EERA BIOENERGY JOINT PROGRAMME

STRATEGIC RESEARCH AND INNOVATION AGENDA 2020

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ABBREVIATIONS

- ABE: Acetone–Butanol–Ethanol.
- APR: Aqueous Phase Reforming.
- BAT: Best Available Techniques.
- BECCS: BioEnergy with Carbon Capture and Storage.
- BECCU: BioEnergy with Carbon Capture and Utilisation.
- Bio-CCS: Biomass with Carbon Capture and Storage.
- Bio-CCU: Biomass with Carbon Capture and Utilisation.
- Bio-CNG: Compressed Natural Biogas.
- Bio-LNG: Liquefied Natural Biogas.
- BTX: Benzene-Toluene-Xylene.
- C-VaR: Conditional Value at Risk.
- CAPEX: Capital Expenditures.
- CBP: Consolidated Bioprocessing.
- CDR: Carbon Dioxide Removal.
- CHCP: Combined Heat, Cooling, and Power production.
- CHP: Combined Heat and Power.
- CIVE: Colour Index of Vegetation Extraction.
- CNG: Compressed Natural Gas.
- CO_2: Carbon Dioxide.
- CSTR: Continuous Stirred-Tank Reactor.
- DM: Dry Biomass.
- DME: 1,2-Dimethoxyethane.
- EE-MRIO: Environmentally Extended Multi-Regional Input-Output Model.
- EERA aisbl: European Energy Research Alliance.
- ERoEI: Energy Returned/Energy Invested.
- EU: European Union.
- FAO: Food and Agricultural Organization of the United Nations.
- FCH: Fuel Cells and Hydrogen.
- FPBO: Fast Pyrolysis Bio-Oil.
- FT-diesel: Fischer-Tropsch diesel.
- GHG: Greenhouse Gas.
- GIS: Geographic Information System.
- HDS: Hydrodesulphurisation.
- HTC: Hydrothermal Carbonisation.
- HTG: Hydrothermal Gasification.
- HTL: Hydrothermal Liquefaction.
- IAM: Integrated Assessment Model.
- IEA: International Energy Agency.
- IED: Industrial Emissions Directive.
- ILUC: Indirect Land Use Change.
- IPCC: Inter Governmental Panel on Climate Change.
- IPCC SR: IPCC Special Report.
- IRR: Internal Rate of Return.
- ISPR: *In situ* Product Recovery.
- JP: Joint Programme.
- KPI: Key Performance Indicator.
- LCA: Life Cycle Analysis.
- LCC: Life Cycle Costing.
- LCI: Life Cycle Inventory.
- LCIA: Life Cycle Impact Assessment.
- LCSA: Life Cycle Sustainability Assessment.
- LNG: Liquefied Natural Gas.
- LUC: Land Use Change.
- MC: Main Challenges.
- NET: Negative Emission Technology.
- NPV: Net Present Value.
- NUE: Nitrogen Use Efficiency.
- OPEX: Operating Expense.
- ORC: Organic Rankine Cycle.
- PEB: Positive Energy Block.
- PEM: Proton Exchange Membrane.
- PSILCA: Product Social Impact Life Cycle Assessment Database.
- RA: Research Area.
- RED: Renewable Energy Directive.
- RES: Renewable Energy Sources.
- RDF: Refuse Derived Fuel.
- RHC: Renewable Heating and Cooling.
- ROI: Return on investment.
- RP: Research Priority.
- RT: Research Theme.
- R&D&I: Research, Development and Innovation.
- SDG's: Sustainable Development Goals.
- SFM: Sustainable Forest Management.
- SET-Plan: Strategic Energy Technology Plan.
- SLCA: Social Life Cycle Assessment.
- SOC: Soil Organic Carbon.
- SOFC: Solid Oxide Fuel Cell.
- SPs: Subprogrammes.
- SRF: Solid Recovered Fuel.
- SRIA: Strategic Research and Innovation Agenda.
- TEA: Techno-Economic Analysis.
- TRL: Technology Readiness Level.
- UN: United Nations.
- WUE: Waste Use Efficiency.
- ZEB: Zero Emissions Building.

EXECUTIVE SUMMARY

This document describes the Strategic Research and Innovation Agenda (SRIA) of the Joint Programme on Bioenergy (JP) within the framework of the European Energy Research Alliance (EERA aisbl), and the structure of the JP adopted to address the SRIA priorities.

The SRIA represents the consensus of EERA Bioenergy JP participants of a global view to address the challenges of these Energy & Environment policies from a research and innovation perspective, with the overall objective to accelerate the SET-Plan priorities and actions in order to contribute to decarbonise the energy sector, an issue where bioenergy is an essential component of a future low-carbon technologies basket in all climate-change mitigation scenarios. In this context, the challenges identified in the SET-Plan Energy Integrated Roadmap[1], the SET-Plan – Declaration of Intent on "Strategic Targets for Bioenergy and Renewable Fuels needed for Sustainable Transport Solutions in the context of an Initiative for Global Leadership in Bioenergy" (SET-Plan DoI), for 2020 and 2030, published by the EC in 2016[2], have been addressed. The SRIA priorities and key performance indicators (KPIs) on biomass conversion technologies are aligned with those identified in the SET-Plan-Priority Action 8 (Bioenergy and Renewable fuels) Implementation Plan (2018)[3], where EERA Bioenergy JP has got involved with the Temporary Working Group in charge of drafting it. Moreover, research recommendations contained in the ETIP Bioenergy SRIA[4], as well as different inputs obtained from international stakeholders and common research priorities agreed upon in other EERA Joint Programmes, have also been considered in preparing the JP SRIA (2020).

Even though the SRIA implementation is in principle planned for the 2019-2020 period, it also gives a perspective of the challenges and priorities out to 2030 and beyond.

Several important principles, key facts and assumptions, with the concept of integration at the top, have inspired the criteria and decisions used in defining the SRIA.

Some of the most relevant:

- The determination and development of sustainable biomass feedstock availability is of capital importance for bioenergy to comply with the increasing demand in the context of a decarbonised energy scenario. The sustainable feedstock must be developed within the broader framework of bioeconomy and circular economy concepts, where bioenergy is an essential part and may play a fundamental role in its deployment. Exploring and developing the potential of still underused or even unused biomass resources are also important aspects to satisfy the increasing future biomass demand.

- In order to assure the sustainability of bioenergy systems, the development of biomass demand must be made in the context of biomass value chains that take into account conversion technology rates in terms of costs, efficiency, carbon balance and feedstock quality, and annual conversion plant demands, rather than making it in a separate stage to conversion in ill-defined integrated application contexts.

- Innovation must play an essential role for bioenergy technologies to meet the highest levels of efficiency and low carbon use while reducing the costs of biofuel production. Working on low TRL bioenergy solutions is capital for the sustainable bioenergy technologies of the future. This approach is an essential part of the research topics in this SRIA.

- Process and system integration approaches offer massive opportunities to increase efficiency and reduce the costs of biofuel production. This approach is also stressed in this SRIA and contributes to achieving a higher integration level of the activities inside and among the JP Subprogrammes.

- Of note in the context of the increasing role of RES to satisfy energy demands is the research to develop the synergies that bioenergy, as a dispatchable resource, may have with other discontinuous RES to increase the efficiency and quality of the energy provided by individual hybrid installations, making the deployment of RES more viable, as well as the production of renewable fuels.

- As in the case of the feedstock, bioeconomy offers many opportunities for integrating bioenergy technologies within the biorefinery production models in order to increase the efficiency, sustainability and viability of the full systems.

- Sustainability and economic competitiveness are two key issues for achieving the social acceptance of bioenergy and biofuels.

[1]SET-Plan Energy Integrated Roadmap(2014).https://setis.ec.europa.eu/system/files/Towards%20an%20Integrated%20Roadmap_0.pdf
[2]SET-Plan DoI (2015).C(2015) 6317 final. Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation
[3]SET-Plan DoI-Action 8 (Bioenergy and Renewable Fuels) Implementation Plan (2018).https://setis.ec.europa.eu/system/files/setplan_bioenergy_implementationplan.pdf
[4]ETIP Bioenergy SRIA (2015).http://www.etipbioenergy.eu/images/EBTP-SRIA-2016.pdf

As envisaged in the previous JP Document of Work for the 2015-2017 period, this SRIA reaffirms the importance that the interest of the bioenergy industrial sector, the national research priorities and the international cooperation on bioenergy are present in its implementation. The alignment and cooperation with other related EERA aisbl Joint Programmes and external research institutions and industries are also key aspects for successfully implementing the SRIA. The promotion of these aspects will be tackled through specific actions that will stress the efforts already initiated in the JP in recent years.

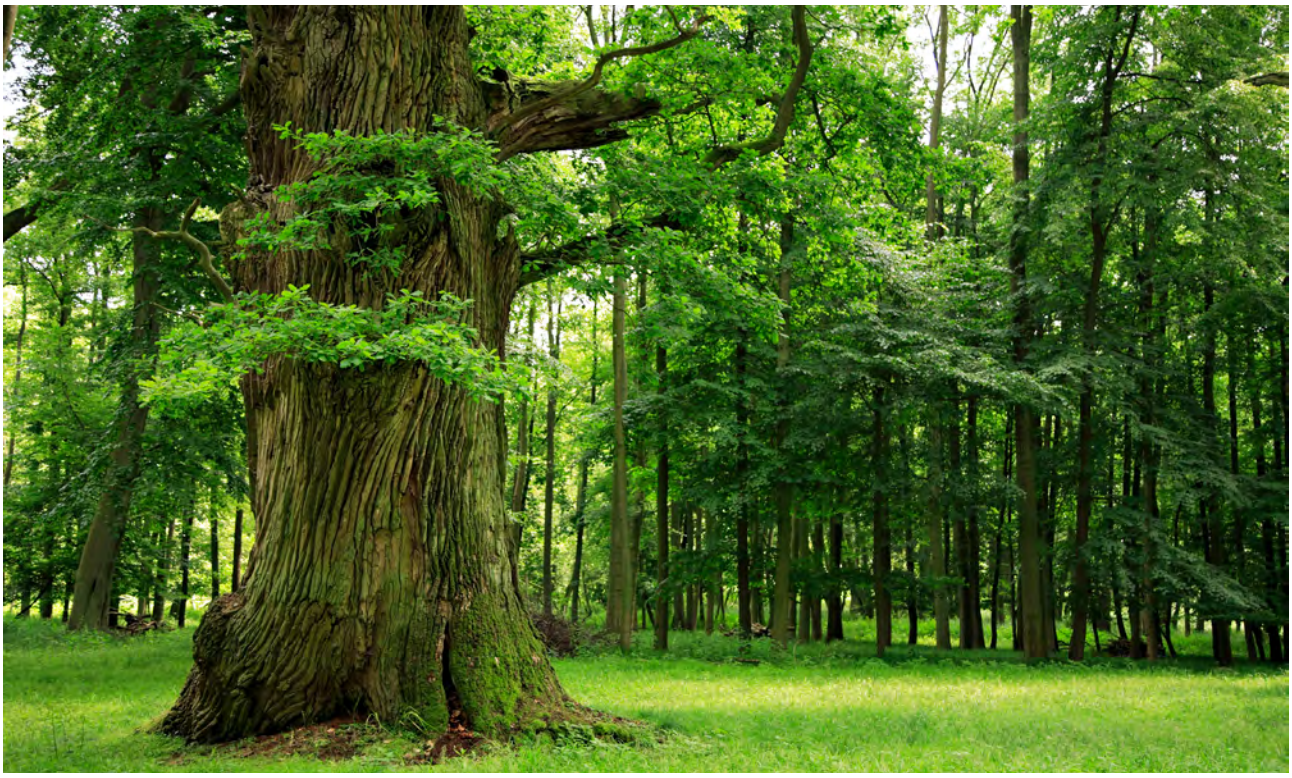
Based on the challenges to address and the research areas identified in the SRIA, the JP has been structured into five Subprogrammes:

- Subprogramme 1 (SP1) - Sustainable production of biomass, contains the R&I.
- Subprogramme 2 (SP2) - Thermochemical processing of biomass into advanced biofuels and bio-based products.
- Subprogramme 3 (SP3) - Biochemical processing of biomass into advanced biofuels and bio-based products.
- Subprogramme 4 (SP4) - Stationary bioenergy.
- Subprogramme 5 (SP5) - Sustainability/Techno-economic analysis/Public acceptance.

While developing the SRIA, the aims of the JP are the following:

- ALIGN research activities at JP institutes to give a technical-scientific basis to further development of advanced bioenergy routes and to promote the possibilities for joint technology development, in order to help accelerate the objectives of the SET-Plan.
- ALIGN research priorities and activities at EERA JP Bioenergy institutions with other external stakeholders, while also promoting international co-operation. Particular attention will be placed on the alignment with the ETIP Bioenergy.
- ASSESS R&I priorities to accelerate the implementation of Bioenergy in Europe.
- BE A PROMINENT ACTOR in the development of R&D&I in Bioenergy to accelerate the SET-Plan objectives.

The challenges, research areas with research priorities and topics of each Subprogramme are described below.



Subprogramme I. Sustainable biomass production

In Subprogramme I on sustainable biomass production, the research focus is on maximizing biomass resources for conversion plants, with the security and flexibility of supply, biomass quality, environmental sustainability, and reducing the costs of biomass feedstocks as the main challenges to be addressed. Four kinds of biomass are considered in this Subprogramme: forest biomass, agricultural biomass, algae biomass, biogenic waste biomass. In addition to yielding sensible improvements in public acceptance and in the security of a long-term sustainable supply of biomass conversion plants, the research proposed in this Subprogramme is expected to contribute, in conjunction with other Subprogrammes, to at least a 30% increase in conversion efficiency, along with a simultaneous reduction in production costs for advanced biofuels and renewable fuels by 2030 compared to current levels.

For forest biomass, in the long term, the development of new, fast-growing tree species suited to specific pedo-climatic conditions through selection and genetic improvement is a key research issue for maximizing biomass production based on the quality needed, while also increasing production efficiency and forest resilience towards climatic accidents. The short-term goals include improving harvesting and transportation technologies and developing efficient machinery, and optimised business concepts for forest harvesting operations that can be applied on many forest species. Other important research topics are the development of new management practices with low environmental impacts and assessment tools to reduce the vulnerability of the forest stands and improve the profitability of forest biomass, along with the development of multicriteria assessment tools and methods for forest biomass. The involvement of stakeholders in sustainable forest biomass production practices could be promoted by searching for the appropriate incentives for carbon sequestration and for decision support tools for integrated forest management.

Another research priority that will significantly help to increase and optimise the production and use of forest biomass is the development of models to be used as decision support tools to organise the forest biomass market, allowing forest owners to identify best management practices to improve the financial profitability of forest biomass resources. These will include tools for analysing factors that affect the supply and demand under short- and long-term perspectives. Models for accurately predicting the availability of sustainable resources and new forest harvesting models that integrate aspects like smart organisation, infrastructure and regulatory framework are relevant examples of activities within this key research topic. Moreover, models to find and determine the impact of globalisation on the sustainable mobilisation of forest biomass in Europe have to be developed.

In addition, promoting the forest biomass market also requires changing the behaviour of the actors involved. This essential issue is addressed in a research priority concretised in topics like the analysis of case studies across European forestry systems to identify the failure and success factors that stimulate or limit the sustainable mobilisation of forest biomass, and the identification of measures to adapt incentives and regulations to the profile of European stakeholders.

Another important biomass resource is the agricultural biomass feedstock. This resource includes the biomass obtained from dedicated crops (annual and perennial), primary by-products from food crops, and solid or semisolid waste streams from secondary biomass processing (rice husk, sugar cane bagasse, molasses, etc.). To optimise the sustainable use of agricultural resources, efforts must be directed towards increasing the economic competitiveness of producing biomass with a reduced environmental impact and without competing with food production. In this context, the first area of research seeks to improve our knowledge of the various types of biomass. The following relevant research priorities have been identified:

a) Increasing our knowledge of food crops and residues utilisation to reduce the environmental impact of biofuel production (soil carbon, alternative combined uses), including maximizing use of residues and by-products.

b) Increasing our knowledge of the optimised use of dedicated lignocellulosic crops by defining appropriate agricultural management solutions for each of them.

c) Increasing our knowledge of the use of legume crops in order to reduce the needs for nitrogen fertilisers.

d) Designing and optimizing innovative systems to intensify agricultural production: agroforestry, combining food and lignocellulosic crops, and intercropping and mixed cropping systems are good examples to be developed.

For agricultural biomass feedstocks, a second research priority concerns the optimisation of feedstock supply systems and logistics chains to maximise the net energy produced in relation to land used and to make the procurement costs more competitive. To address these issues, some relevant research topics are identified: improvements in crop photosynthesis to increase the current very low yield of this process; the co-design of suitable plant characteristics, combining productivity with other characteristics to reduce the costs (e.g. resistance to pests and adverse climatic conditions) and environmental impact of biomass production (e.g. high water and nitrogen use efficiencies, production of favourable soil carbon balance); the development of models for bioenergy cropping systems, including in marginal lands; the exploration of new biomass resources like shrubs, which are colonizing abandoned agricultural and livestock lands and forest fired areas and whose utilisation could help to broaden the potential for biomass resources while reducing environmental risks like forest wildfires. The optimisation of supply chains and logistics (e.g. development of logistics optimisation models, use of less contaminant logistics machinery, increased efficiency of transport and storage, biomass pre-treatment to reduce the specific logistics costs, etc.) are some other relevant research topics in this area.

Another research priority for developing sustainable agricultural biomass resources is an evaluation of the impacts of biomass agricultural production systems on the environment and the certification schemes and public policy frameworks. The method chosen to determine these impacts was a Life Cycle Analysis (LCA) of whole value chains of bioenergy production, and not only of supply chains, which allow us to assess the most appropriate feedstocks for a specific conversion route, as well as the best supply mix options. The development of tools for evaluating other effects of the new bioenergy crops on agricultural landscapes and agroecosystems different to basic ones (GHG, water use, carbon stock), by including other factors like biodiversity and other local impacts, is key to having a complete understanding of the environmental effects of implementing the new crops. Coupling models to identify low iIUC solutions is essential to deriving future high eco-systemic service solutions.

A third research area for developing the potential of biomass resources is boosting the biomass yield from algae, both microalgae and seaweed (macroalgae).

Some important potential advantages of this type of biomass can be identified, and include: much higher specific energy production surface compared to terrestrial crops; the absence of polymers such us lignin, which facilitates the conversion processes; and the possibility to produce it in dedicated installations under controlled conditions, particularly in the case of microalgae, which may have positive effects on maximizing biomass yield and allows the use of industrial CO_2 flows. Moreover, algal biomass contains a large variety of molecules that can be extracted as valuable food and non-food bio-based products, as well mineral content that can be used to close the mineral fertiliser cycle. However, the competitive production and use of algal biomass imposes significant constraints, namely the scaling-up of production technologies, very high production costs and rates far below ERoEI (energy returned/energy invested).

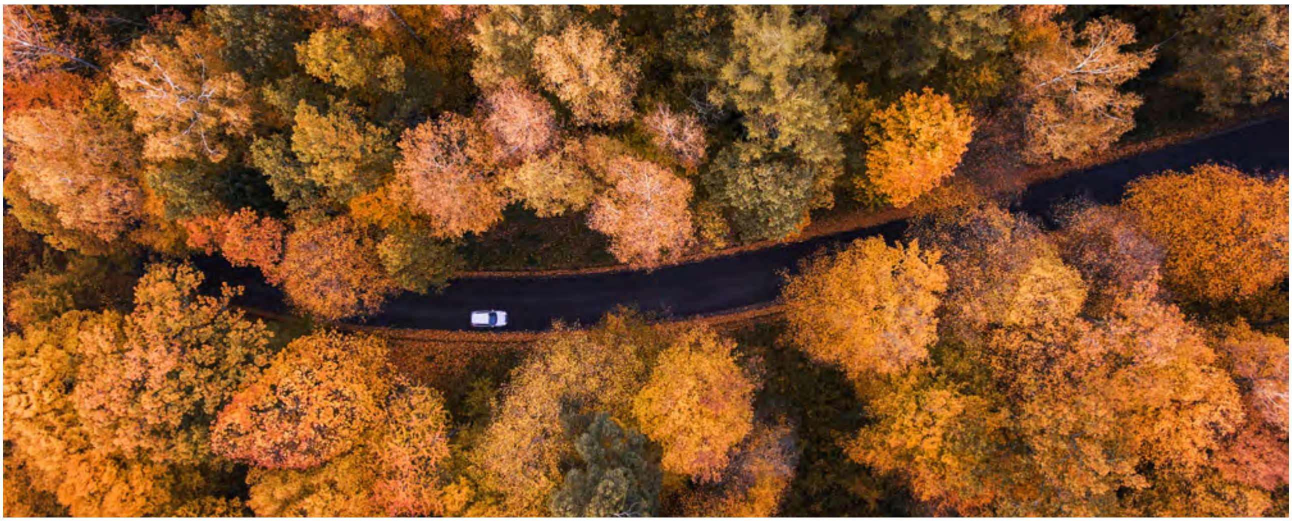
The research priorities and topics for improving the energy efficiency, environmental sustainability and economic competitiveness of algal biomass to produce biofuels involve:

a) The selection and genetic improvement of algal strains towards different characteristics that can have a positive impact on the overall efficiency of the production process, as well as on harvesting or end-product extraction, the productivity in final products and resistance to pollution.

b) Innovation in lighting systems and harvesting processes for microalgae, in order to reduce harvesting energy and costs and to optimise the light radiation distribution in the photobioreactors.

c) The development of innovative methods for macroalgae cultivation and harvesting: predictive models for seaweed quality and best time for harvesting, development of automated systems for harvesting and of simple, effective and fast stabilisation techniques for long-term storage prior to use.

d) The development of systems integration, by co-recovery of biofuel production with the extraction and marketing of valuable by-products (e.g. pigments, proteins, antioxidants, etc.).



Biogenic waste is not directly produced purposefully as an energy source. However, it is another important source of biomass. Biogenic waste is made up of urban waste, agro-industrial waste, livestock effluents, green waste, invasive plants, and other sources. The management and use of these materials shape the fourth research area of Subprogramme 1.

Biogenic waste can be used: a) by thermochemical and biochemical conversion routes that transform low-water-content waste to produce heat and/or electricity, or syngas, which is an intermediate carrier to advanced biofuels or chemicals production, and b) anaerobic digestion, which utilises waste with a high humidity content, in excess of 60%, to produce biogas. Anaerobic digestion leads to the production of biogas, which is a gas mixture with methane and CO_2 as its main components, and a liquid fraction called digestate, which is rich in organic matter and soluble nutrients for plants. Biogas can be used for combustion directly or be purified to separate the methane fraction. The bio-methane can be used as a gaseous biofuel for heat and/or electricity production, it can be injected in natural gas networks or used as an intermediate energy carrier to produce bio-hydrogen. Bio-hydrogen can also be produced in the first stage (hydrolysis + acidogenesis) of the two-stage anaerobic digestion process. Bio-methane and bio-hydrogen can be used in a mixture (5-20% hydrogen) to improve the combustion properties of methane. That mixture is called "Biohythane". The CO_2 fraction of biogas after purification can also be combined with hydrogen obtained from surplus electricity from intermittent renewable sources to produce renewable methane. Bio-waste recovery technologies are discussed in more detail in Subprogrammes 2, 3 and 4.

The recovery of biomass from waste follows four main models that result from combining two parameters: management of supply and quality specification requirements (local waste or optimised composition), and the complexity of the recovery (single or multiple final products).

Research priorities can be identified for the different stages of waste value chains: feedstock mobilisation, conversion processes and the recovery and use of co-products (digestates, ashes, etc.). They have two basic objectives: to condition the waste to avoid health risks and/or according to the specifications of the conversion technologies and the final products, and to increase the transformation yield.

Waste feedstock mobilisation is an important research priority. Relevant research needs are identified to define optimised collection and storage methods to enable the most regular and secure supply. Technologies for efficiently removing unused fractions, for destroying pathogenic microorganisms and for waste pre-treatment prior to conversion into energy, are important research topics in this area. Research priorities for improving the economic viability and sustainability of waste recovery technologies involve topics on conversion process integration, expanded uses of waste feedstock, including the co-production of bio-based products, the development of digital tool technologies for the predictive control of anaerobic digestion based on waste quality, and the acquisition of knowledge on the environmental effects of the use of digestates and other waste-derived biofertilizers on soil. Social and market acceptance of waste technologies are also essential research priorities that need to be addressed. The analysis of economic risks and new business models, as well as of sociological obstacles and levers for implementation of waste conversion technologies, are also important research topics.

Subprogramme 2. Thermochemical processing of biomass into advanced biofuels and bio-based products

In this Subprogramme, research needs to increase the efficiency, sustainability (lower GHG emissions) and cost-competitive production of advanced biofuels and bioenergy carriers from biomass through thermochemical processing are addressed. Research areas are identified for the development of primary thermochemical conversion processes, downstream processing and advanced biofuel and intermediate carrier value chains. KPIs are defined with a horizon of 2030 compared to 2020 levels for both advanced biofuels and intermediate bioenergy carriers in terms of enhanced net process efficiency, GHG savings and costs reduction.

In light of the challenges and KPIs identified, the principles guiding the research are:

a) Process simplification and integration in order to reduce the CAPEX and OPEX and increase conversion plant availability and reliability.

b) Increase the feedstock flexibility (e.g. use of low-quality and cost feedstocks, such as waste or high- and low-grade biomasses) and consider new biomass sources (e.g. algal biomass).

c) Maximise the efficient use of resources, which may involve the combined use of biomass processing products with other sources (e.g. renewable hydrogen) or the obtaining biofuels with bio-based products.

d) Create negative GHG emissions by developing alternatives like combining bioenergy with carbon capture and storage (bio-CCS) and the co-production of biochar.

Gasification, torrefaction, hydrothermal processing and pyrolysis are the primary thermochemical biomass conversion processes that shape the research priorities in this Subprogramme 2. Gasification is the most mature thermochemical process for biomass, although only simple technologies for heat and electricity production have reached the commercial stage, albeit with reduced implementation. Pyrolysis and torrefaction have been demonstrated for intermediate carrier production and have reached first market implementation, while hydrothermal processing technologies (carbonisation-HTC, liquefaction-HTL and gasification-HTG) are still being studied in the laboratory and in pilot and demonstration plants.

Gasification converts biomass into gaseous intermediates: syngas and product gas. While product gas is used for heat and electricity production, syngas is the raw material for synthesizing several gaseous energy carriers (hydrogen, methane) and liquid (methanol, DME…) fuels, as well as other chemicals and bio-products. The processes for advanced biofuel production through biomass gasification have not yet been commercially implemented: significant cost reductions and increased reliability are required. To achieve these objectives, important research topics are identified:

a) Increase feedstock flexibility by utilizing low-cost materials like high-content and low-temperature ash melting biomasses, bio-wastes, biochemical biomass processing by-products, etc.

b) Improve gasifier performance, including development of feedstock pre-treatment, monitoring of properties and improved and flexible feeding systems, and implement alternative gasifier designs or use additives or feedstock blends to reduce the negative effects of ash slagging and sintering.

c) Optimise product gas composition for downstream processing (development of catalysts, use of different agent mixtures, determine proper process conditions, etc.) and maximise biomass carbon utilisation/recovery. This action requires researching the production of methane by combining CO_2 flows from gasification with hydrogen from intermittent renewable electricity sources.

d) Develop innovative gasification processes that can overcome the existing barriers for the technology, like molten bed gasification, reforming gasification and thermal and cold plasma gasification.

The pyrolysis of biomass is, along with gasification, another research priority in Subprogramme 2. Depending on the processing time, we can distinguish between fast and slow pyrolysis. The former yields liquid bio-oils as its main product, while the latter produces charcoal as its main output. The pyrolytic oil can be upgraded to different types of liquid fuels by a few processing routes, or it can be directly used as heating oil. Commercial plants are in operation with these technologies.

Analogously to the gasification case, improving process performance (e.g. standardisation of some relevant properties of bioenergy carriers, biomass comminution processes to be used in flash pyrolysis) and increasing feedstock flexibility, along with developing new models to better understand the mechanistic of the process, are key research topics to reduce costs, improve the efficiency of the production process and also the quality of the bio-oils, which, moreover, facilitates its downstream processing.

Torrefaction technology and related steam treatment and steam explosion technology concepts have been demonstrated and the first full-scale commercial plants built, but the commercial implementation still needs further work in order to make the technologies more competitive and tune them to new product applications, instead of the initially targeted co-firing coal-fired power plants, or as pre-treatments (for the last two treatments) in advanced biofuel production processes. Improving the quality of the final product (e.g. torrefied pellets), including the development of safety protocols and standards for specific product quality while reducing the energy and investment costs, increasing the flexibility of the feedstock quality, and developing new, high added value products (e.g. from the hemicellulose fraction which is volatilised/hydrolysed during the heat/steam treatment processes) are relevant research topics for improving the viability of these technologies.

As mentioned before, the hydrothermal processing of biomass, another research priority in biomass thermochemical processing, involves several water treatment thermochemical processes that yield a diversity of final solid, liquid and gaseous products: biochar, intermediate biofuels (bio-crudes), gaseous energy carriers (e.g. methane, hydrogen, etc.), as well as other chemicals. Significant process and technological barriers still exist for scaling up these processes, and a significant research effort is needed to optimise the production costs, environmental process performance and yields, and to improve equipment design. Therefore, research topics to improve our understanding of the basic mechanics of the process, to include the application of catalysts, the optimisation of the reactor and process concepts, including a better understanding of reaction kinetics, and to develop common and standardized analytical methods and report process data are essential for advancing these technologies towards implementation.

In addition to thermochemical process development, the processing of downstream products is the second research area identified to address the objectives of this Subprogramme 2. Product cleaning, conditioning and upgrading are downstream processes.

The optimisation of gas cleaning processes to obtain products of a given quality must be usually done by following holistic and integrated approaches that combine different processes for scaling-up and for increasing efficiency while reducing the processing costs. Moreover, improved sample measurement and control techniques are, along with the two other areas, an essential research topic that addresses the research priority on gas cleaning.

Further steps in gas cleaning to produce quality biofuels, eventually with co-production of bio-based chemicals from gas cleaning products, are the clean gas conditioning and up-grading. For biofuel production, these steps are essentially carried out utilizing ad-hoc catalytic processing and separation technology. Tuning existing fossil fuel (coal) technologies for conditioning clean biomass gas, including the development of improved catalysts, sorbent and/or membrane formulations that are more tolerant to biomass-derived contaminants in the product gas, along with improving catalyst/sorbent regeneration procedures and spent catalyst/sorbent recycling methods and developing strategies for separating products, are all key research topics to improve the feasibility and competitiveness of the processes. In the last activity, innovative strategies for product gas conditioning and upgrading, in addition to those integrated in to existing petrol refinery capabilities, should also be developed in order to avoid the regulatory complexity of integration.

Biocrude fraction of pyrolysis and HTL process conditioning and upgrading is another research priority within the area of conditioning and upgrading biomass thermochemical processes. A biocrude conditioning process is necessary to allow longer term storage and use as drop-in fuel in refineries or be upgraded directly into advanced biofuels. Biocrude conditioning mostly involves removing ash to avoid undesired polymerisation of the components and using the pyrolytic liquid fraction to improve the energy efficiency of the overall process. The conditioned biocrude can be upgraded by catalytic hydrogenation at high pressure, which notably increases the stability and heating value of the final product. Developing catalysts that are optimised for that process is an important research topic. As far as hydrotreating is concerned, there is a need to develop non-sulfided catalyst, as well as catalysts not only for deoxygenation, but that can remove the nitrogen contained in biomasses, particularly from high-nitrogen content biomasses like manure and algae. A final research topic in this priority is the development of treatments and uses for aqueous effluents, including by-product recovery. Anaerobic digestion and catalytic hydrothermal gasification are two routes to explore to convert the organic compounds contained in the effluents into combustible gases.

As in the case of gas and biocrude fractions, the solid fraction (biochar) that results as the main product or by-product of the thermochemical biomass conversion processes, needs conditioning and upgrading stages before use, which can vary depending on the application. For energy use, pelletisation or briquetting are the most frequent processes that must be optimised in order to increase the density of the final product, reduce the logistical costs and improve performance in combustion devices. In many non-energy uses an activation process is also required. When charcoal is the main process product (e.g. torrefaction), and as far as possible when it is a by-product as well, the production process should be tuned to optimise biochar properties, thus minimizing the requirements for further upgrading. Standardizing the analyses for characterizing biochar, and specific unconventional characteristics, like hydrophobicity, is crucial to facilitating the development of the various applications.

In order to arrive at a high efficiency, cost effective processes for converting biomass into advanced biofuels and intermediate bioenergy carriers with high GHG savings, a key issue is to combine the individual unit operations into a smart system design and, beyond that, a smart overall biomass-to-by-products value chain design. Integrating the process heat system with other industrial activity or industrial symbiosis, process simplification and integration (e.g. combining thermochemical and biochemical based processing) and maximizing internal recycling of the waste streams are some relevant options to be developed to improve the performance of the processes. On the product side, smart co-production schemes that combine energy with bio-based products and the utilisation of surplus H_2 and CO_2 flows are among the options that will also contribute to the desired overall sustainability of the processes. The technical assessment and further development of these various options requires testing and demonstration, supported by R&D&I that is identified in a specific research area in this Subprogramme.

One first priority within this research area concerns the gasification-based production of advanced biofuels. In light of the large number of possible biomass feedstocks and final biofuels, there is no single ideal concept for system or value chain design, but rather a number of options that may find their way into the market place. Three main research topics in this area are:

a) Optimising the gasification-based biofuel production systems (process heat integration, recycling of waste streams, process simplification and intensification, etc.).

b) Developing concepts for producing chemicals/materials to boost biofuels business cases (e.g. partial use of main syngas components to produce higher value bio-based products, use of charcoal as soil fertiliser, etc.).

c) Developing integrated gasification-based biofuel production with renewable hydrogen and/or bio-CCS or bio-CCU options, in order to make use of surplus gas flows and reduce the GHG emitted by the process.

Another research priority is identified to improve the performance of bio-oil and advanced, pyrolysis-based, biofuel processes. Commercially operated pyrolysis plants today are integrated into local or regional networks, which is an excellent way to push new technology into the market, but the maturity of the technology needs to be improved. In the short to medium term, co-refining with fossil fuels may empower the implementation of fast pyrolysis technology beyond today's main use as heating oil. Overall system optimisation, developing technologies with higher flexibility for feedstock and plants with more proven long-term operability, developing process integration options, including aspects like catalyst regeneration, hydrogen recycling, etc., developing options for the combined co-production of biofuels with chemicals, and optimizing integration aspects in the processes are aspects that need significant R&D&I efforts and that are addressed in this research priority.

In addition to the aforementioned R&D&I needed to optimise heat/stream treatment and coupled densification of the products of torrefaction and related steam and steam explosion treatments, one research priority to make these processes more competitive from the energy and economic points of view, and more environmentally friendly, is identified as involving further process optimisation, considering not only the system but the value chain level as well, and for better tuning the production recipes of the bioenergy carriers with their specific applications (e.g. to use them in thermochemical or biochemical processes.) Integrating the overall bioenergy carrier production process with other industrial processing with surplus heat may also be considered as a relevant research topic.

One last research priority to increase the performance of thermochemical processing for advanced biofuels and the production of intermediate bioenergy carriers is dealing with the hydrothermal processing that still needs to make its way into demonstration and commercial scales for applications other than pre-treatment stages to biochemical processes. Important key topics in this area are the development of smart system designs with integrated non-energy co-products (e.g. recovery of plant nutrients from the aqueous phase, integrated hydrogen recovery for upgrading processes, conversion of aqueous phase compounds into chemicals, etc.), and optimising the system design through integration. The design of process schemes and layouts that optimise the value created by smart grid integration, and the identification and evaluation of high efficiency biofuel/biochemical production, including schemes that utilise or sequester the CO_2 produced in the combined process, are two key topics in this research priority.

Subprogramme 3. Biochemical processing of biomass into advanced biofuels and bio-based products

The scope of this research Subprogramme 3 are the biochemical and chemical processes and technologies for producing advanced biofuels, including jet fuels, and the eventual co-production of other bio-based products in biorefinery approaches from all fractions of lignocellulosic biomasses, and including the biogas from anaerobic digestion, the syngas obtained from thermochemical biomass and bio-waste processing, and the hydrogen from biological and renewable origin.

Needs for technological improvements and novel developments and concepts, principally in the field of (bio)catalysis, along with novel conversion route concepts are identified along the overall conversion routes, from the biomass pre-treatment stage to the recovery of side process streams and integration of bio-processing technologies into biorefinery schemes.

The development of improved technologies for feedstock pre-treatment and the conversion processes, including new or improved process catalysts to enhance the biological efficiency and product yields from the conversion of carbon compounds and hydrogen into advanced biofuels, along with an increase in the efficiency of RES-hybrid systems for producing intermediary energy carriers (hydrogen, biogas) and advanced liquid biofuels by integrating biochemical processing, are emphasised as essential R&D&I challenges to increase reliability and energy efficiency, and to reduce the conversion costs as well as the environmental impact of advanced biofuel production under commercial-scale conditions through biochemical processing. Among others, two relevant KPIs derived from the research proposed in this Subprogramme are an increase in the net efficiency of biomass conversion into advanced biofuels and intermediate energy carriers of at least 30% and 75%, respectively, by 2030 compared to present levels, and a significant reduction in the production costs of advanced gaseous and liquid biofuels, reaching below 35€/MWh in 2030 with a cost reduction of at least 30% compared to 2020 levels.

To address the challenges identified, three main research areas are identified, namely:

a) Cell factories and enzymes.

b) Increasing the efficiency of microbial and algal biochemical pathways.

c) Developing novel microbes and pathways to biochemically convert biomass into advanced biofuels and bio-based products.

The cell factories and enzymes area involve improving the robustness and efficiency and reducing the costs of the technologies and enzymes that constitute the enzyme cocktails used in biochemical biomass processing, as well as developing novel ones capable of better performance and/or catalysing new, disruptive processes. The main goals with the new/optimised enzymes are to increase the efficiency and reduce the costs of enzyme production, and therefore of the whole conversion process, since the enzymes are generally one, if not the main, component of the cost structure in biochemical conversion processes. In this context, the production of enzymes that are more stable and more robust to toxic components and to variations in media conditions, and/or that have improved catalytic efficiency and/or new, more favourable characteristics, like thermotolerance or increased efficiency of lignin and hemicellulose deconstruction, are relevant key topics to achieving the objectives of this research area.

A second research priority concerns the development of strategies to deregulate the metabolism of the microbial cells that intervene in the conversion processes, tuning it with appropriate metabolic pathways to increase the efficiency of existing biochemical pathways and algal cell factories. Several research topics are identified to address this issue:

a) Genetically engineering suitable microbial strains with uncoupled growth and fermentation to achieve maximal fermentation activity in non-growing cells.

b) Developing microbial strains with increased activity in accessory metabolic pathways, leading to an increased yield of the desired final products.

c) Engineering microbial strains with improved characteristics for syngas conversion, including more resistance to toxic compounds present in syngas, are examples of important research topics to address in this research priority.

Finally, developing the role of microorganisms and/or enzymes in the context of the so-called "microbial cells", "artificial leaves" and "artificial photosynthesis" systems is a long-term essential research theme to turn this alternative into a reality, one that will probably play a role in the context of the future RES energy mix beyond 2030.

Converting lignocellulosic biomass into advanced biofuels and bio-based products requires a significant effort to reduce the number of operations involved in current processes, including downstream processing. This is tackled by the so-called Consolidated Bioprocessing (CBP), which has very positive effects on the CAPEX and OPEX of biorefineries, thus increasing the economic competitiveness of biofuel production. The main challenge of this third research priority within the Cell Factories and Enzymes Area is to induce mixed cultures or engineered microbial strains to express a larger number of the enzymes involved in advanced biofuel conversion processes as an alternative to reducing the number of operations and/or increasing the conversion efficiency. Engineering selected bacterial strains to express the whole range of hydrolytic enzymes involved in fermenting lignocellulose to biofuels, and non-conventional yeasts to increase the carbon conversion efficiency of the production of long-chain fatty acids for diesel and jet-fuel substitutes, are examples of relevant research topics to be developed within this priority.

Another essential research priority involves improving the current technologies and developing new ones for feedstock preparation, deconstruction and fractionation. This challenge deals with the development of flexible and milder feedstock pre-treatment methods while reducing or avoiding the associated use of exogenous enzymes needed in current methods, like steam explosion, hydrothermal or organosolv processing.

The development of solid materials for syngas and biogas cleaning and up-grading is another essential research priority in order to improve the feasibility of recovering these bioenergy intermediates. Examples of developments required are the use of catalytic membranes to isolate the methane fractions from other fractions of biogas, or the development of zeolites or novel solid absorbents to remove the hydrocarbons and SH_2 contained in biogas and obtain bio-methane. Particular attention must also be paid to improving the current methods and developing novel ones for algae fractionation in the context of a cascade approach, with an emphasis not only on efficiently separating the multiple fractions obtained from that biomass in a biorefinery but on preserving the properties of the high-value, bio-based products obtained. Examples of novel mild extraction technologies are supercritical fluids, ultrasound and microwave assisted extractions and pressurised extraction.

The biomass biochemical (chemical) conversion stage is, as the pre-treatment stage, also subject to improvements. A first research priority in this research area involves increasing the current efficiency of bio-processing for ethanol, higher alcohols, fatty acids, hydrocarbons and hydrogen. Relevant research topics on this issue are the development of more robust yeasts and bacteria which are more performant to ferment lignocellulose hydrolysates, with higher resistance to inhibitory compounds present in lignocellulose hydrolysates, and cell factories with the capacity to, through genetic engineering, transform inhibitory fermentation products formed in those media into bio-based products (e.g. *Clostridium* engineered strains transforming butanol into non-toxic ethers or esters). This research can be combined with process intensification strategies to enhance the energy efficiency and lower the conversion process costs. Such is the case of increasing the initial fermenting sugar concentration in the fermentation media by using a higher ratio of solids in the pre-treatment stage in order to achieve a higher final product (e.g. ethanol) concentration, thus reducing the distillation costs, which is the main operation influencing the overall process energy and economic costs.

Improving the efficiency of (bio) catalytic upgrading of intermediate bioprocessing products into advanced biofuels and bio-based products is another research priority addressing the objectives of the area. The development of novel solid materials for direct catalytic (membrane) upgrading of biomass hydrolysates to produce hydrocarbons for advanced biofuels (e.g. jet biofuel), and the production of bio-based products from alcohols contained in fermentation broths, are research topics addressing the priority.

Improving carbon conversion efficiency is a key priority to achieve the cost-competitive conversion of syngas, hydrogen and/or CO_2 flows from biomass thermochemical and biological processing into advanced biofuels and bio-based products. The development of bioreactors with novel configurations other than the current stirred tank reactors (CSTR), improved design concepts (e.g. to enhance gas solubility, gas-liquid and gas-solid contacting, cell concentration, etc.), and increased fermentation rate by developing microbial strains that are more tolerant to inhibitory compounds in syngas and more efficient at transforming the syngas into final products, also including the use of mixed cultures as an alternative to overcome the need to find a single microbial cell factory, are some relevant key topics in this area. Moreover, increasing the cost competitiveness of using algae and bacteria to produce bio-hydrogen and biomethane is also a key issue for the long-term future use of those intermediate bioenergy carriers to produce advanced biofuels and bio-based products.

The recovery of side streams (e.g. hemicellulose and lignin fractions) resulting from the production of advanced biofuels to obtain high value co-products through biochemical or chemical processes is capital to achieving higher energy efficiencies and cost competitiveness for biofuel production in biorefinery schemes and tackle the development of a circular economy. The production of diesel substitutes from hydrolysed hemicellulose by mild or enzymatic hydrolysis of the oligomers, followed by up-grading by mild hydrothermal treatment of the resulting hydrocarbon mixture, the development of novel methods for the de-polymerisation of lignin, and the use of microbial strains to generate high value products from lignin, are, among other possibilities, examples of relevant research topics to be highlighted within this research priority.

Process, mass and energy integration coupled to waste and by-product integration is the overall goal of any biorefinery focused on minimizing GHG emissions and aiming to reach zero effluents. These challenges concern the objective of this research priority, which is addressed by three research topics:

a) The development of in situ product recovery (ISPR) technologies, such as, for example, removing the inhibitory products in continuous fermentation processes by selective separation methods, which results in increased product yields and reduced economic and energy costs. Another relevant example is the use of zeolites to separate the inhibitory butanol from acetone and ethanol in ABE processes.

b) Life Cycle Analysis of the value chains of the biofuels and bio-based products obtained in the biochemical-based biorefineries, from feedstock to final product use and disposal or recycling, is a well-recognised and essential tool to determine the economy, as well as the environmental and social (social-LCA) impacts, of the biorefineries, which, in turn, is capital to define scenarios regarding process configuration, energy sources and waste/emission reduction approaches.

c) A third research topic is related to the recovery of process side streams into biofuels and other bio-based products. An example is the use of the aqueous fraction resulting from the fractionation of bio-oils, and which contains a diversity of organic oxygenated compounds that can be transformed into hydrocarbons and aromatics via a "one pot" process utilising a newly-designed solid catalyst.

Subprogramme 4. Stationary bioenergy

The scope of the Subprogramme is the development of efficient, flexible, affordable and environmentally friendly heat, power and cooling production from biomass. The Subprogramme covers all plant scales, from small residential/domestic units to medium- to large-scale bioenergy plants focusing on the conversion of woody biomass, especially important for the residential sector, and low-grade feedstocks/residual streams through combustion and gasification technologies.

The Subprogramme also addresses new research opportunities such as digitalisation and advanced operational principles, and hybrid systems, where stationary bioenergy is integrated with intermittent renewables (solar, wind) in domestic hybrid RES systems, or to balance the electricity grid and provide storage options.

Three main challenges are identified: a) the use of low-quality feedstocks/waste streams for increased, secure and lower cost future supply while maintaining the performance of bioenergy plants, b) reduced emissions, particularly NO_x, SO_x, CO and particles, through cost-efficient measures, and c) improved economic competitiveness of bioenergy plants by reducing conversion costs and increasing process efficiency through the development of novel technology concepts, such as hybrid and smart integrated concepts. The KPIs from the research needs outlined in this Subprogramme 4 are: reach a net efficiency of biomass conversion for all types of intermediate bioenergy carriers of at least 75%; reduce GHG emissions by 60% for all types of intermediate bioenergy carriers by 2030; and, reduce conversion system costs for large-scale biomass cogeneration by 20% in 2020 and 50% in 2030.

To address these challenges and KPIs, three research areas and priorities are identified corresponding to:

a) Residential/domestic heating and cooling, including micro-CHP.

b) Medium- to large-scale CHCP.

c) Transformation of fossil fuel plants into bioenergy plants and biorefinery islands.

For residential/domestic biomass heating and cooling systems, including micro-CHP systems, despite the tremendous technical developments in recent decades that have substantially increased the energy efficiency and reduced the emissions of biomass combustion installations, the current societal trends impose a new set of constraints and requirements, including additional emissions reductions. These constraints will require new biomass system innovations, involving both technical and non-technical issues.

One main research topic in residential RHC systems is the development of installations adapted to customer/user behaviour and demands with respect to the performance (economic, environmental) and affordability of the installations. Thermal comfort is also an important issue, as well as the development of flexible systems with respect to biomass feedstock, unit operation and building integration.

In this context, the sector needs to provide "customer driven innovation" while ensuring that the necessary knowledge to operate and manage the installations reaches the public to ensure acceptance and proper real-life operating conditions. Another research topic is the development of biomass burning appliances adapted to the needs of ZEB (zero emissions buildings), with stable and controlled energy release under real operating conditions, avoiding heating power peaks. Smart systems combined with heat storage with controlled heat release and the use of excess heat for micro-power generation systems integrated in ZEB are concepts of interest. Moreover, one key topic is, as mentioned above, the integration of biomass into domestic hybrid RES systems where biomass is used to compensate for the intermittency of another RES. These systems can be especially relevant for off-grid dwellings or energy-plus houses.

Biomass micro-CHP has the potential to provide clean, cost effective and efficient heat and power to small consumers. Integration into RES systems would allow for a CO_2 neutral energy production while avoiding transmission losses and reducing the costs of infrastructures and GHG emissions. However, the technologies available for micro-CHP (e.g. micro-gas turbines, ORC, Stirling and steam engines etc.) need to be more competitive from the economic, energy efficiency and environmental (GHG emissions) perspectives. This can be achieved through different approaches: a) by reducing the CAPEX and OPEX for the electricity generation part, selecting and developing the best technological routes for micro-CHP facing ZEB-specific constraints, b) increasing technology flexibility with regard to the use of multiple feedstocks, for example, by developing novel routes and solutions (pre-treatment) to enable the use of low-grade biomass fuels and bio-waste, including the use of additives or blends, c) developing novel systems optimised for ZEB, which should be highly integrated, flexible and possibly hybridised. The combined production of domestic heating, cooling and electricity in biomass CHCP plants has been shown to have energy saving potential, enhanced efficiency and lower emissions compared to CHP plants. To develop improved performance biomass CHCP plants, similar strategies as described for CHP plants must be developed. Moreover, as in the case with CHP plants, research on Technoeconomic challenges and solutions to transform the existing infrastructure or to integrate new infrastructure is required. The Positive Energy Block (PEB) concept should be further developed.

A second research area involves the development of **medium- to large-scale CHCP plants**. Air emissions from biomass CHCP plants, especially particulates, NO_x and SO_x, constitute a societal problem. An EU Directive has been approved to regulate air emissions from medium (1-50 MWth) size installations using solid fuels, and biomass. This directive establishes stringent limits for those emissions. It is therefore essential to undertake research to develop effective solutions to reduce emissions from biomass CHCP installations. This can be achieved by implementing primary or secondary measures in existing plants, or by developing disruptive technological concepts. Another research topic is the development of cost-efficient measurement and diagnostic techniques, such as soft sensors for thermal process control and gas detection. Research in laboratories and pilot plants involving breakthrough bio-CCS technology is another key research topic to reach the targeted net-negative CO_2 emissions.

A second research priority in this area is digitalisation and the development of advanced operating systems to improve the performance of CHCP plants. In the future context of 100% RES CHCP plants, the introduction of bioenergy into the grid as an energy element to direct balance the fluctuating demand or to provide storage options is a relevant strategy to improve operational reliability and secure the energy supply while increasing efficiency and reducing the operational and maintenance costs and the emissions of those plants. To achieve this, a research topic is the development of smart diagnostic, monitoring and process control systems. Upgrading biomass heating plants to CHCP plants by developing novel power cycles capable of cost-efficiently producing electricity in the plants, and the development of emissions and air pollution control systems (with modelling and simulation tools) are essential research topics to address this priority.

A third research priority to improve the performance of CHCP plants involves the management of feedstock and process residues. The use of low-cost biomass fuels is an approach that helps to reduce conversion costs and the demand for high-quality biomass that can be used in more value-added applications. To achieve this, flexible solid and liquid biogenic fuel handling, storage and feeding systems must be developed. The design of CHCP boilers must also be adjusted to improve their economic and technical performance when using those fuels. The use of process residues as raw materials and feedstocks for other processes with minimised costs (or even providing some income) is also relevant for the economy and efficiency of the conversion installations and is deeply connected with circular economy principles.

A third important research area to further boost the use of biomass in medium- to large-scale plants involves the **transformation of large-scale, fossil-fuel-based power plants (>100MW) into biomass CHP**, and potentially CHCP, plants and the development of energy islands in biorefineries. These two approaches are important for substituting fossil fuels with biomass while avoiding large cost sinks during the transition towards a future sustainable energy system. They can also help to pave the way for a bio-based economy. The main barriers to this option lie in the complicated mobilisation of vast quantities of biomass to satisfy the demands of the plant. This is offset in part by the scale-induced efficiency gains and low retrofit investment costs of using biomass in these plants, particularly when CHP plants are integrated into biorefinery processing. The conversion from fossil-fuel-driven power or CHP plants to biomass CHP plants includes plant adaptations and diversification of outputs due to the higher level of heat versus power delivered, which needs to be addressed according to the conditions of the repowering carried out. A second research topic is the development of flexible solid and liquid fuel storage and feeding systems capable of efficiently and safely handling multiple fuels, which, in conjunction with optimised supply chains, will contribute to the security of supply and reduce the storage costs of feedstock mixtures utilised in the plants.

Flexible and highly efficient plant operation is key to improving the competitiveness of medium- to large-scale biomass repowered plants. This can be achieved by developing and utilising suitable automatic process control systems that allow for improved combustion process control and minimise sintering and corrosion risks, as well as advanced systems and measures for controlling air pollutant emissions, particularly NO_x, and by developing aerosol size particle control concepts. Developing systems for a flexible output of the plant (heat, power or CHP, including flexibility in allowing for rapid load changes) is another research topic in this field.

Finally, as mentioned above, an important research theme will focus, in the context of the circular economy, on using solid process residues as bio-based fertilisers, in construction and building materials and for reuse in biochemical processing.

Subprogramme 5. Sustainability/Techno-economic analysis/Public acceptance

Subprogramme SP5 was created after the other Subprogrammes, as a result of the EERA JP Bioenergy community realising the need to have a Subprogramme entirely dedicated to the issues of sustainability analysis, techno-economic analysis and public acceptance of bioenergy. This Subprogramme addresses issues which are relevant to all other Subprogrammes; hence, in the EERA JP Bioenergy structure, SP5 is horizontal/transverse to all other SP's.

With regard to sustainability, it was clear from the establishment of SP5 that the Subprogramme should aim at a thorough understanding of not only environmental-related aspects, but also consider the broader sustainability dimensions of bioenergy, such as economic and social. SP5 has hence defined 4 main focus areas (Research Areas) which currently comprise the scope of the Subprogramme:

- **Research Area 1:** Environmental Analysis
- **Research Area 2:** Techno-Economic Analysis
- **Research Area 3:** Social Analysis
- **Research Area 4:** Cross-Cutting Sustainability Analysis

The first area of focus, Environmental Analysis, aims at a complete evaluation of the environmental implications of bioenergy systems, as well as at understanding the potential of bioenergy for achieving environmental goals. This Research Area studies a number of environmental impacts related to bioenergy, with a large part of the research focus being on the climate-change-related impacts of bio and the role of bioenergy-based technologies (e.g. bioenergy with carbon capture and storage) in meeting the climate mitigation challenge. Another part of the research effort for this Research Area is to understand other (non-climate change related) environmental consequences of bioenergy, such as impacts on air quality, water use and biodiversity. An important contribution of this Research Area will also be to address issues related to methods (e.g. Life Cycle Assessment, Environmentally Extended Input-Output Analysis) and method development for assessing the environmental impacts of bioenergy.

The next focus area of this Subprogramme is the Techno-Economic Analysis (TEA) of bioenergy systems, where a number of relevant topics will be explored within two main research lines: 1) Conceptual Design and TEA of biorefineries and biomass conversion processes; 2) Metrics for assessing the economic sustainability of bioenergy, including the analysis of uncertainty. The research agenda in TEA is ambitious and includes many topics, such as the definition of conceptual design configurations and technology routes for biorefineries where multiple products are considered, profitability analysis and development of supply chain models and optimisation of economic performance along the production chain. It also includes TEA for micro CHP sources fuelled by 2nd generation biofuels and for energy storage systems based on biofuels and bio-based synthetic fuels, among other topics. As for metrics and uncertainty analysis, SP5 will help identify sources of uncertainty with regard to a) process economic performance, b) overall supply chain and business models (including market effects). The Subprogramme will also do a systematic investigation of the influence of TRL on techno-economic assessment.

Another large share of the research effort of this Subprogramme is dedicated to a third Research Area, namely, Social Analysis. One important social aspect that SP5 hopes to better understand and gain an insight into is that of the public's perception/acceptance of bioenergy, including which factors, strategies or policies may play a role. Beyond social support for bioenergy, SP5 will also focus on innovation processes and commercialisation of bioenergy technologies. Finally, the Subprogramme highlights the challenges facing the application of Social Life Cycle Assessment (SLCA) to bioenergy products and processes, and will contribute to life cycle inventories for SLCA of bioenergy.

Finally, SP5 addresses a fourth Research Area by focusing on Cross-Cutting Sustainability Analysis. While the previous three Research Areas focus on environmental, techno-economic and social analysis per se, this fourth Research Area sheds light on issues where there may be an overlap between these aspects. An overall sustainability assessment should cover these three pillars (economic, social and environmental) and identify potential synergies/trade-offs between these dimensions. SP5 sets an ambitious research agenda within cross-cutting sustainability analysis by addressing questions such as the socio-economic impacts of bioenergy, the links between bioenergy and the UN's Sustainable Development Goals (SDG's), as well as the role that bioenergy may play in the Circular Economy. SP5 will also contribute to a better understanding of issues related to methods of sustainability analysis, namely Life Cycle Sustainability Assessment (LCSA), by investigating its application to bioenergy and how to address trade-offs between the different sustainability dimensions. Finally, an important area of research within this Subprogramme will focus on the political and regulatory framework for bioenergy in Europe, where SP5 will address the several challenges facing the implementation of RED-II (entering into force from 1st January 2021 onwards) for the next decade and analyse the implementation of RED-II in the field of power and heat.

INTRODUCTION

This document describes the Strategic Research and Innovation Agenda (SRIA) of the Joint Programme on Bioenergy (JP) within the framework of the European Energy Research Alliance (EERA aisbl), and the structure of the JP adopted to address the SRIA priorities.

The SRIA represents the consensus of EERA Bioenergy JP participants for a global view to address the challenges of the Energy & Environment policies from a research and innovation perspective, with the overall objective being to accelerate the SET-Plan priorities and actions in order to help to decarbonise the energy sector, an issue where bioenergy is an essential component in future, low-carbon-technologies basket in all climate-change mitigation scenarios. In this context, the challenges identified in the SET-Plan Energy Integrated Roadmap[5], the SET-Plan – Declaration of Intent on "Strategic Targets for Bioenergy and Renewable Fuels needed for Sustainable Transport Solutions in the context of an Initiative for Global Leadership in Bioenergy" (SET-Plan DoI), for 2020 and 2030, published by the EC in 2016[6], have been addressed. The SRIA priorities and key performance indicators (KPIs)for biomass conversion technologies are aligned with those identified in the SET-Plan-Priority Action 8 (Bioenergy and Renewable fuels) Implementation Plan (2018)[7], where EERA Bioenergy JP has formed part of the Temporary Working Group in charge of its preparation. Moreover, research recommendations contained in the ETIP Bioenergy SRIA[8], as well as different inputs obtained from international stakeholders and common research priorities agreed upon in other EERA Joint Programmes, have also been considered in preparing the JP SRIA (2020).

Even though the SRIA implementation is in principle planned for the 2019-2020 period, it also gives a perspective of the challenges and priorities out to 2030 and beyond.

Several important principles, key-facts and assumptions, with the concept of integration at the top, have inspired the criteria and decisions for defining the SRIA.

Some of the most relevant:

- The determination and development of sustainable biomass feedstock availability is of capital importance for bioenergy to comply with the increasing demand in the context of a decarbonised energy scenario. The sustainable feedstock must be developed within the broader framework of bioeconomy and circular economy concepts, where bioenergy is an essential part and may play a fundamental role in its deployment. Exploring and developing the potential of still underused, or even unused, biomass resources are also important aspects to satisfy the increasing future biomass demand.

- In order to assure the sustainability of bioenergy systems, the development of biomass demand must be made in the context of biomass value chains that consider the conversion technology rates in terms of costs, efficiency, carbon balance and feedstock quality, and annual conversion plant demands, rather than making it in a separate stage to conversion in ill-defined integrated application contexts.

- Innovation must play an essential role for bioenergy technologies to meet the highest levels of efficiency and low carbon use while reducing the costs of biofuel production. Working on low TRL bioenergy solutions is capital for the sustainable bioenergy technologies of the future. This approach forms an essential part of the research topics in this SRIA.

- Process and system integration approaches offer massive opportunities to increase efficiency and reduce the costs of biofuel production. This approach is also stressed in this SRIA and contributes to achieving a higher integration level of the activities inside and among the JP Subprogrammes.

- Of note in the context of the increasing role of RES to satisfy energy demands is the research to develop the synergies that bioenergy, as a dispatchable resource, may have with other discontinuous RES to increase the efficiency and quality of the energy provided by individual hybrid installations, making the deployment of RES more viable, as well as the production of renewable fuels.

- As in the case of the feedstock, bioeconomy offers many opportunities for integrating bioenergy technologies within the biorefineries production models in order to increase the efficiency, sustainability and viability of the full systems.

- Sustainability and economic competitiveness are two key issues for achieving the social acceptance of bioenergy and biofuels.

As envisaged in the previous JP Document of Work for the 2015-2017 period, this SRIA reaffirms the importance that the interest of the bioenergy industrial sector, the national research priorities and the international cooperation on bioenergy are present in its implementation. The alignment and cooperation with other related EERA aisbl Joint Programmes and external research institutions and industries are also key aspects for successfully implementing the SRIA. The promotion of these aspects will be tackled through specific actions that will stress the efforts already initiated in the JP in recent years.

[5]SET-Plan Energy Integrated Roadmap(2014).https://setis.ec.europa.eu/system/files/Towards%20an%20Integrated%20Roadmap_0.pdf
[6]SET-Plan DoI (2015).C (2015) 6317 final. Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation.
[7]SET-Plan DoI-Action 8 (Bioenergy and Renewable Fuels) Implementation Plan (2018).https://setis.ec.europa.eu/system/files/setplan_bioenergy _implementationplan.pdf
[8]ETIP Bioenergy SRIA (2015).http://www.etipbioenergy.eu/images/EBTP-SRIA-2016.pdf

I. JP STRUCTURE

In order to organise the JP to address the SRIA priorities, and in order to optimise the impact of the SRIA results, the JP has been divided into five Subprogrammes (SPs), as shown in Figure 1.

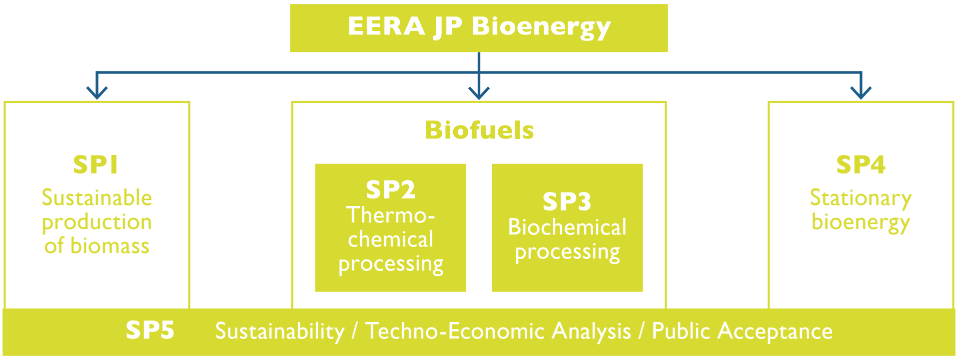


Figure 1: EERA Bioenergy JP structure

- **Subprogramme 1 - Sustainable production of biomass,** contains the R&I challenges, priorities and topics involving the development of forest, agricultural and algal biomass resource production and biomass waste pre-treatment for recovery for energy use, as well as the development of sustainable logistics chains. The activities in this Subprogramme, especially the logistics chains, will be carried out taking into account the needs of the demand of conversion processes and technology demands identified in other Subprogrammes, which, as mentioned earlier, contribute to an integrated common view on sustainable bioenergy and biofuel production pathways.

- **Subprogrammes 2 and 3 - Thermochemical (SP2) and Biochemical (SP3) processing of biomass into advanced biofuels and bio-based products.**
  These Subprogrammes deal with the research priorities on thermochemical and biological/chemical conversion processes, respectively, to produce biofuels and bioproducts. They envisage joint approaches on integrated processes to increase the efficiency and reduce the costs of biomass conversion, including pathways for the integration of renewable fuels of non-biological origin, and biofuel production in biorefinery based contexts.

- **Subprogramme 4 - Stationary bioenergy.**
  It tackles important challenges to improve the sustainability and economic viability of using biofuels for heat, refrigeration and power production in small-, medium- and large-scale applications. Pathways for integrating the use biofuels in hybrid RES plants, and the use of biorefinery residues and the application of circular economy criteria to the use of biomass heat and power plant residues are some of the alternatives being considered for development as part of an integrative strategy to optimise the sustainable use of biofuels while increasing the viability of discontinuous RES and biorefinery production.

- **Subprogramme 5 (SP5) - Sustainability/Techno-Economic Analysis/Public acceptance.**
  The analysis of the environmental sustainability, based on relevant policy requirements, and the techno-economic analysis of bioenergy technologies and value chains are essential to developing optimised alternatives for the successful implementation of Bioenergy. Therefore, a new Subprogramme has been integrated into the JP that aims to create a robust tool to tackle these issues. As an innovation regarding the preceding Document of Work (2015-2017), the evaluation of social acceptance has also been incorporated as an indicator of the sustainability of Bioenergy systems. The determination and definition of measures, conditions and frameworks to foster the deployment of Bioenergy systems is another important purpose of the new Subprogramme 5.

While developing SRIA, the aims of the JP are the following:

- **ALIGN** research activities at JP institutes to give a technical-scientific basis to further development of advanced bioenergy routes and to promote the possibilities for joint technology development, in order to help accelerate the objectives of the SET-Plan.

- **ALIGN** research priorities and activities at EERA JP Bioenergy institutions with other external stakeholders, while also promoting international co-operation. Particular attention will be placed on the alignment with the ETIP Bioenergy.

- **ASSESS R&I** priorities to accelerate the implementation of Bioenergy in Europe.

- **BE A PROMINENT ACTOR** in the development of R&D&I in Bioenergy to accelerate the SET-Plan objectives.

2. SRIA DESCRIPTION BY JP SUBPROGRAMMES

The SRIA descriptions for each SP are provided here. The Great Challenges concerning the scope of each SP are identified, along with Research Areas and Research Priorities addressing the challenges, and the interlinks with those are also identified. Relevant KPIs are defined for each Grand Challenge, which, when applicable, are, in general, those related in SET-Plan DoI- Action 8 (2018), as indicated in the SPs description.

The Research Priorities are addressed by Research Topics, often interconnected with other topics in the SP or with other SPs, thus creating a well interlinked research scheme which has been defined to maximise the synergies between SPs, the work efficiency and the quality of the results obtained. Moreover, common research priorities defined with the EERA Fuel Cells and Hydrogen Joint Programme have also been considered in the research topics for SP2 and SP3.

2. 1 Subprogramme 1. Sustainable biomass production

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2.1.1 SCOPE

This Subprogramme will contribute to the availability of biomass for the bioenergy production purposes that are described in other Subprogrammes (SP2, SP3, SP4) of the JP Bioenergy. The availability of this biomass has to be expressed not only in terms of quantity, but of the quality needed to obtain high yields in transformation processes, of affordable cost, and of sustainable production systems (logistics being included in these systems).

Four main biomass production systems are studied in Subprogramme SP1: Biomass from agriculture (crop residues or dedicated production), biomass from forestry, biomass from algae, and biomass from biogenic waste. Except for the fourth source (biogenic waste), they are all directly linked to conversion of atmospheric CO_2 into carbon stored in biological material through photosynthesis. The positive aspect is that photosynthesis is a naturally occurring, environmentally friendly, quasi permanent and no-cost process in its basic version (forestry); the negative aspect is that photosynthesis is a low-yield reaction, so biomass production is mobilising some land, and biomass has to be harvested, stored and transported before being converted into energy. Some production systems have been designed and optimised to increase their yield, but at the expense of production cost (agriculture vs forestry) or harvesting cost (algae vs agriculture).

Basically, the land use issue and the cost structure of the various type of biomass studied in SP1 may be summarised as follows:

Biomass production system	Land use	Production cost	Harvesting cost	Logistics cost	Ability to adapt to transformation
Forestry	existing	very low	high	high	long time
Agricultural (residues)	low (share)	low (share)	low	middle	low
Agricultural (dedicated crops)	middle	middle	low	middle	middle
Algae	low	high	very high	low	high
Biogenic waste	low		high	middle	few control

Table 1: Land use and cost structure of the biomass types studied in SP1

The sustainability of a given biomass production and delivery system may be assessed by using the Life Cycle Analysis (LCA) methodology, though the data that are used in the calculation have been shown to be very dependent on local situations[9]. In some cases, when the existing situation is heavily modified, it may be wise to use Consequential LCA, which tries to consider land use changes (LUC and ILUC)[10]. It is also important to keep in mind that the higher the transformation yield (into usable form of energy), the better the sustainability index; therefore, the ability to adapt the biomass characteristics to a process should be considered during research work on biomass production systems.

Estimating a "sustainable potential" for biomass remains the holy grail of resource assessment research, given the challenges of accounting for the range of positive and negative impacts incurred by biomass development on the three aspects of sustainability (environmental, economic, and social) and defining acceptable limits. In its Special Report on Renewable Energy, the IPCC quotes a development potential of 100-300 EJ[11]/yr. if limited by water and land availability and predicts a somewhat lower likely range of 80-190 EJ/yr. based on techno-economic modelling.

[9] Life Cycle Assessment (LCA): A guide to approaches, experiences and information sources (EEA).
[10] Earles, J. M., & Halog, A. (2011). Consequential life cycle assessment: a review. The International Journal of Life Cycle Assessment, 16(5), 445-453.
[11] Exa Joule (EJ) 10E18 J or 10E9 GJ. One ton of lignocellulosic (generic) biomass contains about 15 GJ.

2.1.2 MAIN CHALLENGES

SPI aligns its main R&D challenges to the scope of the Subprogramme and defines four main R&D Priorities/Challenges and Key-Performance Indicators (KPIs). These challenges are the same for the different sources of biomass but will be addressed at various degrees depending on the kind of production system (see details in Research Areas below). They are aligned with the Integrated Roadmap of SET-Plan and the SET-Plan DoI, Action 8 (Bioenergy and Renewable Fuels).

- **Main Challenge 1: Ability to maximise the quantity of biomass that can be delivered from a given distance to a transformation plant**

KPI: A main issue regarding the viability of bioenergy plants lies in developing a reliable, integrated biomass supply chain from cultivation, harvesting, transport, storage to conversion and by-product use across Europe. Secure, long-term supply of sustainable feedstock – often by local supply chains -is essential to the economics of bioenergy plants.

- **Main Challenge 2: Ability to decrease the overall cost of the biomass delivered to a transformation plant**

KPI: The target price in 2020 and 2030 for advanced biofuels and renewable fuels should be within a reasonable margin from parity with fossil fuels. However, when policy incentives for CO_2 reduction are considered, they should aim to be on parity with fossil fuel prices in 2030.

- **Main Challenge 3: Ability to optimise the environmental and technological quality of the biomass delivered to a transformation plant**

KPI 1: Sustainability[12] both for bioenergy and biofuels is a concern, as it can reduce public acceptance. It can improve when bioenergy is provided by waste or residual streams of biological materials. These shall comprise land-use footprints, water resources and overall lifecycle performance.

KPI 2: The processing of intermediate bioenergy carriers into advanced biofuels for transport purposes and the development of heat and power from biomass have additional challenges, [...]. These challenges are equally important for both thermochemical and biochemical/biological technological pathways, including the use of algae.

- **Main Challenge 4: Ability to produce biomass suitable for different kinds of transformation process (flexibility)**

KPI: By 2030, improve the net process efficiency of conversion to end-biofuel products by at least 30% compared to present levels, while simultaneously reducing conversion process costs; by 2030, improve the net process efficiency of various production pathways for advanced renewable liquid and gaseous fuels by at least 30% compared to present levels.

Figure 2 shows the proposed new SPI Strategic Research and Innovation Agenda (SRIA) and how the Research Areas (RA) and Research Priorities (RP) relate to the Main Challenges (MC).

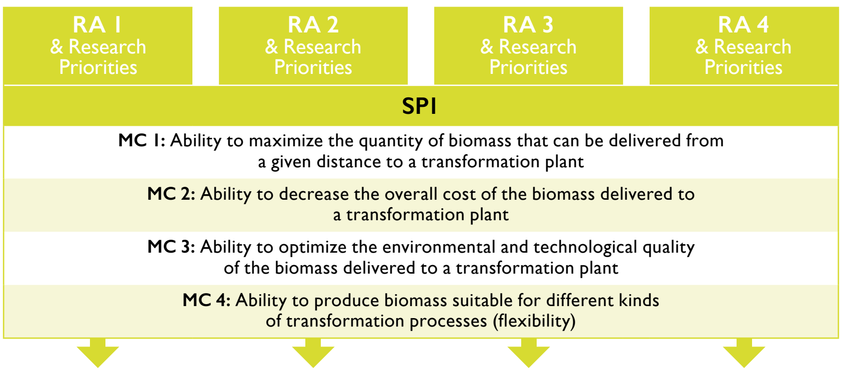


Figure 2: The four main challenges of SPI are addressed through cross-cutting Research Areas and Research Priorities

[12] Challenge #3 only deals with one component of sustainability, which is the environmental aspect, apart from economic and social aspects.

2.1.3 RESEARCH AREAS (RA) AND RESEARCH PRIORITIES (RP)

The needs for research in biomass production has to be considered in the field of bioenergy implementation not only because biomass cost is known to represent a large part of the cost structure of the final products (generally over 50%), but also because biomass production and logistics represent opportunities for employment: for example, it has been shown[13] that using 2G biofuels for15% of transport consumption would create300000 jobs in Europe, of which 83000 for crop residue collection, 50000 for forest waste collection, 13000 for refinery, and 162000 temporary for refinery construction.

This Subprogramme addresses four research areas (RA) (Figure 3), which are the four main production systems for biomass: forestry, agriculture, algae, biogenic waste. For each of them, the research priorities (RP) are targeted to help solve the main challenges described above. This contribution is shown in the figure 3 below.

Biogenic waste is frequently transformed in biogas through an anaerobic digestion process, but some other routes exist (production of H_2, biological fuel cell). In principle, all the research needs on biogenic waste transformation should be in SP3, but the JP Bioenergy Board decided to include classical biogas production in Subprogramme 1, because it is a mature technology, with research needs like those of biomass production (logistics, land use, public acceptance).

Nevertheless, it should be kept in mind that these research priorities must be connected to research on the technological transformation of biomass (as described in SP2, SP3, SP4), and that it is also necessary to understand the interactions between competing uses of biomass resources. Research on this competition is relatively scarce, and models are needed to understand the substitution effects between uses and their impacts on prices and downstream of the supply chains.

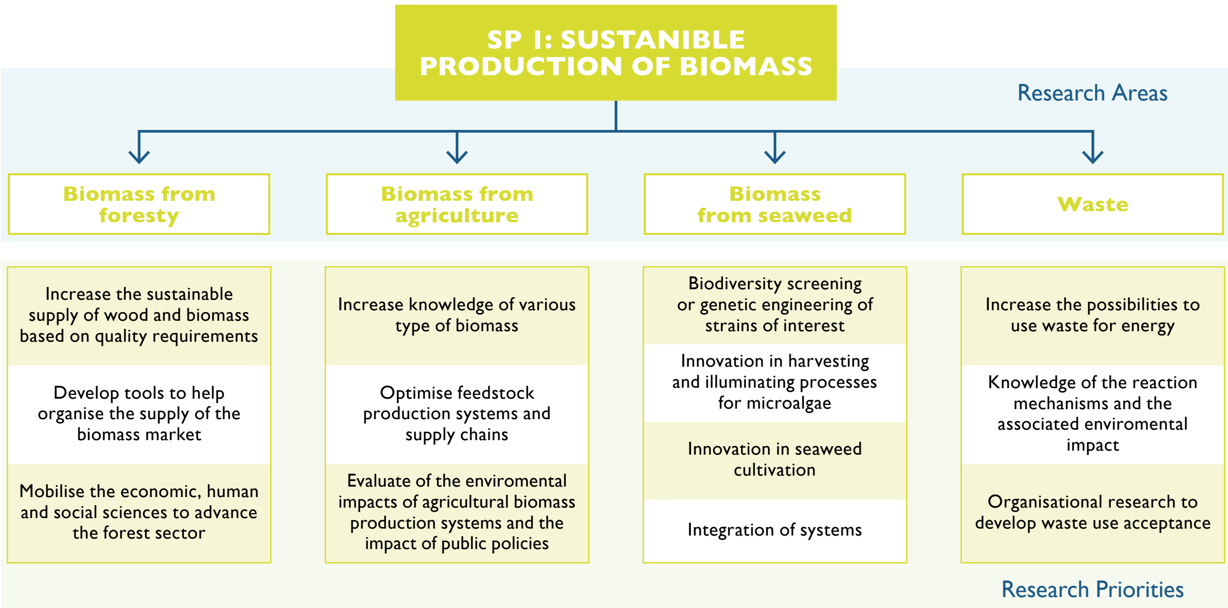


Figure 3: Schemes of the distribution of priorities in each research area of the SP 1

[13] Briefing European Parliamentary Research Service: Advanced biofuels: Technologies and EU policy: http://www.europarl.europa.eu/RegData/etudes/BRIE/2017/603972/EPRS_BRI(2017)603972_EN.pdf

2.1.3.1 RA1 Biomass from forestry

Unlike agricultural biomass, biomass from forestry has to be used "as is", at least in the medium term. It is neither possible to consider geographically moving a forest, nor to change in the trees species that are growing in the short term. In a context of uncertainties involving the effects of climate change (trees' resilience to warmer temperature, massive storms), the research principally aims to overcome three kinds of obstacles:

- Technical and economic obstacles: the fragmentation of forests increases the costs of transporting wood, in a situation of already low financial profits. In spite of this low profitability, investment in harvesting equipment and in logistics is necessary to increase the productivity and competitiveness of the sector, especially for hardwood;
- Organisational obstacles: globally, the wood industry is characterised by highly complex interactions and a multitude of actors with sometimes divergent stakes, and undeveloped or disorganised collaboration, thus limiting the ability of the sector to provide the high quantities needed for bioenergy;
- Sociological obstacles: several studies have been dedicated to understanding the type of interest that owners have in their forest. The main benefits that most owners wish to derive from their forest are primarily material: first, self-consumption, and then immaterial aspects (space for walking and leisure, landscape setting). Forest owners are mostly older and see the forest as a heritage to pass on to their children. The renewal of their forest resource is certainly seen as a necessity but requires very expensive and complex operations.

Research Priorities

Research priorities and research themes are defined to help solve the obstacles above. They are summarised in the table below:

Research priorities	Availability	Cost	Environmental performance	Technological performance	Flexibility for transformation
Increase the sustainable supply of wood and biomass based on quality requirements					
Develop tree diversity and new species		✗	✗	✗	
Develop knowledge and use of new management practices and strategies		✗	✗		✗
Improve harvesting and transportation technologies	✗	✗		✗	
Develop a participatory approach for traditional and non-traditional forest owners for the long-term sustainable management of forests	✗		✗		
Develop tools to help supply the biomass market					
Analysis of supply and demand factors, and the means to provide a link between the them	✗				✗
Digital transition for mobilisation and logistics to improve the economic profitability of forest biomass production		✗	✗	✗	
Mobilise the economic, human and social sciences to advance the forest sector					
Adapt incentives and regulations to the European stakeholders' profile involved in the sustainable mobilisation of forest biomass	✗		✗		✗
Realise and exploit case studies across European forestry systems	✗				✗

Table 2: How research priorities will tackle the obstacles found in RA 1: Biomass from forestry

2.1.3.1.1 RP1 Increase the sustainable supply of wood and biomass based on quality requirements

Climate change will occur, and forest systems will be unable to interact significantly with its evolution. In this context, forestry choices are strategic because of the long-term impact of decisions that must be anticipated given the length of forest cycles. In this situation of climate change, but also economic, environmental and societal changes, foresters need diagnostic tools to guide their choices.

RT1 Develop tree diversity and new species

One of the challenges is to promote tree diversity in order to increase (a) forest productivity by reducing their water and mineral needs, and (b) forest resilience towards climatic accidents. In research terms, it means diversifying the supply of genetic resources and accelerating the diffusion of genetic progress.

The choice of species is certainly an essential factor in maximising biomass production. The potential of some fast-growing tree species (e.g. *Pseudotsuga menziesii, Picea sitchensis,* etc.) could be used under suitable pedo-climatic conditions. Significant productivity gains in biomass can also be expected from genetic selection: in a clonal planting of Sitka spruce, productivity measures reveal a high variability (up to 12x) between extreme clones for tree biomass at 30 years old. These gains must, however, be modulated if we consider the possible need to make selection compromises with other features.

Moreover, part of the trees within a stand could be harvested for wood fuel at an early age (about 20 years, for example), while the remaining ones could be grown for industrial roundwood production (final harvest at about 40-60 years).

Wood waste (also called low-cost biomass) is often considered as the 'no-regret' option for its neutrality with respect to land-use, cheap price and the abundant volumes generated by the products they are issued from. However, these streams come with caveats due to a trade-off with soil quality (for agricultural and forestry residues), suitability in terms of quality with respect to biomass processing, and ultimately availability since some degree of competition with other uses or between bio-based value-chains is likely to interfere.

RT2 Develop knowledge and use of new management practices and strategies

Modelling chains are to be developed to test the combined effects of climate change, technical routes and the associated risks. Research and development organisations need to develop decision support tools related to species selection, tree vitality, water balance of forests, stand biodiversity, biodiversity economic evaluation, etc. In addition, it is important to have a better understanding of the links between management and stand vulnerability, in order to identify the forestry levers and reduce their vulnerability. Recent satellite, optical and radar measurement systems with high temporal and/or spatial resolution offer great potential to, for example, map the impacts of various hazards (drought, storms, fires, avalanches).

For instance, biomass production is strongly affected by stand density: optimum production requires a much higher density of plantations than is customary. Forestry dedicated to the production of biomass will indeed have to consider planting densities on the order of 1600 to 1800 stems per ha. For the moment, it is not culturally or economically feasible to create short-rotation high forests that are totally dedicated to biomass production. However, so-called "semi-dedicated biomass" scenarios are seriously being considered. In these scenarios, a thinning of half of the stems is carried out at 25 years for use as biomass energy, while the rest of the trees are harvested at 40-50 years old for use in lumber.

For sustainability, soils are of major importance: the research goal must be to maintain their long-term fertility, including maintaining or increasing their carbon stock. This also means enhancing knowledge and modelling tools, including the possibility to recycle ash derivatives.

Methods and tools are also needed for multi-criteria assessment of forest-wood systems. This involves better analysing and integrating the study of relationships within forest-wood systems (production, processing, distribution, recovery of end-of-life products), and improving multi-criteria and multi-scale tools to assess the impacts of changes on practices, innovations or new public policies.

RT3 Improve harvesting and transportation technologies

Research should help to develop efficient machinery and optimised business concepts (timing, relocation of equipment) for forest harvesting operations that have a low environmental impact and are able to handle a large variety of wood products and species in all terrains.

The research will aim to develop a user-friendly platform for smart optimisation of wood production with low GHG emissions and optimisation of the forestry-wood chain from tree harvest to primary wood consumers, taking into account the diversity of wood product.

In a given local context, it appears difficult to design supply chains based only on wood waste streams, residues or surplus, which would operate separately from current forestry or agricultural value-chains. On the contrary, bio-based projects should be developed and constructed in synergy with stakeholders from these sectors, to maximise co-benefits and mutualise risks, infrastructure and equipment. Optimal feed-stock mixes should be designed on a case-by-case basis, depending on the biomass quality requirements and on the potential of the local area to provide biomass, whether from wood waste, forestry and agriculture, in a concerted manner between local communities and chain operators.

RT4 Develop a participatory approach for traditional and non-traditional forest owners for the long-term sustainable management of forests

Stakeholder involvement, including small-scale woodlot owners, may be increased by identifying and describing adequate examples and by comparing the different means to improve the cooperation of small forest owners regarding forest biomass availability and production.

For the sustainability criterion, carbon sequestration may be optimised through forest management: research will aim to identify and analyse incentives for carbon sequestration through active forest management and the use of timber and other forest-based products.

The maintenance, conservation and appropriate improvement of biological diversity is one of the six criteria for sustainable forest management (SFM). This criterion thus marks the recognition of the special responsibility of forests in preserving natural heritage. More generally, new integrated forest management systems for wood, biodiversity and other ecosystem functions must be studied by analysing and developing models of integrated forest management systems, including wood production, biodiversity, conservation and/or other ecosystem services, which will have to be implemented in decision support tools.

2.1.3.1.2 RP2 Develop tools to help supply the biomass market

The lack of a true market for supplying biomass for energy is one of the elements that undermines the development and consolidation of this sector. The development of industrial-scale production units requires dialogue with many actors and dealing with resources that are heterogeneous in both nature and quality. The emergence of an international market to supply biomass for energy purposes could favour this structuring.

Just as an international market for pellets is in the process of being set up, a similar phenomenon appears for less sophisticated products, which makes it possible to overcome the uncertainties of local supply for large boiler plants, cogeneration units or biorefineries. It will be necessary to establish a relationship with the downstream value chain in order to improve coherence and cooperation in the value chain.

Decision support tools could allow owners to calculate all the costs associated with forest activity, analyse the profitability and carry out cost management controls. Through social networks, platforms could be organised to share results, allowing the owners to compare their management and logging and exchange best practices to improve the financial profitability of their activity.

RT1 Analysis of supply and demand factors, and the means to provide a link between the two

Conduct market analysis of future demand and supply (long-and short-term perspectives) for forest biomass, including potential new and traditional value chains. This analysis must include an understanding of the most appropriate modes of contracting, which are necessarily dependent on the specific physical, social and institutional context of each region.

Fine quantification of the resource: the knowledge of the potential must be determined at a geographical scale linked to the transport problems of forest owners. Tools like planes or drones may help to work at that level.

Develop new, combined forest harvesting business models including smart organisation, infrastructure (long distance transportation) and regulatory framework conditions, to optimise the sustainable transport of forest biomass.

Increasing the efficient use of resource s through resource cascading (which is "a method for optimising resource utilisation through a sequential re-use of the remaining resource quality from previously used commodities and substances") can be beneficial concerning energy and carbon balances when wood resources are limited, since the use of other, less favourable energy sources and materials is avoided.

RT2 Digital transition for transport and logistics to improve the economic profitability of forest biomass production

Identify and analyse the best options for tailor-made initiatives to enhance regional forest-based value chains and overcome the mismatch of supply and demand of forest biomass, by using collaborative platforms to share data between economic actors (forest and industrial producers), traceability tools, and activity analysis.

Novel generation of decision support tools for different users (owners, professionals) to predict economically feasible wood harvesting while taking into account all forest functions (social, economic and environmental face): precisely locate the wood resource in space and time, including multiple forest functions; identify the obstacles to its mobilisation and transport, including the network of services and social constraints; determine the best techniques and organisations for harvesting and transport; streamline the interactions between these professionals to mobilise both wood and owner-decision makers; develop digital contracting and payment exchanges.

Computer simulation to anticipate the impact of globalisation on the sustainable transport of forest biomass in Europe, including shifts in land-use and land mobilisation, considering Europe's regional profiles of the forest-based sector.

2.1.3.1.3 RP 3 Mobilise the economic, human and social sciences to advance the forest sector

The evolution of the forest sector is linked not only to the development of tools and services (internet platforms, dematerialisation, etc.), but above all to changes in the behaviour of the actors: (a) value chain professionals (from forest owners to industrialists), (b) institutions (in charge of regulating road transport, service plans, financing, etc.), (c) facilitators, solution providers. These changes must be driven by innovative approaches provided by the human and social sciences.

RT1 Adapt incentives and regulations to the European stakeholders' profile involved in the sustainable transport of forest biomass

As the main undeveloped increase in standing volume is assumed to be small-scale (for instance, in France, about 3 million homeowners with less than 4 ha, for 30% of the forest area), use human and social sciences to answer questions such as:

- What is the dominant value system involving forest and wood uses in society? For instance, the maintenance, conservation and appropriate improvement of biological diversity is one of the six criteria for sustainable forest management (SFM). This criterion therefore recognised the special responsibility of forests in preserving natural heritage.
- It is known that the territory is a key factor for the recovery of bioresources, so how to rethink the relationship with the territory and the role of politics?
- What could incentivise the transport of forest biomass, including predictions and scenarios of tailor-made measures?
- What is the impact of consumer, societal and regulatory shifts regarding innovative technologies for the demand and supply of forest biomass?

RT2 Realise and exploit case studies across European forestry systems

Case studies may help to identify success and failure factors that stimulate or limit the sustainable mobilisation of forest biomass, and to summarise how to address these factors and explore the role of innovation and knowledge exchange in addressing them. These case studies may concern, for instance, the:

- Involvement of actors and stakeholders in regional initiatives for forest biomass transport.
- Efficiency of measures for reaching and integrating non-traditional owners.
- Functioning of various existing regional forest ownership organisations across Europe and in its regions: how do long-established and well-performing associations operate? Are there lessons to be learned?
- Impact of external policies on the sustainable transport of forest biomass in European regions.

2.1.3.2 RA2. Biomass from agriculture

Agricultural biomass feedstock may be broadly categorised into dedicated, purpose-grown crops, primary by-products such as cereal straw or corn stover, or secondary waste streams arising from biomass processing (e.g. rice husk, molasses, or sugarcane bagasse from sugar production). Dedicated energy crops may be further broken down into food crops, which are currently used for first-generation biofuels and bioproducts, and lignocellulosic plants, which produce a generic type of biomass utilisable for various biorefinery or bioenergy pathways. These plants range from annual crops, which are sown every year and harvested after one growing season, to perennial species with a lifespan after establishment of 10 to more than 30years, which are harvested every year (for grasses) to every 2 to 8 years for woody species. These crops include perennial grasses such as miscanthus, and woody species in the form of short-rotation coppice, such as willow and poplar.

Research Priorities

As it is of primary importance that the exploitation of agricultural biomass for bioenergy be done (a) without competing with food needs, and (b) with high environmental performance, research priorities range from increasing our knowledge of various types of agricultural biomass, to being able to estimate their environmental footprint and developing various ways to optimise their production. They are summarised in the table below:

Research priorities	Availability	Cost	Environmental performance	Technological performance	Flexibility for transformation
Increase our knowledge of various type of biomass					
Increase our knowledge of trade-offs (soil carbon, other uses) for food crops and residues	✗		✗		
Increase knowledge of lignocellulosic crops		✗	✗	✗	✗
Increase our knowledge of the use of legume crops in biorefinery systems			✗	✗	✗
Design and optimise innovative systems combining different crops	✗	✗	✗		
Optimisation of feedstock production systems and supply chains					
Crop photosynthesis improvement		✗✗	✗		
Co-design of plant characteristics and environmental performances	✗		✗	✗	✗
Models for bioenergy cropping systems including in marginal lands	✗	✗	✗		
Optimise supply chain and logistics		✗			
Evaluation of the impacts of agricultural biomass production systems and public policies					
Life cycle assessment of value chains of bioenergy production, from feedstock production to end-use			✗		
Analysis of the impact of certification schemes and policy frameworks	✗				
Analysis of bioenergy system deployment scenarios and case studies			✗	✗	

Table 3: How research priorities will tackle the obstacles found in RA 2: Biomass from agriculture

2.1.3.2.1 RP1 Increase our knowledge of various types of biomass

The choice of biomass must be a compromise between several criteria: high production per hectare, quality/composition adapted to the market, low input needs and low environmental impacts, including the impact on biogeochemical (and water) cycles. A lot of information is still needed before we can estimate this compromise, particularly on lignocellulosic crops.

RT1 Increase knowledge of trade-offs (soil carbon, other uses) for food crops and residues

Food crops have long been bred to maximise the output of edible components, usually found in storage organs, and specific quality traits favourable to human or animal consumption. Their use for non-food purposes evolved from a diversion of the same edible fractions to alternative end uses. Food crops require relatively large agricultural inputs in the form of fertilisers and pesticides, and their dry matter yields depend on the biochemical composition of their storage organs. They generally export large quantities of nutrients from soils, such as N, P, K, or S. They have harvest rates of around 50%, meaning that half of the biomass produced consists of crop residues, such as wheat straw or corn stalk, which are in turn potential sources of lignocellulose, at a relatively cheap cost.

Primary residues from food crops may provide a potentially large and widespread source of lignocellulose, although the actual extent is controversial due to trade-offs involving the preservation of soil quality and fertility, and competition with other uses (for livestock farming in particular). For example, in France only an estimated 33% of available straw could be removed without jeopardizing soil organic C, and because of other end uses a mere 23% of the straw produced on arable land is actually available for biorefining.

RT2 Increase our knowledge of lignocellulosic crops

Lignocellulose species are less resource intensive and export less nutrients due to remaining in a vegetative phase throughout the growing season or to the limited synthesis of storage compounds compared to food crops. The question of the choice of species to cultivate from among the many candidate cultures is still open and depends on various parameters. For example, annual crops can be grown as main crops (e.g. sorghum) or stolen (CIVE), multi-year crops (e.g. alfalfa), perennial herbaceous plants (e.g. miscanthus), or woody perennial plants (e.g. willow) grown in coppice with short or very short rotations.

Annual lignocellulosic crops such as triticale and sorghum represent an intermediate option between food crops and perennials, since they are easily seeded and only have one growing season. However, they resemble food crops and have higher requirements than perennial crops, as well as lower energy yields per ha.

On the other hand, perennial grasses feature a high productivity because of their long growing cycle and more efficient photosynthesis pathway, termed "C4" because it produces sugars with four carbon atoms, as opposed to the C3 metabolism of temperate crops and tree species. The C4 pathway is typical of tropical crops and results in higher CO_2 fixation rates for a given level of solar irradiance. Crops with C4 metabolism used for biomass production include maize, sorghum, miscanthus[14], and switchgrass.

Woody biomass can be produced in intensive, short-rotation tree plantations dedicated to bioenergy purposes. Woody species suitable for these kinds of plantations must have common features such as a wide, natural distribution range across regions, a high initial growth rate, ease of vegetative propagation, and formation of coppice sprouts or suckers.

[14]Miscanthus is now part of the Ecological Focus Areas under the Common Agricultural Policy (EU Regulation 2017/2393).

RT3 Increase our knowledge of the use of legume crops in biorefinery systems

Legumes include annual crops such as soybeans and peas, and perennial forage crops, which can be harvested several times a year (alfalfa) or grazed (clover). Apart from soybeans (whose oil is used for biodiesel production), there are few examples of legume crops used for biorefining purposes. They have a high protein content, which can be of interest to bioproduct pathways as a substitute for animal proteins.

Legumes have a capacity to take up dinitrogen (N_2) from ambient air through a symbiosis with soil-borne bacteria that fixes N_2 and makes it available to plants as ions in the soil solution. This saves inputs of fertiliser N, which is the most limiting nutrient for crop growth. However, it comes at a cost of reduced biomass production because bacteria feed on organic matter provided by root exudates.

RT4 Design and optimise innovative systems combining different crops

Mixtures of varieties or species provide one way to increase biomass output and the resilience of production systems to climate changes, pests, or other limiting factors. Multifunctional land use in general is an interesting concept to provide several ecosystem services from the same parcel of land.

Combining legumes with lignocellulosic crops is viewed as a promising avenue to reduce costs, input usage, and environmental impacts, particularly, greenhouse gas (GHG) emissions, when producing feedstock. However, it is not clear yet how the harvested material would be recovered. Separating between the two crops could be an option, as would be tuning the conversion process to the mixture (with the drawback of having to handle N-rich compounds, which is not optimal for thermochemical pathways).

The agroforestry system may combine food crops (such as wheat) with trees producing lignocellulosic biomass (poplar, for instance). Other examples include intercropping or mixed cropping systems combining different crops in the same plot or growing an understory food crop and coppicing the lignocellulosic species to produce residual biomass for energy. These innovative systems provide interesting examples of synergistic effects between food and non-food production, since this combination generates mutual benefits for both species.

From the market side, cascading uses of lignocellulose in a biorefinery approach seem to be one of the only possible avenues to ensure viable economics for bio-based value chains while offering a price for biomass feedstock that is enough to incentivise potential growers or providers.

2.1.3.2.2 RP2 Optimisation of feedstock production systems and supply chains

Since a key issue is increasing the global yield for transforming biomass into energy and decreasing land use, it is necessary to mobilise plant biology, plant breeding, plant protection and plant bio-technologies in a multidisciplinary approach with agronomy, processing and logistics.

Another key issue is the procurement costs. At current market prices for fossil sources, it is hard for bio-based products to compete with their non-renewable equivalents, especially for low added value end products such as heat or power. Since logistics are far from being optimal in many of the currently emerging biomass value chains, there is still definitely room for improvement and cost reduction on the supply side.

RT1 Crop photosynthesis improvement

Photosynthesis takes place in the chloroplast, the energy factory of the plant cell. Basically, photosynthesis uses incoming light energy (photons) to combine CO_2, H_2O, phosphate, sulphate, nitrite into amino acids (building blocks of proteins), fatty acids (building blocks of lipids), sugars (building blocks of starch and cellulose), etc. This process is known to be inefficient in terms of energy, as more of 90% of the energy is lost.

A small increase in photosynthesis yield will result in a break-through change in agricultural practices. With the help of biotechnology tools, several routes are studied:

- Management of CO_2 assimilation to reduce photorespiratory losses.
- Management of H_2O: Stomata opening, water uptake.
- Implement mineral nutrition and nutrient uptake to avoid limitation of chloroplast development.
- Molecular optimisation of resource investment among the components of the photosynthetic apparatus.
- Optimisation of light conversion and photoprotection.
- Improving the layout of leaves in crop canopies to enhance light capture and avoid light saturation and oxidative stress.
- Control of chloroplast biogenesis in adverse growth conditions.

RT2 Co-design of plant characteristics and environmental performances

This research theme concerns the genetic improvement of biomass species to yield ideotypes that combine productivity, disease resistance, low environmental impacts, good transformation into end products and tolerance to drought. It should include:

- Development of predictive approaches, systems biology and synthetic biology, including better knowledge of metabolic pathways.
- Mobilisation of biological regulation processes in plant breeding programmes: exploitation of beneficial plant-plant and plant-microbe interactions.
- New breeding technologies: new gene editing systems and implementing them in various crops.

This optimisation of new or existing crops has to consider, simultaneously with increasing productivity, the effects on environmental criteria, such as water use efficiency and quality, N inputs, soil organic carbon:

- Water use efficiency (WUE) is the amount of plant dry biomass (DM) produced per unit water used. Regarding water quality aspects (e.g. nitrate concentration in drainage water), perennial grasses were shown to reduce nitrate leaching compared to annual crops, and especially food crops; however, nitrate leaching in arable systems is also affected by the management of the period between two crops and can be mitigated using catch crops.
- Bioavailable N is the element in soil that is most often lacking, even if phosphorus and potassium are also needed in substantial amounts; moreover, N is costly to supply, and it can affect the surrounding environment negatively. In order to limit losses and create sustainable systems with high productivity and reduced N inputs, the NUE of the crops has to be improved. In general, trees and lignocellulosic grass crops selected for combustion purposes have a higher NUE than common food and feed crops.
- Changes in soil organic carbon (SOC) content depend on feedstock type (architecture and root physiology, root turn-over) and culture management, as well as on the land use history. Increasing the cultivation of whole-plant annual lignocellulosic crops or the rates of residue removal from arable cropping systems is likely to decrease SOC stocks. In contrast, shifting from annual crops to SRC or perennial grasses may increase SOC stocks, with large variations in C sequestration rates.

RT3 Models for bioenergy cropping systems, including in marginal lands

The management of energy crops includes providing seeds or seedlings, establishment and harvest, soil tillage, and various rates of irrigation, fertiliser, and pesticide inputs. The latter depend on crop requirements, target yields, and local pedo-climatic conditions and may vary across global regions for a similar species. Purpose-grown crops may be harvested several times a year (for forage-type feedstocks such as hay or alfalfa), once a year (for annual species such as wheat or perennial grasses), or every 2 to 8 years (for short-rotation coppice). Finding the optimum combination of all these variables in each location close to a transformation unit requires in silico modelling.

These models may help to investigate the use of so-called "marginal" lands, where dedicated crops can contribute to the production of energy biomass with a positive GHG balance. These marginal lands are lands that are not suitable to produce food crops, such as polluted or hard-to-access land, as well as land in ecologically sensitive areas, such as eroded land or catchment basins for water supply, where the use of fertilisers and sanitary products must be severely limited.

Moreover, new resources not yet exploited could contribute to broadening the potential for biomass resources. This is the case of biomass produced in shrub lands. According to the EU official soil database[15], six Mediterranean countries have over 50% of EU28's shrub lands - 21 Mha -, slightly over half of which (10.6 Mha) is located in Spain. The annual biomass potential of shrub resource can be estimated at 5-7 Mtoe.

Shrubs are colonizing pioneer plants in abandoned agricultural and livestock lands, as well as in forest areas cleared by fires, whose biomass resources are barely or marginally exploited, with wildfires commonly consuming the biomass contained in these lands. Therefore, the sustainable management of scrub vegetation must be a priority in fire-fighting plans and provides an opportunity for an additional source of biomass. Recently, the ENERBIOSCRUB Like + Project [16]demonstrated that mechanised tasks for sustainable shrub clearing and biomass collection are also feasible, though cost optimisation and reduction are necessary, since the clearing and logistical costs estimated in this project for shrub biomass generally exceed the current market prices of biomass for energy use.

RT4 Optimise supply chain and logistics

Innovative techniques for crop management, biomass harvesting, storage and transportation provide a route to increasing the biomass supply while reducing costs and minimising negative environmental impacts. The major challenges to deploying biomass supply chains on a large scale are the diffuse and low-density nature of the biomass (15 to 20 MJ/kg.ms vs. around 40 for petroleum), its high moisture content and the risk of spoiling during storage. Research to improve supply chains includes, among others:

- Increased efficiency of the harvest and transport stages.
- Densification of post-harvest biomass, with or without pre-heat treatment, to reduce transport costs on an energy content basis.
- Reduced transport distances or use of low-pollution means.
- Use of biomass production systems to allow staggering the supply over the year while limiting the need for storage and yielding high productivity per hectare.

Defining methods, database and models for integrating, designing and evaluating supply chains for lignocellulosic crops.

In terms of logistics, biomass is typically transported to a collection point on the farm or at the edge of the road before transport to the biorefinery unit or intermediate storage. It may be preconditioned and densified to make storage, transport, and handling easier. Local pre-treatment (coupled grinding-drying, roasting, pyrolysis, and granulation) with pooling, for example with multi-product/multi-user platforms, is conceivable before accessing large centralised units.

[15]LUCAS micro data, 2012. https://ec.europa.eu/eurostat/web/lucas/data/primary-data/2012
[16]http://enerbioscrub.ciemat.es/es

2.1.3.2.3 RP3 Evaluation of the environmental impacts of agricultural biomass production systems and impact of public policies

The production of biomass interacts with a host of environmental, ecological, economic, social and human health issues. Environmental impacts encompass water availability and quality, soil and air quality, biodiversity, and climate through the emissions of greenhouse gases and C sequestration in soils.

RT1 Life cycle assessment of value chains of bioenergy production, from feedstock production to end-use

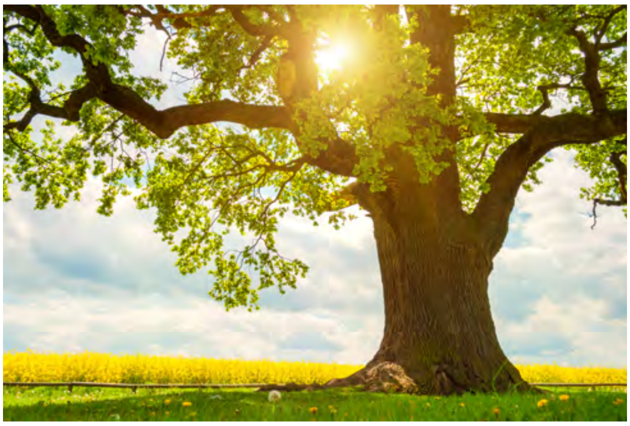
This research theme deals with assessing biomass production and the environmental impacts of cropping systems. References must be acquired (under experimental and agricultural conditions) and modelling methods have to be studied to allow for the development of models (improvement of formalisms, parameterisation and evaluation) that will ultimately lead to the design of innovative cropping systems to produce new products from biomass.

In this perspective, the spatialization of LCA tools represents a methodological need to consider the practices/needs adapted to the conditions of the environment (minimised input routes), to spatially model the "adequate" export rate of co-products and thus bring together scientific elements to argue non-standard allocation choices (bio-refinery by-products, intermediate crops, etc.).

When the impacts are calculated up to the plant gate, they cover the feedstock supply chains, but not the conversion processes and downstream distribution and utilisation steps. This is relevant when comparing feedstocks with similar characteristics that are more or less interchangeable so as to provide guidance on the best options in terms of supply mix. But this is not relevant when the biomass production scheme influences the transformation steps or the final products; in this case, it is necessary to extend the analysis to the end product step, with suitable models.

RT2 Analysis of the impact of certification schemes and policy frameworks

Different certification schemes and processes that aim to bind sustainability criteria for biomass feedstock must be carefully followed and the Subprogramme members have to participate in the discussion proactively.



RT3 Analysis of bioenergy system deployment scenarios and case estudies

Only a few references are available on the impacts of introducing purpose-grown lignocellulosic plants into landscapes currently dominated by annual food crops or grassland. It will certainly lead to marked changes in agroecosystems and agricultural landscapes, especially when perennial crops are grown beside annual crops. It is likely that the processes that maintain biodiversity in both space and time will be affected, but this remains largely under evaluated.

The situation differs considerably when bioenergy crops are grown on former cropland. In areas dominated by agriculture, arable weeds and their associated invertebrates have dramatically declined due to the heavy use of agrochemicals, especially pesticides. Lignocellulosic crops have the great advantages of requiring a single initial planting and no major chemical inputs, which should be beneficial to biodiversity.

It will be necessary to go beyond the basic criteria (water, carbon, GHG) by including biodiversity, water catchments, and soils polluted at the scale of the landscape. Future high ecosystemic service solutions will be derived from an ex-ante evaluation by coupling models to identify "low iLUC" solutions with the three components of sustainability (biomass production, organisational models and environmental performance).

2.1.3.3 RA 3 Biomass from algae

Microalgae have great potential in biofuel production. Their main advantages are: photosynthetic production with higher surface productivities than plants; absence of complex polymers such as lignocellulosic compounds, which facilitates downstream refining; simultaneous consumption of inorganic carbon, allowing for a net-zero carbon balance operation; and possible production in dedicated cultivation (such as closed technologies), allowing for optimised feeding (carbon dioxide and nutrients) and minimising the environmental footprint (minimisation of water supply, control of waste products).

Seaweeds (or Macro Algae) also have great potential in biofuel products for similar reasons as microalgae. Specific advantages are that seaweed can be cultivated on large scales off-shore and, once harvested, yield a high biomass density. In terms of composition, seaweeds are complementary to microalgae as they contain high amounts of carbohydrates. Seaweeds can be grown all over the world and in all seasons, albeit not the same species. The diversity of the carbohydrate-like molecules also opens avenues for novel fuel molecules, etc. Concurrent protein production and mineral recycling can further contribute to food production and to closing the mineral fertiliser cycle.

Their high biodiversity also allows producing a variety of energy-rich substances for use as biofuels, such as hydrogen by water photolysis, lipids for biodiesel or jet fuel production, and sugars for biomass fermentation (methane) or gasification.

However, although highly promising, biofuel production with microalgae also seems to be the most constrained and difficult way to recover this bioresource. It indeed implies setting up mass-scale, cost-effective and sustainable plants.

Cost and ERoEI (energy returned on energy invested) are also two major constraints in biofuel production. A low cost is required to be economically competitive in the energy market, and ERoEI implies achieving a positive energy balance, which is not straightforward considering the different steps required to obtain usable biofuel (production, harvesting and downstream processing of biomass into biofuels). Because of the need for lighting, scaling-up microalgae production systems is a problem on its own.

The economy could, however, be improved by market combinations of biofuels and other commodities obtained from the microalgae biomass.

Research Priorities

The R&D effort should be conducted in an integrated way with a continuous and systematic transposition and validation of fundamental and applied research in industrial conditions. This will allow obtaining proof-of-concepts of the innovations.

Research priorities	Availability	Cost	Environmental performance	Technological performance	Flexibility for transformation
Strains (biodiversity screening or genetic engineering of strains of interest)					
Selection and optimisation of strains having a positive impact on the overall process efficiency		✗	✗	✗	✗
Selection and optimisation of strains for industrial production having a high productivity in final products		✗	✗		
Selection and optimisation of strains for industrial outdoor production resistant to pollution			✗	✗	
Innovation in harvesting and illuminating processes for microalgae					
Harvesting at low cost and low energy		✗	✗		
Development of intensified photobioreactor for mass production		✗			
Development of microalgal production in gaseous and liquid effluents	✗	✗	✗		
Innovation in seaweed cultivation					
Development of advanced cultivation substrates	✗	✗	✗		
Development of automated harvesting		✗		✗	
Development of stabilisation storage and logistics chains		✗		✗	✗
Integration of systems					
Development of microalgal production in gaseous and liquid effluents	✗	✗	✗		
Co-recovery of valuable by-products (for instance, pigments)		✗			
Development of process models coupled with robust economic and LCA models for the entire production chain, including co-products			✗	✗	

Table 4: How research priorities will tackle the obstacles found in RA 3: Biomass from algae

2.1.3.3.1 RP1 Biodiversity screening or genetic engineering of strains of interest

Strain selection is a key issue in algae biomass production. It can be orientated towards process efficiency, productivity in final product, or resistance to pollution. Both biodiversity (natural strains) screening and genetic engineering of strains of interest must be considered.

RT1 Selection and optimisation of strains having a positive impact on overall process efficiency (as on harvesting or end product extraction)

Strain selection/optimisation programmes should take into consideration, as early as possible in the selection process, technological constraints linked to the production, harvesting, extraction and biomass treatment processes.

RT2 Selection and optimisation of strains for industrial production having a high productivity in final products

The selection of strains with high productivity in the final product must take into account both the growth rate and accumulation level of the targeted products.

For microalgae, their ability to grow in a large-scale photobioreactor also must be considered.

For seaweeds, robust, highly productive strain development of locally sourced cultivars optimised for biofuel production: it has been shown that different cultivars or strains from other locations can almost double the amount of certain sugars. Selective breeding has been shown to increase biomass production by 40%.

RT3 Selection and optimisation of strains for industrial outdoor production resistant to pollution

The selection of strains depends on the type of cultivation.

For microalgae, in open systems, it would be necessary to have very robust strains, able to compete with other microorganisms (bacteria or other microalgae). For closed systems, the selection is easier due to the better control of the culture conditions.

For seaweed, the goal is to obtain strains that are resistant to the perturbations of their environment, and of their growing conditions.

2.1.3.3.2 RP2 Innovation in harvesting and illuminating processes for microalgae

For each step of the process, it is necessary to look for the lowest-energy demand technology. In the end, the ERoRI (Energy Return on Energy Invested) must be largely greater than one.

RT1 Harvesting at low cost and low energy

The harvesting step depends on the type of strain, and on the extraction process selected. Autoflocculation and Dynamic Air Flotation are among the technologies that have to be optimised based on the types of strains.

RT2 Development of intensified photobioreactor for mass production (lighting challenge, mixing challenge)

The development of low-energy consuming, intensified photobioreactors for mass production has a high breakthrough potential, especially when connected to the improvement of strains. Another development could be the coupling between photosynthesis and photoelectricity. The conception of a photobiovoltaic reactor relies on using the near infra-red part of solar irradiation to produce electricity, with the visible part being used for photosynthesis.

RT3 Development of microalgae production in gaseous and liquid effluents

The sustainability of the energy produced by microalgae should be largely induced by using gaseous (containing CO_2 and NO_x) and liquid (contained nitrate and phosphate) effluents. In this case, it is necessary to think about the overall process between the producer of the effluents and the producer of microalgae. With liquid effluents, some complexity could be involved, such as mixotrophic cultivation (presence of organic compounds in the effluents) and co-culture (presence of bacteria in the effluent).

2.1.3.3.3 RP3 Innovation in seaweed cultivation

For seaweed cultivation, mechanised cultivation and harvesting systems need to be developed to yield the amounts of biomass needed for biofuel production: a seaweed-based bio-ethanol plant would conceptually process around 1 million metric tonnes of seaweed on a dry matter basis per year to produce ethanol.

RT1 Development of advanced cultivation substrates

Predictive models for seaweed quality (and harvesting times).

RT2 Development of automated harvesting

Advanced cultivation systems optimised for year-round cultivation and mechanised harvesting suitable for the local environment. Highly automated harvesting systems.

RT3 Development of stabilisation storage and logistics chains

Since seaweeds are highly seasonal in Europe, the seaweed needs to be stabilised by simple, effective and fast stabilisation techniques so that it can be stored at least 6 months, preferably 12.

Development of on-sea first processing steps.

2.1.3.3.4 RP4 Integration of systems

RT1 Co- recovery of valuable by-products (for instance pigments)

By-products such as pigments are important economic sources for microalgae. Non-polar pigments (chlorophylls, carotenoids) can be involved in lipid extraction processes and will then be mainly co-extracted.

For seaweed, added product value is provided by plant active components, anti-fungal, anti-bacterial, anti-oxidants, and proteins.

RT2 Development of process models coupled with robust economic and LCA models for the entire production chain, including co-products

It is still a challenge to establish a sustainable and cost-effective production pipeline while minimising energy consumption and environmental impacts. Projects with higher TRLs are needed. Different expertise, as well as biological and engineering aspects of algae cultivation and biorefinery, must be integrated from laboratory and pilot scale research.

2.1.3.4 RA4 Biomass from biogenic waste

Biogenic waste is indirectly produced by photosynthesis, but it is not intended to be used directly. The feedstock source may be: livestock effluents, roadside mowing residues, invasive plants, green waste, industrial waste (agro-food, paper, chemicals, etc.), waste from catering and distribution, household waste, sewage sludge, organic fraction of sewage from stand-alone or small-scale sanitation systems, animal by-products, etc.

Since it is waste, it is generally necessary to make it compatible with the transformation process: the pre-treatment and the preparation of the materials are defined according to the characteristics of the inputs, the process of transformation and the expected characteristics of the final products and co-products (ashes, digestate). The first objective is to eliminate any substance likely to disturb the proper functioning of the process. The second objective is to increase the production yield: physical, biological and/or chemical pre-treatment processes can be implemented to improve, for example, the hydrolysis and the biodegradability of organic matter; sorting and milling can reduce the size of solids and speed up the transformation process.

Depending on the water content of the waste, two main types of processes are used:

- High dry matter raw materials are transformed by thermochemical processes (combustion, pyrolysis, gasification) to produce heat and/or electricity, or to produce syngas, which is an intermediate reaction to chemical (Fischer-Tropsch) or, more recently, biological routes. To facilitate their large-scale transformation, these materials can be pre-conditioned in the form of RDF (Refuse-Derived Fuel);

- Materials with high water content are generally transformed into energy vectors by anaerobic digestion. There are two kinds of anaerobic digestion processes: wet-phase anaerobic digestion, which has a5 to 15% dry-matter content, and the dry process, which is 15 to 40%. Wet anaerobic digestion is generally carried out in infinitely mixed reactors in mesophilic conditions. In the dry process, the anaerobic digestion can be carried out either continuously (piston-type reactor) or in batch and in thermophilic conditions.

Anaerobic digestion is a technology based on the degradation by microorganisms of organic matter, under controlled conditions and in the absence of oxygen, and therefore in an anaerobic environment, unlike composting, which is an aerobic reaction. This degradation leads to the production of:

- Biogas, which is a gas mix saturated with water. The biogas is composed of 50 to 70% of methane (CH_4), 30 to 50% of carbon dioxide (CO_2) and some trace gases (NH_3, N_2, H_2S);

- A wet product rich in organic matter and nutriments (N, P) called digestate. Its recovery consists, in general, in a return to the soil after a possible phase of maturation by composting.

The methane contained in biogas (called biomethane after purification) can be used under various forms: combustion to produce electricity and heat, or after purification, for fuel production (bioCNG) or injection into the natural gas network and, more recently, production of hydrogen (H_2) by catalytic reforming of biomethane for industrial or mobility applications.

In a two-stage anaerobic digestion process, waste hydrolysis and acidogenesis take place in a first reactor under acidic conditions, and methanogenesis in a second digestor with a neutral or slightly alkaline pH. In the first reactor, waste is converted into hydrogen and carbon dioxide and soluble compounds such as short-chain fatty acids and alcohols. Biohythane, which is a mixture of methane and biohydrogen (from 5 to 20%), exhibits improved combustion properties compared to methane. Soluble metabolites produced in the first reactor are generally fed to the second reactor to produce methane, but current research considers this first-stage process fermentation (or dark fermentation using mixed culture) as a biological route for higher value recovery of waste.

Current research aims to also use the CO_2 contained in biogas:

- by coupling anaerobic digestion and electricity production units of renewable origin: this makes it possible to produce synthetic methane by methanation of CO_2 resulting from the biogas with hydrogen produced from electricity by electrolysis of the water (power-to-gas principle); similarly, the hydrogen available at certain industrial sites can be upgraded to synthetic methane;

- by using CO_2 for applications in chemistry, materials and energy (production of dimethyl-ether, methanol, etc.).

Biomass is recovered from waste according to four main models, which are combinations of two parameters, management of supply and complexity of recovery:

- Local supply management and simple recovery.
- Local supply management and multiple recoveries.
- Optimised supply management and simple recovery.
- Optimised supply management and multiple recoveries.

The examples below are for anaerobic digestion, but they could be almost the same for heat and power (see differences between SP1 and SP5 Subprogrammes).

Local supply management and simple recovery: it involves a short distance, i.e. proximity between the place of production of the feedstock and the anaerobic digestion unit. In some cases, the anaerobic digestion unit can be located at the point of production of the inputs. Such is the case with on-farm anaerobic digestion. Biogas energy recovery and agronomic recovery of the digestate are close to the biogas plant, which enables energy autonomy and nitrogen autonomy of farms. It also reduces the consumption of non-renewable raw materials (natural gas, fuels) and chemical fertilisers. Sometimes, groups of local actors manage a shared, collective or multi-part anaerobic digestion unit on all or part of the value chain (supply, anaerobic digestion, treatment and transformation of the digestate, collection, purification, biogas injection).

Local supply management and multiple recoveries: supply is still short distance, based on local resources that must be stable in quantity and quality. The design of the processing unit envisions all the recovery routes for the digestate, which is subjected to a treatment, and the biogas can also be subjected to a post-treatment. The recoveries are agronomic, energy or materials (NP fertiliser, organic fertiliser, organic amendment, energy vectors in the form of heat, electricity, biomethane injected in a network, bioCNG, H_2, CO_2, molecules).

Optimised supply management and simple recovery: in this case, the supplies are selected for their prices and their intrinsic properties based on the “recipe” of the digester, regardless of their proximity to the installation. They can be imported and transported over long distances if necessary. The processing unit is large in size. It is designed to produce energy vectors (biomethane/synthetic methane mix, bioCNG). It can be a building block for other industrial activities, for example to optimise the recovery of the by-products of a biorefinery or to supply renewable CO_2.

Optimised supply management and multiple recoveries: this is the crossover of cases 3 and 2, where supplies are selected, and eventually assembled, and where a wide variety of products are generated. This case is like that of a biorefinery that would operate from selected waste instead of raw materials coming directly from agriculture or forestry.

Research Priorities

Research priorities must be identified at each stage of the supply chain: during feedstock mobilisation, transformation into energy and recovery of co-products (ashes, digestate). The aim is to obtain technological solutions with a very high performance, low environmental impact and high marketing potential. Metrology is needed to improve knowledge and to enable all actors to make progress, whether in the design, construction and operation units or in research, consultancy, inspection and verification.

Technological development of equipment and processes on an integrated scale must be studied in collaboration with SP3, including (a) the valorisation of intermediate products (CO_2) and digestate and (b) coupling heat and power, biomethane vector, electricity grid and exploitation of CO_2.

The R&D on new processes must integrate economic (increase profitability: lower cost, higher yields, coupling with productions of other molecules) and social acceptance approaches, which will be reinforced as the technology matures, so that the overall industrial process is in line with the expectations of the market.

Research priorities	Availability	Cost	Environmental performance	Technological performance	Flexibility for transformation
Increase the possibilities of using waste for energy					
Increase waste feedstock mobilisation	✗				✗
Enlarge uses of waste feedstock		✗	✗	✗	
Project planning and engineering	✗		✗	✗	✗
Knowledge of the reaction mechanisms and the associated environmental impact					
Detailed understanding of the biological, chemical and physical mechanisms and their interactions		✗	✗	✗	✗
Metrology needs and new digital tools			✗	✗	✗
Develop knowledge on the positive and negative impact of wastes transformation on climate, water, air quality, odours, soil	✗		✗		
Organisational research to develop waste use acceptance					
Analysis of economic risks and new business models		✗			✗
Sociological obstacles and levers	✗				✗

Table 5: How research priorities will tackle the obstacles found in RA 4: Biomass from organic waste

2.1.3.4.1 RP1 Increase the possibilities of using waste for energy

RT1 Increase waste feedstock mobilisation

- Develop optimised systems to collect both recurring and one-off feedstock combined with a suitable method of storage to enable the most regular possible supply.
- Develop technologies to pre-treat organic matter using biological, chemical or physical methods or mechanical preparation.
- Develop technologies to destroy pathogenic germs while preserving the microbial populations necessary for digestion and useful for soil biodiversity.
- Develop packaging removal and unbagging equipment.

RT2 Enlarge uses of waste feedstock (in collaboration with SP1, SP2, SP5)

- Develop "flexible" solutions that can produce different qualities of energy (biogas) and co-product (digestate) from various feedstock based on demand.
- Develop multimodal waste and biomass treatment platforms, with a combination of dry and wet treatments and a full spectrum of possibilities between the two.
- Develop micro-transformation units for optimised energy or biomethane production.
- Develop fermentation processes to recover biohydrogen and soluble metabolites and develop downstream processing to purify metabolites.

RT3 Project planning and engineering

- Create decision support tools to help integrate local waste transformation into a local energy mix and to design sustainable supply plans.
- Develop information resources on biogas and other opportunities (fuel, hydrogen, CO_2, etc.) to evaluate the need for purification based on public specifications or the requirements of private-sector users.
- Develop tools to design "tailored" projects (with significant risks and potential benefits) and generic projects (with more limited risks and potential benefits).

2.1.3.4.2 RP2 Knowledge of the reaction mechanisms and the associated environmental impact

RT1 Detailed understanding of the biological, chemical and physical mechanisms and their interactions

- Knowledge of seasonal or local variations in waste sources and their consequences for industrial processing.

- Knowledge of the impact of emerging micropollutants and pathogenic micro-organisms on transformation and their fate during the process, in order to better understand their interactions with the industrial transformation and the conditions favourable to their control in feedstock.

- Understand carbon modification processes, how its stability evolves and the transformations throughout its life cycle, including several years after it is returned to the soil.

- Understand the antagonistic and/or synergistic effects of microbial populations depending on the physical and chemical conditions in the digester.

- In the case of anaerobic digestion of waste:

  - knowledge of the biological activity throughout the process, including the use of digestates and their impact on soil biodiversity;

  - understand the biological orientation of digestion towards preferable biogas compositions (CH_4, H_2, CO_2 etc.), including the effect of additives;

  - select microbe strains and consortia suited to biological methanation to promote the production of synthetic CH_4 from H_2 injected into the digester while maintaining the production of biogas through anaerobic digestion.

RT2 Metrology needs and new digital tools (collaboration with SP1, SP2, SP5)

- Measurement, analysis and diagnostic tools, together with new protocols for characterizing feedstock sources, their variability, the presence of pathogens and micro-pollutants (e.g. antibiotics), beyond the parameters usually measured today; these tools must be portable and carry out their analyses quickly.

- Reliable, fast, connected in situ sensors to analyse processes, particularly gas meters and gas composition (nanochromatography, laser and infrared measurement) (see SP1 and 5).

- New digital tools for real-time remote operational management of transformation installations, involving easy-to-monitor indicators. These tools should also incorporate algorithms that predict the installation's operation based on the quality of the feedstock in order to help the operator optimise the recipe and operating conditions. This means going beyond existing modelling tools, by incorporating coupling between biological and chemical phenomena.

- New digital tools to plan and incorporate renewable energy into local energy plans, with possible synergies between networks and energy vectors, in order to optimise feedstock logistics.

- New digital tools to predict the agronomic behaviour of co-products (ashes, digestate) based on the soil and climate conditions where they are spread, including spreading over long periods.

RT3 Develop knowledge on the positive and negative impact of waste transformation on climate, water, air quality, odours, soil

- Improve the quality of impact studies and multi-criteria evaluations using a life-cycle approach, particularly for (a) the influence of biogas leaks, (b) emissions (N_2O, NH_3) when spreading co-products, (c) impact of catch crops, (d) impact of removing crop residues on soil quality.

- Develop an evaluation for the monetary value of externalities, in order to optimise choices in multi-criteria decision issues.

2.1.3.4.3 RP3 Organisational research to develop waste use acceptance

RT1 Analysis of economic risks and new business models

- Breakdown the financial risk by type of installation, in order to improve the financial prospect of the projects, the visibility of financial stakeholders in the sector and control over key profitability parameters for project backers.
- Involvement and role of insurance in relation to the risks.
- Think about the future of sites that benefited from the first electricity purchase tariffs.
- Develop new business models with a different distribution of value; create new services or costing for the services provided apart from biogas and digestate exploitation, such as waste treatment or the impact on the social and community economy.

RT2 Sociological obstacles and levers

- Understand the obstacles, levers, support and learning required to encourage the ecological and energy transition and behavioural change among actors.
- Analyse participatory civic approaches to projects incorporating waste (design, funding etc.).
- Measure the social impact of waste transformation using a multi-criteria approach based on life cycle.

2.2 Subprogramme 2 (SP2) -Thermochemical processing of biomass into advanced biofuels and bio-based products

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2.1.1 SCOPE

The scope of SP2 of EERA Bioenergy JP includes advanced biofuels[17] for sustainable transport and solutions for overcoming the barriers of feedstock mobilisation. The main goal is to support the development of improved technology for:

- Production of advanced biofuels through thermochemical biomass processing.
- Thermochemical production of solid, liquid and gaseous intermediate bioenergy carriers, in the context of a circular bio-economy.

Biomass may comprise biomass fractions, including sustainable raw biomass, biomass by-products/residues, biogenic wastes and aquatic biomass. Biomass residues (from forestry, agriculture and other biomass processing) and (biogenic) wastes will be prioritised. Advanced biofuels comprise liquid and gaseous biofuels for road transport (in particular heavy-duty road transport), aviation and shipping (e.g. diesel, kerosene, alcohols, bio-methane, bio-CNG, bio-LNG). In all technology development efforts, increasing the added value by co-producing bio-based products (chemicals/materials) will be considered to boost the business case and reduce the costs of the energy products (energy-driven biorefinery concepts).

Although this SP is dedicated to actual technology development, it is recognised that technology development and implementation are often hampered by non-technical barriers, which need to be addressed as well. This includes, e.g., a lack of financial or regulatory incentives, a unstable political framework, an inadequate legal framework, deficiencies in sustainability certification and insufficient public support. These issues will be addressed in the new SP5.

[17]As defined in the RED II directive.

2.2.2 MAIN CHALLENGES

SP2 aligns its main R&D challenges with the Integrated Roadmap of the SET-Plan, the Declaration of Intent on *"Strategic targets for bioenergy and renewable fuels needed for sustainable transport solutions in the context of an initiative for global leadership in Bioenergy"* of Nov 16th, 2016, and the SET-Plan TWP Implementation Plan – Action 8: Bioenergy and Renewable Fuels for Sustainable Transport. The two main Challenges selected and their associated Key Performance Indicators (KPIs) to be addressed are:

- **Main Challenge 1: To develop advanced liquid and gaseous biofuels through thermochemical processing of sustainable biomass with improved net process efficiency, reduced costs and higher GHG savings.**

Developments may focus on one or more of the sub-processes, e.g. feedstock pre-treatment, primary conversion, upgrading to or formation of ready-for-use product, considering both stand-alone processing and co-processing in existing refineries. The associated KPI's are:

KPI 1: By 2030, improve the net process efficiency of biomass conversion to end biofuels products by at least 30% compared to present levels.

KPI 2: GHG savings from the use of advanced biofuels shall be at least 60% (including biomass feedstock contribution).

KPI 3: Reduce costs for advanced biofuels to <50 €/MWh in 2020 and <35 €/MWh in 2030, i.e. at least by 30% from 2020 levels (excluding taxes and feedstock cost).

KPI 4: Reduce costs for algae-based advanced biofuels to <70 €/MWh in 2020 and <35 €/MWh in 2030, i.e. at least by 50% from 2020 levels (excluding taxes and feedstock cost).

- **Main Challenge 2: To develop solid, liquid and gaseous intermediate bioenergy carriers through thermochemical conversion from sustainable biomass, with improved net process efficiency, reduced costs and high GHG savings.**

Liquid intermediate bioenergy carriers include, e.g. pyrolysis oil and microbial oils, while solid intermediate bioenergy carriers include, e.g. torrefied biomass and biochar. Gaseous intermediate bioenergy carriers include, e.g. syngas, but also gaseous compounds which may be considered as gaseous biofuels as well, e.g. hydrogen and bio-methane. Existing thermochemical conversion concepts include gasification, pyrolysis, torrefaction and hydrothermal processing, and in addition to single-product concepts, also multiple output concepts (e.g. gas and biochar, liquid and biochar) are considered.

KPI 5: By 2030, improve net process efficiency of biomass conversion to intermediate energy carriers by at least 75%, with GHG emission savings of 60% obtained by using all types of intermediate bioenergy carriers.

KPI 6: Reduce costs for liquid and gaseous intermediate bioenergy carriers to <20 €/MWh in 2020 and <10 €/MWh in 2030 (for e.g. pyrolysis oil) or <40 €/MWh in 2020 and <30 €/MWh in 2030 (for higher quality, e.g. microbial oils) (excluding taxes and feedstock cost).

KPI 7: Reduce costs for solid intermediate bioenergy carriers to <10 €/MWh in 2020 and <5 €/MWh in 2030 (for e.g. biochar, torrefied biomass, lignin pellets) (excluding taxes and feedstock cost).

Moreover, it is recognised that the development of gasification-based technology for advanced biofuel production requires addressing many issues that are directly relevant to the main challenge of developing high-efficiency gasification-based co-generation cycles as well. Since this latter challenge is addressed in SP4 – Stationary Bioenergy, close interactions with this SP will be ensured.

Furthermore, it is felt that the KPI targets should not, and even sometimes cannot, be applied rigidly, but merely to direct the developments. For example:

- If a 30% cost reduction can just be reached by doubling the size of the plant, this should not stop us from looking for more fundamental cost reductions.

- In several cases, efficiencies are already very high, and a 30% efficiency improvement would lead to unrealistic values. Moreover, pushing the efficiency limits often comes with added cost, which has a negative impact on reaching the cost target if not outweighed by the extra revenues due to the efficiency gain.

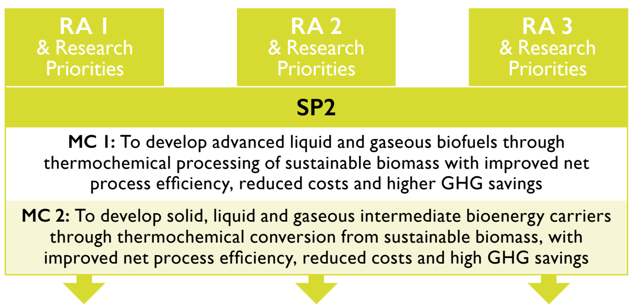


Figure 4: The two main challenges of SP2 are addressed through cross-cutting Research Areas and Research Priorities

Figure 4 shows the proposed new SP2 Strategic Research and Innovation Agenda (SRIA) and how the Research Areas (RA) and Research Priorities (RP) relate to the Main Challenges (MC).

2.2.3 RESEARCH AREAS (RA) AND RESEARCH PRIORITIES (RP)

The main governing principles that will be applied in the technology development to reach the main challenges in terms of higher efficiencies, lower costs and higher GHG savings, are:

- **Process simplification and intensification.** Clearly, this may have a significant cost dimension, in terms of CAPEX, OPEX and plant availability and reliability, and it may lead to higher net plant efficiency.
- **Increase feedstock flexibility and allow application of (cheaper) biomass low-quality feedstock,** mainly aiming at cost reduction.
- **Maximise resource efficiency,** which may also involve combining biomass processing with other sources, e.g. renewable hydrogen produced from solar and wind.
- **Create negative GHG emissions,** involving concepts like BioEnergy + Carbon Capture & Storage (BECCS) and biochar co-production.

The proposed SP2 Research Areas and their associated Research Priorities are:

RA1. Primary thermochemical conversion processes

- Gasification
- Pyrolysis (fast and slow)
- Torrefaction (and steam treatment / steam explosion)
- Hydrothermal processing (HTC – HydroThermal Carbonisation, HTL – HydroThermal Liquefaction, HTG – HydroThermal Gasification)

RA2. Downstream processing (product cleaning, conditioning and upgrading)

- Gas cleaning processes
- Conditioning and upgrading of clean gas and product recovery
- Cleaning, conditioning and upgrading of biocrude
- Solid product conditioning and upgrading

RA3. Value chain design – Integral pathways for biomass conversion into advanced biofuels and intermediate bioenergy carriers

- Gasification-based production of advanced biofuels
- Pyrolysis-based production of pyrolysis oil and advanced biofuels
- Heat/steam-treatment-based production of solid bioenergy carriers
- Advanced biofuels and intermediate bioenergy carrier production based on hydrothermal processing

The three Research Areas and associated Research Priorities are described in more detail in the following sections.

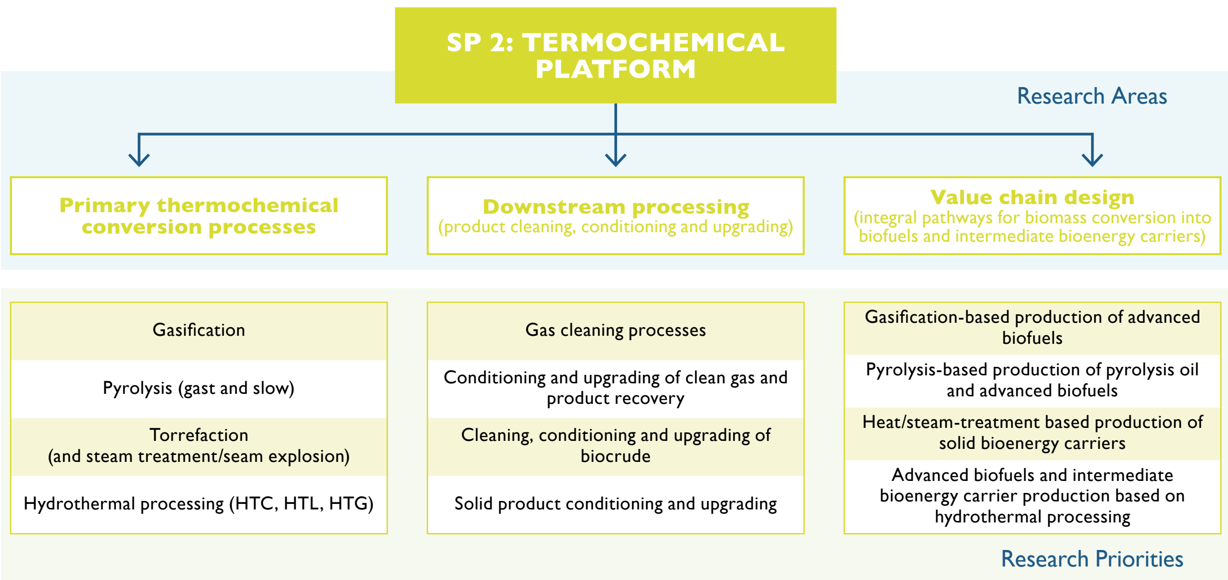


Figure 5: Schemes of the distribution of priorities in each research area of the SP 2

2.2.3.1 RA1. Primary thermochemical conversion processes

The scope of this research area is to arrive at improvements of the primary thermochemical conversion processes for advanced biofuel production as well as to produce intermediate bioenergy carriers. The main thermochemical conversion processes considered for advanced biofuel production are gasification, pyrolysis and hydrothermal processing. The main thermochemical pathways to produce intermediate bioenergy carriers are based on:

- Gasification
- Torrefaction, steam treatment (e.g. steam explosion) or hydrothermal carbonisation to produce solid bioenergy carriers
- Hydrothermal liquefaction to produce liquid bioenergy carriers
- Pyrolysis to produce liquid and/or solid bioenergy carriers depending on the process conditions.

Biomass gasification is the most mature technology, but market implementation is still limited mainly to relatively straightforward heat and power generation. Pyrolysis and torrefaction have been demonstrated for intermediate bioenergy carrier production and are reaching first market implementation. Hydrothermal processing technologies (carbonisation, liquefaction and gasification) are emerging from the laboratory scale into pilot plants and demonstrations and are therefore the least developed.

Increasing feedstock flexibility and enabling the use of (cheaper) low-quality feedstock is a general research theme, aimed at cost reduction and recognizing that high-quality biomass will be applied increasingly for higher-added-value chemical/material applications. Also, better monitoring and control, and improving process performance to limit unscheduled outages, increase efficiency and minimise/optimise residues are common research themes.

2.2.3.1.1 RP1. Gasification

Many thermochemical processing pathways for biomass are based on gasification as the key unit operation. Through gasification, biomass is converted into a gaseous intermediate (syngas or product gas) which is easier to clean, and which allows for the clean and high-efficiency production of a wide range of end-products including chemicals, transportation fuels, power and heat. Consequently, large efforts have been dedicated to the R&D&I of different gasification technologies. However, the market implementation of biomass gasification technologies is still limited to relatively simple power and heat applications; gasification technologies for biofuels (or biochemical) have not yet had a commercial breakthrough. There is a need for cost reduction, improved reliability and reduced technical and availability risks. There is room to further improve gasifier process performance and increase feedstock flexibility. Different gasifier concepts are being considered, including fixed-bed, fluidised-bed and entrained-flow gasification. Furthermore, different gasification agents may be applied, including enriched air, oxygen and steam or so-called indirect or allothermal gasification concepts, to adjust the product gas composition to the requirements of the downstream processing.

RT1: Improve gasifier process performance

A wide range of aspects should be considered to improve overall gasifier process performance. Firstly, this concerns feedstock pre-treatment, monitoring of feedstock properties and optimisation of feeding systems. Furthermore, improved diagnostics, monitoring and control may help to suppress operational problems. On one hand, in non-slagging gasifiers, ash-related problems like slagging, fouling and bed agglomeration should be addressed. On the other hand, in slagging gasifiers, alkali-rich fluxing agents may be considered to allow reducing the reactor temperature and increasing the cold gas efficiency. Alkali-rich additives may also aid in maximising the carbon conversion. Ash quality should be considered in view of utilisation as a fertiliser or in construction, as well as zero-waste configurations (e.g. by feeding process residues back to the gasifier) to minimise the environmental footprint. Operation at elevated pressure may also be considered.

RT2: Increase feedstock flexibility

The use of biomass residues from forestry, agriculture, and other biomass processing, and waste as a resource has the potential to reduce feedstock cost and increase the amount of feedstock mass available for carbon-neutral fuel production. Moreover, biochemical biomass processing yields significant quantities of residues (e.g. lignin-rich fractions), for which gasification-based valuation to biofuels and biochemicals may be an attractive option, but which pose specific challenges, such as gasifier feedstock. The gasification systems and their associated feeding systems should then allow the use of these feedstocks. Generally, these residues and waste have higher ash content, have more difficult ash (e.g. alkalis and Cl, heavy metals) in terms of slagging, fouling agglomeration and emissions, have higher moisture content and/or poorer flow characteristics. Options like an adapted/flexible feeding system, fuel blending and/or the use of additives may be cost-effective alternatives to, or additional measures to, feedstock pre-treatment.

RT3: Optimise product gas composition for downstream processing and maximise biomass-carbon utilisation/valuation

In general, downstream processing often imposes rather strict requirements concerning the product gas composition, both in terms of inorganic and organic contaminant levels as well as in terms of the concentrations and ratios (in particular the H_2/CO ratio) of the main compounds (e.g. H_2, CO, CH_4, H_2O, N_2). Bringing the product gas into spec for downstream processing may be accomplished downstream of the gasifier, but various possibilities exist and may be further developed for in-situ measures inside the gasifier, which may be more economically appealing. This involves applying proper gasifying agent mixtures (e.g. steam, oxygen, air), proper process conditions, specific bed materials and additives/catalysts, as well as applying feed-in of hydrogen from intermittent energy sources and/or recycling of the CO_2 available as a by-product from other (renewable) processes. A driver for renewable hydrogen feed-in may also be to maximise biomass-carbon utilisation/valuation and create appealing overall biomass + renewable hydrogen business cases.

RT4: Novel gasification-related conversion concepts

In addition to the more conventional gasification concepts, in TRL stages between 7 and 9, several novel concepts have been identified and generally are still less developed. This includes molten bath gasification, reforming gasification and thermal and cold plasma gasification. It is worthwhile to further assess their potential in parallel with the efforts to bring the conventional concept to market.

2.2.3.1.2 RP2. Pyrolysis

There is a wide variation in pyrolysis technology options under development, depending on feedstock characteristics and desired product. A main distinction can be made between fast and slow pyrolysis. Fast pyrolysis aims at direct thermal liquefaction of biomass. Liquid bio-oil is the main product. Besides, char and non-condensable gas is produced, both of which are normally used for process energy production. A number of different reactors are employed. Fluid-bed and auger reactors are the most common and are integrated into a heat carrier loop to facilitate rapid heat-up and short reaction times on the order of seconds. Depending on the feedstock characteristics, product yields and quality can change considerably. Fast pyrolysis plants in commercial operation today are mostly operated with unproblematic wood. Fast pyrolysis bio-oil (FPBO) is applied as heating oil today. Recent R&D&I aims at utilising FPBO as co-feed to produce drop-in fuels in existing refineries, as gasification fuel for syngas production and subsequent fuel production, and for stand-alone production of fuel components after substantial upgrading. Slow pyrolysis processes conducted at long residence time (> min) generally focus on biochar production, which can be used as an intermediate bioenergy carrier (solid fuel), as a reducing agent in metallurgical applications, or be applied as a material for, e.g. soil improvement, fertilisation or as a replacement for fossil-based activated carbon.

Catalysts might be incorporated into the pyrolysis process (catalytic pyrolysis) to reduce the temperature of the process and improve liquid production instead of solids and gases. However, the main bottlenecks in these attempts are catalyst recovery and the strong catalytic deactivation due to coke deposition on solid surface, these being key issues to be solved.

RT1: Improve process performance to improve reliability and biocrude quality

This research theme concerns a wide range of aspects of pyrolysis processes that still allow further improvement in order to improve process reliability and biocrude quality. Improving biocrude quality will reduce the cleaning and conditioning requirements, and therefore offers the potential to reduce cost. This includes, e.g. innovative processes for biomass comminution to be used in flash pyrolysis, biomass pre-treatment (drying, washing), measures to increase process efficiency and the application of special (catalytic) heat carrier material or dedicated catalysts.

RT2: Increase feedstock flexibility

Along similar lines as those outlined for gasification, the pyrolysis-based options also offer a large potential for cost reduction by applying lower-quality biomass feedstock. Given the fact that currently mainly relatively high-quality biomass (clean woody biomass and straw) is being considered, the shift towards cheaper, lower-quality biomass still poses substantial R&D challenges.

RT3: Model development to improve mechanistic understanding

There is a continued need to further improve our mechanistic understanding of pyrolysis (fast, slow, catalytic) and translate this understanding into models at the particle and reactor level.

2.2.3.1.3 Torrefaction (and steam treatment/ steam explosion)

Generally, torrefaction technology and related steam treatment and steam explosion technology concepts for solid intermediate bioenergy carrier production have proceeded to TRL 6-8, with a range of demonstration units in place and the first full-scale plants being built. There is a quite thorough mechanistic understanding and a wide range of reactor and process configurations are being applied, partly depending on the type of feedstock applied.

However, further development work is needed in order to make the technologies more competitive and tune them to new applications, instead of the initially targeted co-firing in coal-fired power plants. These new applications include industrial and residential heat (and CHP), application in metallurgical processing and as solid intermediates in biofuel value chains. Moreover, the quality of the resulting solid bioenergy carrier could be improved and there is a desire to expand the portfolio of suitable feedstock, to include lower quality biomass and biomass (-containing) residues (including RDF and SRF) in addition to woody feedstock and straw. Finally, there is a potential for the (co-)production of products with a higher added value.

RT1: Improve solid bioenergy carrier quality

Generally, torrefaction and heat/steam treatment are combined with a densification step (e.g. pelleting or briquetting) to arrive at a solid bioenergy carrier with superior logistics, storage and conversion properties. However, this densification step is often still challenging involving high energy consumption and high wear of equipment parts and limited quality of the pellets or briquettes. Moreover, the mostly claimed hydrophobic nature (good water resistance enabling outdoor storage) is in practice not always accomplished to a sufficient extent. Densification at elevated temperature levels may be one of the solutions. Safety (e.g. in terms of explosion and self-ignition risks) and further development of protocols and standards for specific bioenergy carrier properties (e.g. hydrophobicity and explosion) are also important issues to be addressed further.

RT2: Increase feedstock flexibility / enable treatment of lower-quality feedstock

Lower quality feedstocks may require specific pre-treatment to minimise operational problems. Moreover, a combination with washing may have to be applied to deal with a higher level of impurities (e.g. ashes, Cl, S, N, alkali matter).

RT3: Develop new high-added-value products from heat/ steam treatment processes

Options to recover (compounds from) the product gas of heat/ steam treatment in general (e.g. acetic acid) may be explored further, recognising that hemicellulose is largely devolatilising and forms a range of (valuable) condensables. Separation and fractionation of these compounds will require dedicated technology approaches. Moreover, new high-added-value products may be produced from the solid heat/steam treated biomass itself, like composite materials.

2.2.3.1.4 RP4. Hydrothermal processing

Hydrothermal processing is a wet thermochemical conversion process used to convert biomass into higher value chemicals, biochar, biofuel intermediate (biocrude) or gaseous energy carriers such as CH_4 or H_2. Water is fundamental as a reaction medium at pressures and temperatures close to the critical point. HydroThermal Carbonisation (HTC) typically occurs at low pH at lower temperatures, up to approx. 250 °C, and pressures around 100 bar; HydroThermal Liquefaction (HTL) in the temperature range 250-450 °C and pressures up to 350 bar; and HydroThermal Gasification (HTG) at temperatures above 500 °C. For HTL of lignocellulose, alkaline conditions favour oil products. At near-critical conditions, water properties change to facilitate depolymerisation through mechanisms such as decarboxylation, dehydration and repolymerisation of water-soluble reaction intermediates through different condensation pathways to insoluble oil compounds (HTL) or biochar (HTC), or further breakdown into gas compounds by radical reactions (HTG). HTL produces the most complex product by way of a multicomponent, partially oxygenated biocrude, which by upgrading can replace fossil crude oil or supply various chemical processes.

Barriers related to scaling up the technology include the lack of opportunities to demonstrate technology feasibility (energy balance); challenges in pumping the slurried biomass; transport issues for downstream products; and problems with equipment stability, reliability, and dependability. An integrated process analysis and optimisation of HTL — including everything from biomass to fuel and resource recovery — should help to optimise costs, environmental considerations, yield, and equipment during scale-up. Identifying and validating viable solutions for nutrient recycling will enhance process economics too.

RT1: Improve (basic) mechanistic understanding

This research theme concerns improving the basic mechanistic understanding of hydrothermal processing in order to avoid/mitigate operational problems, improve efficiency and optimise product quality. The chemical pathways (and their kinetics) of the de- and re-polymerisation, leading to both the transition from water soluble to water insoluble as well as to coke and char formation and precipitation, will have to be clarified. This is crucial to achieving a high conversion rate for the feed carbon into the valuable product (i.e. in HTC to maximise the formation of HTC char, and in HTL/HTG to maximise HTL oil or HTG gas by suppressing the undesired formation of coke) and to influencing product quality. Furthermore, the mechanisms for achieving a stable, high dry-matter content feedstock slurries while keeping good flowability and pumpability need to be better understood and improved methods need to be developed to characterise these slurries. This research theme also includes development and application of in-situ catalysts, e.g. to reduce the number of chemical compounds formed during HTL, which is crucial to reducing the upgrading (hydrotreating) effort downstream of the HTL, which would reduce costs. However, as with pyrolysis, here too major challenges still exist with respect to catalyst recovery and maintaining catalyst activity over many cycles.

RT2: Optimise reactor and process concepts and scale-up

More reliable and robust process performance is required to reduce costs. Firstly, the findings of RT1 will have to be translated into concrete reactor and process solutions. For example, the principles and kinetics of coke formation need to be considered together with fluid dynamics to control coke/char precipitation, and the mechanistic understanding of making slurries that are stable and have a high dry-matter content need to be applied in slurry preparation technology. Moreover, issues including reliant pumping of non-Newtonian liquids, internal product stream recycling and product phase separation and materials selection need to be addressed. The reduction of inorganic and organic (e.g. organic sulphur) contaminants either upstream or downstream of the hydrothermal stage needs to be considered to increase the availability of the process and to reduce costs of catalyst regeneration/replacement. Finally, a better understanding of reaction kinetics is required to optimise heating systems, reactor volumes and holding times, leading to optimised process designs.

RT3: Develop analytics and common/standardised reporting of data from hydrothermal processing

In order to facilitate the continued and efficient development of these technologies, it is crucial to improve and harmonise analytics and agree on a common, reproducible nomenclature and data reporting procedure. For example, the chemical structure of intermediate and oligomeric compounds must be known, and the results should be comparable. Currently, the definitions of "solid", "water soluble" and "water insoluble" products depend on the procedure and/or solvents used to separate products from hydrothermal processing, leading to incomparable results and, ultimately, failure to effectively incorporate data from various sources into subsequent steps. Likewise, total inconsistency in reporting of yields is a problematic issue. Establishing solubility metrics to define a single definition of the different product phases will be a priority.

2.2.3.2 RA2. Downstream processing (product cleaning, conditioning and upgrading)

The scope of this research area is to arrive at improvements of the secondary thermochemical conversion processes for advanced biofuel and intermediate bioenergy carrier production, downstream of the primary conversion step. The downstream processes considered are product cleaning, conditioning and upgrading. Research is needed to improve individual unit operations, e.g. single process steps for removing specific components from the gaseous, liquid or solid product of the primary processing, in terms of reliability, costs, efficiency and environmental footprint, but also possibilities for process simplification and intensification, e.g. by integrating unit operations.

Clearly, this should not be considered in isolation, but in relation to the primary conversion process. Adjusting the primary conversion process, or even incorporating part of the cleaning and conditioning in it, may require less downstream processing and may lead to more cost-effective approaches overall.

2.2.3.2.1 RP1. Gas cleaning processes

There exist numerous concepts for gas cleaning at different TRL levels today. For these concepts, the key to success is process simplification and intensification. Based on developments over the past 20 years, each value chain defined by feedstock, end-product and scale of installation will require its own specific optimum gas cleaning process. For the more challenging applications, like biofuel (and biochemical) production where further conditioning and upgrading generally require very low impurity levels, there is a need to increase reliability, reduce costs and minimise the residues (or finding utilisation options for the residues) of gas cleaning.

Gas cleaning processes should be improved holistically. Typically, a range of impurities is removed in multiple gas cleaning steps/units such as filtration, sorption or catalytic conversion. A detailed mechanistic understanding is required to improve and scaleup the individual gas cleaning steps, or even develop completely new, superior ones. But beyond that, more R&D work is needed on the smart integration of the individual cleaning steps into gas cleaning systems. This should include process simplification and intensification, but also take measures in the primary conversion process into account.

RT1: Improve individual gas cleaning processes

The gas cleaning processes of most interest is particle removal, and tar and sulphur management. However, the production of H_2, bio methane, other gaseous hydrocarbons and liquid hydrocarbons generally requires the removal of a range of other compounds present in the product gas as well (e.g. HCl, NH_3, HCN, heavy metals, etc.). This holds in view of the requirements of conditioning and upgrading processes, but also in view of the required specifications of the final product.

With respect to tar management, processes may be developed that minimise the need for tar separation and its subsequent combustion, or that allow converting it to either valuable co-products or to producer gas. This requires developing thermal and catalytic processes to convert tar into gaseous hydrocarbons and further into H_2, CO and CO_2. Proper sulphur management should involve optimising the choice of gas cleaning process steps based on the origin of the biomass-derived gas and the downstream process, i.e. cost-efficient combinations of low- and high-temperature gas cleaning steps, such as for example activated carbons or mixed oxide sorbents with hydrodesulphurisation (HDS) catalyst and subsequent zinc oxide. Here, trace sulphur compounds, e.g. organic sulphur, deserve attention.

RT2: Develop integrated gas cleaning systems

There still is a large potential to increase the reliability, reduce the cost and minimise the residues of gas cleaning through smart integration of the individual cleaning steps, which should be explored further. This involves minimising temperature swings, smart heat integration, selecting proper pressure levels (in case of conditioning and/or upgrading taking place at elevated pressure), recycling/utilisation of gas cleaning residues, process integration (e.g. application of multifunctional catalysts; example: reforming catalysts that work in the presence of impurities such as sulphur and are also able to convert S and N compounds), etc. In addition to thermochemical gas cleaning processes, biochemical processes should also be considered.

Clearly, the cleaning requirements depend on the biomass type, the measures taken in the primary conversion step as well as the requirements of conditioning/upgrading processes and the specifications of the final product. Both primary measures and the application of more tolerant catalysts/sorbent for conditioning/upgrading or more tolerant alternative conditioning/upgrading processes (as claimed for syngas fermentation) reduce the requirements for, and cost of, the cleaning step.

RT3: Improve sampling, measurement and control techniques

Accurate sampling and measurement techniques should be (further) developed for all relevant and potentially harmful (trace) species (such as S and N species, Cl, heavy metals, Se, P, etc., but also aerosols), even in very small concentrations, to validate the performance of the chosen gas cleaning steps. Moreover, biofuel production systems require proper control techniques and strategies to ensure long catalyst life and meet product requirements.

2.2.3.2.2 RP2. Conditioning and upgrading of clean gas and product recovery

This Research Priority concerns the conditioning and upgrading of product gas after gas cleaning to produce biofuels and to co-produce biochemicals. The co-production may involve a partial conversion of the main product gas compounds, H_2 and CO, to higher-added-value non-energy products. However, especially when gasification is carried out at relatively mild conditions (lower temperatures), the product gas also contains compounds like BTX and ethelene, which represent a significant (added) value when they can be extracted selectively. These co-production options will be addressed in Section 2.3.3.1.

Here, the focus will be on the conditioning and upgrading to biofuels, where catalytic processing and separation technology are the dominant technology options.

RT1: Tune conditioning/upgrading biomass processes or develop more tolerant alternatives

Many of the unit operations, required for conditioning and upgrading, are commercially available already for existing fossil-based value chains. In principle, these can be applied if the gas cleaning is able to meet their (generally very strict) specifications. However, given the differences between coal/oil conversion and the various biomass gasification processes, and the resulting deviant composition of the product gas, this may lead to a very complex and costly gas cleaning system. This provides a major driver for R&D to tune existing fossil-based processes to biomass applications. Improved catalyst, sorbent and/or membrane formulations should be developed that are more tolerant to biomass-derived contaminants in the product gas. Alternatively, more tolerant alternative conditioning/upgrading process concepts may be developed. Syngas fermentation is claimed be such an alternative and it appears worthwhile to assess the potential of this option in more detail.

RT2: Improve catalyst/sorbent regeneration procedures and develop spent catalyst/sorbent utilisation/recycling

Due to the high cost of catalysts, it is imperative to develop processes with high catalyst regeneration capabilities to reduce the overall costs and ensure good resource management. In addition, strategies for spent catalyst/sorbent utilisation or recycling should be developed.

RT3: Develop strategies and technology for product separation

Generally, catalytic synthesis processes yield a mixture of products, which requires further processing to yield a dedicated product that meets market specifications. Here, integration with existing refinery capabilities may be considered, but alternatively, dedicated separation strategies may be developed to avoid the regulatory complexity of mixing fossil-based and bio-based processing.

2.2.3.2.3 RP3. Cleaning, conditioning and upgrading of biocrude

Biocrudes from pyrolysis and HTL processes require proper conditioning and upgrading in order to be stored, applied as a drop-in feedstock in existing refineries or converted directly into useful products, especially biofuels. The upgrading is normally achieved by means of catalysts, often applying processes originally developed for the refinery field and then adapted for the case of biocrude. There are several challenges to fully developing these conditioning and upgrading processes, whose goal is continuous and reliable operations and to maximise value production.

RT1: Develop biocrude cleaning and conditioning

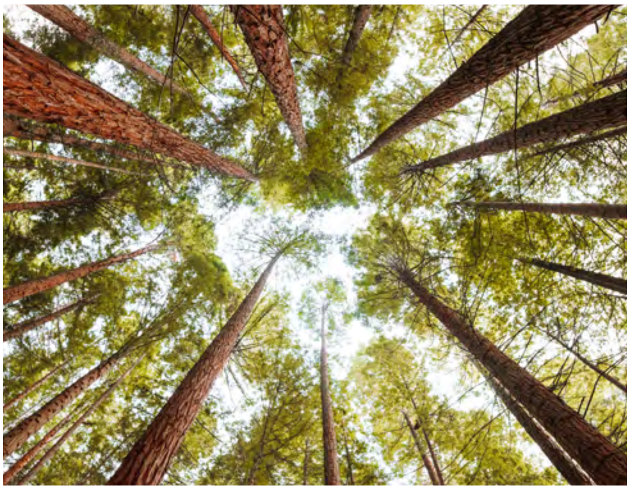
Even after cleaning, the direct use of biocrude is only reasonable in a few cases, since the biosyncrude at this stage is not adapted to the planned utilisation. Biocrudes need proper conditioning to allow longer-term storage and in order to be applied as a drop-in or to be upgraded directly into products like biofuels. One common problem is the reduction of the ash content. High amounts of ashes can catalyse polymerisation, resulting in a very viscous oil. Moreover, the ash content should not exceed a few hundred ppm, since metal ions can easily deactivate catalysts involved in subsequent upgrading operations. Leaching with an acidic aqueous solution or solubility modifications can be adopted to reach this goal. Another problem is posed by the water content, which is further increased by the polymerisation reactions. Phase separation may occur, resulting in an aqueous light phase and a high viscous heavy phase. The aqueous phases have a low heating value and alternatives to thermal conversion of these streams have so far not been established, though they are highly recommended regarding energetic efficiency. In the case of catalytic upgrading, the water content should preferably be kept low in order to extend the operating life of the catalyst. The heating value and stability of the main organic product can be increased reasonably by catalytic hydrogenation at high pressure. This option is connected to the aforementioned cleaning of biocrude (removing the nitrogen, sulphur and chlorine heteroatoms) and to the research on suitable catalysts: optimisation of stability and development of regeneration techniques for long-term use. This approach preferably needs a source of renewable hydrogen, which might be provided through water electrolysis with electricity generated from solar or wind.

RT2: Develop and test catalysts for effective upgrading of liquids

Catalyst development is a crucial topic, which is strongly connected with the upgrading process selected. As far as hydrotreating is concerned, an important topic is the development of non-sulphided catalysts, which could avoid the prior spiking of biocrudes with sulphur-rich chemicals. Additionally, it is important to develop catalysts that are effective not only for deoxygenation but also for denitrogenation. Nitrogen removal from biocrude is important for many residual biomasses, especially for manure and algae. It is also of utmost importance to develop catalysts for (hydro) cracking the distillation residue of biocrude. This could lead to additional oil recovery and could pave the way to differentiated treatment routes for light and heavy fractions respectively.

RT3: Develop treatments and uses for aqueous effluents, incl. by-product recovery

Hydrothermal processing, but also various pyrolysis concepts (e.g. when combined with staged condensation), result in the production of considerable amounts of aqueous effluents. These liquids still contain relevant amounts of dissolved organics, which could be effectively recovered. Moreover, concentrated organics are normally not compatible with direct disposal into the environment, thus requiring proper treatment. Possible ways to achieve both aims are represented by anaerobic digestion or catalytic hydrothermal gasification, which could effectively convert a large part of these organics into valuable combustible gases (CH_4, H_2, CO), thus allowing for additional energy recovery. Furthermore, the aqueous effluent can be the source of important nutrients such as N, P, Ca and Mg, which can be recovered by means of separation techniques such as precipitation, extraction or adsorption.



2.2.3.2.4 RP4. Solid product conditioning and upgrading

Solids may be the main product, as in torrefaction and HTC, but may also be considered as a major by-product, as in pyrolysis, HTL or (low-temperature) gasification. They may serve as an intermediate bioenergy carrier to be applied for heat and power generation, biofuel production, as a reducing agent in metallurgical applications, or be applied as a material for, e.g. soil improvement, fertilisation or as a replacement of fossil-based activated carbon. For the most part, however, the solids from the primary thermochemical conversion cannot be applied as such. They may need, e.g. purification, activation and/or densification. Moreover, their characterisation in view of the various utilisation options requires specific attention. For the solid product, various names may be used, such as biocoal, biochar, biocokes, thermally treated biomass, torrefied biomass, etc. In this section, biochar will be used as the universal name.

RT1: Biochar separation/purification and characterisation

Especially in processes where biochar is the co-product, proper methods for the "harvesting" (i.e., isolated collection from the process) and purification have to be developed/applied, which often is not a straightforward issue. Moreover, the biochar and the upgraded biochar product (see below) need to be characterised in view of the various utilisation options. This involves a range of rather standard properties (e.g. prox. and ult. analysis, density, particle size (distribution), internal surface area, pore size distribution) and unconventional properties like hydrophobicity. In order to facilitate the development of various application options, it is crucial to improve and harmonise analytics and reach common, reproducible nomenclature and data reporting procedures.

RT2: Biochar upgrading (e.g. activation, densification, etc.) and assessment of utilisation options

The biochar resulting from the primary process mostly needs further processing. Depending on the application this may involve various steps, but often includes densification (e.g. pelleting or briquetting) and in many non-energy cases (also) activation. If biochar is the main product, then, clearly, the primary conversion process should be tuned already to yield optimum biochar properties, to minimise downstream upgrading requirements. If biochar is a by-product, there may be fewer possibilities for this, but it should be considered as well. An assessment of the various utilisation options requires close collaboration with experts in the application (e.g. application as soil improver or fertiliser) in order to allow for an overall optimisation.

2.2.3.3 RA3. Value chain design – Integral pathways for biomass conversion into advanced biofuels and intermediate bioenergy carriers

In order to arrive at high-efficiency, cost-effective processes with high GHG savings and low environmental impact, the individual unit operations for primary conversion and subsequent product cleaning, conditioning and upgrading have to be combined into a smart system design and, beyond that, a smart overall biomass-to-bioproducts value chain design.

Attaining a certain biomass-main bioproduct combination generally starts with the design of the supply chain and a detailed analysis of the biomass (residues) to determine the best technology options and the optimum system size. High overall conversion efficiency requires proper system heat integration, but may also benefit from integration with other industrial activities or industrial symbiosis (e.g. by exchanging heat, power, steam, etc.). Process simplification and intensification, e.g. by integrating unit operations, may also contribute to increasing efficiency as well as reducing cost. The system may consist of (thermo) chemical or (bio)chemical unit operations only, but it is increasingly recognised that combinations of thermochemical and biochemical processing (e.g. combining gasification and syngas fermentation) may have benefits. To minimise the environmental impact, residue/waste streams from the process should be minimised aiming for zero discharge/zero waste, e.g. through internal recycling of residue streams.

On the products side, smart co-production schemes that combine energy products (biofuels, power and/or heat) and chemicals/materials with a higher added value may lead to more appealing business cases with lower specific production costs. Therefore, energy-driven biorefinery concepts (i.e., where the energy products are the main products) may preferentially be aimed for. Moreover, the H/C ratio in the biomass feedstock often does not match with the required H/C ratio in the product(s), leading to a surplus in H_2 or CO_2 (in most cases the latter applies). This latter case gives room either for collecting the surplus CO_2 as a concentrated stream and using it for BECCS concepts (BioEnergy combined with Carbon Capture and Storage) or BECCU (BioEnergy combined with Carbon Capture and Utilisation), or for adding additional (renewable) hydrogen to arrive at the proper H/C ratio for the product(s). Both options may improve the overall business case and contribute to high GHG savings.

Finally, several of the system options indicated above imply that the system should not be considered in isolation, providing only products to the energy sector, but that couplings with other industrial/economic sectors come into play. This may concern the exchange of utility services, chemical intermediates for the chemical industry, biochar applied as fertiliser, soil improvement or filter material, etc.

The technical assessment and further development of these various options requires pilot projects and demonstrations, supported by R&D at lower TRL-levels to reach further efficiency gains, cost reductions and increases in GHG savings through additional process and system innovations.

2.2.3.3.1 RP1. Gasification-based production of advanced biofuels

The design of systems and overall value chains for the gasification-based production of advanced biofuels basically involves all the aspects and options outlined above. Given the wide variety in biomass (residues) feedstock and the different biofuels aimed for (e.g. FT-diesel, (higher) alcohols, CNG/LNG), there will not be one ideal system concept, but rather a whole suite of options to be introduced into the marketplace. Although in practice, all the aspects described above will have to be addressed, the following three aspects require R&D attention and are therefore distinguished as separate research themes here.

RT1: Optimise gasification-based biofuels production systems

To maximise efficiency and minimise costs, optimisation here may include heat integration and optimisation of the overall heat and energy balance, zero-discharge/zero-waste concepts involving recycling of residue streams, process simplification (e.g. incorporating once-through synthesis processes), process intensification by combining unit operations, etc.

RT2: Develop chemical/material co-production concepts to boost biofuel business cases (energy-driven biorefineries)

Gasification-based biofuel production allows for a wide range of chemical/material co-production options, which could make a significant contribution to boosting biofuel business cases by increasing the overall value added to the biomass feedstock. These concepts, where energy products are still the main products, are called energy-driven biorefineries, in contrast to product-driven biorefineries where chemicals/materials are the main products. The co-production may involve a partial conversion of the main product gas compounds, H_2 and CO, to higher-added-value non-energy products. In this respect, (partial) syngas fermentation deserves special attention as an option that is attracting more and more interest. However, especially when gasification is carried out in relatively mild conditions (lower temperatures), the product gas also contains compounds like BTX and Ethylene, which represent a significant (added) value when they can be extracted selectively. Low-temperature gasification generally leads to fewer operational problems in terms of agglomeration and fouling, but carbon conversion may be lower. However, this may be turned into an asset if the remaining carbon-rich char (biochar) can be extracted and made fit for applications, like a reducing agent for the metallurgical industry, a soil improver or fertiliser, or a filter material.

RT3: Integrate gasification-based biofuel production with renewable hydrogen and/or BECC(U)S

Given the scarcity of biomass, recognising that in the foreseeable future biomass is the only affordable sustainable carbon source, and in order to minimise the overall cost of sustainable energy generation and GHG emission reductions, it is important to maximise the effective utilisation of the biomass, and the biomass-carbon. Various technology options arise that require further (experimental) assessment and development, including coupling of biomass processing with renewable hydrogen to match the H/C ratio required for the planned product mix (and maximise the product mix yield), BECCS by capturing and storing surplus C in the form of biochar, and BECCS or BECCU by extracting the surplus C as a concentrated CO_2-residue stream.

2.2.3.3.2 RP2. Pyrolysis-based production of bio-oil and advanced biofuels

Commercially operated pyrolysis plants today are integrated into local or regional networks, which is an excellent way to push new technology into the market. For fuel production on a large scale, the maturity of the technology needs to be improved. In the short to medium term, co-refining with fossil fuels may empower the implementation of fast pyrolysis technology beyond today's main use as heating oil. R&D efforts should aim at the following.

RT1: Overall system optimisation and validation

The technical optimisation opportunities should be exhausted to improve plant availability, reduce conversion costs, further increase efficiency and minimise the environmental footprint (incl. GHG emissions). Higher feedstock flexibility is desired to make plants fit for multi-feed supply. For drop-in fuel production, catalytic upgrading must be applied, for which the TRL needs to be increased and long-term operability has to be proven. Due to the expected, much higher degree of technical complexity compared to existing applications of the biocrude (i.e. as heating oil), process integration must be planned for the multistep processing, including hydrogen recycling, catalyst regeneration, heat shift operations and the like.

RT2: Co-production of fuels and chemicals

Combined processes promise to provide better economics than the single use of complex bio-oil mixtures as fuels only. Examples could be the separation of small molecules, followed by mild catalytic upgrading. Products will consist of C2-components (acetol, acetic acid…), fuel (aliphatic molecules) and phenolic substances for chemistry or as fuel components (as proposed in the FP7 EU BioBoost project).

RT3: Integration optimisation

Integration of renewable energy into pyrolysis and bio oil upgrading processes. Intelligent multi-stage upgrading processes must be established, different from those usually adapted from crude oil applications (sugar chemistry is different from crude oil). Integration of catalyst regeneration, hydrogen supply and recycle, and heat integration should be considered.

2.2.3.3.3 RP3. Heat/steam-treatment-based production of solid bioenergy carriers

As mentioned, torrefaction technology and related steam treatment and steam explosion technology concepts for solid intermediate bioenergy carrier production have proceeded to higher TRL, but further development work is still needed in order to make the technologies more competitive and tune them to new applications. In addition to further R&D on heat/steam treatments and coupled densification, there is a need for further optimisation at the system or value chain level. Moreover, solid bioenergy carrier production recipes may be better tuned to specific applications.

RT1: Integral system / value chain optimisation

There is a need for further optimisation of integral heat/steam-treatment value chains in order to optimise efficiency and reduce CAPEX and OPEX. Smart process integration is required to optimise the heat/energy balance. This involves not only the heat/steam treatment itself, but even more so pre-drying if required. System optimisation becomes even more relevant, if washing must be applied to deal with higher levels of impurities. In that case, not only should the heat/energy balance be optimised, but fresh water make-up should be minimised, and the effluent stream should be minimised, and a proper, cost-effective treatment of this stream should be developed. Depending on the heat requirement of the overall solid bioenergy carrier production process, integration with other (bio-based) industrial processing with surplus heat may be considered.

RT2: Tune solid bioenergy carrier production recipes to specific applications

This may involve incorporating dedicated additives into the bioenergy carriers to mitigate operational problems (e.g. agglomeration, fouling, emissions) in the conversion processes, in which the bioenergy carriers are to be applied. An assessment may also be necessary of whether recipes can be developed that allow subsequent biochemical processing (enzymatic hydrolysis and fermentation) as well.

2.2.3.3.4 RP4. Advanced biofuels and intermediate bioenergy carrier production based on hydrothermal processing

Hydrothermal processing is yet to make its way into demonstration and commercial scale (for other applications than pre-treatment stages to biochemical processes). Thus, value chain designs cannot rely on existing examples, but must rely on models and data derived from lab and pilot scale processes. However, it also offers a unique opportunity to design integrated scenarios for implementation in which all parts of the value chain are co-optimised to reach a global optimum, rather than a sequential optimisation where this cannot be achieved to the same extent. It also allows bringing in learning from other similar technologies such as pyrolysis, that are at higher TRL already. In this context, there are several aspects to focus on as key research themes.

RT1: Develop smart system designs with non-energy co-products

This theme involves the development of smart hydrothermal processes/systems to produce advanced fuels or intermediate bioenergy carriers, together with other valuable products, in order to make biofuels/bioenergy carriers cheaper. Technology options to be considered include recovery of phosphorus from aqueous phases, usage of aqueous phases, for instance, via anaerobic digestion, internal recirculation or gasification, extraction of chemicals prior to hydrothermal processes or from HTL biocrude, integrated hydrogen recovery for upgrading processes, etc.

RT2: Optimise system design through integration

Firstly, this involves integrating HTL and hydrogenation processes to produce hydrocarbon-rich intermediate bioenergy carriers by co-optimising material and energy flows, including heat integration. This includes scale-of-plant studies to identify optimal co-location of liquefaction and upgrading stages vs decentralised hub-and-spoke structures. Moreover, downstream integration of HTL with existing refinery infrastructure will have to be assessed and optimised, including integration points and mixing strategies, as well as the scale of the plants to be integrated. Business scenarios to investigate the value points of such integration from the perspective of marginal profit unit operations and final product value will have to be devised. Finally, the integration of HTL and upgrading with the electric grid should be assessed to provide buffer capacity into a future grid, which might be expected to have significant but highly fluctuating surplus electricity. Process schemes and layouts that optimise value created by smart grid integration and high efficiency biofuel/chemical production should be identified and evaluated, including schemes that utilise or sequester CO_2 produced in the combined process.

2.3 Subprogramme 3 (SP3) - Biochemical processing of biomass into advanced biofuels and bio-based products

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2.3.1 SCOPE

The cost-effective co-production of advanced biofuels and bio-based products from (bio)chemical processing of all fractions of biomass (including energy crops, forestry and agribusiness side-streams, organic fraction from municipal solid wastes, macro and microalgae, etc., but also e.g. biogas (from anaerobic digestion)) and syngas from thermochemical processing of biomass and other wastes is the main goal of SP3 of EERA Bioenergy in the context of the bio-economy and the circular economy.

Moreover, Europe urgently needs the fast deployment of technological processes based on medium and small biorefineries due to decentralised and low levels of sustainable biomass availability and supply for large-scale biorefineries (e.g. >300.000tonnes feedstock/year). This goal prioritises the use of residual biomass as well as wastes, in full observance of the EU Waste Directive.

2.3.2 MAIN CHALLENGES

SP3 aligns its main R&D challenges with the Integrated Roadmap of the SET-Plan and the Declaration of Intent on *"Strategic targets for bioenergy and renewable fuels needed for sustainable transport solutions in the context of an initiative for global leadership in Bioenergy"* of Nov 16th, 2016, and selected **four main R&D Priorities/Challenges and Key Performance Indicators (KPIs) to be addressed:**

- **Main Challenge 1: To develop cost-effective biological and chemical technologies and improve the biological efficiency of production processes for ethanol, higher alcohols, fatty acids, and bio-based hydrocarbons to replace petrol, diesel, and jet fuel.**

KPI: By 2030, improve net process efficiency for converting biomass (as a % of useful energy output compared with the net sum of energy inputs) to biofuel products by at least 30% compared to present levels while simultaneously reducing the conversion process costs.

- **Main Challenge 2: To increase the efficiency of converting lignin and (hemi)celluloses feedstock into biofuels and/or bio-based chemicals to boost the economic viability of advanced biorefineries.**

KPI: By 2030, obtain a net efficiency for converting biomass (as a % of useful energy output compared with the net sum of energy inputs) to intermediate energy carriers of at least 75%, with GHG emission savings of 60% obtained by using all types of intermediate bioenergy carriers.

- **Main Challenge 3: To develop long-term research for improving the biological efficiency and product yields for converting hydrogen and C1 compounds into advanced gaseous/liquid biofuels.**

KPI 1: Reduce production costs of liquid or gaseous advanced biofuels by biochemical processing, reaching < 50€/MWh (in 2020) and 35€/MWh (in 2030). The cost reduction should be at least 30% lower compared to 2020 levels.

KPI 2: Improve net process efficiency for producing algae-based advanced biofuels by biochemical processing, reaching <70€/MWh (in 2020) and 35€/MWh (in 2030), René van Ree at least by 50% from 2020 levels.

- **Main Challenge 4: To increase the efficiency of RES-Hybrid systems for producing intermediary bioenergy carriers (e.g. hydrogen, biogas) or biofuels by integrating biochemical biomass conversion pathways into other renewable energies (e.g. CSP, water electrolysis).**

KPI: By 2030, improve net process efficiency for producing renewable hydrogen from biomass and other RES systems, reaching a maximum production cost of <7€/Kg by 2020 and <4€/Kg by 2030.

Fig. 6 shows the new SP3 Strategic Research and Innovation Agenda (SRIA) and the interlinks amongst Research Areas (RAreas), Research Priorities (RPriorities) and Main Challenges (MC).

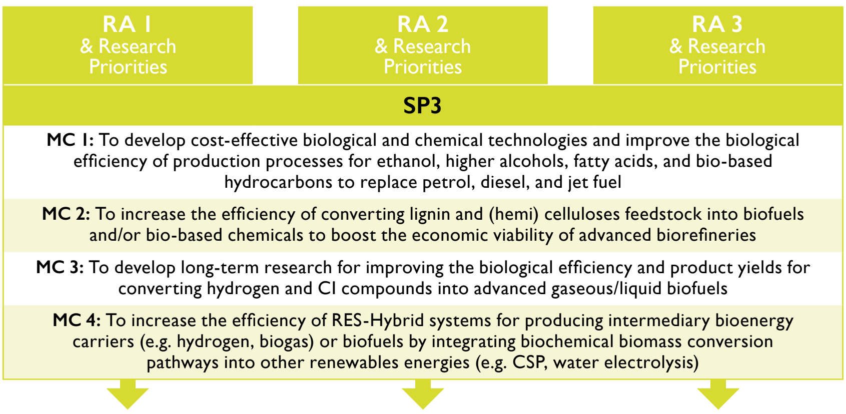

Figure 6: The four main challenges of SP3 are addressed through cross-cutting Research Areas and Research Priorities

2.3.3 SP3 RESEARCH AREAS (RA) AND RESEARCH PRIORITIES (RP)

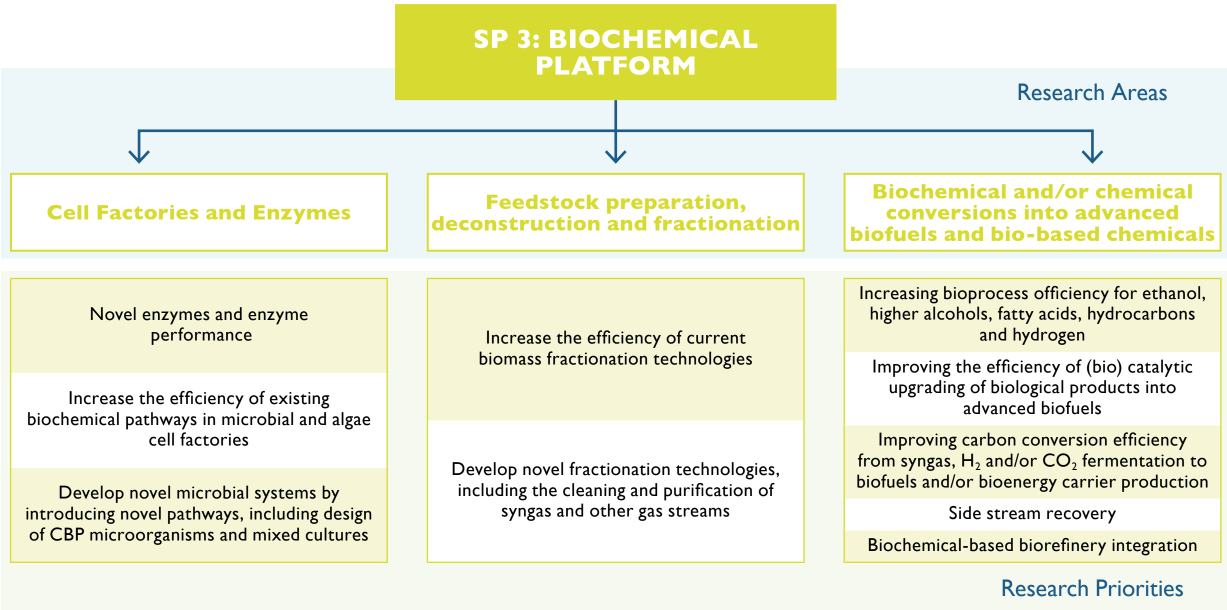

Figure 7: Schemes of the distribution of priorities in each research area of the SP 3

The three Research Areas are described as follows:

2.3.3.1 RA1. Cell factories and enzymes

A second-generation biofuel technology using dedicated cell factories, either for simultaneously fermenting C5 and C6 sugars to ethanol (at the commercial scale) or into more hydrocarbon molecules (e.g. isobutanol or fatty alcohols to produce diesel, petrol and jet fuel substitutes - still at the demonstration scale), appears to be close to the commercial market. However, its efficiency and robustness under optimal commercial-scale conditions still needs to be improved considerably to enhance product yields and productivity and decrease product unit cost. In addition, new technologies still must be developed for other innovative biofuel molecules (e.g. butyl butyrate, limonene, isobutene derivatives) with improved properties and better compatibility with existing fuels and engines, as well as for use in aviation. Furthermore, improved enzymes and enzyme production systems are needed to ensure and demonstrate the cost-efficiency of entire value chains from biomass feedstock to biofuel product generation. Process integration will be another key to address that challenge. The following research priorities and research topics will contribute to solving these technical barriers.

2.3.3.1.1 RP1. Novel enzymes and enzyme performance

Enzymes in bio-based processes are still a major cost driver. More efficient new and improved enzymes and enzyme technology are needed to render biofuel and other bulk biorefinery production processes more cost-effective. The major challenges still to be overcome include cost-inefficient enzyme production, sub-optimal activity, and low stability in biofuel production process settings. These are addressable by discovering more efficient and more stable enzymes, and/or enzyme engineering, including using innovative, (ultra-)high throughput enzyme screening systems (FACS, microfluidics, IVTT, broad host-range, etc.). Concerning lignocellulosic biomass conversion, so far most of the attention has been devoted to thermotolerant enzymes because of their advantages in the Separate Hydrolysis and Fermentation (SHF) process. However, for Simultaneous Saccharification and Fermentation (SSF), as well as Consolidated Bioprocessing (CBP), novel enzymes with high catalytic efficiency and stability at fermentation temperatures of 35-50 °C would be highly beneficial.

RT1: Enzymes for bio-based chemical synthesis and biofuel synthesis

New low-cost microbial enzyme production systems are needed (e.g. co-production of multiple enzymes, whole-cell biocatalysis), as well as improved enzyme technology for efficient enzyme recycle in both biomass breakdown and bio-based chemical synthesis (e.g. immobilisation of polymeric particles, membranes, cells, etc.). New enzyme discovery should thereby address the entire microbial biodiversity, e.g. by using metagenomics and meta-transcriptomics approaches and involve both bioinformatics- and function-based approaches. Suitable new enzymes should be more robust against inhibitors present in pre-treated feedstock and withstand other harsh process conditions, like changes in pH and temperature, and the presence of chemicals and solvents. New thermostable enzymes are needed to develop more efficient and more durable enzyme cocktails, applicable in processes at elevated and fluctuating temperatures. Beyond the main application of enzymes in cocktails for biomass hydrolysis, the use of enzymes to synthesise biofuel compounds needs more attention, e.g. by converting microbial produced intermediates into final biofuel compounds (e.g. esterases, decarboxylases, lyases).

RT2: Biological lignin depolymerisation

New enzymes and enzyme mixtures are also needed to efficiently depolymerise lignin into aromatic monomers, that can in turn be used for controlled (enzymatic) polymerisation into polymers e.g. for the bio-plastics market.

RT3: Increasing the efficiency of hemicellulases for pre-treated lignocellulosic biomass

The efficiency of enzymatic cellulolytic cocktails in terms of cellulosic materials has been greatly improved in the last decade. A similar improvement was not achieved with hemicellulases and accessory enzymes for industrial bioprocesses. Advanced biofuels utilise a wide range of feedstocks and the optimal integration of the operation unit's pre-treatment – enzymatic hydrolysis needs to be fully addressed, which mainly includes research on hemicellulases. Enzyme engineering can thereby be extended to enzyme systems engineering for more efficient (hemi)cellulose breakdown into fermentable sugars.

2.3.3.1.2 RP2. Increase the efficiency of existing biochemical pathways in microbial and algae cell factories

The metabolic pathways of microbial cells (yeast, fungi, bacteria and algae) are tuned to support cell growth and are generally not designed to overproduce single metabolites. These goals could be met by effective deregulation of cell metabolism, which could lead to an increase in the efficiency of pathways for synthesising the desired end products, including biofuels.

RT1: Uncoupling growth and fermentation

Suitable microbial strains need to be engineered for maximal fermentation activity in non-growing cells, maintaining at least 50% of the fermentation activity in growing cells. These strains need to remain viable over extended periods of time while producing the required single metabolites.

RT2: Increasing flux in accessory metabolic pathways

Many bio-based compounds are produced as end-products of accessory biochemical pathways, e.g. fatty acid or amino acid biosynthesis pathways, in which the carbon flux is much lower than in the sugar to ethanol fermentation pathway. Research should therefore focus on engineering suitable modifications in these pathways to enhance the flux to a level of least 50% of the flux in the regular sugar to ethanol fermentation pathway.

RT3: Engineered bacteria for syngas conversion into liquid biofuels and other bio-based products

The concept of engineering suitable bacterial strains, e.g. the thermophilic acetogen *Moorella thermoacetica*, to produce 1-butanol from syngas from biomass gasification with a mass yield of at least 25% of the theoretical yield, will contribute to rendering microbial biofuel production more flexible with respect to biomass feedstock composition. Testing different ratios of H_2/CO using engineered strains is crucial for the optimal conversion of syngas into alcohol. Butyric acid production from H_2/CO (syngas) using other bacterial sources, e.g. *Clostridium tyrobutyricum*, is another target molecule that needs substantial yield improvement before reaching the demo level. 1-butanol can be chemically converted with butyric acid into the ester butyl butyrate, a precursor with high potential as a heavy-duty transport biofuel and potentially, aviation bio-jet fuel. For optimal conversion of syngas into butyric acid, stable and highly active mixed cultures of homoacetogenic syngas-utilisers and *Clostridium tyrobutyricum* need to be developed. The tolerance to potential inhibitors presents in syngas derived from heterogenous biomass needs to be co-addressed by strain adaptation concomitant with improved syngas purification technology.

RT4: Making artificial photosynthesis a reality

Novel technologies, currently still at the bench scale, to harness solar energy and store it in fuels in a CO_2-neutral way should play a role in the future RES energy mix beyond 2030. This comprises e.g. the direct production of electrons by microorganisms and/or enzymes in so-called "microbial fuel cells" (H_2 route), "artificial photosynthesis", or "artificial leaves". For cost-effective future bioprocesses in this field, it is still necessary to expand our fundamental knowledge across the different disciplines involved and towards increasing photosynthetic efficiency well above the level of natural systems, like plants.

2.3.3.1.3 RP3. Develop novel microbial systems by introducing novel pathways, including design of CBP microorganisms and mixed cultures

Current processes for biorefining lignocellulosic biomass, especially for biofuels, are built upon several unit operations, including pre-treatment, enzymatic hydrolysis, fermentation, and finally downstream processing. For cost-effective advanced biofuel production, the number of operation units should be decreased, resulting in savings in investment and savings in operational costs. There is currently not a single microorganism known that contains the complete biochemical machinery for the full biorefinery biological process from raw feedstocks. Therefore, there is a strong industrial need to make consolidated bioprocessing (CBP) a reality, featuring microbial enzyme production and concomitant microbial conversion of suitable feedstock into value-added products in a single step. This offers great potential for establishing cost-effective bioconversion of lignocellulosic feedstocks.

RT1: Towards one-step conversion of lignocellulosic biomass directly into biofuels using yeast/bacteria as a model

For a successful biorefining process, metabolic engineering, systems biology, and synthetic biology are needed as tools to construct suitably robust and efficient cell factories for CBP. Fungal, yeast or bacterial genes expressing secreted hydrolytic enzymes should be integrated into the genome of industrial C5+C6 fermenting Saccharomyces cerevisiae, non-conventional yeasts or bacterial cell factories (e.g. *Clostridium acetobutylicum*) to develop the CBP concept to a TRL of 5-6.

RT2: Consolidated Bioprocessing for production of advanced ethanol as a platform for novel biofuels

Existing co-fermenting pentoses and hexoses and highly inhibitor-tolerant industrial yeast or, alternatively, bacterial (e.g. *Clostridium* sp., *Z. mobilis*) strains should be engineered to express the whole range of secreted hydrolytic enzymes required for CBP at adequate levels, i.e. to lower the requirement to add commercial enzymes by at least 80%, and to increase their thermotolerance to at least 42°C to improve enzyme catalytic efficiency. The production of novel biofuel molecules also needs to be addressed as an alternative for the current fossil-based jet fuel. As an example, the CBP yeast for bioethanol production or the CBP *Clostridium* for (iso) propanol and butanol production might be used as platform strains to engineer the capacity to produce high levels of long-chain fatty alcohols reaching at least 90% of the maximum theoretical yield. For that purpose, fatty alcohol synthesis capacity should be introduced, the capacity of the fatty acid biosynthesis pathway enhanced while ethanol production should be downregulated.

RT3: Increasing the efficiency of producing long-chain fatty acids by non-conventional yeasts for diesel and jet-fuel substitutes

Some oleaginous industrial non-conventional yeasts, e.g. *Trichosporon* sp., can directly produce high titers of triacylglycerides from lignocellulosic sugars; however, the efficiency is still low. *Yarrowia lipolytica* is also a very promising industrial cell factory for long-chain fatty acid production and several genomic tools are already available. New genome-scale metabolic models of oleaginous yeasts in computational models are needed, together with a parallel metabolic engineering approach, in order to improve the carbon conversion efficiency of long-chain fatty acid production to over 90% of the maximal theoretical yield (0.32 g fatty acids/g glucose) and at least 75% of the maximal theoretical yield from xylose. The current state-of-the-art yields are 85% and 44%, respectively.

2.3.3.2 RA2. Feedstock preparation, deconstruction, and fractionation

This research area needs to go hand in hand with the research area "cell factories and enzymes" to reach a meaningful integration of biology and engineering concepts. The target is to transform lignocellulose into intermediate streams with low toxicity, high sugar concentrations and useable lignin for biological and thermochemical upgrading to biofuels and bioproducts with minimal waste generation and energy use. The following research priorities and research topics will help to reduce costs and improve biomass fractionation efficiency.

2.3.3.2.1 RP1. Increase the efficiency of current biomass fractionation technologies

Biomass pre-treatment is one of the main technological barriers for efficient conversion of biomass into clean streams containing sugars and/or other molecules from feedstock. This is valid for lignocellulosic biomass as well as for algae. There is a very large number of biomass fractionation options, as potential technologies to produce biofuels and (bio) chemicals. In the case of lignocellulosic biomass, steam explosion, hydrothermal processing and organosolv are the main pre-treatment technologies for advanced bioethanol and other bio-based products. Complementarily, microalgae and macroalgae biomass also requires advances in fractionation technologies to lower the costs of bioenergy and bio-based product production.

RT1: Improving the conversion yield, energy efficiency and minimising the environmental impact of the most used lignocellulosic biomass pre-treatments in current advanced biofuel plants

Steam explosion (uncatalysed or acid-catalysed), hydrothermal processing, dilute acid, alkaline hydrolysis and organosolv pre-treatment technologies are being used at the demo and commercial scales. Although some of them work well with agricultural residues (e.g. wheat straw, sugarcane straw), all display technical problems when more recalcitrant materials, such as forest residues, are used as feedstock. Moreover, there are other limitations, such as the formation of fermentation inhibitory products during downstream processing, the use of solvents, acids or alkalis, high energy consumption, and low energy efficiency.

RT2: Algae fractionation

The wet process must be favoured from an ERoEI point of view. Among the potential technologies, ball milling is able to treat media with about a 5% dry-matter content. The removal of the lipid phase must, however, be optimised: e.g. direct liquid-liquid extraction or membrane separation. Moreover, recovery of the whole algae biomass includes the production of multiple marketable fractions (products) coupled with final leftover biomass use, which is currently the most economically appealing and feasible cascading biorefinery approach, considering the limited amount of algal biomass that is still available presently. One of the main challenges during the biorefinery approach is to preserve the compounds in the remaining fractions, especially their bioactive properties, requiring cost-effective, less energy demanding and milder fractionation operations, together with high yields and selectivity. All these aspects highlight the need for a careful design of whole downstream processing for an algae-based biorefinery, bearing in mind that the specific pre-treatment, extraction and fractionation steps are algae-specific and target compound-specific as well.

Novel mild extraction technologies have been triggered due to the need to reduce solvent use and to produce algal products while keeping their valuable properties, such as supercritical fluid-extraction, ultrasound-assisted extraction, microwave-assisted extraction, and pressurised liquid extraction.

2.3.3.2.2 RP2. Develop novel fractionation technologies, including cleaning and purification of syngas and other gas streams

The development of suitable fractionation technologies, including the removal of impurities and toxics, are important barriers to the development of advanced (bio) chemical-based technologies, as well as to their integration with thermochemical ones. Studies on lignocellulose fractionation, algae fractionation and purification, biogas and syngas upgrading, and liquid biorefinery product stream fractionation are key operation units for developing integrated value chains for bioenergy and bio-based products. Another approach is the use of homogeneous and mainly heterogeneous catalysts to enhance lignocellulose depolymerisation.

RT1: Development of new disruptive methodologies for biomass fractionation

Although multiple alternative pre-treatment methods are being developed, either the technology is not yet mature, or the cost is too high. The use of new techniques, e.g. ionic liquids or deep eutectic solvents may become a gamechanger in the pre-treatment field. Low-energy-consumption pre-treatments will radically differ from the (acid catalysed) steam explosion and organosolv pre-treatments, since they will work in the 120-160°C range or even below, which largely reduces the amount of inhibitory compounds generated.[18] In the future, the ideal biomass pre-treatments should be multi-feedstock and have enhanced sustainability as long as they minimise environmental impacts and reduce/avoid the use of exogenous enzymes, which currently have a major negative impact on life cycle impact analysis. Alternative, one-pot low-energy and low-cost non-hydrolytic pre-treatments coupled with biocatalysis/microbial systems is another way to advance innovation in this field.

RT2: Development of solid materials for biogas cleaning and upgrading (Cooperation of SP3 + SP2 and JP FCH)

Biogas production via anaerobic digestion is a well-established technology for biomass treatment and recovery, including lignocellulosic (e.g. forest, agricultural, and paper residues) and organic residues (i.e. municipal solid waste). However, the biogas produced also has impurities like N_2, O_2, CO_2, S compounds (mainly H_2S), some hydrocarbons, and others that need to be eliminated to finally attain pure methane. Catalytic membranes offer the possibility to separate N_2, O_2 and CO_2 from biogas, this being a viable alternative for biogas purification and an interesting research line. Other solid materials, such as zeolites, could be employed to separate hydrocarbon from CH_4. In addition, the design of novel solid absorbents could be useful for the selective and efficient elimination of H_2S and other impurities (chloride and silicon compounds) present in the biogas. In addition, high quality biogas and other gases (e.g. syngas) are requiered when it intended to feed, e.g. PEM or SOFC fuel cells for power production.

[18] A. M. da Costa Lopes and R. Bogel-Lukasik, ChemSusChem, 2015, 8, 947-965.

2.3.3.3 RA3. Biochemical and/or chemical conversions into advanced biofuels and bioproducts

Advanced biofuels and bioproducts can be produced from biochemical and/or chemical conversion processes. Both types of conversion routes require the use of (bio) catalysts; in the case of biochemical ones, they will be developed and optimised within sub-section 2.3.1. (RA1-Cell factories and enzymes). Transesterification and hydrotreatment chemical processes using biological products, like lipids under co-processing in a petrochemical refinery environment, is a powerful technology for producing greener fuels. However, in general, chemical processes beyond those already used in an oil refinery need innovations, mainly in catalyst research. Furthermore, the conversion efficiency of direct biochemical and/or chemical routes into advanced biofuels and bioproducts still needs improvement. The most relevant research priorities identified within this research field are the following:

2.3.3.3.1 RP1. Increasing bioprocess efficiency for ethanol, higher alcohols, fatty acids, hydrocarbons and hydrogen

Bioprocess intensification aims to make dramatic reductions in plant size by replacing the traditional unit operations with novel and very compact designs, often by combining two or more traditional operations into one hybrid unit. Some of the associated benefits are cost reduction as well as a reduction in energy consumption and environmental impacts.

RT1: Improving the robustness of industrial recombinant yeast and bacteria for lignocellulosic hydrolysates

Lignocellulose hydrolysates contain multiple microbial cell inhibitors that are generated during the pre-treatment and hydrolysis processes and compromise fermentation efficiency when producing ethanol or any other biochemical compound. In addition, many economically appealing compounds to be produced by cell factories are toxic in high quantities, and therefore inhibit production efficiency or even inactivate/kill the cells. Hence, increasing the robustness of cell factory microorganisms is a universal requirement for establishing efficient, bio-based production processes.

The performance of second-generation yeast using lignocellulosic hydrolysates is still behind that of the fast fermenting first-generation yeasts. It is also known that bacterial systems, in general, have comparably poor robustness when cultivated under harsh industrial conditions. Indeed, the removal of toxic or inhibitory compounds from the fermentation media turns out to be a challenge for all biochemical conversion processes. Two complementary approaches are needed: 1) the search for new detoxification processes, e.g. low-cost membrane-based technologies (i.e.: ultrafiltration, nanofiltration), seems to be a promising way to eliminate the inhibitory compounds while increasing sugar concentrations in the media; 2) metabolic engineering, evolutionary engineering, genome shuffling and site-directed genetic engineering studies of established stress tolerance targets to create more robust (yeast and bacterial) strains are essential to increase product yields and productivities.

RT2: Bioprocess intensification

Biochemical/microbial processes leading to the production of various alcohols and related reduced compounds are often cost- and energy-inefficient mainly because the final product concentration is relatively low, resulting in expensive recovery technologies that increase the overall product cost. There are three major reasons for these increased production costs: 1. In the case of bioethanol as product, its final concentration in the fermentation broth below 40 g/L leads to an extremely costly distillation process to obtain 99.5% pure fuel-grade ethanol; 2. In the case when the product (e.g. butanol) is toxic to the producing microorganism, this toxicity leads to low productivity and final concentration, and 3. In the case when the producing microorganism is a strict anaerobe (e.g. anaerobic bacteria), lower rates of carbon conversion are observed, leading to lower productivity.

There are various strategies for mediating these intrinsic hurdles. One of them is to start with as high as possible a solid ratio during biomass pre-treatment before fermentation takes place. More sugars at the start of the bioprocess means more carbon conversion into the main product (e.g. ethanol), decreasing the distillation costs and leading to an overall lower production cost of bioethanol. Another strategy is to utilise, as much as possible, cell factories that are tolerant to high concentrations of the desired metabolites by selecting the producing microorganisms based on high tolerance and rapid growth in the presence of toxic metabolites and under anaerobic conditions, and/or by adapting the cell factories to high concentrations of the desired end-product. Another strategy is to engineer tolerance to toxic compounds by e.g. introducing efficient export systems for the toxic compounds or to engineer detoxification pathways by converting the toxic metabolites in non-toxic end products. An example of the latter strategy is to introduce esterases in *Clostridia* that lead to direct conversion of toxic butanol, and other alcohols, into non-toxic esters or ethers.

2.3.3.3.2 RP2. Improving the efficiency of (bio) catalytic upgrading of biological products into advanced biofuels

After the fractionation of biomass via biological or enzymatic routes, also including enhanced and/or disruptive pre-treatment methods, the resulting intermediate fractions or hydrolysates need further upgrading to produce biofuels. The chemical conversion of these streams is not straightforward, mainly due to the low concentration of bio-molecules, the existence of impurities and non-desired compounds, and the presence of huge amounts of water.

RT1: Direct catalytic upgrading of biomass hydrolysate streams to produce hydrocarbons for advanced biofuels (e.g. jet-biofuel) *(cooperation between SP3 and SP2)*

Catalytic (membrane) upgrading is a plausible and integrating alternative to be studied, but novel solid materials need to be designed and developed for that purpose. Additionally, aqueous fractions derived from biomass primary biological treatments could be (thermo)-chemically converted into hydrocarbons and mixtures of aromatics that are useful as biofuel components by means of solid catalyst processing under mild reaction conditions[19]. The use of catalytic membranes for partial water/bio-molecule separation in those systems will provide clear advantages for the further processing of bio-derived fractions.

RT2: Catalytic upgrading of biological products from fermentation broths *(cooperation between SP3 and SP2)*

Production costs for biofuels, fuel additives, and other bioproducts can also be significantly reduced by enabling the direct catalytic conversion of fermentation broths containing alcohols, ketones or aldehydes into the required biofuel or bio-based chemical. For this purpose, it is necessary to increase productivity in the fermentation process so that the final product concentration after fermentation is significantly enhanced. In addition, in situ concentration and/or separation strategies should be developed, using i. e., specific absorbents or two-phase fermentation fluids, and combined with direct (chemical or enzymatic) conversion of the metabolites within the absorbent or the (hydrophobic) phase.

2.3.3.3.3 RP3. Improving carbon conversion efficiency from syngas, H_2 and/or CO_2 fermentation to biofuels and/or bioenergy carrier production

For future consideration of syngas fermentation as a source for biofuels and other bioproducts, it is essential to improve the conversion efficiencies of this process. Various strategies are considered, such as novel bioreactor concepts, improved robustness of the syngas cell factories, mixed cultures of syngas-utilisers and alcohol-producers, and integration of syngas production and syngas utilisation.

RT1: New bioreactor concepts for gas fermentation

Continuous stirred-tank reactors (CSTR) have been the most used in syngas fermentation, but other configurations such as bubble column, monolithic biofilm, trickling bed, and microbubble dispersion stirred-tank reactors have been studied under both continuous- and batch-mode operations. The development of new bioreactor concepts and technical approaches that enhance gas solubility, gas-liquid and gas-solid contacting, cell concentration as well as product titers in the fermentation media, is crucial to improve carbon conversion efficiency in gas fermentation processes. The design of novel bioreactor concepts will demonstrate increased mass transfer rate, enhanced gas solubility, cell concentration and product titers in the fermentation media[20].

RT2: Improve the fermentation rate and robustness of hydrogen- and CO-fermenting bacteria under raw syngas *(Cooperation between SP3 and SP2 of JP Bioenergy)*

A universal problem with the optimal use of cell factories is the sensitivity of living cells to the stressful environmental conditions when biomass is first converted using a thermochemical technology. In the case of biomass gasification, many chemical contaminants are present in raw syngas that are toxic to microbial strains, particularly bacteria. Bacterial adaptation to improve tolerance to toxic compounds potentially present in the syngas also needs consideration. In addition, syngas-utilising cell factories need to be tolerant to and active at various compositions of syngas. Indeed, the carbon conversion yield of syngas bacterial fermentation also depends on a proper CO/H_2 ratio. It will be necessary to study the fermentation performance of cell factories at various concentrations and ratios of hydrogen and CO and, when necessary, to adapt them to CO/H_2 ratios above 1. An alternative approach is to use mixed microbial cultures by combining efficient converters of syngas to acetic acid with efficient producers of various alcohols using acetic acid as substrate, thus overcoming the need to find a single microbial cell factory.

[19] M. E. Domine, J. M. López-Nieto, D. Delgado, A. Fernández-Arroyo, WO 2017162900, 2017.
[20] Pradeep Chaminda Munasinghe, Samir Kumar Khanal. Biomass-derived syngas fermentation into biofuels: Opportunities and challenges. Bioresource Technology 101 (2010) 5013–5022.

RT3: Bio-hydrogen or biomethane production from algae or bacteria *(Cooperation between SP3, SP1 and JP FCH)*

The production of bio-H_2 or biomethane using microalgae or anaerobic bacteria is still far from the energy markets. Significant research efforts must be made to achieve cost-competitive biological production of these gaseous biofuels, which have a wide range of applications both for mobility (hydrogen as the main energy carrier in fuel cell vehicles) or for stationary applications (PEM and SOFC fuel cells for electricity production). Cooperative research between JP Bioenergy and JP FCH of EERA is needed to design novel breakthrough technologies at higher TRLs in this field. Complementarily, close cooperation with SP1 of EERA Bioenergy is foreseen to design Anaerobic Digestors and/or Methaniser Reactors for optimal production of biogas and H_2.

2.3.3.3.4 RP4. Side stream recovery

The economic competitiveness of bioenergy could be improved in biorefineries with the side production of high-added-value co-products in addition to biofuels, power and process heat. This research area aims to reduce costs of biofuels through the recovery of hemicellulose and lignin platforms and other side streams as a source of higher level of biorefinery revenues using technologies based on biochemical and chemical pathways for obtaining chemicals, food ingredients, antioxidants and other high-value products. This is crucial to the deployment of modern multi-product biorefineries that create value chains by leveraging industrial synergies, especially in small-scale plants. This should contribute to strengthening the bioeconomy and circular economy.

RT1: Recovery of hemicellulose platform in biofuel plants through biological and/or chemical conversion

Previously separated hemicellulose/pentoses aqueous fractions could be treated without the need to separate the different compounds present in the mixture via catalytic processes for the transformation of C5 molecules into C9-C12+ hydrocarbons that are useful for fuels. This is a challenging strategy in which an initial mild hydrolysis or enzymatic pre-treatment of the stream could also be considered to avoid the presence of oligomer-type compounds. The resulting (low O content) hydrocarbon mixture would then be upgraded in a second step consisting of a mild catalytic hydrotreatment process to produce the final fuel or diesel substitutes in high yield. The one-pot catalytic reaction system approach is a more efficient and energy saving option, but further development (mainly in multi-functional) of solid catalyst design is needed to achieve this target.

RT2: Recovery of lignin platform in biofuel plants through biological and/or chemical conversion

Lignin depolymerisation could in principle be performed by means of both biological (i.e. enzymatic or microbial) and thermo-chemical (i.e. catalytic) processes. This is not straightforward and industrial and academic R&D is continuously focused on finding the most efficient technology. After depolymerisation, a mixture of lignin derived compounds corresponding to oxygenated aromatic monomers (i.e. phenolics, guaiacyl, and anisoles derivatives), dimers and trimer types of oxygenated aromatics diluted in water is generated. This mixture could be treated by a catalytic hydrogenation/hydro-deoxygenation process carried out over metal supported catalysts to generate liquid hydrocarbons that are useful as fuel additives[21]. The process implies reducing the O-content and the aromatic character of the compounds mixture obtained from the lignin depolymerisation. The direct (one-step) depolymerisation is more desirable and more research studies are needed in this direction. The search for and/or development of lignin, or lignin breakdown product utilising microbial strains to generate the value-added products, is also an approach that needs to be explored further.

RT3: Recovery of other biorefinery side streams

Besides lignin, cellulose and hemicellulose, biomass usually contains (sometimes large amounts of) proteins and fats. In addition, organic-rich wastewaters originating in the biorefinery also need to be smartly re-integrated into the biorefinery to have a zero-effluent plant. In order to develop cost-effective and sustainable processes for biofuels from biomass, conversion of these side streams needs to be considered. As for separating the proteins from the rest of biomass, this is usually the first step in any biorefinery process. The protein fraction that results from this first step can be used directly for animal feed, it can be hydrolysed to free amino acids as possible additive for dietary foods or it can be used as a substrate for biochemical conversion into high-value nitrogen-containing products such as vitamins and various biogenic amines. As for the lipids and fatty acids present in biomass, various microbial processes are available, i. e., to reduce the chain-length of fatty acids from C18-C24 into the much rarer, and thus high-value, C8-C14 fatty acids. Microorganisms such as *Pseudomonas (P.) putida* or *P. oleovorans* thrive in almost pure lipid environments and are known for their partial degradation of higher lipids and fatty acids. By combining this process with the previously described alcohol-producers, various highly interesting and valuable alcohols can also be produced.

[21] A. Gutiérrez, K. Vilonen, T. Strengell, P. Eilos, M. E. Domine, M. Cháves-Sifontes, FI 2016/050528, 2016; and FI 2016/050530, 2016.

2.3.3.3.5 RP5. Biochemical-based biorefinery integration

Process, mass and energy integration coupled to waste and by-product integration is the overall goal of any biorefinery focused on minimising GHG emissions and reaching zero effluents. Depending of the feedstock, multi-layers can be designed, and their interactions should be optimised in a smart way. The goal is to increase the carbon conversion yield of any holistic bioprocess and system structure. Three research themes have been identified as key activities in this RP.

RT1: Development of in situ product recovery (ISPR) technologies

Most biochemical conversion processes generate still limited product titers and low volumetric productivities, mainly due to product inhibition or to the presence of inhibitors that slow down the biological activity, which hampers the downstream processing and increases costs and energy demand. Other processes still suffer from side reactions decreasing the yield (total product produced vs total substrate consumed) of the process. This leads to an increase in overall costs, and therefore efficient and low-cost separation technologies should be addressed.

Research on increasing the selective separation of the product or the inhibitory compounds during fermentation, if it is continuous, is needed to improve new-generation biofuel productivity and yields and to simultaneously reduce the production of toxic products/compounds. In-situ product recovery (ISPR) technologies can be coupled to different fermentation processes to help overcome these shortcomings of the technology. Several ISPR techniques can be used and applied to remove ethanol and ABE products, among others, but all need tailor-made bioprocess since they strongly depend on the chemical nature of the product/s to be removed from the media[22]. For example, butanol production via ABE fermentation could be enhanced by downstream purification by using zeolites to separate the butanol from the acetone and ethanol[23]. Additionally, aqueous fractions derived from biomass primary biological treatments could be transformed into hydrocarbons and aromatics mixtures that are useful as biofuel components by means of solid catalyst processing under mild reaction conditions[24]. The use of catalytic membranes for partial water/bio-molecule separation in those systems will provide clear advantages for further processing of bio-derived fractions.

RT2: Developing LCA sub-models for the Biochemical-based Biorefinery (cooperation SP3-SP1)

LCA is a recognised method for determining the environmental impact of a product (or good or service) during its entire life cycle, from raw material extraction through manufacturing, logistics, use and final disposal or recycling. In LCA, substantially broader environmental aspects can be covered, ranging from GHG emissions and fossil resource depletion to acidification, toxicity, water and land use aspects. Social indicators include, among others, number and quality of jobs created (income and educational degree), as well as land use, level of accidents and labour qualification. These impacts can be estimated using the input-output and social-LCA methodologies, with the help of computer-based tools such as SimaPro (Ecoinvent databases, and others).

Research on life cycle inventory (LCI) is needed as an input for overall LCIA models (cooperation with SP1) by evaluating the biochemical-based biorefinery section in terms of input (feedstock, raw materials, energy by type, manpower, etc.) and output (products, waste, emissions, etc.) flows, considering the boundaries of the system. Different scenarios can be envisaged regarding process configuration, energy sources and waste/emission reduction approaches. The environmental assessment will be performed using a Life Cycle Assessment (LCA) methodology for the different scenarios selected before. The whole value chain from feedstock to final products will be assessed in cooperation with SP1.

[22] Wouter Van Hecke, Guneet Kaur Heleen DeWever Advances in in-situ product recovery (ISPR) in whole cell biotechnology during the last decade. Biotechnology Advances 32 (2014) 1245–1255.
[23] S. Van der Perre et al., ChemSusChem, 2017, 10, 2968-2977.
[24] M. E. Domine, J. M. López-Nieto, D. Delgado, A. Fernández-Arroyo, WO 2017162900, 2017.

RT3: Integration of side streams with advanced biofuel plants or retrofitting existing energy and/or industrial plants

Different side streams in advanced biorefineries could be treated/upgraded and re-injected into existing industrial plants (i.e. biorefineries and petro-refineries). Bio-oils derived from biomass pyrolysis could be fractionated in organic and aqueous phases by water addition. While organic fractions can be further processed for applications such as liquid fuels, aqueous fractions containing C1-C4 acids, aldehydes, ketones, alcohols and low amounts of heavier water-soluble compounds nowadays constitute waste effluents at bio-refineries[25]. Aqueous phase reforming (APR) approaches developed by Dumesic et al.[26] could be applied to produce H_2 from these aqueous fractions, although with high-energy consumption and low atom economy (low C balance). Recovery of these oxygenated compounds in water into a mixture of hydrocarbons and aromatics useful for blending with petroleum feedstocks is more desirable and could be performed via a "one pot" process (including condensation and ketonization reactions) by using highly resistant, newly designed solid catalysts[27 28] .

Aqueous side streams containing low concentrations of organic compounds, such as ABE and succinic acid fermentative mixtures, levulinic acid hydrolysates, among others, could in principle be upgraded to produce hydrocarbon mixtures via consecutive catalytic condensation processes. For this challenging strategy, an initial biological (or enzymatic) hydrolysis pre-treatment of the stream could also be considered to avoid the presence of oligomer-type compounds. The generated hydrocarbon mixtures could be useful for blending with automotive fuels.

[25] D. Radlein, A. Quignard, US 2014/0288338, 2014.
[26] R. D. Cortright, R. R. Davda, J. A. Dumesic, Nature, 2002, 418, 964-967.
[27] A. Fernández-Arroyo, D. Delgado, M. E. Domine, J. M. López-Nieto, Catal. Sci. & Tech., 2017, 7, 5495-5499.
[28] A. Fernández-Arroyo, M. A. Lara, M. E. Domine, M. J. Sayagués, J. A. Navío, M. C. Hidalgo, J. Catal., 2018, 358, 266-276.

2.4 Subprogramme 4 (SP4) - Stationary Bioenergy

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2.4.1 SCOPE

This Subprogramme focuses on the development of efficient, flexible, affordable and environmentally friendly heat, power and cooling production to contribute to the decarbonisation of the thermal power sector in Europe. The Subprogramme covers all plant scales, from small residential/domestic units to medium-to-large bioenergy plants focusing on the conversion of low-grade feedstocks/residual streams through combustion and gasification technologies.

The Subprogramme also addresses new research opportunities such as digitalisation and advanced operation, and hybrid systems, where stationary bioenergy is integrated with other intermittent renewables to balance the electricity grid and provide storage options.

2.4.2 MAIN CHALLENGES

SP4 aligns its main R&D challenges with the Integrated Roadmap of SET-Plan and the Declaration of Intent on *"Strategic targets for bioenergy and renewable fuels needed for sustainable transport solutions in the context of an initiative for global leadership in Bioenergy"* of Nov 16th, 2016, and selected **three main R&D Priorities/Challenges and Key-Performance Indicators (KPIs) to be addressed:**

- **Main Challenge 1: Use low-grade feedstocks/residual streams to allow for secure, long-term supply of sustainable feedstock and low fuel costs while maintaining performance of bioenergy plants**

KPI: Improve performance and reduce GHG emissions by increasing efficiency: Obtain net efficiency of biomass conversion to intermediate bioenergy carriers of at least 75% by 2030 and reduce GHG emissions by 60% from using all types of intermediate bioenergy carrier products resulting in contribution of at least a 4% reduction in EU GHG emissions from 1990 levels.

- **Main Challenge 2: Reduce emissions (NO_x, particles) through cost-efficient measures.**

KPI: Improve performance and reduce GHG emissions by increasing efficiency: Obtain net efficiency of biomass conversion to intermediate bioenergy carriers of at least 75% by 2030 and reduce GHG emissions by 60% from using all types of intermediate bioenergy carrier products resulting in a contribution of at least a 4% reduction in EU GHG emissions from 1990 levels.

- **Main Challenge 3: Improve economic competitiveness through increased energy efficiency and lower production costs by developing novel concepts such as hybrid systems and smart integrated concepts**

KPI 1: Reduce conversion system costs for high efficiency (>70% based on net calorific value, of which >30% electrical), large-scale biomass cogeneration of heat and power by 20% in 2020 and 50%.

KPI2: Improve performance and reduce GHG emissions by increasing efficiency: Obtain net efficiency of biomass conversion to intermediate bioenergy carriers of at least 75% by 2030 and reduce GHG emissions by 60% from using all types of intermediate bioenergy carrier products resulting in a contribution of at least a 4% reduction in EU GHG emissions from 1990 levels.

The Fig. 8 exemplifies how the Research Areas and Research Priorities interlink with the Main Challenges/Priorities of SP4.

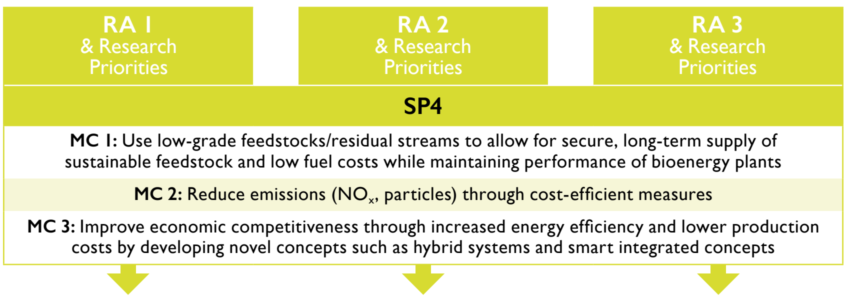

Figure 8: The four main challenges of SP4 are addressed through cross-cutting Research Areas and Research Priorities

2.4.3 SP4 RESEARCH AREAS (RA) AND RESEARCH PRIORITIES (RP)

Each Research Area (RA) consist of several Research Priorities (RP), which in turn include a few Research Themes (RT).

This Subprogramme addresses three research areas, listed below:

4.3.1. Residential/domestic heating and cooling, including micro-CHP
4.3.2. Medium-to large-scale CHCP
4.3.3. Transformation of fossil fuel plants and biorefinery energy islands

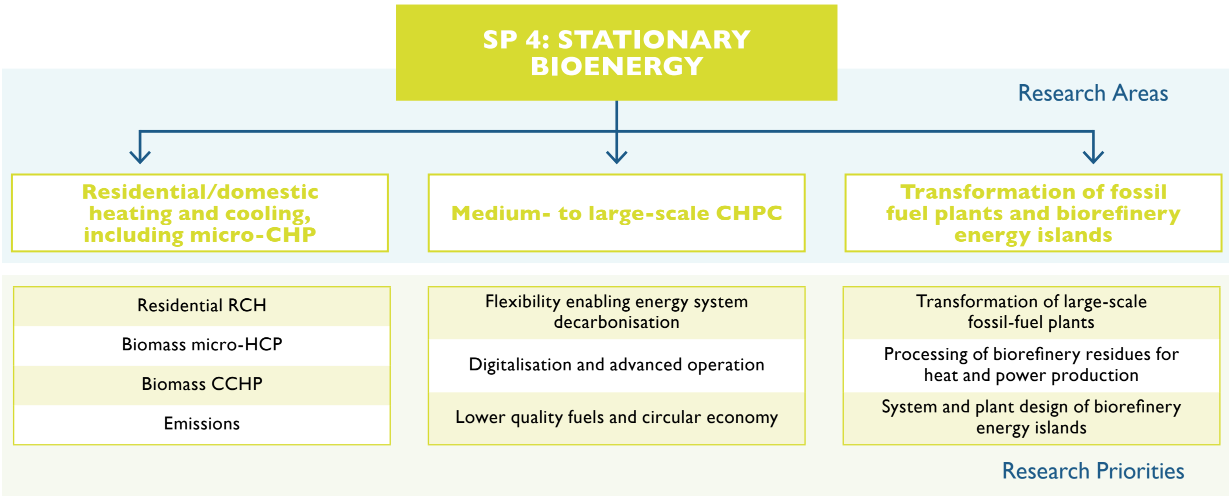

Figure 9: Schemes of the distribution of priorities in each research area of the SP4

2.4.3.1 RA1. Residential/domestic heating and cooling, including micro-CHP

The scope of this research area is to arrive at new or improved biomass-based heating and cooling solutions, including micro-CHP, for residential/domestic buildings. This addresses performance (energy, environmental), affordability and the user perspective. Adapting or developing technologies for the needs of energy-efficient buildings is key to satisfying the user expectations with respect to performance and affordability. Thermal comfort is an important issue, and involves heating, cooling and the interplay or integration with other systems in the buildings. Broadening the feedstock base while improving performance is desirable, i.e. flexibility becomes a key issue with respect to biomass feedstock, unit operation and building integration.

2.4.3.1.1 RP1. Residential RHC (Renewable Heating and Cooling)

Residential bioenergy solutions (wood stoves, wood chips, pellet stoves) have seen tremendous technical advances in the last two decades, especially when it comes to energy efficiency and emissions (CO, hydrocarbons, particles), which have been reduced several times over[29]. However, the current societal trends (see "The mission") impose a new set of constraints and requirements (but also opportunities) that will bring forward further (r)evolution for bioenergy to maintain its place as the main RES in Europe. Both technical and non-technical questions should be addressed.

RT1: The user/customer perspective

A main feature of the residential bioenergy sector is that the equipment is overwhelmingly operated by non-professionals (i.e. the general public) with little or no understanding of its intricacies and inner workings. Customers/users will directly affect the operation of the system. This brings forward both non-technical and "socio-technological" aspects to be addressed, including:

- User behaviour. How does it affect performance? How can "user errors" be limited and/or the user be educated?
- Customer demands. Customers are always right and their wishes when it comes to design, large flame picture or automation (user-friendliness) do not usually consider technical limitations/ challenges and have to be addressed with no significant price increase.

In other words, the sector needs to accompany "customer-driven innovation" while ensuring that the necessary knowledge reaches the public to ensure acceptance and proper utilisation.

RT2: Re-invent household wood-burning appliances

The extremely low energy demands of ZEB, as well as their specific patterns and interaction with other RES (solar, wind, district heating), impose a series of new demands on bioenergy systems; in short, the system should operate low-load, e.g. 1-2 kWh versus 6 kWh for most of the current wood stoves[30], and the energy should be delivered evenly (i.e. no heat peak), since the dwellings are well insulated. This can be done either through smart design and/or heat storage followed by controlled release[31]. Distributed power production is an important feature of ZEB[32]. In this context, bioheat that cannot be utilised directly should be employed to produce power. However, at this scale, heat-to-power concepts (ORC, Stirling engine, etc.) still exhibit poor efficiencies (10-14% gross for ORC generators of ca. 300 kW_e to 1.5 MW_e) and require further development (ash-related challenges, power consumption, etc.) in terms of integration into ZEB (see RT3 for hybrid systems).

RT3: Hybrid systems (collaboration with other EERA JPs)

The trend is clear: intermittent RES will represent an increasing share of the EU energy mix soon, especially in ZEB. For example, solar PV capacity has grown almost 30-fold between 2006 and 2015 (Eurostat). Bioenergy is a strong, natural candidate to complement these or, in other words, to compensate for their main shortcoming (i.e. intermittency). In this context, residential bioenergy is the central contributor in 100% RES-based systems. Different settings/cases will arise and the concepts to be developed will be diverse, but flexibility and complementarity will be key features. The two "extreme cases" can be described as *bioenergy as base load RES and bioenergy as peak load RES*. Balance between heating, cooling and electricity production will also play a role in the hybrid concepts that will be competitive in ZEB settings. These systems can be especially relevant for off-grid dwellings or energy-plus houses.

[29]The Handbook of Biomass Combustion & Co-firing. IEA Bioenergy, 2008. ISBN 978-1-84407-249-1.
[30]Ø. Skreiberg et al. (2015). Bioenergy and buildings. Pan European Networks Government 13, 2015, pp. 96-97.
[31]New solutions and technologies for heating of buildings with low heating demand: Stable heat release and distribution from batch combustion of wood, 2014, ISBN 978-82-594-3660-3.
[32]ZEB (The Research Centre on Zero Emission Buildings) Final Report 2009-2017, 2017, ISBN 978-82-690808-1-0.

2.4.3.1.2 RP2. Biomass micro-CHP

Several micro-CHP prime movers exist; e.g. fuel cells, steam engines including ORC, Stirling engine, micro gas turbines and IC (internal combustion) engines. They have different characteristics and costs. Micro CHP has the potential to provide efficient, clean and cost-effective energy for smaller consumers. Characteristics like compact size, light weight, low maintenance, low noise, low emissions and multi-fuel capabilities would make micro CHP technologies promising for competitive, secure and sustainable micro-scale polygeneration (including cooling), which, integrated with RES, would allow for CO_2-neutral power generation, eliminate transmission losses and reduce the cost of energy infrastructures. However, there is a need to improve micro CHP technologies by minimising their investment, operation and maintenance costs, making them more competitive in the market, integrating them with RES and energy storage, and increasing the technology flexibility as well as energy efficiency. The SET-Plan working group dealing with technologies for energy-efficient solutions for buildings sets two specific targets for micro CHP/CHCP: 1) 50% reduction in the equipment and installation costs compared to 2015 market prices, and 2) 20% increase in the energy efficiency of Micro CHP/CCHP compared to 2015 levels by: a) increasing the operational electrical efficiency close to nominal, and b) maintaining the thermal efficiency of the entire operating range of micro and small scale CHP/CCHP. i.e. costs and energy efficiency are the key issues.

RT1: Tailored fuels. Pre-treatments, blends and additives to develop a wide range of fuels ensuring stable, efficient and clean micro-CHP operation (collaboration with SP1)

A common challenge is sensitivity to fuel quality, since small-scale gasification and combustion systems are typically more sensitive than larger ones, and secondary emission reduction measures are more expensive or not feasible. Hence, tailored fuels such as blends of fuels, possibly with additive blending, and thermally pre-treated fuels are options for fuel upgrading to arrive at reliable, flexible, efficient and clean micro-CHP operation. Using biogenic residues and wastes could be a low-cost starting point for fuel upgrading. This research area is an important part of the biomass micro-CHP value chain, focusing on biomass sourcing and upgrading to provide the appropriate but affordable sustainable biomass fuel assortments needed for optimum biomass micro-CHP operation in the residential sector of the future.

RT2: CHP technologies for ZEB. Researching, evaluating, selecting and developing the best (incl. disruptive) technological options/routes for micro CHP facing ZEB-specific constraints – environment, energy, economy. Balancing power

Micro-CHP technologies can provide the heat needed for single dwellings or for several dwellings connected to a central heating or a small district heat network, as well as cover or contribute to covering the electricity demands. However, due to the different characteristics of the micro-CHP systems, e.g. typical size and power-to-heat ratio, there is a real need to look more closely into applying these systems in ZEB, as well as into their interplay with other RES, and targeted and efficient research and development actions should be defined accordingly. At the end of the day, the micro-CHP systems must become cost-competitive and find their natural place in ZEB, giving a reasonable CAPEX and OPEX cost for the electricity generation part of the system, satisfying the end-user with respect to technical and economic performance, as well as emission regulations. NO_x and particulate emissions are particularly relevant environmental concerns.

RT3: Novel systems: integration/hybridisation/combination. Multi-fuel bio CHP systems in smart thermal and power grids (balancing power, heat base load, etc.)

A step forward in biomass micro-CHP for ZEB would be to design novel systems specifically for ZEB. These systems should be highly integrated, possibly hybrid or work in combination with other systems, in sum acting as a cluster covering the electricity and heat demands, and preferably being able to store heat for later use. Alternatively, upgrading current heat-only systems to CHP could be of interest. Fuel flexibility as well as load flexibility is preferable, i.e. multi-fuel biomass CHP systems in smart thermal and power grids, balancing power and providing heat base load as well as being able to, as a system, cover the peak heat load. Automation and digitalisation are keys in these smart systems.

Examples of novel systems are e.g. small-scale gasification based on locally sourced residues coupled with a boiler or a gas engine, producing a flue gas suitable for horticulture, and possibly also biochar, and which additionally can be coupled with high-temperature heat storage (e.g. using PCM). Alternatively, the gas could be provided to a local gas grid after moderate upgrading, or as SNG to the natural gas grid after full upgrading, to be utilised in e.g. fuel cells.

2.4.3.1.3 RP3. Biomass CCHP

Energy use in buildings accounts for over 40% of the total energy consumption in the EU[33], thus making it one of the main sectors were drastic action has to be taken to reduce greenhouse gas emissions. The production of electricity, heat and cooling from biomass through combined cooling, heat and power (CCHP) has been shown to have energy saving potential, enhanced high-efficiency and low emission characteristics[34]. Studies indicate that biomass-based CCHP systems have overall efficiencies in the 60% - 70% range[35]. Improving on these overall efficiencies would generate several benefits, including higher resource efficiency and lower environmental impact. Relevant aspects for further research include the following:

RT1: Low-cost energy carriers to improve profitability. Mobilisation of residues, including mixtures. Cost-efficient conversion of various types of biomass wastes to primary products (collaboration with SP1)

Developing cost-efficient energy conversion processes for biomass waste would improve the cost efficiency of CCHP. Biomass wastes vary in several aspects, including their physical and chemical compositions. Forest residues and agricultural residues are candidates for substituting high-grade fuels such as log wood. However, using low-grade fuels will give rise to more difficulties during combustion and gasification processes, such as higher emissions and ash-related problems. Furthermore, low-grade fuels could be more challenging to store than high-grade fuels. Therefore, research on mixing fuels in order to reduce the challenges of each fuel type is of interest. Another topic of interest is finding cost-effective additives that can reduce emissions as well as minimise ash-related problems during combustion and gasification processes. Finally, cost-effective innovative ways of fuel pre-treatment must be developed.

RT2: New technological routes: Cost-efficient conversion of low-grade waste heat to electricity and cooling

Utilisation of low-grade waste heat in CCHP plants can go a long way to enhancing the overall efficiency of the plants. The demand for cooling is increasing in the EU[36], and there is also an increasing trend towards electrical mobility[37]. Producing cooling or additional electricity from low-grade waste heat is thus worthwhile. Research that can increase the efficiencies of existing technologies to produce cooling (e.g. absorption chillers) and electricity (e.g. Organic Rankine Cycle) from low-grade waste heat, or that can lead to the development of new technologies, is greatly needed.

RT3: Cost-efficient distribution of heating and cooling to residential buildings

According to an EU directive, all new buildings in the EU must be nearly zero-energy buildings from the year 2020[38]. Old buildings are also being refurbished in some EU countries to make them more energy efficient. Consequently, heat demand and the temperature needed for consumer space heating may decrease in the future[39]. Research on techno-economic challenges and solutions for transforming the existing heating and cooling distribution infrastructure into that needed in the future or for integrating new infrastructure into the existing infrastructure is required. The development of hybrid systems is therefore required. The Positive Energy Block (PEB) concept, which comprises a few closely located buildings of different characteristics such that it can generate a positive net energy flow by moving energy from buildings with an energy surplus to those with an energy demand, should be further developed.

[33]1. X. Cao, et al., Energy and Buildings, vol. 128, pp. 198-213, 2016/09/15/ 2016.
[34]2. H. Cho, et al., Applied Energy, vol. 136, pp. 168-185, 2014/12/31/ 2014
[35]3. Y. Huang, et al., Applied Energy, vol. 186, pp. 530-538, 2017/01/15/ 2017
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[37]5. J. Seixas, et al., Energy Policy, vol. 80, pp. 165-176, 2015/05/01/ 2015.
[38]6. P. Seljom, et al., Energy, vol. 118, pp. 284-296, 2017/01/01/ 2017.
[39]7. H. Averfalk, et al., Energy Procedia, vol. 116, pp. 217-225, 2017/06/01/ 2017.

2.4.3.1.4 RP4. Emissions

Emissions of particulates (e.g. PM10), nitrogen oxides (NO_x), sulphur oxides (SO_x), and other pollutants from CCHP plants into the atmosphere constitute a societal problem. To prevent or limit the impact of these substances on society, the EU has passed directives to reduce the threshold limits for the emission of certain pollutants from power plants. For example, according to EU directive 2015/2193 (MCP Directive), which went into effect in 2018, NO_x emission limits from existing CHP plants in the 5–50 MW range are set to 325 mg/MJ, while those for new CHP plants in the same range are set to 150 mg/MJ[40]. Accordingly, CCHP plants must optimise existing measures or develop new ones to reduce emissions of pollutants. Primary and/or secondary measures could be applied to limit the emissions of certain pollutants (e.g. NO_x) from CCHP[41]. Primary measures are those taken prior or during the energy conversion process to limit the formation of pollutants and/or convert them to less dangerous forms. Secondary measures are those taken downstream of reactors to prevent the emission of pollutants into the atmosphere. Given that the cost of investing in new secondary measures could be prohibitive to existing power plants, it could be more economically feasible to optimise existing primary measures and/or develop new ones to reduce emission levels of pollutants from CCHP.

RT1: Development of new or optimisation of existing primary and secondary measures to reduce NO_x, SO_x, and particulates

The efficient reduction of NO_x emissions may be achieved by applying the right additive during combustion. However, the application of commercial additives will increase operating costs. Finding suitable waste streams that can be used as additives for NO_x reduction during combustion would be an economically viable option for CCHP plants. Existing primary measures, such as air staging and flue gas circulation, have been shown to significantly reduce NO_x emissions[42]. To meet future stringent threshold emission limits, existing primary measures need to be optimised and new primary measures have to be developed.

The reduction of particulates is of utmost importance. Therefore, in addition to optimising the combustion, the use of filters, such as ESP and cyclones, and other countermeasures must be taken into consideration. The mechanisms by which small particles coalesce to form larger particles should be investigated.

RT2: Development of cost-efficient measurement and diagnostic techniques

To better limit the emissions of pollutants from CCHP plants into the atmosphere, research and development of cheaper and efficient measurement and diagnostic techniques for real-time monitoring of the formation and transformation of pollutants during energy conversion processes is needed. The development of cheap sensors, also called soft sensors, can be used to better control thermal conversion processes is required. Cheap sensors to detect various gases should be developed and utilised.

[40] EU Directive 2015/2193; 2015.
[41] E. Houshfar, et al., Energy & Fuels, vol. 25, pp. 4643-4654, 2011/10/20 2011.
[42] H. Liu, et al., Fuel, vol. 103, pp. 792-798, 1// 2013.

2.4.3.2 RA2. Medium-to large-scale CHCP

Bioenergy represents two-thirds of the total renewables sector and will thus continue to play a key role in helping Europe to reach its ambitious targets for greenhouse gas emission, renewable energy production and energy efficiency[43]. Medium- and large-scale CHCP contribution is needed to decarbonise and secure the future renewable energy system, as it cannot rely only on highly variable (intermittent) wind and solar or only on decentralised production, with its limited feasibility and applicability. The development of medium- and large-scale CHCP is needed to adapt it to a future energy system that is flexible, digitalised and capable of utilising lower quality fuels/feedstocks with re-use and circulation of residues.

2.4.3.2.1 RP1. Flexibility enabling energy system decarbonisation

Although the power output from a CHCP system is controllable to the same extent as other boiler-steam systems, CHCP plants are primarily operated to follow a local heat load. However, district heating systems typically contain other components such as heat pumps and accumulators, besides CHCP and heat-only boilers. This gives the system more flexibility to change operation based on price signals. Such combinations have a potential for both generation and demand-side interaction to control the energy balance, if the entire combination were available for balancing purposes. The constraints in the flexibility of operating medium- to large-scale biomass CHCP plants are mainly on the firing side with regards to the minimum stable load, and mainly on the steam system and turbine side for the dynamic rates of load change and start-up times. The state-of-the-art steam system allows load rate changes on the order of a few percent per minute, and secondary and tertiary control can therefore be limited. Integrating bioenergy into the grid for balancing or storage options will open completely new application areas for bioenergy, ranging from operations during peak demand to other services needed to maintain a reliable and secure renewable power supply with a low environmental impact.

RT1: Flexible CHCP production by improved performance

CHCP process improvements, integrations and novel concepts are needed to enhanced load change rate and load range (minimum and over load) performance, resulting in an improved capability to respond to fluctuating energy demands. More fluctuating operation, including more shut-downs and start-ups, sets new challenges for availability and maintenance. Other targets involve higher availability, lower emissions and lower operation and maintenance costs through smart diagnostic, monitoring and process control systems.

RT2: Flexible CHCP production of power, heat, cooling or CHCP

Improved flexibility in future energy system is required to produce heat, power and cooling – separately or combined – in different market conditions. The conceptual development of optimal steam-splitting and decompression options, and heat-side integrations both on- and off-site, are needed. The future integration of small-scale (residential) heat and cooling generation into district heating and cooling systems requires developing production forecast tools, revised designs and control systems capable of flexible production, and new business models for the existing CHCP infrastructure.

RT3: Biomass combustion hybrids and bio-CC(U)S (collaboration with EERA JP CCS)

The target of novel hybrid concepts is to improve load controllability by combining secure biomass with variable renewables. Hybrid systems can include energy storage/release technology to convert surplus renewable energy (e.g. solar) into storable energy that can be released when needed, and at the same time improving the maximum load change rate and load range. Sharing process components (e.g. common steam cycle) may yield economic benefits, but it also poses controllability, maintenance and other challenges.

Breakthrough bio-CC(U)S technologies must be developed in laboratories and on pilot scales to pave the way for full-scale applications and for net-negative CO_2 emissions in tens (or hundreds) of millions of tons per year in 2030 globally. The main characteristics of breakthrough technologies are low CO_2 capture energy penalty and costs, the capability to use various biogenic feedstocks, and operational (e.g. load change) flexibility. The bio-CC(U)S technology can also be part of a hybrid system.

[43]Renewable Energy Directive (2009/28/EC) and COM(2014) 15 final.

2.4.3.2.2 RP2. Digitalisation and advanced operation

The potential of new digital solutions and advanced approaches has not yet been efficiently realised in the design and operation of CHCP plants, although the need for smart solutions is evident due to the increasing complexity of the energy system. Traditionally, CHCP boiler operation and control are based on a few measured inputs, typically drum level, air and fuel flows and flue gas oxygen. In any case, a larger number of variables are measured but the data available from power plant automation system is poorly utilised to support process diagnosis and control. In addition, many variables in CHCP plants will be more critical in the future to ensure safe, economic and efficient operations due to the more challenging operational requirements.

RT1: Smart operation and fully automatic control of CHCP (medium scale 1-20 MWth) plant

Smart monitoring and fully (or almost fully) automatic process control systems are needed to improve plant performance in changing conditions, and to lower (personnel) costs and avoid human errors. For example, further development and integration of advanced performance monitoring tools and measurement/ sensor technologies into the existing combustion process control systems and development of new control systems (e.g. model predictive control) with large pilot and industrial-scale demonstrations are anticipated to make the technology ready for full deployment.

RT2: Upgrading of heating plant to CHP(C)

Novel power cycles that are also able to produce electricity cost efficiently in (green-field and/or brown-field) heating plants is the primary target. The development work may be targeted to specific markets/areas, where the grid is not well developed, e.g. rural areas or islands.

RT3: Advanced emissions and air pollution control

To meet the near future and longer-term requirements, advanced emission and air pollution control systems are needed. Advanced methods can include e.g. the use of new additives, catalysts, flue gas scrubbers, advanced control systems, fuel processing, combustion process modifications, etc. The development and utilisation of modelling and simulation tools is a beneficial and cost-effective way when developing emissions and air pollution control systems.

2.4.3.2.3 RP3. Lower quality fuels and circular economy

The use of lower quality feedstock and residual streams as fuels is needed to allow for the secure, long-term supply of sustainable feedstock and low fuel costs while maintaining the performance of CHCP plants. Lower quality feedstock comes from e.g. agriculture and forestry, and side streams from food production and landscape conservation, etc. The use of lower quality fuels also reduces the demand for traditional (virgin) biomass, which can thus be used in more value-added purposes and products. A wide range of conversion technologies is under continuous development to produce bioenergy carriers for both small and large-scale applications. Organic residues and wastes are often cost-effective feedstocks for bioenergy conversion plants, and provide a market for forest, food processing and other industries.

RT1: Flexible solid and liquid biogenic fuel handling, storage and feeding

Flexible solid and liquid fuel handling, storage and feeding should be developed for future fuels and feedstocks. The technology solution should be cost-effective yet safe, and capable of handling multiple fuels with changing quality over the time (e.g. seasonal fuels). The development work can include a geographic analysis of biogenic feedstock availability for selected areas, in the EU and world-wide. Fuel handling systems may include thermo-chemical upgrading options, both off- as well as on-site. Fuel and feedstock logistics is an important part of the fuel supply chain. The design of CHCP boilers (green- and brown-field plants) can be adjusted to improve their economic and technical performance with future fuels and feedstocks.

RT2: Circular economy and solid residue management (collaboration with SP1, SP2, SP3 and other EERA JPs)

New ways have to be developed to utilise solid residues as products, raw materials and feedstocks for other processes with minimal costs or even some incomes. The whole chain, from feedstocks to residue processing, must be considered, when e.g. by changing the feedstock processing, flue gas emission control system or ash discharge system, the quality of residues can be modified as desired. Processing – chemical, thermal, etc. – of the residues may be an essential part of optimising the management of solid residue. The development and utilisation of ash chemistry modelling tools could be beneficial, with validation in pilot and large-scale applications.

2.4.3.3 RA3. Transformation of large-scale fossil-fuel plants and biorefinery energy islands

This research area is first aimed at making the existing highly-efficient large-scale thermal power generation infrastructure fossil-fuel free. This should result in avoiding large sunk cost situations during the transition towards a future sustainable energy system and will aid in paving the way for the biobased economy. In addition to converting to biomass, the plants will have to allow more load flexibility in order to better fit with the intermittent renewable power generation from solar and wind. Co-generation of power and heat to increase overall efficiency will be a pre-condition. The required mobilisation of vast quantities of sustainable biomass can act as a stepping stone for the similarly large-scale production of biofuels and bio-based chemicals and materials. Moreover, further efficiency gains and cost reductions may arise from integrating the (existing) large-scale CHP plants in biorefinery processing.

Finally, with the increasing market penetration of biorefinery processes, optimising these plants from an energy point of view becomes a prominent issue. This has received limited attention thus far but is crucial to maximise CO_2 emission reductions and minimise costs. For example, in lignocellulosic bioethanol production, the energy island typically constitutes up to 50% of the overall investment cost. Dedicated energy islands will have to be developed and implemented and then integrated into the overall plant design, including optimum use of the biorefinery residues and smart heat integration.

2.4.3.3.1 RP1. Transformation of large-scale fossil-fuel plants

Large-scale solid fossil-fuel-fired power plants currently still form the backbone of the power system in the EU. In recent years, they have become the focal point of political and societal scrutiny, and for instance in the Netherlands, binding legislation is being drafted that would prohibit the use of coal for power generation beyond 2030. At the same time, thanks to the recent implementation of the stringent emission rules compiled in the IED/BAT acts, the surviving commercial units are generally characterised by very low emission levels of NO_x, SO_x and PM. Also, many of the units use non-fossil fuels already, in part in order to satisfy the minimum CO_2 intensities defined by the IED. Collectively, these solid-fuel-fired units thus provide an excellent base for the smooth transition to a CO_2-neutral power system, matching in terms of capacity and increasingly ramp-up time the need for back-up power. Currently, this function is almost exclusively limited to natural gas-fired plants (hence also fossil), for which no commercially viable large-scale non-fossil substitute yet exists. Also, the solid-fuel-fired systems offer more options for the expanded use of heat, which is necessary to achieve not only sufficient greening of the electrical power system, but also contribute to the significant reduction in the CO_2 footprint of the primary energy used, for instance, in the chemical industry. However, significant further efforts are necessary to enable commercially-viable operations, detailed in further sections as research tasks.

RT1: Towards full repowering

One of the three main elements to address is transformation of large fossil-fuel-driven power or CHP plants (>100 MWe) to biomass-fired CHP plants, including plant adaptations necessary to meet thermal and electrical load requirements with as little derating as possible, and diversification of the output or increasing the levels of heat vs power delivered. The latter is not as straightforward as it may appear. High- or medium-pressure steam delivery might not be directly suitable for specific industrial or domestic heat applications due to the typically supercritical or even ultra-supercritical steam conditions generated in the steam boiler.

A second main research focus is related to flexible solid and liquid fuel handling, storage and feeding (e.g. mill operation, spraying, dispersion, burner and low-emission firing concepts). In this case, efforts will be concentrated on assessing the fuel handling and feeding characteristics of biomass feedstock, as well as on developing dedicated cost-effective, yet safe, technology solutions capable of handling multiple fuels.

A third and final key research focus towards full repowering is the development of the biomass-to-bioenergy supply chain for retrofitted large-scale fossil fuel plants. Also, the supply needs of future high-end biomass applications will have to be taken into account. The emphasis should be on achieving the highest overall chain efficiency and CO_2 emission reductions possible.

RT2: Flexible and highly efficient plant operation

The initial research focus is on smart monitoring and automatic process control systems; on the further development and integration of advanced performance monitoring tools into the existing combustion process control systems, e.g. towards optimal 3D balancing of the firing and minimisation of corrosion risk, and hence increased combustion efficiency, decreased emissions and maintenance costs. A second topic of interest is advanced emissions and air pollution control, particularly concentrating on the development of NO_x performance improving measures and the development of alkali-aerosol control concepts. Finally, this research theme addresses heat-side integration and flexible output: H, P or CHP, including flexibility of rapid load changes.

RT3: Solid residue management in a circular economy (collaboration with SP1)

This research theme will focus on the efficient re-use of the solid residues (ashes/chars) resulting from the biomass, and include any additional minerals from the boiler system (e.g. mineral additives used in the combustion systems for emission, deposition and corrosion control). Specific utilisation options considered are novel utilisation options in construction and building materials, fertiliser and soil improvement applications, and re-use in biochemical processing.

2.4.3.3.2 RP2. Processing of biorefinery residues for heat and power production

The vast majority of the biorefinery concepts under development or emerging onto the market produces residues, for which no efficient utilisation routes exist. At the same time, fossil-based energy still covers an important part of the overall energy demand of these novel processes. Within this research priority, the main goal is to unlock the potential for the efficient use of the above-mentioned residues as an alternative source of energy. This will be achieved by way of an integrated approach throughout the whole use chain of the lignocellulosic biomass. This means, firstly, achieving the highest efficiency at the biorefinery plant level, i.e. where the residues are created and can potentially replace non-sustainable energy carriers within the existing technical infrastructure. However, this RP looks also at integrating the whole production and use process into the broader energy landscape. Within this research priority, the following tasks are envisaged:

RT1: Upgrading biorefinery residues into energy carriers and heat and power production (collaboration with SP2 and SP3)

Biorefinery residues from advanced biomass processing are currently emerging onto the market. However, as is typical in the early stages of market penetration, the diversity of the residue quality is large, as there are many competing concepts in terms of both fractionation/pre-processing as well as the main biorefinery conversion processes. The main emphasis within this research theme will be on options to upgrade these diverse residues into energy carriers with superior logistical and combustion properties, particularly focusing on the dewatering/concentrating of liquid, water-based residues and on the removal of soluble (alkali) salts and organic compounds.

Two additional research topics on the production of heat and power from gaseous, liquid and solid biorefinery residues will be addressed, namely conversion kinetics, encompassing exhaustive testing in lab- and pilot-scale systems prior to large-scale deployment, and ash behaviour control (primarily in terms of slagging/fouling/deposition/corrosion) and ash utilisation.

RT2: Residue quality improvement by primary biorefinery process measures (collaboration with SP2 and SP3)

The quality of biorefinery residues can likely be optimised by a multitude of measures already at the production stage. For instance, by properly aligning the pH-control and water management of the process, much of the potential issues in the combustion step can likely be avoided. In close interaction with the EERA Bioenergy Subprogramme on biochemical conversion, the research interests will focus on pH control changes and adjusting the hydrolysis conditions to better control salts, as well as on integration with biodigestion and waste water treatment.

2.4.3.3.3 RP3. System and plant design of biorefinery energy islands

Alongside RP2, this research priority will also focus on the efficient use of resources within the biorefinery processes. While RP2 investigates achieving the highest chain efficiency within the existing technical infrastructure (i.e. allowing the use of fossil-fuel based processes whenever the economics so dictate), RP3 will strive for an overall new design of the process that eliminates fossil-fuel and inefficient local, small-scale systems. This will be achieved by integrating different operations within larger clusters of operations (per definition gaining in overall system efficiency) but will also try to re-design the biorefinery process itself to better tune the on-site operations. The following research tasks are envisaged:

RT1: Integration of existing power/CHP plants into biorefinery concepts and larger industrial settings (collaboration with SP2 and SP3)

This research theme will focus on assessing the potential of integrating existing power/CHP plants as an energy island into biorefinery concepts and in larger industrial settings. Activities will include process design and modelling.

RT2: Residue quality improvement by primary biorefinery process measures (collaboration with SP2 and SP3)

Investment in energy islands constitutes to be a major part of the overall investment cost of biorefinery processes. For lignocellulosic bioethanol production, this amounts to typically 50%. Moreover, optimisation of the energy island and energy integration in the plant is crucial in terms of overall efficiency and CO_2 footprint. This research area will be aimed at developing dedicated (integrated) biorefinery energy island systems and plant designs, including the optimum use of biorefinery residues and smart heat integration. This will be primarily achieved through system modelling; however, wherever possible within the research infrastructure of the partners involved in this RP, testing of the residues from experimental processing in-line with the new primary biorefinery process design will be undertaken.

Subprogramme 5 (SP5) – Sustainability, Techno-Economic Analysis, Public Perception

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2.5.1 SCOPE

Bioenergy deployment needs to balance a range of environmental, social and economic objectives which are not always compatible. According to a recent study[44], several factors play a role in the consequences of bioenergy implementation, such as (i) the technology used, (ii) geography and scale/pace of implementation (iii), land type used, (iv) the governance systems and (v) business models and practices.

The aim of SP5 is to contribute to a better understanding of the environmental, economic and social effects of bioenergy systems. These aspects are relevant to all other Subprogrammes in EERA JP Bioenergy (SP1 to SP4); hence, in the EERA Joint Programme Bioenergy structure, SP5 is a horizontal Subprogramme[45].

The Scope of this Subprogramme is as follows: the first three Research Areas (RA's) will analyse environmental, techno-economic and social aspects per se, while the fourth Research Area will take a cross-cutting perspective, looking at issues where there is an overlap (or potential overlap) between each of these three aspects: environmental, economic and social.

The Research Areas in SP5 are as follows: RA1: Environmental Analysis, RA2: Techno-Economic Analysis, RA3: Social Analysis and RA4: Cross-cutting Sustainability Analysis.

The Scope of each RA is as follows: RA1 will focus on the environmental assessment of bioenergy, and will cover aspects such as climate impacts of bioenergy systems, eco-system impacts (including air quality, biodiversity impacts, etc.) and issues related to methods for assessing the life cycle environmental impacts of bioenergy systems. RA2 will address aspects related to the techno-economic assessment of bioenergy, including the conceptual design and techno-economic assessment of biorefineries and biomass conversion processes, as well as the definition of suitable metrics for assessing the economic sustainability of bioenergy, including uncertainty analysis. As for RA3, it will cover aspects related to the social acceptance of bioenergy technologies, Social Life Cycle Assessment (SLCA), as well as the innovation process and commercialisation of bioenergy technologies and bio-based systems. The fourth RA (Cross-cutting sustainability analysis) will address all issues where there may be an overlap between the environmental, economic and social aspects. Thus, RA4 will focus on aspects such as analysing the land-use impacts of bioenergy, the links between bioenergy and the UN's Sustainable Development Goals (SDG's), macro-economic impacts of bioenergy development, bioenergy and its role in the Circular Economy and Life Cycle Sustainability Assessment (LCSA). This RA will also take a closer look at the political and regulatory frameworks for bioenergy in Europe, addressing issues related to the implementation of RED-II, which will enter into force in the EU from 1st January 2021.

[44]Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., ... Masera, O. (2015). Bioenergy and climate change mitigation: an assessment. GCB Bioenergy, 7(5), 916–944. https://doi.org/10.1111/gcbb.12205
[45]http://www.eera-bioenergy.eu/eera-bioenergy/#structure

2.5.2 MAIN CHALLENGES

SP5 aligns its main R&D challenges with the Integrated Roadmap of SET-Plan and the Declaration of Intent on "Strategic targets for bioenergy and renewable fuels needed for sustainable transport solutions in the context of an initiative for global leadership in Bioenergy" of Nov 16th, 2016, and selected **three main R&D Priorities/Challenges and Key-Performance Indicators (KPIs) to be addressed:**

- **Main Challenge 1: GHG emissions from bioenergy value chains.**

KPI: Environmental analysis of bioenergy value chains, measured as % of GHG emission reduction, should be more than 80%;

- **Main Challenge 2: Investment profitability of biorefineries.**

KPI: Techno-economic analysis of bio-refineries, measured as ROI, should be more than 20%;

- **Main Challenge 3: Public acceptance of biorefineries.**

KPI: Social analysis impact of bio-refineries, measured as positive public perception, should be more than 50%.

Fig. 10 exemplifies how the Research Areas and Research Priorities interlink with the Main Challenges/Priorities of SP5.

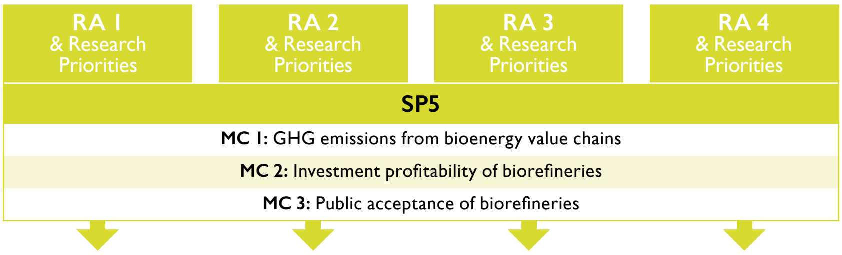

Figure 10: The 3 main challenges of SP5 are addressed through cross-cutting Research Areas and Research Priorities

2.5.3 SP5 RESEARCH AREAS (RA) AND RESEARCH PRIORITIES (RP)

Each Research Area (RA) consist of several Research Priorities (RPs), which in turn include a few Research Themes (RTs).

This Subprogramme addresses four research areas, listed below:

5.3.1. Environmental analysis
5.3.2. Techno-economic analysis
5.3.3. Social analysis
5.3.4. Cross-cutting sustainability analysis

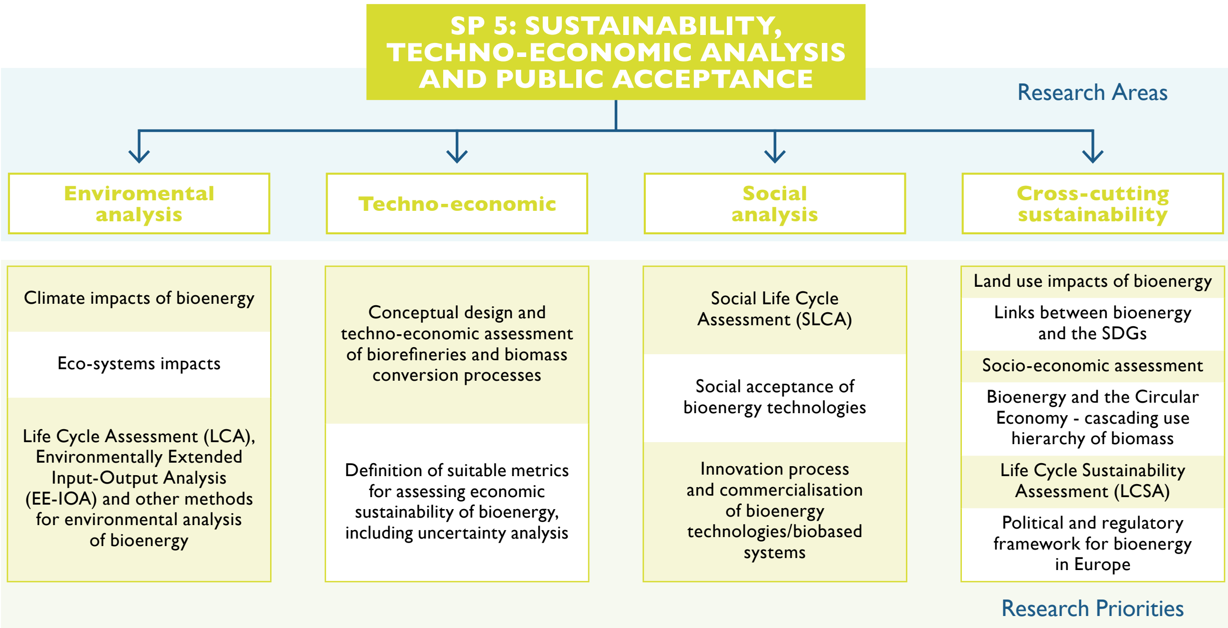

Figure 11: Schemes of the distribution of priorities in each research area of SP5

2.5.3.1 RA1. Environmental Analysis

The scope of this research area is to investigate what environmental consequences may result from the production of energy from bio-based resources. While bioenergy originates from renewable resources, its use and development may give rise to issues that compromise its overall environmental performance. This RA will address both climate-change and non-climate-change related environmental impacts of bioenergy. It will also address issues related to methods for assessing the environmental consequences of bioenergy.

2.5.3.1.1 RP1. Climate impacts of bioenergy

This RP aims to investigate what climate impacts may result from bioenergy deployment, as well as the potential of bioenergy-based technologies for mitigating climate change.

RT1: Identify the influence of negative emissions from biomass/bioenergy through advanced technologies such as Bioenergy with Carbon Capture and Storage (BECCS), afforestation/reforestation, improved agricultural management and biochar conversion.

The objective of the Paris Agreement is to limit the temperature increase to 1.5 °C above pre-industrial levels to achieve a balance between anthropogenic emissions from sources and removals by sinks of GHG's in the second half of this century. The only way to limit global warming to <2 °C is to reduce the net amount of CO_2 released into the atmosphere. This goal could be achieved by two methods: 1) produce less CO_2 (conventional mitigation), or 2) capture more CO_2 (negative emissions). Scientific studies show the difficulty of achieving these goals by only implementing mitigation strategies. Investigations into the possibility of carbon dioxide removal (CDR) from the atmosphere using negative emission technologies (NET's)[46,47,48] show additional research is needed in several topics:

- Assess the land-based negative emissions technologies;
- Evaluate the risk associated with negative emissions technologies;
- Estimate the annual carbon capture potential of the different possibilities;
- Uncertainty associated with the different capture methods;

Some of the key research questions are:

1) Bioenergy with carbon capture and storage (BECCS): Can biomass always be considered to be carbon neutral? Could the overall CO_2 from biomass burning plants be stored underground? Can we guarantee that the CO_2 will not escape from underground storage over time? What are the environmental trade-offs?

2) Afforestation/reforestation: Large areas of land and soil are needed, so competition for land and soil with food/feed production will increase. Forests only store CO_2 emissions for decades or centuries and there is a concern that future changes in land use could provoke the release of stored carbon. Besides albedo changes, increased evapotranspiration, harvesting (legal and illegal logging), fires, pests and diseases of trees could also modify the amount of carbon sequestered. Other uncertainties involve the influence of climate change on afforestation and reforestation vegetation, as well as water availability in a changing climate.

3) Improved agricultural management: Several different agricultural techniques may implement soil carbon sequestration: decreased soil disturbance (no till, reduced tillage), grazing management, planting legumes, mixture of forest and crops, use of manure as natural fertiliser, etc. Some research questions to explore further are: What is the maximum storage? When is the soil saturated?

4) Biochar conversion: Selection of both appropriate biomass feedstock and pyrolysis conditions to produce the biochar required for each specific application, is one of the topics requiring further research.

RT2: Biogenic carbon accounting

Biogenic carbon can be defined as the carbon fluxes circulating between the vegetation and the atmosphere: CO_2 from oxidation of carbon in bio-materials harvested for energy (both at the conversion plant and through the various life-cycle stages), CO_2 from dead organic matter decomposition, and CO_2 sequestered by biomass growth.

Bioenergy is commonly considered "carbon neutral" since the carbon released during combustion has previously been sequestered from the atmosphere and will be sequestered again as the plants regrow. The Renewable Energy Directive (RED) considers biomass combustion to have "zero" emissions. However, the IPCC does not automatically consider biomass used for energy as carbon neutral, even though the biomass has been produced sustainably. Other studies do not consider bioenergy as carbon neutral, mainly when the raw material comes from woody forest. The carbon neutrality of a process or activity that uses biomass depends on many factors: the feedstock type used, the technology applied, and the time frame considered. There are several definitions of carbon neutrality, so which one is the most suitable for the bioenergy sector? The crucial point is the timing of fluxes in bioenergy systems. Carbon emissions usually occur at a particular time; however, carbon sequestration, depending on the type of vegetation, could range from one year for annual crops to decades or centuries for forests. Biogenic carbon fluxes are species- and time-dependent, but also are very site-specific attending to soil and meteorological conditions[49]. Albedo disturbance, as a consequence of biomass production for bioenergy, is one of the new topics to assess in carbon fluxes.

[46]https://re.public.polimi.it/retrieve/handle/11311/961659/154659/NCC_negative_emissions.pdf
[47]https://mediamanager.sei.org/documents/Publications/Climate/SEI-WP-2016-08-Negative-emissions.pdf
[48]https://unfccc.int/sites/default/files/resource/28_EASAC%20Report%20on%20Negative%20Emission%20Technologies.pdf
[49]https://iopscience.iop.org/article/10.1088/1748-9326/7/4/045902/pdf

RT3: Soil carbon sequestration

Enhanced soil carbon sequestration is one of the strategies available to lower CO_2 emissions and mitigate climate change. Rates of soil carbon sequestration depend on species, soil characteristics, environmental conditions, and management practices. Several initiatives try to increase the organic carbon content in the soil. Focusing on terrestrial pools, there are several agricultural practices recommended by FAO and other institutions to enhance carbon sequestration in agricultural soils: keeping soil disturbance to a minimum (no till and reduced tillage), organic fertilisation (organic matter and crop residues), crop rotation, adding legumes or N-fixing crops plantation in rotation, etc. In forest ecosystems, best management practices involve afforestation, reforestation, promoting natural regeneration, reducing excessive logging, and applying silvilcultural techniques.

However, several uncertainties remain involving the carbon dynamics over time. What factor determines whether the carbon remains in the soil or is released again to the atmosphere? What is the potential level of saturation in different soils and ecosystems? How could increasing temperatures affect carbon fluxes between soil and atmosphere? What is the role of nutrients, such as nitrogen, in carbon sequestration by soils? Which management practice can best increase carbon sequestration in soil? How can existing soil carbon stocks be preserved?

RT4: Hierarchy in cascading use of biomass residues and wastes in "single product system" and biorefineries

The cascading use philosophy maximises resource efficiency by using biomass in products that create the most economic value over multiple lifetimes[50]. This approach indicates that energy recovery should be the last option, and only after all higher-value products and services that were economically viable have been exhausted. Biomass use for energy, heat and cooling purposes should therefore be located as the final step in a cascade. As it is not always profitable to extract these resources and biomass residues in mountainous, remote or isolated areas, if their use is not allowed for the production of pellets or chips in local plants, they could be abandoned in the field and encourage forest fires or be burned in the field to avoid problems with fungus proliferation.

The forestry sector warns that the introduction of a rigid hierarchy in the use of products and by-products would create unforeseen negative consequences, such as market distortions and innovation bottlenecks. In order to avoid this, the sector proposes that the approach to resource efficiency in the forest sector should be bottom-up[51], market-based and well-grounded in innovation and based on an appropriate understanding and shared knowledge of proven best practices. How to reconcile different expectations and sustainable uses would be the work line to explore.

2.5.3.1.2 RP2. Eco-system impacts

This RP focuses on assessing the environmental impacts of bioenergy systems besides climate change impacts. Some of the issues investigated are those related to air-quality, water use and the biodiversity impacts of bioenergy. The role of environmental regulation and certification schemes will also be covered in this RP.

RT1: Analysis of the effect of biofuels combustion on air quality in case of distributed heating and power generation

One of the solutions to achieve the EU goal to decrease CO_2 emissions and therefore reduce fossil fuel consumption is to introduce biofuels to already existing combustion processes, with the assumption that biofuels are carbon-neutral. In some EU countries, a large part of heating systems, both at the household/individual scale, as well as in city district heating systems, are fuelled by fossil fuels. Especially in regions where coal is the dominating fuel, the air pollution problem is raising public awareness. Hence, this RT will analyse in depth the influence of incorporating different types of biofuels (solid, liquefied or gasified) on air quality, especially in distributed/individual heating systems on a mass scale. One of the crucial assumptions in the analysis is to base it on existing installations, with regard to the fact that the costs required to modernise heating systems should be minimised. The results of the analyses should help answer the questions regarding which biofuels are worth implementing in distributed and central district heating systems, what their influence on air quality will be and how their economic potential would differ.

RT2: The implications of large-scale bioenergy deployment on water resources within the context of changing climate and demographic patterns

Water resources across Europe and globally are likely to undergo significant changes over coming decades due to factors such as climate change and changing demographic patterns. Bioenergy will interact with water resources across the entire value chain. Research has highlighted the global implications of large-scale bioenergy deployment for water resources in terms of crop production[52]. Furthermore, pressure on water resources may serve to impose constraints on the feasibility of some bioenergy technologies, for example, by limiting the availability of cooling water for operating bioenergy with carbon capture and storage plants during periods of low flow[53]. There is a need to improve the representation of bioenergy within hydrological models to provide policy makers with the tools that they need for water resource planning.

[50] Guidance on cascading use of biomass with selected good practice examples on woody biomass. https://publications.europa.eu/en/publication-detail/-/publication/9b823034-ebad-11e8-b690-01aa75ed71a1/language-en/format-PDF/source-80148793
[51] A bottom-up approach to the use of forest biomass. https://eustafor.eu/uploads/Joint_Statement_EfficientUse_17092018.pdf
[52] Bonsch, M. et al. Trade-offs between land and water requirements for large-scale bioenergy production. GCB Bioenergy 8, 11–24 (2016).
[53] Byers, E. a. et al. Cooling water for Britain's future electricity supply. Proceedings of the ICE - Energy 168, 188–204 (2015).

RT3: Bioenergy within the context of broader environmental regulations at national, regional and global scales

Beyond climate targets, the deployment of bioenergy has a range of both positive and negative environmental implications (e.g. air quality; water resources; biodiversity)[48,54]. However, it is unclear the extent to which broader regulations such as those relating to water resources (e.g. EU Water Framework Directive) or biodiversity (e.g. EU Habitats Directive) are considered when examining bioenergy deployment options. There is a need to better understand bioenergy value chains within this broader regulatory context and to consider the extent to which tools used within other domains (e.g. water resource models) incorporate bioenergy. A critical question is the extent to which energy and environmental domains interact when developing policy[55].

RT4: The efficacy of biofuel feedstock certification schemes within differing national contexts of sustainable development

A growing number of countries have national targets or policies supporting renewable energy, of which energy from biomass is a key component. This has led to widespread growing global demand for biomass, with some of the regions with the greatest demands having comparatively low resource availability[56]. The increasing trade and movement of biomass resources around the world has led to many hard sustainability questions, and certification schemes are often used as the mechanism to assess performance. With the vast ranges in the type of biomass resources produced and variations in geographic and developmental settings, it is important to understand the effectiveness and transferability of bioenergy feedstock certification schemes and to what extent they support development[57,58]. To what extent is the structure of existing certification schemes helping or hindering the deployment of bioenergy, and what are the social, environmental and economic impacts? What barriers exist and how might certification be designed that can recognise such contexts without undermining the safeguards they provide?

RT5: Representation of biodiversity and the impacts of bioenergy deployment in ecosystem services within modelling frameworks

Progress towards globally agreed targets to halt the loss of biodiversity and ecosystem services is measured and reported using a range of indicators[59]. Predicting the implications that commercial-scale bioenergy deployment has on biodiversity and ecosystem services is complex, as impacts vary across the value chain and are contingent on factors such as feedstock type, technology, scale of deployment, etc. [9]. Improving our understanding of these interactions is essential in order to inform the development of a bioenergy policy that does not undermine our ability to meet biodiversity and ecosystem service objectives. A research priority in this area is to develop methods to integrate existing and future biodiversity and ecosystem service indicators within existing energy models in order to both assess implications and act as constraints on bioenergy options.

2.5.3.1.3 RP3. Life Cycle Assessment, Environmentally Extended Input-Output Analysis and other methods for environmental analysis of bioenergy

This RP focuses on methods for assessing the environmental impacts of bioenergy, covering issues related to both existing methods and method development.

RT1: Prospective LCA of bioenergy systems

Bioenergy systems are expected to play a key role in making the future energy sector greener, with a focus on the transport and heat/power generation sub-sectors. From a systems analysis perspective, a relevant need refers to planning the long-term contribution of bioenergy systems to future technology mixes under a number of energy scenarios. In this sense, the combination of Energy Systems Modelling and Life Cycle Assessment arises as a combined approach to the prospective assessment of global energy systems. This research theme focuses on the identification and techno-economic and environmental characterisation of bioenergy technologies for their subsequent implementation in energy systems models, thereby allowing the exploration of different energy scenarios with a focus on the evolved life-cycle aspects regarding bioenergy options. Europe and European countries represent the target geographical scope of this research theme.

[54] Gasparatos, A., Doll, C. N. H., Esteban, M., Ahmed, A. & Olang, T. A. Renewable energy and biodiversity: Implications for transitioning to a Green Economy. Renewable and Sustainable Energy Reviews 70, 161–184 (2017).
[55] Holland, R. A. et al. Bridging the gap between energy and the environment. Energy Policy 92, 181–189 (2016).
[56] Welfle, A. Balancing growing global bioenergy resource demands - Brazil's biomass potential and the availability of resource for trade. Biomass and Bioenergy 105, 83–95 (2017).
[57] Scarlat, N. & Dallemand, J. F. Recent developments of biofuels/bioenergy sustainability certification: A global overview. Energy Policy 39, 1630–1646 (2011).
[58] Van der Horst, D. & Vermeylen, S. Spatial scale and social impacts of biofuel production. Biomass and Bioenergy 35, 2435–2443 (2011).
[59] European Commission. Biodiversity Strategy. Available at: http://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm. (Accessed: 22nd March 2019)

RT2: Life Cycle temporal and spatial analysis of bioenergy systems

Some research has been done into the temporal impacts of differing bioenergy systems, but as of yet this is restricted to some case studies and has limited analysis. In the temporal sphere, few studies look at both dynamic inventory and dynamic impact. A gap analysis of the current work in this area, including both temporal and spatial impacts, would be useful to sit alongside some further assessment of where and how we can minimise impact.

RT3: Life Cycle comparison of different vector options

Optimising the use of finite bioenergy resources requires substantial and comparable life cycle assessments of pathways. In this regard, it would be good to see some sort of harmonised study of options that helps industry and policy makers determine how best to utilise resources.

RT4: Impact Assessment methods for calculating environmental impacts

Life Cycle Assessment is a robust methodology to assess environmental impacts; however, outcomes are difficult to compare between studies due to the different impact assessment methods used. The European Union tried to solve this problem and recommended a set of methods for LCIA, but authors are free to use the preferred methodology. Requesting LCA studies to be accompanied by the inventories could help to re-calculate other studies with a common impact assessment method, making it possible to compare studies in the same field/technology/products.

RT5: New metrics to calculate environmental impacts

IEA Bioenergy Task 45 (Climate and Sustainability Effects of Bioenergy within the broader Bioeconomy) is integrated with Task 38 (Climate Change Effects of Biomass and Bioenergy Systems), whose main objective is to identify critical issues on sustainability of bioenergy and bio-based products. An updated standard methodology is proposed for calculating life cycle climate change impacts that incorporates current and emerging issues, technologies and topics. It has been planned to analyse metrics, methods and tools for assessing the sustainability effects of bioenergy, including climate change effects. The common adoption of this updated standard methodology developed into the IEA framework will benefit from harmonisation by quantifying environmental impacts under the LCA. A novel aspect is the inclusion of "sustainability stakeholders", who can collaborate to focus the issue with a broad vision for developing approaches to assist in governance decision-making by governments, land-owners, communities and businesses. The inclusion of these variables could enrich the analysis of environmental impacts.

RT6: Reference system definition and its importance to calculating bioenergy impacts

The study of environmental impact effects from bioenergy use requires a comparison between the bioenergy system and the selected reference system producing the same number of products and services. This statement is also valid for bio-refineries, co-produced biofuels, bioenergy, biochemicals, and biomaterials with different functions and functional units. Biomass use for bioenergy and/or bio-based products analysis must cover impacts associated with land use change management, the consequences of removing residues, changes in N_2O emissions and the influence of allocation issues on soil carbon sequestration.

Guidance for selecting reference system to quantify the climate effects of bioenergy on climate change with a broad approach has been recently proposed. The inclusion of the framework for defining the appropriate land reference attending to the goal and scope of the bioenergy system is essential so as to align the reference system with the purposes of the bioenergy scheme.

RT7: Representing the natural capital/ecosystem service implications of bioenergy at multiple spatial and temporal scales to improve global and regional modelling (e.g. IAMs, EE-MRIOs)

Tools used to craft national, regional and global energy policy, e.g. Integrated Assessment Models (IAMs) and Multi-Region Input-Output (MRIO) models, commonly use highly aggregated values to represent natural capital and ecosystem services that may exhibit complex spatial and temporal patterns at sub-national scales[60]. The use of such aggregate measures also ignores the fact that the provision of ecosystem services is highly dependent on spatial context[61] and can change over time[62]. Management must take into account such dynamics and scale effects to deliver policy goals[63]. A priority area for research is therefore to identify how high-resolution spatial and temporal information can be incorporated into modelling frameworks that operate at coarse scales in order to reduce uncertainty around bioenergy deployment strategies.

[60]Holland, R. A. et al. Incorporating ecosystem services into the design of future energy systems. Applied Energy 222, 812–822 (2018).
[61]Anderson, B. J. et al. Spatial covariance between biodiversity and other ecosystem service priorities. Journal of Applied Ecology 46, 888–896 (2009).
[62]Holland, R. A. et al. A synthesis of the ecosystem services impact of second generation bioenergy crop production. Renewable and Sustainable Energy Reviews 46, 30–40 (2015).
[63]Spake, R. et al. An analytical framework for spatially targeted management of natural capital. Nature Sustainability 2, 90 (2019).

2.5.3.2 RA2. Techno-economic analysis

RA2 analyses the economic sustainability of bioenergy deployment. On the one hand, this RA will address the conceptual design of biorefinery and biomass conversion processes; on the other hand, it will look at method-related questions, namely the definition of suitable metrics for assessing the economic sustainability of bioenergy systems, including uncertainty analysis.

2.5.3.2.1 RP1. Conceptual design of biorefinery and biomass conversion processes

RP1 will look at a wide range of issues related to the conceptual design of biorefinery and biomass conversion processes, including the definition of potential design configurations and technological routes for biorefineries with multiple products, profitability analysis for biorefinery processes and development of supply chain models aimed at optimising economic performance along the whole chain. In addition, a number of TEA's (techno-economic analyses) will be performed, including micro CHP sources fuelled by 2nd generation biofuels, flexible energy storage systems based on bio-based synthetic fuels and energy and resource efficient processes for synthesising platform molecules from biomass resources. Finally, the RP will analyse process modelling of large-scale biomass-based manufacturing of high-added value products.

RT1: Definition of possible conceptual design configurations and technology routes for biorefineries where multiple products are considered (e.g. heat & power, fuels, chemicals)

Based on the technologies, models and results attained in Subprogrammes 1-4, a conceptual design is devised to identify possible bio-refinery configurations[64]. Process design will be driven both by economic sustainability and productivity. Energy (i.e. heat, power and fuels) is at the core of the design effort. However, the possibility of exploiting side-products and/or of converting biomass residues/waste into valuable products is assessed and incorporated into the design task. A model is created to describe key unit operations (e.g. bioreactors or thermochemical conversion units). The process flowsheet is defined and assessed via process simulation. Tailored analyses of mass fluxes are carried out to minimise waste production. Heat integration techniques (e.g. pinch analysis or superstructure optimization) are adopted to increase the process sustainability and energy outputs.

RT2: Profitability analysis for processes; identification and assessment of key technological parameters affecting profitability; process optimisation (e.g. energy integration)

A cost and profitability assessment is carried out for the selected processes. In particular, major economic bottlenecks that may hinder the investment profitability are identified. Technological routes for profitability improvement are analysed and implemented. At the end, the most promising technology platforms are selected. Process-wide optimisation is carried out to improve the configuration and economic performance of biorefineries.

RT3: Development of supply chain models involving the technology platforms identified so as to assess and optimise the economic performance along the entire production chain (possibility of incorporating LCA metric for multi-objective economic and environmental optimisation)

The economic and environmental performance of a biorefinery is closely related to the overall production supply chain[65]. Factors such as the availability of biomass feedstock (in terms of quantity and type), distance and logistics, market demand for energy products and chemicals, all affect technological choices, the size and locations of conversion facilities and the production organisation (e.g. distributed vs. centralised). Considering the information generated within SP1, models are developed to assess and optimise the production chain, taking into account biomass cultivation and/or waste collection, transport means, conversion technologies and product portfolio. A geographically explicit approach is adopted to allow identifying optimal choices depending on regional differences. The supply chain environmental impact (based on an LCA approach) is incorporated within the modelling framework in order to assess whether different strategies may lead to different results in terms of economic performance or environmental benefits.

[64] Cardona et al (2007), Bioresour. Technol., 98:2415–2457.
[65] Yue et al (2014), Comput. Chem. Eng., 66: 36–56.

RT4: Techno-economic analysis of micro CHP sources fuelled by 2nd generation biofuels

The aim of this research theme is to assess and compare the economic potential of 2nd generation biofuels in CHP installations on a micro scale. The growing interest both from researchers and industry in biofuels such as bioDME, bio-derived hydrogen or bio-methane, is yielding a wide range of production and utilisation system concepts. This RT will analyse and compare the techno-economic potential of selected 2nd generation biofuels in already developed micro-CHP systems, especially of the conventional type, such as gas micro-turbines, piston engines, ORC or conventional Rankine systems. However, the analyses may also contain other technologies, such as fuel cells. The results of the analyses should allow for a comparison of costs of 2nd generation biofuels used in micro-CHP systems and provide the basis for implementation forecasts.

RT5: Techno-economic analysis of flexible energy storage systems based on bio-based synthetic fuels

In recent years, the rapid increase in the installed capacity of renewable energy sources across EU countries has led to stability issues in electrical grids and to a mismatch between electricity production and consumption. A general awareness of the adverse impact of batteries on the environment is fostering the development of alternative, most preferably rare-earth elements-free technologies for the system-level storage of energy. Energy storage based on biofuels and bio-related energy carriers may be a promising and flexible technology for distributed and centralised grid balancing systems. This RT will analyse bio-based energy storage systems in terms of their capital expenditures, operational costs and technical feasibility in reference markets under given scenarios. This includes variant analysis of efficiency, CAPEX/OPEX and cost of recycling/disposal for given nominal capacities. The results of the analyses should allow for a comparison of the economic potential of selected energy storage systems.

RT6: Techno-economic potential assessment of one-pot energy and resource efficient processes for synthesising platform molecules from biomass resources

The use of biomass as a feedstock for the production of high-added value products through platform molecules has been extensively investigated, although the number of economic studies on this aspect is very scarce due to the lack of experience or relevant industrial practice. Current approaches involve several chemical reaction steps; each step of the process involves side reactions, separation and purification of intermediates, which increase the cost of the target products. However, new multifunctional catalysts, or multifunctional catalytic systems (with homogeneous and heterogeneous catalysts) can be used in one-pot reactors, which eliminates the need for intermediate separation processes and yields significant cost savings. This research theme focuses on evaluating the economic potential of existing one-pot reaction models in scaled-up technologies to produce high-value added products from biomass.

Further, the comprehensive integration of reaction engineering and process design of reactors and sub-sequent downstream processing is evaluated to develop innovative energy- and resource-efficient processes.

RT7: Process modelling of large-scale biomass-based manufacturing of high-added value products

The use of process modelling to study biomass processes for the production of high added-value products has certain limitations on evaluating scalability and replicability. In many cases, process modelling is abstracted to black-box models where process yields are taken from the literature or from experimental data, so they cannot evaluate the consequences of changes in feedstock properties, process parameters and operational conditions. Therefore, there is an inherent need for biomass process modellers to know more about the fundamentals of these processes. This RT focuses on (i) biomass composition models using realistic and predictive models, where biomass reactivity can be represented by the reactivity of a series of surrogate molecules, and (ii) actual predictive models that can predict the mass and energy balances of biomass-based processes through kinetic, thermodynamic and semi-empirical models.

2.5.3.2.2 RP2. Definition of suitable metrics for assessing the economic sustainability of bioenergy, including uncertainty analysis

RT1: Identification of sources of uncertainty of concern to a process's economic performance; assessment of uncertainty effects on profitability (and environmental) performance; proposal of mitigation measures

Looking at process size, sources of uncertainty which would affect a process's economic performance are identified and assessed. These may comprise: technology performance, feedstock composition (particularly in the case of wastes), seasonal feedstock availability, feedstock price, product (energy and chemicals) price and demand. The impact on the environmental performance is also to be assessed. Strategies for uncertainty-resilient biorefinery designs are proposed[66]. For instance, the product portfolio can be optimised to guarantee higher flexibility in an uncertain environment. Uncertainty analysis will allow defining a set of metrics required to assess the economic performance: for instance, apart for some standard profitability criteria (IRR, NPV, etc), more effective indices will be introduced to evaluate the investment risk, such as the downside risk or the conditional value at risk (C-VaR).

RT2: Identification and assessment of uncertainty sources involving the overall supply chain and business models (including energy market effects); definition of mitigation measures (e.g. robust supply chain design, etc.)

The above sources of uncertainty can be translated to a higher scale of the supply chain for a comprehensive business evaluation. The objective is to assess how the overall supply chain is affected by uncertainty factors and to optimise its structure to be more robust to fluctuations in feedstock prices and product demand and prices[67]. It analyses how supply chains can be designed to reduce investment risk related to uncertainty in the actual performance of new technologies[68] and how technology learning curves can be exploited to assess future business changes.

RT3: Evaluation of assessment criteria in dependence of TRL, assessment of process chains with low or very different TRL, development of recommendations

In many cases, various processing routes can be followed for bioenergy production. Usually, detailed assessments can only be done when reliable pilot plant data becomes available; however, pilot plants are expensive and time consuming to plan and operate. Therefore, it is desirable to assess alternative process chains as early as possible. In the early stages of technological development, uncertainties become larger and thus influence the basis for taking decisions. The same is true if a high-TRL technology is combined with parts of the value chain where only low TRL have been achieved so far.

There is a need to develop procedures and/or tools to estimate the economic and environmental viability of new processes early in the development process. These procedures are currently not well developed and depend strongly on the experience of the individual. Working toward a joint understanding of these challenges enables comparing different technologies on a similar basis.

The work carried out in this Research Theme seeks to systematically investigate the influence of TRL on techno-economic assessment in terms of mass and energy balances, as well as of the fixed and variable costs of a process. The effect on life cycle assessment can be included later, also depending on the mass and energy balances of a given process. Apart from the sensitivity analyses already in place today to account for variable parameters, new indicators will be developed to mark the stage of technological readiness.

Further, an integrated assessment of individual business cases might be embedded, although the selection here has a comprehensive influence on the result of an assessment. Splitting these two aspects - the costs of a process and business case - is vital for any given analysis.

In dedicated workshops, case studies will be presented and discussed. Once they are further analysed, recommendations can be made on how to characterise early stage assessments and how to indicate the degree of uncertainty which may be caused.

[66] Geraili and Romagnoli (2015), AIChE J., 61: 3208-3222.
[67] Gargalo et al (2017), Ind. Eng. Chem. Res., 56: 11870-11893.
[68] D'Amore and Bezzo (2017), Energy, 138: 563-574.

2.5.3.3 RA3. Social analysis

The analysis of social effects associated with bioenergy development will be covered by RA3. As for the previous RA's, RA3 will cover method-related issues, which in this case will focus on Social Life Cycle Assessment (SLCA). Furthermore, RA3 will analyse issues related to the social acceptance of bioenergy technologies, as well as innovation processes and the commercialisation of bio-based technologies.

2.5.3.3.1 RP1. Social Life Cycle Assessment (SLCA)

This RP, dedicated to Social Life Cycle Assessment (SLCA), will focus on an issue hindering the applicability of this method to bioenergy, namely the development of life cycle inventories of bioenergy products.

RT1: Life cycle inventories for SLCA of bioenergy products

When compared to other life cycle-based methodologies such as environmental LCA, SLCA is still immature. However, the development of tools such as the PSILCA database and the Social Hotspots Database has paved the way for a robust methodology for the SLCA of products. Unfortunately, inventories for the SLCA of bioenergy products (biofuels, heat, power…) are not readily available. Within this context, this research theme seeks to generate a significant number of inventories that allow the SLCA of bioenergy products. Given SLCA features, key aspects include the identification of relevant bioenergy case studies at the European level, the identification of the country-specific economic sectors involved, the quantification of economic flows and working hours, and the final preparation of inventories ready for the SLCA of bioenergy products.

RT2: Methodological challenges of the SLCA of bioenergy products and processes

Social Life Cycle Assessment (SLCA) is an instrument for conducting comparative social/socio-economic evaluations of products, processes and entire supply chains. It offers holistic indicators that satisfy the informational needs of all relevant stakeholders while also considering qualitative indicators in its evaluation. The establishment of the SLCA has remained in an early developmental stage so far due to methodological difficulties, and a thorough evaluation of this method is still ongoing. Methodological problems, such as the lack of suitable procedures for objectively measuring qualitative aspects (e.g. the negative perception of changes in the landscape), have so far strongly hampered the application of SLCA. Further research is needed to overcome these methodological challenges and to develop a modified, empirically based method of running a regionally-differentiated SLCA.

2.5.3.3.2 RP2. Social acceptance of bioenergy technologies

RP2 will study aspects related to the social acceptance of bioenergy technologies and which factors and strategies may play a role in this.

RT1: Public acceptance of bioenergy technologies/biofuels across countries

A recognition and understanding of the needs, views and acceptance of stakeholders in the field of bioenergy are crucial for the further and future development of bioenergy technologies. Research is needed to identify and analyse the factors that drive public acceptance or rejection of technologies.

RT2: Analysis of factors and strategies that influence social support for bioenergy systems through public survey

The expansion of the bioenergy sector will depend, in part, on levels of public support. In fact, public support can influence policy-making and the willingness of farmers and forest owners to produce additional biomass feedstock for bioenergy. A better understanding of public opinion towards bioenergy and the factors that influence public opinion is crucial in this regard.

This research line aims to provide insights into the main factors shaping and affecting public support of bioenergy technologies. Social acceptance is a complex issue and specific to local circumstances and culture. That is why social acceptance of bioenergy in different European countries, and even in different regions of a country, can be very diverse. A review of previous studies on opinions and support for bioenergy, followed by case specify surveys, will help to identify and analyse the factors that influence social support.

Many past studies/publications have focused on public perceptions of bioenergy and biofuels for transportation by studying the general public[69,70,71,72]. However, biomass production is a local activity and the direct impacts of a biorefinery plant, for instance, occur in the surrounding region. A good understanding of public opinions at a local level will provide valuable input for defining strategies to increase social acceptance of bioenergy value chains.

Through public surveys, the current public opinion and attitudes towards biomass use for energy purposes will become clear. Moreover, reaching out to the people and surveying their understanding will help to increase awareness. It will also aid in analysing societal preferences and perceptions.

RT3: Transdisciplinary research

In the context of complex societal challenges with significant uncertainties, such as the application of biomass to mitigate climate change, traditional expert knowledge is generally insufficient to fully analyse the possible consequences, intended or unintended, of bioenergy technologies. As such, traditional approaches are unlikely to lead to sustainable solutions. Thus, the co-design and co-production of knowledge offered by transdisciplinary research is likely to lead to improved problem solving. However, significant obstacles remain, and implementation of true transdisciplinarity is even more challenging. If transdisciplinarity is to expand from a marginal theoretical concept into a mainstream approach to scientific research in the field of bioenergy, important questions must be resolved, including about methods and practice.

2.5.3.3.3 RP3. Innovation process and commercialisation of bioenergy technologies/ bio-based systems

How do bioenergy technologies transition from R&D to uptake/ commercialisation, and what is the role of social capital and innovation in the different stages? This will be the focus of RP3.

RT1: Analysis of the nexus of social capital rules and cooperation

Several innovative bioenergy technologies face difficulties moving from R&D to commercialisation. Some of them would even remain in the "valley of death", i.e., their transition to the market is delayed or unsuccessful. This research line focuses on factors that influence the commercialisation of research.

Social capital[73] and subsequent network structures and shared beliefs are particularly interesting to innovation processes[74,75]. Case study-based insights regarding the network structure, social capital, as well as the shared beliefs of the organisations involved, will help to identify the drivers and barriers regarding the social acceptance of innovative bioenergy processes.

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[70]Evans, H and Newton-Cross, G. (2016). Public Perceptions of Bioenergy [online]. Available at: www.eti.co.uk/insights/public-perceptions-of-bioenergy-in-the-uk
[71]http://stargate.cnr.ncsu.edu/index.php/BioRes/article/viewFile/BioRes_10_4_Review_Radics_Bioenergy_Perception_Studies/3968.
[72]https://www.sciencedirect.com/science/article/pii/S0959652613009141.
[73]Social capital refers to the connections among individuals expressed through social networks and the norms of reciprocity and trustworthiness that arise from them (Putnam, 2001).
[74]Hellsmark, Hans, Frishammar, Johan, Söderholm, Patrik and Ylinenpää, Håkan, (2016), The role of pilot and demonstration plants in technology development and innovation policy, Research Policy, 45, issue 9, p. 1743-1761.
[75]The impact of Academia on the Dynamics of Innovation System, Doctoral Thesis, Eugenia Perez Vico, Chalmers Univsity of Technology, 2013.

2.5.3.4 RA4. Cross-cutting sustainability analysis

This Research Area will address issues that overlap across the three pillars: environmental, techno-economic and social.

The research in RA4 will focus on aspects such as the land use impacts of bioenergy, links between bioenergy and the United Nations Sustainable Development Goals (UN SDG's)[76], the socio-economic implications of bioenergy deployment and methods to assess it. Other topics in this RA include the role of bioenergy in achieving a Circular Economy and how Life Cycle Sustainability Assessment (LCSA) methods can be applied to jointly analyse the environmental, social and economic consequences of bioenergy systems. Finally, RA4 will take a closer look at the political and regulatory framework for bioenergy in a European context.

2.5.3.4.1 RP1. Land-use impacts of bioenergy

This RP focuses on the study of aspects related to land-use for bioenergy, from the impact of policies on land-use decisions and their consequent environmental/social/economic implications, to the application of new GIS methods and tools for quantifying land cover conditions, as well as certifying low indirect land-use change (ILUC) risk biofuels/biomass fuels.

RT1: Impact of bioenergy sustainability policies on land-use decisions and their associated environmental and socio-economic effects

The European Commission's implementation of bioenergy sustainability policies towards the improved use of energy from biomass in heating, electricity and transport (as part of its Climate and Energy Package for 2030) has been impacting land use decisions and options. Precautions need to be considered in order to guarantee that bioenergy delivers climate benefits, is resource efficient and avoids detrimental consequences to water, soil, land use, biodiversity and citizens. A study of a comprehensive framework to understand the impact of bioenergy policies on land-use decisions and options, as well as their related socioeconomic and environmental effects and risks, is required in the near term.

RT2: Application of GIS methodologies and tools for modelling and quantifying land cover conditions, biomass and bioenergy productivities and GHG emissions/savings for further socio-economic and environmental evaluation.

Geographic-specific characteristics play a major role in the evaluation and selection of land use. Geographic Information System (GIS) methodologies and tools relate spatially land use selection and changes. The GIS methodology will involve a multiplicity of functions such as the capture, collection, measurement, storage, organisation, modelling, editing, analysis, processing, mapping, sharing and publication of data with relevant information. An extensive database for georeferenced mapping of land cover for further evaluation, quantification and integration of land uses and changes should be created. Applications of GIS for precise agronomic and forestry resource assessment, biomass logistic and power plant design in sustainable bioenergy planning are emerging.

GIS can be used for either modelling or estimating biomass, GHG emissions/savings or bioenergy productivities under different scenarios, technological options and conversion pathways. Special interest should be paid to identifying areas with a low carbon charge that are inadequate for food and feed crops. Real case-studies can be selected and conducted in order to check the suitability of GIS methodologies for optimal land use allocation and changes, as well as innovative and useful decision support systems. The data acquired, generated and processed can be of crucial importance to technologists, entrepreneurs and decision (policy) makers. GIS provides the appropriate data for quantifying land cover conditions and measuring the environmental and socioeconomic impacts of land-use change.

RT3: Evaluation, quantification and integration of Land Use and Increased Land Use Efficiency in Agriculture, Forestry and effects on Greenhouse Gas Emissions and bioenergy

GIS, together with data from other sources, can be managed and used in order to evaluate, quantify and integrate Land Use and Increased Land Use Efficiency in agriculture, forestry and other anthropogenic activities. Its derived effects on Greenhouse Gas Emissions and savings can be used as an input for resource assessment, regional planning and for useful decision support systems.

[76]https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

RT4: Setting out criteria for certifying low ILUC-risk biofuels, bioliquids and biomass fuels

High ILUC-risk biofuels, bioliquids and biomass fuels are those produced from feedstocks for which a significant amount of expansion is observed into high carbon stock areas. The conversion of lower to higher carbon stock drives ILUC emissions. For sustainability reasons, the identification of feedstocks at a regional level that might be categorised as high ILUC-risk is required before RED-II goes into effect.

To implement a low ILUC-risk certification, appropriate and accurate measurement protocols should be set up. ILUC is a major issue and high uncertainties still persist even when robust modelling and a large number of data are available, such as crop yields (including baselining) and gains, displacement effects, time-related CO_2 emissions and savings and other issues. Crop yield variability is geographically related and makes baselining difficult. This variability is large compared to the yield gains claimed in many reports.

2.5.3.4.2 RP2. Links between bioenergy and the SDG's

In 2015, the United Nations Member States adopted the 2030 Agenda for Sustainable Development, at the core of which are the 17 Sustainable Development Goals (SDG's)[77]. The SDG's address key global sustainability areas of concern, such as poverty, economic growth, education, health, climate, ecosystems, sustainable ocean use, among other challenges. How can bioenergy help us address the different global sustainability challenges, and what are the potential synergies and trade-offs for the different SDG's when it comes to bioenergy systems? These issues will be addressed within this RP.

RT1: Modelling synergies and trade-offs between UN SDG's from the context of bioenergy, in order to inform policy

There is growing understanding that the United Nations Sustainable Development Goals (UN SDG's) cannot be considered individually, but that all the goals interact to varying degrees [1]. This can take the form of trade-offs whereby strategies targeted in one area (e.g. economic goals) can have the effect of undermining development in other areas (e.g. environmental or social goals) [2].

Alternatively, synergies may exist whereby targeted investment in one area delivers ancillary benefits across multiple SDG's. Designing an effective bioenergy policy requires increasing our understanding of where these synergies and trade-offs exist.

For example, efforts to achieve SDG7 (Affordable and clean energy) using bioenergy systems may also have unintended consequences regarding SDG2 (zero hunger) due to the availability and price of food[78] or SDG15 (Life on land) for the ecosystem as such. Fuso et al.[79] identified more than 113 SDG targets that require actions to change energy systems and established the links between 143 targets and SDG7. As recognised by the recent IPCC SR[80], climate policies pursued under SDG13 (climate action) may have synergies or trade-offs with the other proposed SDGs. As for SDG 1 (no poverty), it has been proved that access to modern energy forms that could be attained by the deployment of bioenergy technologies is fundamental to alleviate poverty[81]. Furthermore, the transition towards low-carbon energy technology will mitigate climate change and reduce the exposure and vulnerability to climate-related extreme events. Modern bioenergy development may also create income-generating opportunities along the entire supply chain, positively affecting SDG1 (no poverty) and SDG8 (decent work and economic growth), but concentrating bioenergy feedstock production may lead to the undesirable exclusion of small holders and small entrepreneurs from these positive effects[82,83,84]. Additionally, modern energy access that will be provided by the implementation of bioenergy systems is also critical to enhance agricultural productivity and increase food security (target 2.3 under SDG 2 zero hunger). Although the potential for synergies is larger than for trade-offs, it is utterly important to understand and quantify the impacts of bioenergy on the various SDG's. This is the only way to inform and support the decision-making process at the different policy levels.

[77]https://sustainabledevelopment.un.org/?menu=1300
[78]McCollum DL, Echeverri LG, Busch S, Pachauri S, Parkinson S, Rogelj J, et al. Connecting the sustainable development goals by their energy inter-linkages. Environ Res Lett 2018;13:033006. doi:10.1088/1748-9326/aaafe3.
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[80]Myles Allen (UK), Mustafa Babiker (Sudan), Yang Chen (China) H de, Coninck (Netherlands), Sarah Connors (UK), Renée van Diemen (Netherlands) OPD, (Botswana), Kris Ebi (USA), Francois Engelbrecht (South Africa) MF (UK/France), James Ford (UK), Piers Forster (UK), Sabine Fuss (Germany) TG (Germany/Nicaragua), Jordan Harold (UK), Ove Hoegh-Guldberg (Australia), Jean-Charles Hourcade (France) D, Huppmann (Austria), Daniela Jacob (Germany), Kejun Jiang (China) et al. GLOBAL WARMING OF 1.5 °C, an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. 2018.
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[84]Petrini MA, Rocha JV, Brown JC. Mismatches between mill-cultivated sugarcane and smallholding farming in Brazil: Environmental and socioeconomic impacts. J Rural Stud 2017; 50:218–27. doi:10.1016/J.JRURSTUD.2017.01.009.

RT2: Identify the available sustainability assessment methodologies that are able to measure quantitatively or qualitatively these links and identify the goals, targets and indicators not covered by these methodologies

Decision making in the energy sector can no longer be made isolated from policy-making activities in other areas. There is a need to integrate policies in a way that synergies are maximised, whilst minimising trade-offs. To respond to the challenge described above in RT1, it is necessary to identify the methodologies that can be used to estimate and quantify the interlinked effects that bioenergy investments may have in achieving the various SDGs at different levels. This endeavour requires a transdisciplinary collaboration and approach that will be ensured by the collaboration of diverse institutions in the framework of EERA Bioenergy SP5.

RT3: Bioenergy systems and cross-sector integration to support SDG's

Access to affordable, clean energy is a key sustainable development goal (SDG), which also underpins other SDG's since energy access facilitates economic development, food security, health, education and other related objectives. Utilising the great biomass-based potential in the global south can play an important role in providing energy access to urban and rural communities. This is particularly relevant as biomass production and sourcing is often closely related to land use and interfaces more closely with human livelihoods than any other renewable technology. Bioenergy is therefore perfectly placed to provide people in poverty with access to energy and participation in bioenergy supply chains. Moreover, if sustainability is integrated into existing agricultural and forest systems, but also processing industries, biorefineries or waste and waste-water management, bioenergy can provide many other economic and societal services and benefits and address various SDG's. To this end, a cross-sector and holistic understanding of the bioenergy system becomes part of and the trade-offs and synergies with the integrated bioenergy systems are important. This might also mean that bioenergy is more integrated into another sector/system whose main driver is not energy, but maybe waste management or value-added products and would require very different governance frameworks compared to just bioenergy/energy supply.

2.5.3.4.3 RP3. Socio-economic assessment

This RP will address methods for analysing the socio-economic consequences of bioenergy deployment, including their potential and limitations.

RT1: Quantification of the socio-economic implications of bioenergy: available methodologies and limitations

There are several methodologies available to estimate the socio-economic implications of bioenergy, and the selection will depend on the type of question to be answered. On the one hand, the relevance of the bioenergy industry (and its upstream activities) in sectoral employment and growth can be assessed; on the other hand, the interest can be on the impact on economy-wide employment and growth (in all economic sectors)[85]. Different methodologies can be applied in each case and the RT will critically review these methodologies and available applications to bioenergy chains in the scientific literature.

2.5.3.4.4 RP4. Bioenergy and the Circular Economy – cascading use hierarchy of biomass resources

RP4 will investigate the role of bioenergy within the context of the Circular Economy.

RT1: Robust systemic methodologies for assessing the role of (bio)waste-to-energy in the circular economy

Novel schemes for managing waste are being proposed under the new paradigm of the circular economy, which aim to increase the amount of recovered materials. Changing production patterns naturally have to be evaluated using a life cycle approach. However, LCA exhibits a major limitation in the evaluation of waste management, since several predefined scenarios are usually compared in order to select the best option. In this analysis, the best scenario may not have been considered. The LCA approach for waste and biowaste needs to be enhanced in this RT by (i) considering full systems rather than a technology-oriented assessment and (ii) by applying optimisation models to identify the most eco-efficient solutions in local or regional systems. Only in this way can the role of (bio)waste-to-energy options be fairly evaluated in the framework of the circular economy.

[85] Breitschopf, B., Nathani, C., Resch, G., 2012. Methodological guidelines for estimating the employment impacts of using renewable energies for electricity generation. Study commissioned by IEA's Implementing Agreement on Renewable Energy Technology Deployment (IEA-RETD). Available at: http://iea-retd.org/wp-content/uploads/2012/12/EMPLOY-Guidelines.pdf (accessed January 2018).

2.5.3.4.5 RP5. Life Cycle Sustainability Assessment (LCSA): assessing the three pillars in an integrated way

LCSA refers to the evaluation of all the environmental, social and economic impacts (and benefits) of products/systems. RP5 will look at the application of this method to bioenergy and will also explore issues related to interpreting the results of LCSA: how these can be reported and be made useful for different stakeholder groups, including decision makers.

RT1: Application of the LCSA methodology to bioenergy

LCA is a widely applied tool, primarily for policy development and performance-based regulation aimed at bioenergy. The last ten years have seen a broadening of environmental LCA to include life cycle costing (LCC) and social LCA (S-LCA), drawing on the triple bottom line, or three-pillar model of sustainability. There are three dimensions along which LCA is expanding, as compared to environmental LCA[86]:

1) broadening of impacts: LCSA = LCA + LCC + SLCA[87];

2) broadening of analysis, from product to sector to economy-wide questions;

3) inclusion of other aspects such as physical, economic and behavioural relationships.

Some of the challenges that the LCSA framework needs to overcome are related to efficient ways of communicating LCSA results (dealing with the weighting issue among the three dimensions of sustainability), and the need for data and methods, in particular quantitative and reliable SLCA indicators. A number of other challenges have also been highlighted in the literature[84].

This RT will explore how the LSCA can be applied to bioenergy systems, what the main results are, and which limitations must be overcome for future analysis.

RT2: How to report results from LCSA and how to address trade-offs between different aspects of sustainability

LCSA results can be used to support decision-making and comparison of products/processes from a sustainability perspective, but a problem with this method is that the results could be too disaggregated and comparison less than straightforward[88]. For example, a certain product/process may perform well from an environmental point of view, but have low performance in terms of economic impacts. In order to increase the communicability of the results, the so-called sustainability dashboard can be used, offering the possibility of presenting LCSA results by means of a graphical representation combined with a colour scale and ranking score. This RT will focus on the issue of how to report results from LCSA studies and how to address trade-offs for the different pillars of sustainability. The goal is to increase the transparency and communicability of LCSA results to all stakeholders involved in decision/policy-making process.

2.5.3.4.6 RP6. Political and regulatory framework for bioenergy in Europe

RED-II will enter in force on 1st January 2021 with new provisions for promoting advanced biofuels in the transport sector and, for the first time, sustainability criteria have been introduced for biomass for heat and power sectors.

RP6 will be an active component by carrying out research activities to help the Member States and the EC with the different implementing acts that will comprise the RED-II, and it will closely track each Member State's National Plans for Energy and Climate.

[86] Guinée J. (2016) Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges?. In: Clift R., Druckman A. (eds.) Taking Stock of Industrial Ecology. Springer, Cham.
[87] Kloepffer, W. Life cycle sustainability assessment of products. Int. J. Life Cycle Assess. 2008, 13, 89-94.
[88] Traverso, M., Finkbeiner, M., Jørgensen, A., Schneider, L. Life Cycle Sustainability Dashboard. Journal of Industrial Ecology. 16 (5), 680-688.

RT1: Implementation of RED-II in the field of biofuels for transportation

Several challenges facing the implementation of RED-II for next decade need to be addressed through research activities. For example, the blend wall challenges and how to introduce higher level biofuels to achieve or exceed the 10% target in 2020 and 14% target in 2030. Other challenges involve the introduction of crop caps and the ill-defined concept of high-ILUC risk biofuels and low-ILUC risk biofuels. Sustainability at the global level needs to be addressed and robust methodologies are needed to rigorously quantify the soils available for low-ILUC risk biofuel certification. Research studies are needed on the impacts of e-mobility (including battery production) in terms of life-cycle GHG emissions.

On long-term strategies, it is necessary to define the uptake of biofuels in aviation and maritime and in heavy-duty (long distance) vehicles. RT1 intends to contribute to the EU discussion in this field, e.g. by doing research on the possible impact of deploying biomethane and hydrogen in all transport sectors.

RT2: Implementation of RED-II in the field of power and heat

RED-II did introduce two main sustainability criteria for using solid biomass in the power and heat sectors: Land criteria (both for agricultural biomass feedstocks and for forest biomass feedstock) and end-use criteria (GHG emission savings criteria and efficiency criteria for biopower plants). This applies to all bioenergy consumed in the EU, regardless of whether it is produced domestically or imported.

RT2 will consider the role of bioenergy in meeting national targets, how to address cross-acceptance issues between markets for wood, fuels, biogas and bio-based products, resource efficiency through mobilisation away from current inefficient practises, development of trade and the creation of efficient markets for biomass.

The main focus of this RT will be to: 1) analyse the implications of extending the verification of sustainability criteria for heat and power to biomass fuels; 2) address the open questions of RED-II for solid biomass certification systems, e.g. the carbon debt and the verification of wood origin and how to address the risk of fraud without individual certification.

3. SRIA IMPLEMENTATION TOOLS

The purpose of these tools is to facilitate and foster the development of the R&I in order to address SRIA priorities, disseminate the results, reinforce the professional image of the JP, as well as to standardise the procedures to promote transparency in the everyday work of the JP. Therefore, these tools form part of the JP as an essential complementary activity to improve the implementation of SRIA priorities.

The main implementation tools are the following:

3.1 Workshops

The main objectives of the workshops are:

- Exchange information and network in order to align views on Bioenergy challenges, priorities and needs, particularly in the SET-Plan context, internally and with external stakeholders, including the industrial sector, external research organisations and national and regional bioenergy agencies and authorities.

- Assess actions, activities and priorities internal and external to JP, particularly in SET-Plan context to maximise the JP impact

- Identify of core research questions relevant to the prioritised topics in the SRIA.

- Explore opportunities for collaboration in joint proposals in response to H2020 or other related topic calls and including external stakeholders.

Depending on its objective, the workshops will be organised for JP members only or in conjunction with other partners and can also be attended by industries and other relevant stakeholders.

3.2 EERA Quality Label

Increasing the level of integration of activities among JP participants through involvement in common funded activities/ projects promoted by the JP remains an essential strategy, as in the previous period, for realistic addressing the R&I topics identified in the SRIA and therefore for achieving SRIA priorities. However, involving JP participants in common projects and their follow-up to comply with SRIA priorities requires a tool that assures the necessary transparency and defines common protocols to address these issues.

The EERA quality label is a transparent procedure for defining projects, forming consortia, and preparing joint proposals and follow-ups within the JP. It is in force at present, approved by the JP Steering Committee in 2017.

3.3 Position Documents

The final purpose of this activity is to conduct studies, like this SRIA, containing the view of the EERA Bioenergy JP in relation to Bioenergy R&I needs and challenges, as well as to establish the position of EERA Bioenergy regarding relevant issues that may affect the implementation of bioenergy in Europe. This activity will help to define its own image and reinforce the advisory and influential capacity of EERA Bioenergy JP.

The calendar for writing position documents will be established by the JP Management Board and approved by the JP Steering Committee.

3.4 Promotion and Dissemination Activities

The development of a professional Promotion and Dissemination (PAD) programme is considered key for the image and the impact of the JP, as well as to boost the SRIA development.

An essential part of the PAD is the JP website to disseminate JP results, while facilitating communication among participants.

The PAD activities programme will be approved by the JP Steering Committee at the proposal of the JP Management Board.

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EERA BIOENERGY JOINT PROGRAMME