sub-Programme 4: Stationary bioenergy.
- Sub-Programme 5: Sustainability/techno-economic analysis and public acceptance of bioenergy.

As an alliance for excellent research, it is of utmost importance for EERA Bioenergy to define strategic areas of research and the key research questions that need further research efforts, in each of its Sub-Programmes. In 2019, EERA produced its SRIA[5] identifying the main challenges, research areas, and research priorities within each of the SP's. However, the European policy context has since then had several fundamental changes, which will have a direct impact on European bioenergy/biogas/biofuels targets and implementation. After COVID-19 the European Commission responded by launching the Fit-for-55 Package (which implied the revision of 11 EU Directives). And after the Russian invasion of Ukraine the REPowerEU, ReFuelEU Aviation, the FuelEU Maritime, and the Biomethane Action Plan were released as means to respond to the energy crisis. Also recently, the revised Renewable Energy Directive entered into force[6]. All these elements have direct implications for bioenergy/biogas/biofuels deployment in Europe and it is timely for the EERA Bioenergy community to identify key research gaps that need to be addressed and reflect on the role of bioenergy for the successful achievement of European energy and climate policy goals, and main barriers. This position paper gathers inputs from European experts working on different aspects of bioenergy/biogas/biofuels, from biomass feedstock production to valorisation processing, economic and environmental sustainability aspects, etc. The paper provides a summary of key issues to be addressed in the near future and recommendations on research and innovation areas to prioritise within the European bioenergy research community.

[4] https://www.eera-bioenergy.eu/
[5] https://www.eera-bioenergy.eu/publications/#sria-2020
[6] https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

Policy context: summary of current European policies with relevance for the Bioenergy sector

Some of the current EU policies influencing bioenergy and its implementation are summarised in Figure 1.

Figure 1: From Maria Goergiadou's (senior expert at European Commission) presentation on "R&I policy for renewable fuels", held at the EERA Bioenergy meeting, Crete, November 2023 and own elaboration EERA Bioenergy Secretariat.

• European Green Deal

The European Green Deal, launched by the Commission in 2019, is a package of policy initiatives with the main goal of setting the EU on the pathway to reach climate neutrality by 2050. The package includes initiatives on climate, the environment, energy, transport, industry, agriculture, and sustainable finance, which are all strongly interlinked. A cross-sectoral approach is applied, in which all relevant policy areas contribute to the ultimate climate-related goal.

The Clean Energy policy area within the Green Deal focuses on three key principles:

1. Ensuring a secure and affordable EU energy supply.
2. Developing a fully integrated, interconnected, and digitalised EU energy market.
3. Prioritising energy efficiency, improving the energy performance of buildings, and developing a power sector based on renewable sources.

Fit for 55

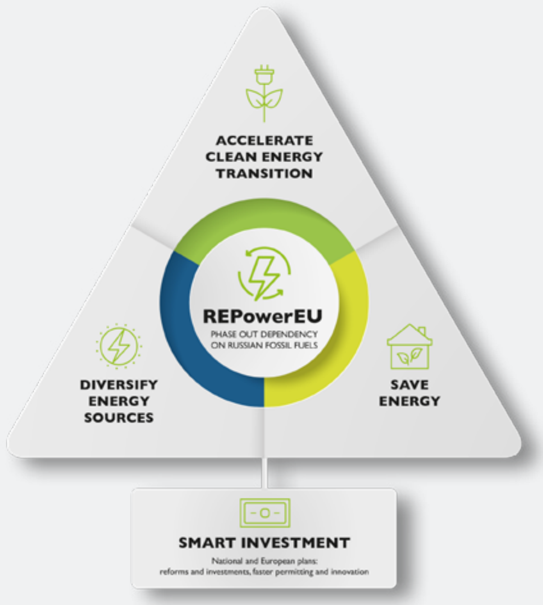
The Fit for 55 package is one of the several initiatives included in the Green Deal and refers to the EU target of reducing net greenhouse gas emissions by at least 55% in 2030, as compared to 1990 levels. The following initiatives in Fit for 55 have relevance for bioenergy:

1. Sustainable Aviation Fuels Initiative (ReFuelEU Aviation): Sustainable aviation fuels (SAF, i.e., advanced biofuels and electrofuels), which have lower CO_2 emissions as compared to fossil fuel kerosene, only represent 0.05% of total fuel consumption in the aviation sector. The main objective of this initiative is to increase both demand for and supply of SAF[7]. It set ambitious objectives, beginning with a minimum blend of 2% SAF in 2025 and escalating to 70% SAF by 2050.
2. Decarbonised fuels in shipping (FuelEU Maritime initiative): the goal of this initiative is to reduce the greenhouse gas intensity of the energy used onboard ships by up to 80% by 2050. The new rules promote the use of renewable and low-carbon fuels in shipping.
3. Renewable energy: under the Renewable Energy Directive II (RED II), the EU was obliged to ensure that at least 32 % of its energy consumption comes from renewable energy sources (RES) by 2030. The 'fit for 55' revision increased this target to 40 %, and this was further increased to 45% under the REPowerEU plan of May 2022. The revised RED (RED III) entered into force in November 2023. For bioenergy, it also strengthens the sustainability criteria for the use of biomass for energy, to prevent the risk of unsustainable bioenergy production. EU member states must ensure that the cascading principle is applied.

In addition, several other initiatives are also part of Fit for 55, these are listed in the Appendix.

• REPowerEU Plan

REPowerEU is about rapidly reducing the EU's dependence on Russian fossil fuels by fast-forwarding the clean transition and joining forces to achieve a more resilient energy system and a true Energy Union [1]. The REPowerEU Plan builds upon the Fit for 55 packages and maintains to achieve at least -55% net GHG emissions by 2030 and climate neutrality by 2050, while introducing additional measures to achieve the following goals:



- Save energy.
- Diversify supplies.
- Accelerating EU's clean energy transition and quickly substituting fossil fuels.
- Smartly combine investments and reforms.

This will result in a structural transformation of the EU's energy system.

Biomethane Action Plan

Biomethane, which can be made of organic waste like manure, food scraps, or damaged crops, is a renewable and dispatchable energy source and can be used to replace fossil gas. Published as part of the REPowerEU plan, the Biomethane Action plan calls for the establishment of the Biomethane Partnership to reach the ambitious target of delivering 35 bcm of biogas/biomethane per year by 2030.

Biomethane Industrial Partnership

The Biomethane Industrial Partnership is a public-private partnership open to all interested stakeholders, aiming at supporting the goal of the Biomethane Action Plan of increasing the annual production and use of biogas/biomethane to 35 billion cubic metres by 2030.

[7] https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/

- **Hydrogen and decarbonised gas markets package**

Natural gas (fossil methane) represents around 95% of today's gaseous fuels consumed in the EU. The "Hydrogen and decarbonised gas markets" initiative enables the market to decarbonise gas consumption and introduces measures needed for supporting the creation of optimum and dedicated infrastructure, alongside efficient markets. The aim is to support a dedicated hydrogen infrastructure and market and facilitate the integration of renewable and low-carbon gases into the existing gas network. It will also facilitate a more integrated network planning between electricity, gas and hydrogen networks.

- **The Green Deal Industrial Plan**

This is a major initiative of the EU Green Deal with the goal of placing Europe's net-zero industry in the lead. The initiative creates conditions favourable to scaling up Europe's manufacturing capacity for the net-zero technologies and products needed to meet the climate targets in the region. The four key pillars of the Green Deal Industrial Plan are:

1. Predictable and simplified regulatory environment.
2. Faster access to funding.
3. Enhancing skills.
4. Open trade for resilient supply chains.

- **Strategic Technologies for Europe Platform (STEP)**

STEP is a measure for boosting investments in critical technologies in Europe and will support investments in companies that contribute to preserving a European edge on critical technologies, throughout companies' full life cycle. The initiative aims to reinforce, leverage, and steer current or upcoming EU funds to investments in deep, digital, clean, and bio technologies in the EU.

- **Updated Bioeconomy Strategy and Action Plan**

The bioeconomy strategy supports the Commission's political priorities. Its objective is to accelerate the deployment of a sustainable European bioeconomy. It has 5 goals: Ensure food and nutrition security, manage natural resources sustainably, reduce dependence on non-renewable, unsustainable resources limit and adapt to climate change, strengthen European competitiveness and create jobs. The strategy contributes to the European Green Deal, as well as industrial, circular economy and clean energy innovation strategies. They all highlight the importance of a sustainable, circular bioeconomy to achieve their objectives. The strategy is implemented by means of an action plan. The bioeconomy action plan contains 14 concrete actions which aim: To strengthen and scale up the biobased sectors, unlock investments and markets; deploy local bioeconomies rapidly across the whole of Europe, and to understand the ecological boundaries of the bioeconomy.

- **Common Agriculture Policy (CAP)**

The common agricultural policy supports farmers and ensures Europe's food security. It's a partnership between agriculture and society, and between Europe and its farmers. It aims to: Support farmers and improve agricultural productivity, ensuring a stable supply of affordable food; safeguard European Union farmers to make a reasonable living; help tackle climate change and the sustainable management of natural resources; maintain rural areas and landscapes across the EU; keep the rural economy alive by promoting jobs in farming, agri-food industries and associated sectors. The CAP 2023-27 entered into force on 1 January 2023. Support for farmers and rural stakeholders across the 27 EU countries is based on the CAP 2023-27 legal framework and the choices detailed in the CAP Strategic Plans, approved by the Commission. The approved Plans are designed to make a significant contribution to the ambitions of the European Green Deal, Farm to Fork Strategy and Biodiversity Strategy.

Research Gaps

1. Research gaps: Sustainable production of biomass

1.1. Biomass commodities

Too little research is done on the development of real (lignocellulosic) biomass commodities. They are needed to be able to mobilise the diverse types of biomass, to the large biorefinery plants that are envisioned to produce advanced biofuels, SAF, and chemicals in the coming decades. These facilities cannot rely on local facilities as their size will be too large. Research has shown that a limited number of commodities are necessary that can be made from a wide range of biomass types. The final objective should be the development of true biomass commodities. The benefits of commodities are that a larger share of the biomass potential can be mobilised, and security of supply can be guaranteed to justify the large investment in conversion technologies. Per commodity a high degree of tradability is necessary. There is a real challenge to bring these commodities about. There is a requirement for international cooperation projects that address all relevant aspects to make intermediates into real commodities that offer the cost-lowering effect, security of supply, and increased biomass mobilisation of potentially available biomass.

- In Europe, information on biomass availability or the potential to make biomass available is scattered. Especially in Southern, Central, and Eastern Europe regions, data can be found in diverse formats and platforms and no comprehensive dataset in time series is available[8]. The access to reliable data[9] supports the development of realistic strategies and their implementation, aiming at a sustainable and bio-based economy in line with the Sustainable Development Goals of the United Nations.
- Little information about possible bandwidths of future availability of biomass in the mid and long-term (possible scenarios), which will be important for the planning of future conversion and uses.
- Identification and assessment of the goals, biomass commodities should deliver, e.g. should be easy to transport and store, for that high energy density and dry matter is needed.
- Consider all possible biomass types e.g. biomass dedicated crops, like camelina or carinata[10], urban gardening, agroforestry, paludiculture, etc.

Recommendations for future biomass resources potential studies:

- Need for standardisation to increase the consistency and comparability of biomass potential data (e.g. through a more uniform assignment of individual biomasses to categories with clear designation of biomass potential levels).
- Digitisation and full transparency of biomass potential data (including methodology and assumptions) instead of static tools (databases instead of PDF files).
- Long-term transfer of data and calculation elements into digital knowledge models (ontologies) to enable a "discourse" between biomass potential studies and the corresponding intuitions[11].
- Integration of the future development of biomass demand of different sectors (e.g. chemical industry, peat substitutes, biochar, biofertiliser, construction sector, etc.).
- Deepen the integration of sustainability indicators and regulatory requirements (e.g. EU LULUCF Regulation, EU Biodiversity Strategy, RED III Article 29) into the estimation and quantification of biomass potentials.
- Address quantitative effects of delayed cascade effects on residual and waste material potentials based on assumptions about future biomass use scenarios as a field of research[12]. The competing demands on biomass need to be harmonised. Circular or cascading systems need to be understood and developed.
- International/global evidence of e.g. feedstock and commodity potentials (in low resolution only), but lacking details (in high resolution) at local and regional levels, best assessed with harmonised methods and tools for comparative studies.

[8] BOOSTing the bioeconomy transformation FOR (4) the BIOEAST region: https://cordis.europa.eu/project/id/101133398
[9] See as example the DBFZ Resource Database (not complete yet). It covers numerous biogenic waste and residues. The data volume extends along five dimensions: biogenic resource, estimated quantity (e. g., theoretical or technical biomass potential), space and time (e. g., Saxony 2023), and underlying methodology. In the Database, several interactive views on the data volume could be found.
[10] CARinata and CamelINA to boost the sustainable diversification in EU farming systems: https://www.carina-project.eu/
[11] Brosowski, A.: National Resource Monitoring for Biogenic Residues, By-products and Waste. Development of a Systematic Data Collection, Management and Assessment for Germany, Universität Leipzig Dissertationsschrift. Leipzig 2021
[12] https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2017-06-13_texte_53-2017_biokaskaden_summary.pdf

1.2. Mobilisation of feedstock

Residual biomass derives from different sources (e.g. agricultural, forestry, food processing residues, municipal and other industrial wastes), therefore its mobilisation is still challenging. Research priorities that would accelerate the use of these largely available but unexploited resources should focus on:

- ***Feedstock availability.*** Research priorities in biomass resource availability have to converge on understanding their potential, variability, limitations, and spatial distribution at regional and local levels. In particular, the focus should be on:
  - *Biomass Resource Assessment.* Conduct comprehensive biomass resource assessments to quantify the availability, distribution, and characteristics of biomass feedstocks at local, regional, and national scales. This includes evaluating biomass residues from agriculture, forestry, municipal solid waste, and other sources. In such assessments opportunities for biomass resource recovery from industrial waste streams and circular use have to be investigated.
  - *Biomass availability modelling.* Develop models and tools to predict biomass availability under different scenarios, including land use changes, climate variability, and socio-economic factors. This includes integrating spatial data, remote sensing, modelling techniques, and digitisation to assess the spatial and temporal dynamics of biomass resources.
  - *Feedstock diversity, suitability, and flexibility.* Investigate the diversity of biomass feedstocks and their suitability for different conversion pathways and end uses. This involves characterising biomass feedstocks based on their chemical composition, energy content, moisture content, ash content, and other relevant properties. Based on feedstock properties, the flexibility of biomass feedstocks for various conversion technologies, product pathways, and biorefinery systems can be evaluated.
  - *Soil quality issues.* Research to address the competing uses particularly the need for maintaining soil quality and methods for maximising the availability of biomass while returning nutrients to the soil and supplying carbon to the soil. This aspect and the way to optimise this is not well understood leading to underutilisation or overexploitation of the resource. Different strategies have to be developed to maintain soil quality while still maximising the use of field residues for the biobased economy. Strategies have been proposed but have not been further developed. They include switching to no-till planting, field refining of high and low ash parts of straw to leave the high nutrient part behind, biogas production from the residue and returning digestate when most appropriate, etc.
  - *The role of bioenergy/biofuels/biogas in circular biomass use.* Circular biomass use decreases the need for land, and other inputs and reduces GHG emissions.
  - *Recycling of biomass ash.* Nutrients (P, K) are now often lost when the ash is used in non-agricultural applications. Methods are needed to ensure the return of these nutrients to agriculture.
  - *Recycling of digestates from anaerobic digestion.* Research to enhance its use as organic fertiliser for agriculture thereby reducing the need for chemical fertilizers while providing C to the soil.

- ***Feedstock Logistics and Supply Chain Management.*** Investigating strategies to improve the collection, storage, and transportation of biomass residues from field to conversion facilities. This includes addressing logistical challenges, biomass handling techniques, and supply chain optimisation to ensure a reliable and cost-effective feedstock supply. Focussing on this aspect, strategies for mobilising biomass residues effectively are listed below:
  - *Field Collection and Harvesting Techniques.* Develop efficient methods for collecting biomass residues directly from fields or forest sites, to minimise environmental impacts, maintain soil health, and preserve biodiversity. This may involve harvesting timing and intensity, specialised equipment, and techniques tailored to different types of biomass, such as crop residues, forestry residues, or other agro-industrial waste, and effects on ecosystem services, carbon sequestration, and wildlife habitat.
  - *Logistics Planning and Optimisation.* Strategic planning and optimisation techniques to minimise transportation costs during several stages in the biomass supply chains are required to maximise the cost and quality efficiency of the supply chains. This includes route optimisation, scheduling, and coordination of biomass collection, storage, and delivery activities. Enabling technologies, such as digitalisation, is essential to improve feedstock mobilisation at the regional and local levels.
  - *Storage Infrastructure.* Establish appropriate storage infrastructure to store biomass residues at collection points or centralised depots (biohubs) before transportation to conversion facilities. This may involve designing storage facilities that minimise degradation and maintain the quality of biomass materials. Such storage infrastructures may also serve to store intermediate bioenergy carriers (i.e. pellets, torrefied biomass, etc.), which derive after biomass is subjected to pre-processing and pre-treatment technologies.
  - *Biomass Handling and Processing Equipment.* Invest in equipment and machinery for handling and processing biomass residues efficiently and improve handling characteristics. This includes shredders, balers, chippers, and other equipment for reducing biomass size, increasing density, and facilitating handling and transportation as well as techniques such as drying, size reduction, densification, torrefaction, and other chemical or biological pre-treatment.
  - *Interaction of sectorial policy and mobilisation of residues and wastes.* Development and implementation of innovative best practices regarding the mobilisation of residues and wastes.

- ***Building Integrated Biomass Supply Chains.*** Explore integrated biomass supply chain models that optimise the collection, transportation, and processing of biomass feedstocks from field to conversion facilities. This includes assessing logistical challenges, infrastructure requirements, and cost-effective strategies for biomass mobilisation.

- ***Community and Stakeholder Engagement.*** Engage with local communities, farmers, forest owners, and other stakeholders is required to support biomass mobilisation efforts. This may involve providing incentives, training, and technical assistance to encourage participation in biomass collection and supply activities. Following the stakeholders' engagement at the primary level (biomass procurement), establishing partnerships between biomass producers, collection agencies, transporters, and conversion facilities will help build cost-efficient biomass supply chains. This includes developing contractual arrangements, supply agreements, and risk-sharing mechanisms to ensure a reliable and sustainable biomass supply throughout the year.

- ***Market Development and Incentive Mechanisms.*** Creating markets and incentive mechanisms to stimulate demand for biomass residues will encourage their mobilisation. This may involve implementing policies, subsidies, tax incentives, renewable energy mandates, and carbon pricing mechanisms to promote the use of biomass feedstocks in bioenergy/biofuels/biogas and bioproducts production.

- ***Techno-Economic Analysis.*** It is necessary to conduct a techno-economic analysis to evaluate the cost-effectiveness and feasibility of different biomass mobilisation strategies, including assessing the overall economics of biomass supply chains (capital and operating costs, revenue streams, and financial viability).

- ***Continuous Improvement and Innovation.*** Overall, it is crucial to continuously evaluate and improve biomass mobilisation processes through innovation, research, and development. This includes exploring new technologies, operational practices, and supply chain management strategies to enhance efficiency, reduce costs, and minimise environmental impacts.

By implementing these strategies, stakeholders can effectively mobilise biomass residues and ensure a sustainable and reliable supply of feedstocks for bioenergy and bioproducts production, thereby contributing to the transition to a more sustainable and low-carbon economy.

1.3. Innovative cropping systems

Innovative cropping systems aim at integrating the production of food, feed, energy and other bio-based products to increase the sustainability of the whole value chain. The additional biomass feedstock produced in these low ILUC risk systems could become an incentive for farmers to introduce such practices (without affecting the main scope of agricultural systems to produce food/feed) and increase their incomes and ecosystem services in accordance with the additionality measures set out by the Delegated Regulation of RED III. Despite their potentialities, such systems are still underdeveloped and underutilised, mostly because the design of low ILUC risk cropping systems require further developments and studies in terms of i) crop species compatibilities, ii) definition of fine-tuned agronomic management practices, and iii) evaluation of potential environmental benefits.

- Among the large variety of annual and herbaceous perennial non-food crops that could be integrated within conventional food cropping systems, annual dedicated crops, including leguminous crops, are the most adaptable ones to be considered. However, the introduction of a dedicated biomass crop within a conventional cropping system requires a careful evaluation in terms of its compatibility with the main (food) crop, adaptability to the site-specific pedo-climatic conditions, and specific agronomic management practices. From the biological point of view, the designing of an innovative cropping system should take into account the species compatibility in the use of the soil resources (i.e. water, nutrients), their growth length, their rooting patterns, and their overall performance.

- The safe implementation of innovative cropping systems also requires a better definition of the most appropriate agronomic management strategies within the circular bioeconomy context. More information is needed on how to: Increase the efficient recycling of internal nutrients and reduce the use of agrochemicals, maintenance of the long-term productivity of the land including conservation agriculture techniques, avoidance of the accumulation of diseases and pests associated with monocropping and minimise the energy requirements for harvesting and related pre-treatment and supply operations.

- To contribute to more efficient use of cropped areas and expansion to lower agricultural value lands (unused, abandoned, and degraded lands) and avoid conflicts with food markets and high-risk ILUC it should be further investigated the potential impacts of these innovative cropping systems have on soil conservation, soil health, soil quality, soil biodiversity, and soil carbon storage capacity.

- From the energy conversion technologies point of view, information is required on feedstock qualitative flexibility, alternative feedstock sources, and best crop mixes to reduce supply risks and comply with certain qualitative conversion process requirements. Research on potential pre-treatments to increase feedstock flexibility is also needed.

- Agri-based dedicated crops:

- Research is needed to be integrated into the eco-regimes (also known as eco-schemes) of the Common Agricultural Policy as a good environmental practice.

- Forest-based dedicated crops:

- Feedstock diversification (e.g. alternative/new/non-native climate change-resilient tree species in forest management) needs further Research (i.e. future management scenarios under climate change).

1.4. Safety issues for biomass storage

In modern bioenergy, long-term storage of substantial volumes of biomass is inevitable. This requirement, however, poses significant challenges, particularly concerning bioenergy/biofuels/biogas plant safety, since the intrinsic self-heating of biomass piles, caused by exothermic microbial and chemical reactions, can lead to spontaneous ignition. Recent years have witnessed many serious fire incidents due to self-heating and self-ignition of stored biomass across various countries.

To date, there is little effort addressing the safety issue of stored biomass and a notable absence of reliable tools for real-time monitoring or prediction of self-ignition of large biomass piles. To facilitate the large-scale widespread deployment of biomass in bioenergy and biofuel production shortly, the safety issue associated with the long-term storage of large volumes of biomass must be properly addressed through advanced modelling and monitoring.

2. Research gaps: Thermochemical platform

2.1. Fuels

Fuels are derived from fossil resources. This is a century-long development, based on an abundance of feedstock. A feedstock that has a very different composition than biomass. Today the focus is on advanced biofuels and most developments that can be observed, are still based on this fossil history. To ramp up the deployment of advanced biofuels, several elements are of crucial importance and need proper support:

- Biomass has a completely different availability and composition, for which research is needed on the pre-treatment and conversion site. But also, on how to make the economics work concerning logistics.
- Back-end applications, such as MeOH[13] or FT[14] synthesis, are still too focused on syngas as is derived from fossil resources. More support for research is needed to develop pathways suited for biobased synthesis gas, perhaps explicitly stating this in the call.
- Co-production schemes can be valuable, however are more difficult to develop. Bio-refineries are one concept but often this leads to a range of products. Integrated biorefinery schemes also including symbiosis between bio(catalytic)-chemical and thermochemical processes need further development. To be successful and competitive nowadays, focus on two products is needed, which can be expanded upon in the future.
- Electrochemical upgrading of liquefied biomass, such as fast pyrolysis oil and black liquor, followed by further refining can produce energy-dense bio-oils and premium transport fuels.
- The inclusion of renewable energy (direct) or hydrogen (indirect) can boost the overall conversion efficiency towards fuels. With bioprocesses, there are many variations to do this and further investigations are needed on how renewables should be incorporated.
- Fully integrated demonstrations for periods of up to 10 years will give a better understanding of all the parameter in the value chain, feedstock growth, harvesting, supply chain, technology performance, economics and social aspects.

[13] Methanol
[14] Fischer-Tropsch

2.2. Thermochemical bio-refineries

Biorefineries represent a key concept for the efficient usage of renewable sources. They are facilities that integrate biomass conversion processes and technologies to sustainably and efficiently generate valuable products and bioenergy.

Co-processing biomethane production with waste management activities creates synergies in resource utilisation and waste management and can be utilised to convert waste materials and residues into valuable products, such as energy, fuels, and chemicals. This process involves treating or valorising different materials or streams simultaneously. Thermochemical processes, such as pyrolysis or gasification, can be used as waste management technologies in a co-processing context. However, for biorefineries based on thermochemical processes to become more prevalent, full process chains from feedstock to final products must be established.

An exemplary co-processing approach is the hybrid biorefinery concept which integrates gasification and electrolysis technologies to improve product yields. Multiple feedstocks from different sources can be used to produce syngas through gasification, while electrolysis can use treated wastewater to produce hydrogen using renewable energy. By combining syngas and green hydrogen, the number of end products, such as synthetic or renewable natural gas and liquid transportation fuels, can be increased.

Despite other concepts, RD&D investment is still required to evaluate and compare different process chains. Machine learning and AI can be the supporting tools to do these evaluations much faster and need to be brought into the R&D on bioenergy as well. The same holds for scaling up these coupled processes and determining their economic feasibility requires rigorous research. The integration of different processes supports the idea of the circular economy, involving multiple stakeholders from different sectors, such as power generation or chemical synthesis, or even stakeholders using different bioenergy technologies.

Within the topic of technological integration, the industrial use of biorefinery technology is an important factor. The development of these technologies frequently shifts from the findings of academic studies. The economic analysis, which considers the investment cost and potential profit, is one of the primary elements that is frequently disregarded. Conducting economic assessments for the integration of different technologies is essential for supporting the circular economy. Comprehensive scale-up studies bridge the knowledge gap between industry and academia, enabling the efficient integration of innovations into existing plants..

2.3. Flexibility

Different from other renewable energy sources, such as PV, wind, and hydropower, biomass-derived energy carriers allow for significant flexibility in the time, location, and type of their use. Due to the inherent option to store and transport these fuels in existing infrastructure, and to decide whether they are used for heat and electricity, for chemicals, or transport, they can increase the resilience of the overall energy system. This flexibility can be further increased by two options, which however need further research.

To support e.g. the seasonal flexibility, the extended part-load operation should be possible to adapt production to available feedstock and storage capacity. Also, feedstock flexibility is helpful to enable more economic operation.

Second, even more important, the production of biofuels allows the incorporation of renewable hydrogen to increase the conversion of biogenic carbon to the desired fuels, thus enabling (seasonal) energy storage. As renewable hydrogen is not available all year in the same amount, e.g. not in winter, biofuel production downstream of anaerobic digestion or gasification should allow for flexible hydrogen addition in their process technologies. Further, they could allow for the separation of biogenic CO_2 in times without hydrogen addition to allow for CO_2 sequestration and thus negative emissions. Carbon efficiencies of processes therefore should also include the part of carbon ending up sequestered, rather than a carbon loss.

To better understand the use of such flexibility, it is also necessary that they are represented in an appropriate way in the energy systems model.

2.4. Next -generation biomass pellets via mild thermochemical conversion of biomass

Currently, white biomass pellets, as a densified form of biomass, are commonly used in the bioenergy sector, due to their obvious advantages over raw biomass in terms of transport, storage, and use.

However, the advent of next-generation biomass pellets, known as black pellets, presents an opportunity for cost-effective production by integrating current densification processes with a mild thermochemical pretreatment of raw (dry or wet) biomass materials. This involves subjecting the raw biomass to mild pyrolysis (or dry/wet torrefaction) before mechanical densification. Black pellets offer significant advantages over traditional white pellets, e.g. lower moisture content, higher calorific value, diminished risk of self-heating and self-ignition, improved hydrophobic property, facilitated handling/milling in stationary bioenergy production plants.

3. Research gaps: Biochemical platform

The valorisation of biomass as an energy source is key in the transport sector being the second largest energy consumer in the EU. The development of biofuels from renewable biomass feedstock can play an important role in getting 32% of transport fuels derived from renewable sources by 2030 (REDII and ReFuelEU Aviation) and biomethane targets (REPpowerEU).

Forest, agricultural, or industrial lignocellulosic waste are sources for the production of energy, fuels, and bioproducts in the biorefineries framework. Biochemical processing is one of the platforms to get this type of fuel such as ethanol or biomethane.

The cost-effectiveness of biomass to fuels depends on increasing the production of high-value chemicals, materials, or commodities as co-products so the research gap is developing integrated biorefineries on a demonstration scale with a sustainable biomass value chain.

One of the key challenging points in the biochemical process is to get stable and robust biocatalysts with better performance for the production of bioethanol and advanced fuels via sugars fermentation, as well as improvements in the production of biogas by anaerobic digestion from waste biomass (including algae and other organic residues). In addition, the symbiosis between bio(catalytic)-chemical and thermochemical processes in integrated biorefinery schemes is essential to enhance biofuels and bio-chemicals productivity and competitiveness in the actual market. In this sense, some identified research gaps in the bio(catalytic)-chemical processing are:

i) Increasing knowledge on the synthesis of cell wall components, and the microbiology and biochemistry of the anaerobic digestion process.
ii) Bio-augmentation strategies.
iii) Cost reduction of enzymatic cocktails.
iv) Novel biocatalysts with better performance against inhibitors.
v) Engineering yeast and bacteria for C6 and C5 sugar fermentation.
vi) Novel fractionation techniques capable of handling multi-feedstock.
vii) Incorporation of diverse waste biomass streams or feedstocks (i.e. MSW, etc.).
viii) Downstream chemical process to transform ethanol into advanced biofuels (i.e. SAFs).
ix) Production of valuable bio-products from all the main constituents of lignocellulosic biomass.
x) Lignin processing through bio(catalytic)-chemical and/or thermochemical processes (symbiosis).

3.1. Next-generation biorefineries

Next-generation biorefineries imply the treatment and transformation of lignocellulosic biomass in integrated schemes via cascade-type processes to co-produce more than one bio-product (biofuels, bio-chemicals, biomaterials). Primary treatments mostly aim to fractionate sustainable lignocellulosic biomass streams into their main constituents. These fractionation technologies result in the isolation of cellulose-enriched fibers, hemicellulose sugars and their derivatives (HMF, furfural), and high-purity lignin, thus allowing for the full valorisation of such streams. Several key technology options such as novel organosolv fractionation and lignin-first approaches are seeking validation or have been validated at the pilot-scale before entering the commercialisation phase.

However, the commercialisation of biorefinery technologies has proven to be challenging as recently demonstrated by the discontinuation of Clariant's commercial bioethanol plant. This example along with other examples from the past indicates that the conversion of biomass to fuels only is economically challenging. Therefore, next-generation biorefineries that allow valorisation of, for example, hemicellulose-type fractions, lignin fractions, and other side-streams aqueous or even gaseous fractions to high-value applications have the potential to co-produce biofuels and bio-chemicals, while maintaining the economic viability of such processes. In the last years, different EU projects have been launched to develop novel technologies and integrated strategies to valorise intermediates and bio-products to more valuable fuels and chemicals (i.e. bioethanol to ethylene and then to fuels, bio-methanol to DME, bio-alcohols to SAFs and aromatics, sugars and furanics to SAFs and aromatics, lignin and derivatives to marine fuels, among others). These research developments, their upscaling, as well as the exploration of new value chains are crucial for the deployment of the EU biofuels and bio-based products sector.

Key aspects for further development of next-generation biorefineries comprise:

- Novel technologies development and upscaling to TRL 6.
- Biorefinery feedstock flexibility.
- Biorefinery product versatility (co-production model).
- Process intensification.
- Improving the cost-effectiveness of novel value chains.

However, over the last several years, a cope tightening within biorefinery call topics seriously limits the access of such next-generation processes to further development and upscaling. Note that technologies that enable full valorisation of sustainable feedstocks, thus including the production of high-quality lignin (the second most abundant biopolymer on earth), are a necessity for the transition to a circular and biobased economy. In addition, next-generation biorefineries provide the materials for optimal interplay between cellulose fibers, sugar-derived chemicals and lignin to provide limitless opportunities for (tailoring) new products. Examples therefore are the sugar-derived crosslinkers for circular lignin-based polymers and the use of lignin in cellulose-based packaging and insulation materials for improving barrier properties, moisture resistance and fire retardancy.

Integrated biorefineries have to be capable of ensuring biomass feedstock supply, processing intermediate to get added-value products, developing innovative bio-products for market applications, being economically viable and increasing product portfolio.

New biorefineries will have the capability to align with renewable electricity sources and/or renewable H_2 as an energy vector and adopt innovative, sustainable approaches for chemical production, including sugar-derived carboxylic acids and other relevant derivatives, essential raw materials for diverse products. Such processes hold promise in replacing conventional thermochemical methods, which heavily depend on imported materials such as nitric acid and fossil fuels.

3.2. Quality and price of products

Nowadays, different biorefinery concepts exist, such as bioethanol, bio-succinic acid, and levulinic acid, among others biorefinery models optimised for the production of one desired main product are readily built up and developed around the world. Nevertheless, although the obtained bio-based products are more eco-friendly than the fossil-derived ones, they are often more expensive and/or less competitive in an always highly demanding market. Among the main targets and challenges to be afforded by the biorefinery industry in the next years, the quality of the bio-products and their price appear as strategic key issues. Availability and quality of biomass feedstocks and biomass fractions (cellulose, hemicellulose, lignin) are essential to achieve better product quality. For example, lignin colour and quality (attained via organosolv fractionation) and bio-aromatic mixture yield and composition (attained from lignin-first approaches) are important parameters for its future application as a source of biofuels and bio-chemicals with sufficient added-value. In addition, the quality of the bio-product strongly depends on the new technologies' developments for improvement of biomass conversion, further processing of intermediates, and efficient separation of final bio-products. In the case of advanced biofuels for aviation or maritime usage, for example, fulfillment of required specifications for drop-in fuels is essentially needed. Finally, the economic competitiveness of the biofuels and bio-chemicals produced in biorefinery is challenging and it needs to be addressed in the next years. In this sense, reduction in feedstock prices (more availability), less expensive and more efficient and sustainable technologies for biomass conversion, together with adequate financial and political/government support against fossil or non-renewable sources derived products could be the key points for the near future.

3.3. Fermentation processes

Fermentation processes to produce fuels have an inherent low carbon efficiency. More targeted R&D is needed to overcome this shortcoming. Further strengthening between the field of biorefining and biotechnology is required for the development of new fermentation routes, strain tolerance to fermentation inhibitors, and further integration of heat, mass flows, and zero-waste strategies.

Bioethanol by means of fermentation process is the most used liquid biofuel. Bioethanol comes from corn and sugarcane crops mainly but food-versus- fuel debate is strong in the EU so advanced bioethanol is being promoted. Lignocellulosic biomass yeast fermentation to ethanol requires the following steps of technologies: pretreatment, hydrolysis of cellulose and hemicellulose, sugar fermentation, separation of lignin, and purifying to meet fuel specifications.

The gap of research in the pretreatment step is the insufficient separations of cellulose and lignin, inhibitors, and the high demand for chemicals and energy. Besides, the optimisation process is performed for just one biomass being necessary to hand multi-feedstock.

Advanced analytical techniques are revising to identify the effects of enzymes on different biomass features. The cost of the enzyme is another barrier so there is research to improve enzyme and yeast performance through metabolic engineering strategies, genetic modification, or Synthetic biology (SynBio).

The bioethanol cost production via biochemical processes would be lower if it improves the C5 sugar fermentation, simplifies the process stages, it performs on-site enzymes, or downstream processing is optimised.

Advanced drop-in biofuels for aviation are in demand being cellulosic ethanol is one possible pathway to produce it. Hybrid conversion (biological and chemical) processes can transform sugar into larger hydrocarbon molecules for jet-fuel applications. In one of the strategies, bioethanol is dehydrated to ethylene then via alpha-olefin oligomerisation reaction into C4-C8 hydrocarbons, and then by selected distillation process into C6-C16, which are jet-fuel fractions hydrocarbons. Research is needed in each step from bioethanol to jet-fuel range hydrocarbons production for catalytic processes improvement to achieve aviation fuel standards, also including the production of cellulosic ethanol in sufficient quantities and at acceptable costs.

By incorporating electrolytic hydrogen into a biomass fermentation or anaerobic digestion process, bio-e-fuels can be produced. Carbon can be obtained through capture from CO_2 point sources such as ethanol production, bioenergy power plants, cement production, or other industrial processes. The combination of hydrogen and carbon oxides can yield a range of fuels through different technologies of synthesis, the most consolidated are methanation, methanol synthesis, and Fischer–Tropsch (FT). Feedstocks like animal manure, organic waste from food processing, straw, and various energy crops are viable sources for digestion or fermentation. The combination of fermentation with the production of bio-e fuels improves carbon efficiency, however, their production is energy-intensive, and renewable energy is required to effectively ensure a low environmental impact.

Flexible biogas production and utilisation of proteins, fats, and fibre in combination with biogas production is a transversal research gap. Proteins and fats can be used as feed for farm animals or pets as well as in a variety of ways and, in the end, for biogas production.

3.4. Anaerobic digestion process

Anaerobic digestion (AD) is a complex biological process that converts organic wastes into biogas. Biogas makes a full contribution to the main targets of the current energy transition by replacing fossil resources and reducing the methane emissions related to the disposal of biodegradable waste, thus reducing the amounts of greenhouse gas (GHG) emissions. Furthermore, the use of the resulting digestates for enriching agricultural soils also contributes to creating carbon sinks. Research to understand better the condition of the AD process is necessary as well as optimise the pretreatments and operating conditions to achieve higher biogas yields from the different biomasses.

Biomethane is an alternative to natural gas helping to decarbonise the intensive energy-consuming industry. Biogas can be used directly to produce heat and power or converted into biomethane through a wide variety of upgrading technologies. There is a research gap in developing new cheaper upgrading technologies with less environmental impact. Biological upgrading both in situ and ex. situ is one of these new technologies but still needs improvements.

Biogas is produced from a wide variety of feedstocks, including animal manure, crop residues, wastewater sludge, and the organic fraction of municipal and industrial solid waste. Pretreatments and co-digestion strategies plus biological indicators that allow monitoring this biochemical process are being studied.

Biogas and digestate can be platforms to produce value-added chemicals. Also, in the bioconversion of organic material to methane, there are different processes and types of microorganisms involved. Sugar, alcohols volatile fatty acids (VFAs), acetic acid, carbon dioxide, and hydrogen are released before being converted to methane. Some of these components are precursors of other chemicals such as VFAs to PHA, microbial oil for application in the oleochemical industry, and omega-3 fatty acids for food use.

The production of methane depends on the resistance of the microorganisms in the AD process to inhibitors contained in residual biomass such as ammonia, sulfur, or phenols. Anaerobic co-digestion improves the nutrient balance diluting some toxics. Furthermore, it can supplement micronutrients such as Fe, Co, or Ni which are essential for the growth of microorganisms. The research gaps in this matter could be better knowledge of the co-digestion processes and bioaugmentation strategies introducing exogenous microorganisms that are resistant to inhibitors. Another priority research need is the potential chemical storage of excess wind/PV-derived power electrochemically or via H_2 into biogas.

4. Research gaps: Stationary bioenergy

4.1. Optimisation of energy performance and emissions

The domestic biomass heating applications (wood stoves, etc.) need to research on the reduction of their emissions and the increase of their energy efficiency, with a special focus on black carbon emissions. Energy production could be optimise by biobased materials production applications, such as pyrolysis for the production of biochar for various applications, including carbon long-term storage. Synergies between energy and material recovery (e.g. WtE & recycling) should be researched.

4.2. Utilising existing combustion infrastructure

The global pandemic followed by the Russian invasion of Ukraine has tough us that the energy supply is at risk if too dependent on non-EU supply. The reduction in NG from Russia has led to all kinds of startling developments with nuclear gaining traction, lignite plants being restarted, and coal being imported. However, the assets in the EU capable of burning oil, coal, and gas could also be retrofitted to biogenic residues. This is of course a temporary solution until our energy supply is fully transitioned to renewables, however as a short-term solution it is an approach to reduce fossil dependency, build up biogenic value chains, and keep existing infrastructure in operation for the coming decades.

- R&D needs relate to feedstock quality and how it will affect running operations.
- Blending opportunities for different kinds of residues and how they can contribute to an improved emission profile of a power plant.

4.3. Innovating oxy-combustion in stationary bioenergy for CO_2 capture

Among the prevalent biomass combustion technologies, implementing oxy-fuel combustion in grate-fired systems poses challenges due to significant air leakage. Conversely, both suspension-firing and fluidised bed combustion technologies offer promising opportunities for retrofitting existing stationary bioenergy facilities for oxy-fuel combustion. This adaption facilitates carbon capture in stationary bioenergy plants, potentially achieving negative CO_2 emissions. Key research and development (R&D) areas include:

- Exploring novel oxy-steam combustion methods for biomass, as an alternative to the current oxy-RFG (recycled flue gas) combustion approach.
- Investigating the potential for MILD (Moderate or Intense Low-oxygen Dilution) combustion of biomass dust in suspension-firing facilities.
- Developing and validating comprehensive CFD (Computational Fluid Dynamics) model tools for oxy-biomass fluidised bed combustors and suspension-firing furnaces. This entails refining essential sub-models of combustion physics & chemistry specific to biomass combustion under various oxy-fuel conditions and integrating these sub-models into a CFD-based digital model.
- Performing comprehensive virtual testing using the validated CFD models to innovate and advance oxy-biomass fluidised bed and suspension-firing technologies, and thus to achieve more efficient and cleaner energy production with below-zero CO_2 emissions for stationary bioenergy applications.

Other complementary research and development (R&D) areas that must be developed are:

- Importance of feedstock transport, energy distribution, and storage. Cost-optimal feedstock and energy transport/distribution are equally important as storage optimisation – Research is lacking in both cases.
- CDR and CCU potentials with different technologies.
- Technological handshakes. Necessary handshake between users/sectors of the same feedstock – i.e. New European Bauhaus-type long-term C-storage in the building sector (wood) and bioenergy/ pellets producers (optimal feedstock use regarding max. mitigation/sink, minimising damage to e.g. biodiversity).
- BECCS (including WtE).
- Hydrothermal processes for wet feedstocks (HTC, HTL, SCWG).
- Gasification of challenging biomass residues.

5. Research gaps: Sustainability assessment

5.1. Socio-economic impacts at community/ household levels and societal engagement

5.1.1. The use of CGE models to understand macro-economic implications of bioenergy

It is important to understand the impact that the emergence of new technologies to produce bioenergy exert on the economy. These effects can stretch beyond the bioenergy sector itself and ripple over several other industries in ways that might not be easy to anticipate. In this respect, the employment of Computable General Equilibrium (CGE) models provides a viable and comprehensive way to analyse the policy and technology impacts associated with the emergence of, e.g. a biofuels industry. This is due to several inherent strengths of CGE models in capturing the complex interactions within an economy.

Computable General Equilibrium (CGE) models are a class of economic models that analyse how an economy might react to changes in policy, technology, or other external factors. They are used extensively in economic research and policy analysis due to their comprehensive nature and ability to capture complex interactions within an economy. Key characteristics of CGE models include:

- **Economy-Wide Interaction:** CGE models consider the entire economy, encompassing multiple sectors, agents (such as households, firms, and government), and markets (like goods, labour, and capital markets). They simulate how these elements interact with each other.
- **General Equilibrium Framework:** These models are based on the concept of general equilibrium from economic theory, where supply and demand in all markets are in balance. They consider the simultaneous determination of prices and quantities in all markets.
- **Microeconomic Foundations:** CGE models are grounded in microeconomic theory, particularly the theory of consumer and producer behavior. They typically assume that consumers maximise utility and producers maximize profits, subject to their respective budget and production constraints.
- **Data-Driven:** The models are data-intensive, typically calibrated to a Social Accounting Matrix (SAM) or a similar dataset that provides a snapshot of the economy. This matrix includes data on production, consumption, income distribution, and the interaction between different economic sectors.

CGE models are used for conducting scenario analysis, allowing economists to compare the outcomes of different hypothetical scenarios or policy choices. They offer a complete representation of the economy, encompassing various sectors, agents (e.g. households, firms, and the government), and markets (such as for labour, capital, and commodities). For example, the biofuel industry is intrinsically linked with several other sectors, notably agriculture (for feedstock), transportation, and manufacturing. CGE models can effectively capture these linkages, allowing for an analysis of how changes in the biofuels sector ripple through to other parts of the economy. CGE models are particularly suited for assessing the impacts of policy interventions. This includes policies directly related to biofuels, such as subsidies, mandates, and tariffs, as well as broader economic and environmental policies. The models can simulate different policy scenarios and compare their outcomes in terms of economic efficiency, sectoral outputs, employment, and income distribution.

Once again considering the example of the emergence of a biofuels industry, this would often involve significant technological changes; CGE models can incorporate these changes in the production functions of the biofuels sector and related industries. This includes improvements in biofuel production efficiency, the development of new biofuel types, and advancements in feedstock cultivation. Finally, CGE models can simulate the market dynamics of biofuels, including supply, demand, and price formation. This is crucial for understanding the competitiveness of biofuels compared to other energy sources and the impact of biofuels on energy and commodity markets as well as its implications in the job market.

In the context of bioenergy, CGE models can be pivotal in understanding two key areas:

- **Effects of Emerging Bioenergy Technologies:** The development of new bioenergy technologies influences both the bioenergy sector and the broader economy. CGE models can simulate these impacts by incorporating technological advancements in bioenergy production into the model. This integration allows for the examination of how these technologies affect the production costs, competitiveness, and market share of bioenergy, compared to traditional energy sources. Additionally, the models can explore the wider economic implications, such as changes in trade patterns, sectoral outputs, and gross domestic product (GDP).
- **Implications of Geographical Locations of Resources:** The geographical location of resources necessary for bioenergy production has significant economic implications. CGE models can simulate the impact of these geographical factors on the European economy, focusing on aspects like regional development, job creation, and price effects. By integrating geographical data with economic variables, these models can reveal how the concentration of biofuel resources in certain regions affects local economies, labour markets, and the distribution of economic benefits across Europe.

In applying CGE models to the European context for biofuel analysis, several factors are crucial:

- **Market Development and Prices:** CGE models can evaluate how biofuel market development influences energy prices, both directly (through changes in the supply and demand of biofuels) and indirectly (through impacts on related sectors like agriculture and transportation).
- **Employment and Regional Development:** CGE models can assess the potential for job creation, not only in the biofuel sector but also in related industries. This includes direct employment in biofuel production and indirect employment generated through supply chain and income effects.
- **Policy Analysis:** CGE models can simulate the effects of various policy scenarios, such as subsidies for biofuel technology, tariffs on biofuel imports, or sustainability criteria. This helps in understanding the optimal policy mix for promoting biofuels while considering economic, social, and environmental objectives.

5.1.2. Further economic modelling approaches

Dynamic game-theoretic models of industrial organisation and regulation can be gainfully applied to understand the market processes and strategic interaction between incumbent (fossil or first innovating) firms and newcomers (developers or providers of renewable energy, developers of underlying technology) that ultimately govern the widescale adoption or not(!) of novel bioenergy technologies, as well as the research and development into innovation in the first place. Policy makers anticipate the strategic interaction amongst the market participants and intervene to get the market closer to a first-best social welfare outcome. Issues of market capture, strategic entry deterrence, market foreclosure, strategic greenwashing, policy lobbying, and platform shifting, are crucial for the success or failure of an energy transition. These issues, as well as the implications for adequate regulation, cannot be properly addressed within CGE models, which by design have a macroeconomic focus and mostly rely on a perfect competition assumption. They rather require dynamic models of strategic and imperfect competition and dynamic regulation, many of which still require development.

This is crucial for EU policies like the Green Deal Industrial Plan and STEP, where the application of these modelling approaches will help in exploring the issues with regulatory environments, funding access, and investments in, e.g. nascent but critical biofuel technologies.

Models that allow to study of the implications of bioenergy transitions for the distribution of economic outcomes and opportunity and wellbeing (see also Section 6.3): Beyond their macroeconomic impacts, bioenergy transitions have profound ramifications at regional or local levels, as well as at the household/individual level of affected populations. Again, to understand these, more granular models are required, including regional economic approaches and/or models, such as life-cycle and overlapping generations models that help to trace out how individuals and households (a) respond in terms of their behaviours (consumption choices, including the sourcing of bioenergy and/or adoption of household-level technology, labour supply, investment choices, etc) and (b) are affected by the transition in terms of their economic and non-economic outcomes, including ultimately their welfare/wellbeing. By integrating rich socio-economic heterogeneity within and across generations such models also allow an assessment of the distributional consequences.

In terms of supply of biomass feedstock, such granular models could be utilised for designing policies for engagement with farmers, forest owners, and other stakeholders that are important for developing sustainable and resilient biomass supply chains.

Financial economic models allow an understanding of how the development and widespread adoption of innovative bioenergy technologies can be funded. This includes the recognition that such investments are typically subject to high technological and economic uncertainty and, therefore, are of a high-stake and high-risk nature. Furthermore, the environmental externalities they mitigate or cause over time imply dynamic public goods issues (and issues of ownership) that require the intelligent mixing of private and public sources of finance. Finally, regarding the regional, local, and community contexts of bioenergy, models of community finance may be useful (see also Section 6.1.3).

5.1.3. Bioenergy in Europe: societal engagement and governance

Social engagement in bioenergy has emerged in Europe and is identified as a key requirement for the transition from non-renewable to renewable energy. The lack of involvement of social actors in the decision-making process creates a distorted picture of the priorities to be set and limits the possibilities for application and success. It is important to have clear insight into what the social implications of deploying the different bioenergy technologies would be, at various levels. Only by enhancing social acceptance and engagement, will there be better conditions for increasing the market share for bioenergy.

Research shows that social acceptance and engagement of bioenergy concerns are non-static at both country and community levels. Fears, caused by lack of information, knowledge, and environmental concerns on biodiversity and emissions, often lead to conflicts, resistance, and low acceptance of bioenergy projects. The attitude of the local community towards the bioenergy project is more dependent on its specific characteristics than on the functional characteristics of the technology. Studies show that communities were unhappy that they were not consulted before setting decisions for pilot plants. In addition, there was widespread concern about the future viability of the pilot plants. The public tends to be concerned about pollution and odours from the plants, and traffic issues due to truck movement. Another important factor influencing the acceptability and engagement with bioenergy projects is the perception of increased competition for water resources from other needs of the town/city.

The literature shows that governance issues are also critical for social engagement in bioenergy, mostly related to stakeholder participation and the rule of law. In addition, corporate ethics (or business ethics) is shown to be of utmost importance within governance. There is equally societal questioning about the overall status of (national and European) bioenergy governance as it seems to be one of the obstacles to a good level of social engagement and in a broader sense sustainability. To overcome this hindrance, the decision-makers must deal with different regulatory frameworks and try to harmonise them taking into consideration the social factors and perceptions.

To promote and ensure societal engagement and reach social sustainability, it is vital among others, to:

- **Spread information** about bioenergy technologies, resources, and systems, on policy integration, and strategies implementation, with a focus on sustainability.
- **Engage with stakeholders and communities** in all the stages of the bioenergy project; A collaborative approach to decision-making is the best option. Stakeholders expect to be included in truly collaborative planning, interactive communication, public participation, and collective learning processes.
- **Tackle the public perceptions about potential environmental, social, and economic (positive and negative) impacts.** People are generally concerned about water resource scarcity and competition with existing food supply and price. Following food security, labour rights, and working conditions were the most relevant social issues. On the other hand, an increase in local employment tends to favour acceptability.
- **Governance of bioenergy needs to be more transparent** by revealing salient value-related and regulation-related conflicts, by clearly showing the goals as well as the constraints of bioenergy governance, and by keeping the inherent trade-offs in the open.

The path of social sustainability of bioenergy requires a commitment of all stakeholders to ensure that the deployment of bioenergy projects is done in a fair way, which includes not only sound procedural aspects (e.g. widespread community engagement) but also a proper distribution of benefits of the projects that include the communities involved and those most vulnerable. Equally relevant, is finding adequate ways to compensate those who are negatively affected by the bioenergy projects (e.g. due to heavy traffic).

5.2. Environmental sustainability

5.2.1. LCA for bioenergy

Life cycle assessment (LCA) is a holistic method for assessing the environmental sustainability of product systems. Inputs (e.g. energy and raw materials), as well as outputs (e.g. emissions and waste), are accounted for across the whole life cycle of a product system and translated into impacts for a range of environmental impact categories (e.g. global warming, human toxicity, biodiversity, acidification, etc.). Regarding the application of LCA for bioenergy systems, the LCA community has identified some current main limitations:

1. **Lack of "proprietary" industry-relevant data:** access to specific data with detailed mass and energy balances for relevant bioenergy routes is crucial. While obtaining information directly from the industry is highly recommended, LCA practitioners often rely on data from computational simulations and literature. Closer collaboration with the industry is essential for establishing life cycle inventories (LCIs) for the main bioenergy routes, adding credibility to LCA studies.
2. **Lack of clear methodological setpoints:** LCA practitioners often deal with a cascade of processes with co-products and waste streams which require a clear and transparent manner on how these should be handled within the system boundaries, including biorefineries.
3. **Lack of clear up-scaling rules:** when conducting ex-ante LCAs associated with lower TRL technologies, it is necessary to adapt data and methods. Proper upscaling of the product system is required to ensure that environmental assessments reflect commercial-scale conditions, facilitating a meaningful comparison with well-established fossil routes.
4. **Lack of forecast scenarios:** LCAs should also consider the effects of future technological changes in the value chains associated with or supporting bioenergy production (e.g. feedstock production chain, power generation, production of chemicals, transportation. In this sense, prospective LCAs would better reflect the expected reduction in carbon intensity across multiple sectors due to the implementation of climate mitigation policies in the coming years.
5. **Lack of a definition of key environmental impact categories.** Sustainability criteria are often based on carbon footprint, which can be more easily tracked with transparent and open data. However, in an energy transition context, this impact category tends to be near zero, which poses the question of what should be compared within several bioenergy pathways. Moreover, the fate of carbon captured in biomass needs careful consideration. While biogenic carbon emissions are generally not treated as contributing to climate change, their long-term storage and potential for release must be addressed, adding to the complexity of the time dimension. The last limitation will add complexity to sustainability evaluation, nevertheless, it is important to be aware of that aspect.
6. **LCA is an assessment tool considering environmental impacts that can be quantified.** However, bioenergy options can also have environmental impacts that are difficult to quantify and/or not directly quantifiable, e.g. impacts on biodiversity or soil or water quality. Approaches are being explored to include these environmental impacts in LCA. These efforts should be continued and, in the meantime, risks to the environment should be described qualitatively, in addition to the LCA.

7. **The results of an LCA often need additional context for a meaningful interpretation.** Only a comparison with a previously defined target or reference system as a benchmark allows an assessment of the environmental impacts caused. On the one hand, the choice of the benchmark has a major impact on the result. It should therefore be well justified. On the other hand, benchmarks need to be adapted to changing circumstances over time. Further research is needed to develop benchmarking values, especially for new and innovative biobased products.

8. **LCAs are generally case-specific.** This means that an LCA is linked to a specific objective and the results are based on certain methodological assumptions. For this reason, the transferability and generalisability of the results are very limited and should be carefully justified when interpreting the LCA results.

9. **Regionalised LCAs can support the assessment of sustainable biomass potentials,** when considering regionalised data and when they are linked with additional elements such as, for example, remote sensing and balancing of soil organic carbon. The application of LCA for this specific purpose is however still in its early stages and is recommended for regionally focussed research questions.

5.2.2. Sustainability criteria in the revised RED

To accelerate the European Union's clean energy transition, the Renewable Energy Directive (RED) was revised in 2023. The revised directive (REDIII), EU/2023/2413 [2], entered into force on November 20, 2023. EU member states have 18 months to transpose most provisions into national law, with a tighter deadline of July 2024 for permitting related to renewable energy projects. The revised directive sets a binding EU-wide target of at least 42.5% renewable energy by 2030, with an aspirational goal of reaching 45%. The greenhouse gas emissions saving criteria should also gradually apply to existing biomass-based installations to ensure that bioenergy production in all such installations leads to greenhouse gas emission reductions, compared to energy produced from fossil fuels. This reinforces the need for transparency, traceability, and supervision of the supply chains for bioenergy and pinpoints publicly available data in an open, transparent, and user-friendly manner, while also respecting the principles of private and commercially sensitive data protection.

RED III mandates member states to design RES (renewable energy sources) support schemes adhering to the cascading principle. This principle prioritises using biomass for higher-value applications, like materials production, before resorting to bioenergy. Furthermore, it prohibits the use of biomass (organic matter used for energy) from primary forests, highly biodiverse forests, and peatlands for any purpose, including bioenergy production. This expands the protected areas beyond just those with high biodiversity value in 2008, as stipulated in RED II. It also explicitly prohibits the use of stumps and roots from forests for bioenergy production, further protecting forest ecosystems. Moreover, it introduces a requirement for biofuels to be certified by independent bodies to ensure compliance with the revised sustainability criteria.

The stricter sustainability criteria in RED III aim to ensure that bioenergy contributes to the EU's renewable energy goals without compromising environmental sustainability.

However:

- Besides economic, social, and environmental goals, there are multiple further goals, that biomass in its different use options has to fulfill, and these are not assessed in an integrative way. E.g. in the framework of the Green Deal, a secure, efficient, affordable, and diverse energy supply should be ensured. There is a need to assess such contributions in an overall and integrative way, to be able to measure current contributions and monitor them over time.
- There is no "standard" method to measure cascade use (e.g. biomass utilisation factor).

5.2.3. Phasing out of first-generation biofuels worldwide and switching to advanced biofuels based on lignocellulose

Worldwide first-generation biofuels are being implemented for different policy priorities such as import substitution. In many cases, there are doubts about the impacts of these fuels on GHG emissions directly or indirectly and on food security. The EU should set up research collaborations on sustainable production of biofuel feedstocks including the introduction of lignocellulose based advanced biofuels.

5.2.4. Environmental impacts: hydrogen and/or CO_2

Leakage of hydrogen (H_2) and carbon dioxide (CO_2) can occur at various stages of bioenergy production and use, impacting the overall environmental sustainability of the process. Hydrogen and CO_2 leakage can occur during its transportation and storage in compressed gas or liquefied form. Leakage consequence is releasing no usable energy and potentially even contributing to the greenhouse effect.

The increasing interest in the development and deployment of renewable hydrogen as well as infrastructures for the use and sequestration of renewable carbon dioxide, can be associated with leakage effects and losses of both gases, which can be relevant for the assessment of the climate impacts from both systems. Contrary to CO_2, hydrogen is not a direct greenhouse gas. Besides emissions related to the production of hydrogen as an energy carrier, a complete conversion of hydrogen to energy would result only in water vapour. However, incomplete hydrogen combustion, as well as hydrogen emissions from distribution infrastructure and throughout the value chain can potentially cause indirect climate impacts (Bond et al. 2011; Weger et al. 2021). (Derwent et al. 2006 + 2020; IPCC 2007; Schultz et al. 2003). Furthermore, hydrogen emissions can influence O_3 concentrations, leading to additional potential impacts on air pollution and a potential contribution to the depletion of the O_3 layer in the stratosphere (Sand et al. 2020). Thus, LCA and other assessment approaches might be employed to accompany future research and demonstration, as well as commercial activities supporting the development of hydrogen concepts and deployment infrastructures. In this regard, also issues on environmental impacts associated with e.g. water as a resource for electrolytic hydrogen need to be considered.

Appendix

In addition, several other initiatives are also part of Fit for 55:

1. EU's emissions trading system (EU ETS), the EU's carbon market based on a system of cap-and-trade of emission allowances for energy-intensive industries and the power generation sector; a new self-standing emissions trading system is now created for buildings, road transport, and fuels for additional sectors.

2. Social Climate Fund, aiming to address the social and distributional impact of the new emissions trading system for buildings and road transport.

3. Cross-border Adjustment Mechanism (CBAM) aims to ensure, in compliance with international trade rules, that the emissions reduction efforts of the EU are not offset by increasing emissions outside the region. In its transitional phase, CBAM will only apply to imports of cement, iron and steel, aluminum, fertilisers, electricity and hydrogen.

4. Member states emissions reduction targets, which refers to binding annual GHG emissions targets for member states in sectors that are not covered by the EU ETS or the regulation on land use, land use change, and forestry (LULUCF), including road and domestic maritime transport, buildings, agriculture, waste, small industries.

5. Emissions and removals from land use, land use change, and forestry, setting an EU-level target of at least 310 million tons of CO_2 equivalent net removals of greenhouse gases for 2030.

6. CO_2 emission standards for cars and vans, setting an EU-level target of at least 310 million tons of CO_2 equivalent net removals of greenhouse gases for 2030.

7. Reducing Methane emissions in the energy sector, as methane is the second most important greenhouse gas after CO_2.

8. Alternative fuels infrastructure ensures easier access to infrastructure network for recharging and refueling road vehicles and ships with alternative fuels.

9. Energy efficiency in which the revised directive will reduce final energy consumption at the EU level by 11.7% in 2030 compared to projections from 2020.

10. Energy performance of buildings, which will aim at the following:
    - all new buildings should be zero-emission buildings by 2030.
    - existing buildings should be transformed into zero-emission buildings by 2050.

11. Hydrogen and decarbonised gas market package, which proposes revised/new rules to lower the carbon footprint of the gas market with the goals to shift from natural gas to renewable/low-carbon gases and boost their uptake in the EU by 2030 and beyond.

12. Energy taxation, for which a proposal for a revision of the Council directive aims to:
    - align the taxation of energy products and electricity with the EU's policies on energy, environment and climate.
    - preserve and improve the EU internal market.
    - preserve the ability to generate revenues for the budgets of the member states.

13. EU Deforestation-free Regulation (EUDR) is the new EU initiative to limit deforestation caused by forestry and agricultural activities all over the world. This will also impact bioenergy in several ways as biomass used will need to show that it is not derived from deforested areas, but it also will limit expansion of agriculture meaning that maintaining soil productivity and circular use of residues becomes more important. The world will have to make do will less land. Bioenergy plays an important role in making this possible or preferably not obstructing this.

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