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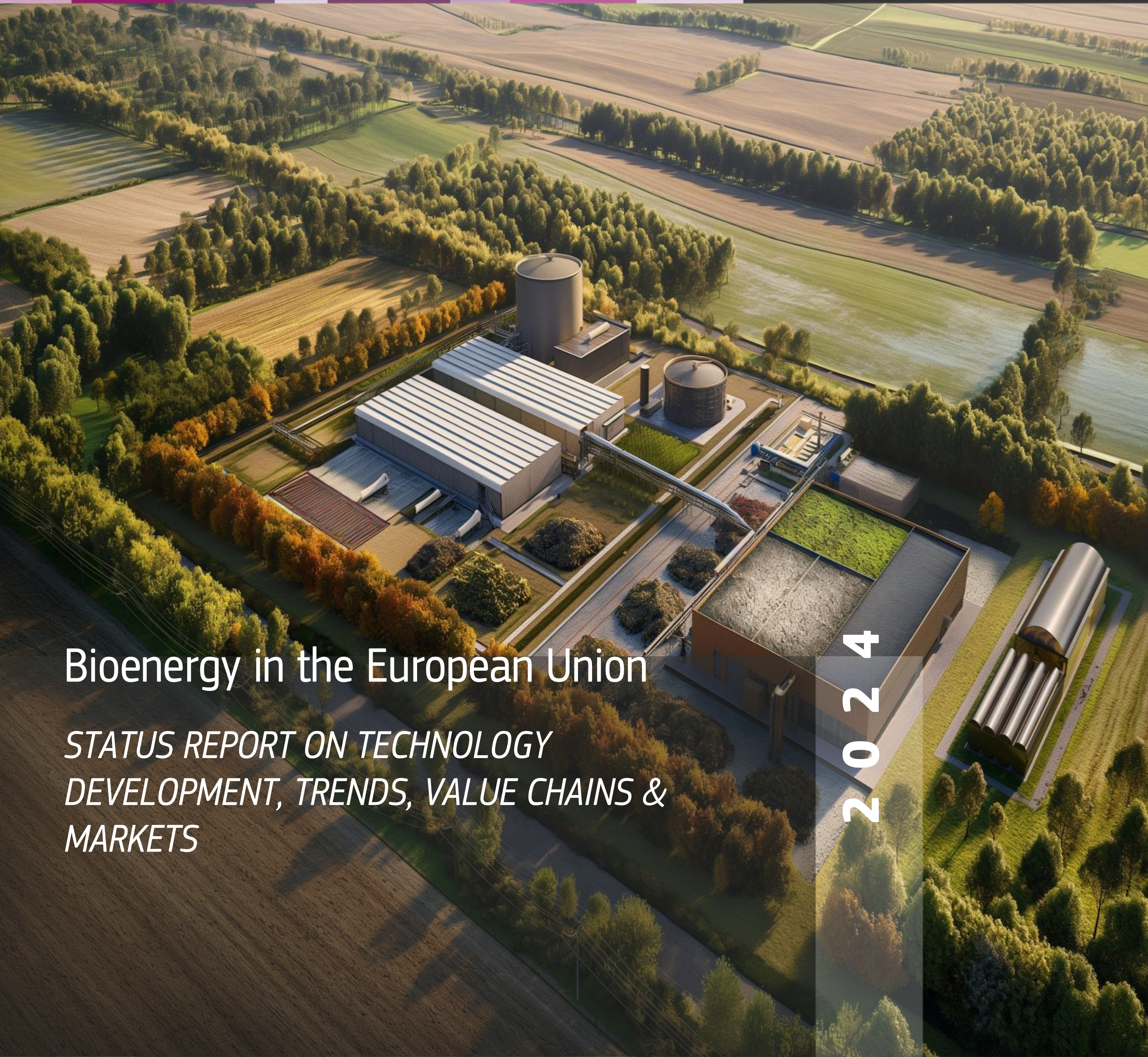

Bioenergy in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

2024

EUR 40062

Joint Research Centre

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Contents

Abstract

The report provides a detailed examination of the bioenergy sector within the European Union (EU), highlighting its significance in the global context and its role in the transition towards a low-carbon economy. The report is an update of the CETO 2023 report.

The report offers insights into the development and status of various bioenergy technologies, funding landscapes, economic contributions, and employment trends within the EU. The report also contrasts the EU's bioenergy sector with that of other regions, particularly the US and China.

The report details the Technology Readiness Level (TRL) of various bioenergy technologies, such as anaerobic digestion, biomass combustion, gasification, pyrolysis, hydrothermal processing, and torrefaction.

The report provides comprehensive data on the growth of biogas and biomethane production in the EU, illustrating significant increases in production capacity and the number of new plants. These metrics highlight the rapid development and scaling of bioenergy projects within the EU.

The report includes detailed information on public and private funding for bioenergy research and development (R&D). The report also discusses the role of various funding agencies and programmes. The report highlights the volatility in private R&D funding and the disparity in investment stages between the EU and the US, providing a nuanced understanding of the funding landscape.

The report also delves into the economic indicators essential for understanding the sector's impact on the broader EU economy.

The report underscores the importance of continued investment, technological development, and international collaboration to ensure the bioenergy sector's growth and sustainability.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognising the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate-General Research and Innovation (DG RTD) and Energy (DG ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal;
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market;
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020);
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform.

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore);
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport;
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis;
- Clean Energy Outlooks: Analysis and Critical Review;
- System Modelling for Clean Energy Technology Scenarios;
- Overall Strategic Analysis of Clean Energy Technology Sector.

More details are available on the CETO web page.

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Executive Summary

The report provides a comprehensive overview of the bioenergy sector in the European Union (EU). It is an update of the CETO 2023 report. The EU plays a leading role in global bioenergy production, which is crucial for the transition towards a low-carbon economy.

The development of bioenergy technologies is essential for maintaining this leadership and ensuring sustainable energy solutions. The report outlines the status of various bioenergy technologies using the Technology Readiness Level (TRL) framework. Anaerobic digestion and biomass combustion are well-established commercial technologies (with TRLs of 8-9). Gasification is at the demonstration stage (with TRLs of 6-8). Emerging technologies such as pyrolysis and hydrothermal processing have TRLs ranging from 5 to 7 and require further development for reliable, long-term operation. Torrefaction aimed at improving biomass properties for easier handling, storage, and transport, is currently at the pilot and demonstration stage.

The growth in biogas and biomethane production in Europe underscores the sector's potential to contribute significantly to the energy mix. Biogas production increased from 72 Terawatt-hours (TWh) in 2011 to 179 TWh in 2022. Biomethane production more than quadruped from 11 Gigawatt-hours (GWh) in 2014 to 44 GWh in 2022. The number of new biomethane plants has rapidly increased, with 254 new additions in 2022 alone. The production capacity of Bio-Liquefied Natural Gas (Bio-LNG) plants is projected to increase from 1.4 TWh in 2022 to 15.4 TWh by 2025.

The cost-effectiveness of bioenergy production is influenced by several factors, including feedstock availability and price, production process configuration, plant size, and geographical considerations. Ongoing reductions in Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), along with improvements in process efficiency, are expected to enhance the economic viability of bioenergy in the future. The Levelised Cost Of Electricity (LCOE) for bioenergy has seen a notable reduction over the years. For example, the LCOE for solid biomass-fired power plants has decreased by 20% since 2008, primarily due to reduced wood costs and lower CAPEX levels. However, the LCOE for biogas-fired plants in the EU remains higher compared to other regions, largely due to the smaller scale of projects.

Public funding for bioenergy research and development (R&D) in the EU has been substantial, with an average of €50 million per year allocated to solid biofuels and biogas from 2014 to 2022. This funding is managed by various agencies, including the European Climate, Infrastructure and Environment Executive Agency (CINEA). The funding landscape involves multiple programmes such as Horizon Energy, LIFE, Connecting Europe Facility (CEF)-Transport, and the Innovation Fund, which collectively support a wide range of bioenergy initiatives.

Private R&D and Innovation (RD&I) funding in the bioenergy sector is primarily driven by Venture Capital (VC) and Private Equity investments, which have seen significant growth from 2018 to 2023. Global VC and Private Equity investments in bioenergy exceeded €1.60 billion during this period, surpassing the investments made in the previous six years. The EU accounted for just over one-quarter of the global VC investments between 2018 and 2023. However, the volatility in funding poses challenges for bioenergy firms in securing consistent funding for their growth. For instance, global VC investment in bioenergy firms nearly quadrupled in 2022 compared to the previous year, reaching an all-time high of €752.1 million, but dropped to less than €400 million in 2023.

Another challenge is the disparity in investment stages between regions. The EU focuses on early-stage funding, such as grants, Seed and Angel funding, and Early-stage VC, while the US shows a stronger inclination towards later-stage investments, including Late-stage VC, Small Mmergers and Acquisitions, and Growth Private Equity. This difference in investment focus can create challenges for bioenergy firms in different regions, as they may need to adapt their funding strategies to align with regional investment trends.

The EU's patenting activity in bioenergy technologies is robust. The EU accounted for a 62% share of high-value patents during the triennium from 2019 to 2021, out of a total of 190 patent applications. In contrast, China applied for a total of 1,179 patents, with only 44 being high-value. The flow of inventions indicates that EU inventions mainly flowed to other countries, particularly the US and China.

The EU leads globally in scientific publications on biogas, with 385 articles from 2010 to 2022, including 47 highly cited ones. The EU has also led biomethane publications during this period, reaching 160 publications in 2021. Additionally, the EU has been a leading actor in scientific publications related to biomass feedstock with 42 highly cited papers, and to processes for heat and power with 45 highly cited papers during the period 2012 to 2022. These metrics indicate the quality and impact of the EU's research in this field. However, there is a

need for stronger collaboration networks within the EU to maintain the leading position in scientific research on biomass.

The bioenergy sector's contributions to the EU economy are significant. The turnover related to solid biomass increased from around €30 billion between 2018 and 2020 to €38.5 billion in 2021, before a slight decrease in 2022. The biogas sector's turnover peaked at €8.4 billion in 2018 but declined €5.8 billion in 2022. The gross value added by the bioenergy sector to the EU economy is substantial, with each additional Million Tons of oil Equivalent (Mtoe) of biomass for energy impacting GDP by EUR 359 million.

Employment in the bioenergy sector is another critical area. The solid biomass sector saw an increase in employment from 283,000 jobs in 2020 to 332,000 jobs in 2022. Conversely, the biogas sector experienced a decline in employment, from a peak of 62,700 jobs in 2018 to 49,300 jobs in 2022. The feedstock supply sector had the highest number of direct jobs, with 153,000 out of 233,043 total direct jobs in the bioelectricity sector.

The value of energy carriers produced in the EU Member States has shown a steady increase, from €5,073 million in 2016 to €10,648 million in 2022, followed by a 10% decrease in 2023. Pellets and wood chips were the most significant contributors, representing 47% and 25% of the value produced in the EU in 2023, respectively.

Challenges in the biomass sector include competition between different uses of biomass, such as food, feed, fibre, and bioenergy. The EU's trade balance for bioenergy feedstock has been trending increasingly negative, indicating a growing dependency on imports Trade dynamics reveal that the EU has significantly increased its imports of biomass energy carriers and feedstock from extra-EU countries, doubling the value from €1,010 million in 2015 to €2,589 million in 2022. However, extra-EU exports have remained relatively stable, averaging €500 million from 2015 to 2020, with a peak of EUR 900 million in 2022. In 2023, both imports and exports saw a decline.

The availability of sustainable biomass is essential for meeting the EU's energy and climate targets for 2030 and 2050.

Table 1 shows a comprehensive SWOT analysis of bioenergy, highlighting its strengths, weaknesses, opportunities, and threats. The analysis is particularly relevant from the perspective of the European Union (EU), as it discusses the potential impacts on trade balance and rural development within the EU.

Bioenergy presents several strengths that enhance its competitiveness. For instance, there are multiple technologies available and demonstrated at various scales, from small to large. This versatility allows bioenergy to contribute significantly to energy diversification and security, reducing dependency on fossil fuels. Additionally, a wide range of feedstocks is available in large quantities, making bioenergy production feasible in decentralised small plants. This not only supports rural development by valorising residues but also generates additional income through the production of co-products. Furthermore, bioenergy has a high potential for reducing greenhouse gas emissions, which is crucial for meeting environmental targets.

However, there are notable weaknesses that could hinder the competitiveness of bioenergy. One major issue is the potential competition with alternative uses of feedstocks and land, which can complicate logistics for collection, transport, and storage due to the low energy density and variable characteristics of biomass. The economic viability of bioenergy is heavily dependent on the availability of low-cost feedstock. Additionally, small-scale combustion, especially in residential areas, can be a significant source of air pollution, negatively impacting air quality. There are also potential negative effects on ecosystems and biodiversity due to intensified management practices aimed at maximising productivity. The import of biomass energy carriers can lead to a negative trade balance for the EU, further complicating the economic landscape.

Opportunities for bioenergy are abundant and can enhance its competitiveness. Bioenergy can facilitate the integration of variable renewables into the electricity grid, contributing to energy diversification and security while reducing dependency on fossil fuels. It can also aid in the remediation of marginal and degraded land through sustainable and certified cultivation systems. Bioenergy serves as a driver for agriculture, forestry, and industrial development in rural areas, promoting economic diversification. Additionally, it can reduce the risk of fires caused by residues like straw and forest debris. In many cases, bioenergy is cost-competitive with fossil-derived energy, making it an attractive alternative.

Despite these opportunities, there are several threats that could undermine the competitiveness of bioenergy. Competition with alternative uses of feedstock and the low availability and affordability of feedstock in the long term pose significant challenges. The lack of a long-term stable policy framework can create uncertainty, hindering investment and development. Public awareness of best practices and how to avoid potential negative impacts is generally low, which can lead to suboptimal implementation and negative perceptions. Moreover, bioenergy faces competition from the electrification of buildings for heating supply, which could limit its market share.

In summary, while bioenergy has numerous strengths and opportunities that enhance its competitiveness, it also faces significant weaknesses and threats that need to be addressed. The EU, in particular, must navigate these challenges to fully realise the potential of bioenergy in contributing to a sustainable and diversified energy future.

Table 1. CETO SWOT analysis for bioenergy competitiveness

Strengths	**Weaknesses**
• several technologies are available and demonstrated from small to large scale • contribution to energy diversification and energy security and decrease dependency on fossil fuels • a wide range of feedstock are available in large amounts for bioenergy • bioenergy easily produced in decentralised small plants. • contribution to rural development, valorising residues • production of co-products provides additional income • reliance on short supply chains • high greenhouse gas emission reduction potential	• potential competition with alternative uses of feedstock and land • complex and costly logistics for collection, transport and storage related to the low energy density and variable characteristics • economic viability depends on availability of low-cost feedstock • significant source for air pollution and negative Impacts on air quality especially due to small-scale combustion in residential areas • potential negative effects on ecosystems and biodiversity due to increased intensity of management targeting to maximise the productivity • import of biomass energy carriers, substance or system that allows energy from a primary energy source to be stored and transferred in a usable form, then released at the appropriate time and place, and the consecutive negative trade balance for the EU, when the balance of the trade value of imports exceeds that of exports
Opportunities	**Threats**
• contribution to energy diversification and energy security and decrease dependency on fossil fuels • facilitating integration of variable renewables in the electricity grid • contribution to the remediation of marginal and degraded land trough a sustainable and certified cultivation system • driver of agriculture, forestry and industrial development in rural areas and diversification of the rural economy • reduction in the risk of fire caused by residues (i.e., straw, forest residues) • cost competitive with fossil-derived energy in many cases	• competition with alternative uses of feedstock • low availability and affordability of feedstock in the long term • lack of long-term stable policy framework • low public awareness on best practices and how to avoid potential negative impacts • competition with electrification of buildings for heating supply

Source: JRC analysis

1 Introduction

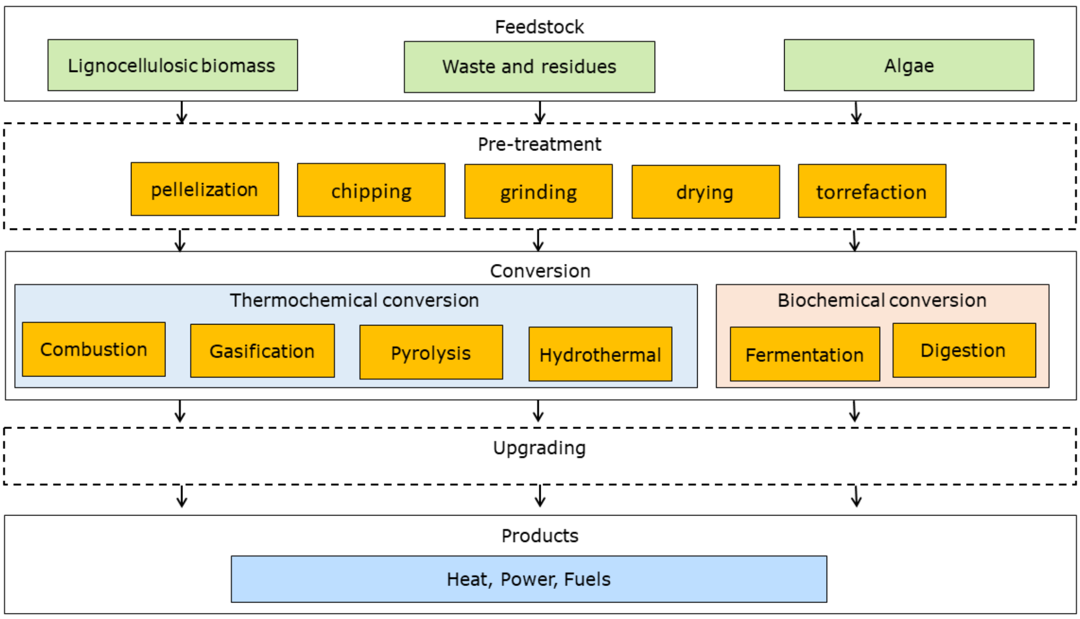
1.1 Scope and context

The report presents an assessment of the state of the art of key technologies for bioenergy production from biomass to produce biomethane and biogas. The various biomass technologies are analysed based on their technological advancement and their potential to provide a significant contribution to decarbonisation of the European energy system in the short- and medium- to long-term period. The analysis builds on previous European Commission studies (Padella, Georgiadou, and Schleker, 2019).

The analysis focused on the main technologies that are currently used for heat and power production, i.e., biomass combustion, anaerobic digestion. The analysis focused also on intermediate energy carriers, substances that allows energy from a primary energy source to be stored and transferred in a usable form, then released when needed, that have good prospects to enter soon on the market, namely torrefaction, pyrolysis, hydrothermal processing and gasification. The technologies are different stages of development. The report assesses them based on the Technology Readiness Level (TRL). The TRL scale, ranging from 1 (the least mature) to 9 (the most mature), is a widely used tool for a maturity assessment. It allows a consistent comparison of maturity of different types of technologies. The technologies have undergone significant improvements and technical advances in the last years. However, most of them face technical and non-technical challenges and barriers that impede on their large-scale commercial application. Some technologies still require research support to improve their technical, economic and environmental performances to achieve commercial operation (TRL).

Technologies based on biochemical conversion are explored in the chapter 2.1.1 of the report, thermochemical conversion, including combustion, is explored in the chapter 2.1.2. Bioenergy carriers are explored in the chapter 2.1.3 of this report.

Figure 1 Flowchart of Heat & Power production from biomass



Source: JRC own elaboration

1.2 Methodology and Data Sources

The methodology for the technology development reports is based on three pillars:

- JRC peer review and expert judgement
- Monitoring, data compilation; definition and use of indicators, for which the focus is the Technology Readiness Level (TRL) parameter, using the guidelines set out in the 2017 report for DG RTD
- Modelling results of long-term deployment trends

The main data sources used to assess the state of the art of the technologies and to identify the relevant European R&D projects came from several sources of information; from literature and R&D project data as follows (links are provided in the References section):

- R&D projects in CORDIS database, IEA and Innovation Fund
- Patents statistics, patents filed on technologies/sub-technologies on PatStat service
- Scientific statistics from the JRC's TIM (Tools for Innovation Monitoring) software

  POTEnCIA and POLES Models
- EUROSTAT and EurObserv'ER online database
- Scientific overviews and compilations

2 Technology status and development trends

2.1 Technology readiness level

In the frame of the SET Plan Action 8 Bioenergy and Renewable Fuels for Sustainable Transport, the Technology Readiness Level (TRL) indicator was applied as recommended by the European Horizon 2020 Research Programme. This indicator offers a classification based on nine levels:

TRL 1 – basic principles observed
TRL 2 – technology concept formulated
TRL 3 – experimental proof of concept
TRL 4 – technology validated in lab
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies).

Anaerobic Digestion and Biomass Upgrading have already reached the TRL 9 (commercial scale) while other processes like Pyrolysis, Gasification, Hydrothermal liquefaction range from TRL5 (pilot scale demonstration) to TRL 7 (pre-commercial), as shown in Table 2.

Table 2. TRL Bioenergy processes

	TRL (Technology Readiness Level)								
Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Biomass combustion									■
Anaerobic Digestion									■
Pyrolysis					■	■	■		
Hydrothermal Processing				■	■	■			
Gasification					■	■	■	■	
Pelletisation									■
Torrefaction								■	■

Source: SET Plan

2.1.1 Biochemical processing

2.1.1.1 Anaerobic digestion and biogas upgrading

Anaerobic digestion is an established, commercial technology for manure, food and agricultural waste or sewage sludge, around TRL 8 - 9. It processes feedstock by microorganisms under anaerobic conditions to produce biogas. Anaerobic digestion includes a series of biological conversion processes in which microorganisms break down biodegradable material in the absence of oxygen: hydrolysis; acid genesis; acetogenesis; and methanogenesis. The biogas produced contains methane (50 - 70%), carbon dioxide (30 - 40%) and other gases, such as hydrogen (H_2), nitrogen (N_2), hydrogen sulphide (H_2S), ammonia (NH_3), and trace amounts of saturated or halogenated carbohydrates, organic silicon compounds (e.g., siloxanes), oxygen (O_2) and particles. Biogas is a fuel that can be used to produce electricity, heat or astransport fuel. Biogas could be upgraded to biomethane (bio-natural gas), by removal of the CO_2 and the contaminants, to be used as transport fuel or injected into the natural gas grid.

Anaerobic digestion can use a large variety of feedstocks (resources), e.g., organic residues and wastes collected from agricultural, industrial, and municipal generation, animal fats and slaughtering residues, sewage sludge (accumulated solid waste that settles as sediment in a sewage treatment plant), or aqueous biomass (micro and macro algae). The agriculture-based biogas plants are based on biomass feedstocks coming from agricultural residues (usable material recovered primarily from annual crops as byproducts of food and fibre production), energy crops (fast-growing crops that are grown for the specific purpose of producing energy), sequential cropping (growing one crop after another in the same year). Industrial-based biogas plants use as biomass feedstock food and beverage industry waste, organic municipal solid waste, and sewage sludge. The last category of biogas plants is based on landfill gas, i.e., gas that is generated by decomposing organic material at landfill disposal sites.

Co-digestion of various feedstocks (e.g., energy crops, organic solid waste, or animal manure) is a common practice that allows to maintain the optimum Carbon/Nitrogen (C/N) ratio of the substrate and to maximise the biogas yield. More difficult feedstocks (such as straw, food waste and other residues) might require additional pre-treatment to achieve higher gas yields and/or post-processing to remove various contaminants (Amin et al., 2017).

There are two main types of anaerobic digestion, which differ mainly by the specific temperatures: thermophilic digestion, that occurs at 50–60 °C, and mesophilic that develops at 25–40 ° C. The choice of system depends mainly on the feedstock to be processed. Nowadays, mesophilic digesters using animal slurry (faeces and urine mixed or not with some litter material and some water to give a liquid manure with a dry matter content up to about 10 % that flows under gravity and can be pumped) mixed with industrial and food wastes are the most common. Thermophilic conditions are applied mostly in large-scale centralised biogas co-digesters using feedstock mixtures of garden and food waste. Thermophilic digestion requires shorter retention time due to faster degradation at the higher temperature and better pathogen and virus removal. It also requires lower digester volume. It entails more expensive technology and higher energy consumption (Ricardo, 2022; Nguyen et al., 2021).

The anaerobic digestion process may operate both as a wet or a dry process, depending on the water content of the material in the digester (closed container where anaerobic biodigestion takes place). The wet process typically uses feedstocks with low solid content, up to 15% dry matter, while the dry digestion process uses feedstocks with dry solids content between 15–40% dry matters. Wet digestion is by far the most widespread and proven system. Dry digestion is more suitable to the processing of food waste, household waste, green waste, crop residues and the biological fraction of Municipal Solid Waste (MSW). As it is generally not feasible to pump dry waste, the waste is typically moved mechanically, by screw conveyors (conveyor with transport medium in the form of a screw with constant or varying pitch, enclosed in a trough or a tube) rather than a liquid/sludge pumping. Dry anaerobic digestion plants offer several benefits, including greater flexibility in the type of feedstock, shorter retention times (the key parameter to separate, identify and quantify compounds of interest from complex mixtures), lower water usage and lower capital costs (costs of fixed assets).

Energy production options with anaerobic digestion include gas engines (internal combustion engines that use gaseous fuel), stirling engines (external combustion engines), gas turbines (any rotating machine which converts thermal energy into mechanical work), and micro turbines. Anaerobic digestion plants are mostly connected to gas-fired engines for heat and power production. The heat generated can be used to meet the local heat demand on a farm, or delivered to external users, e.g., district heating or industrial applications. Electricity conversion efficiencies vary between 30% and 45% for gas engines, 25–32% for micro turbines, 30-45% for gas turbines, and 18–22% for stirling engines, depending on equipment type and size (Mott MacDonald, 2011). The capacity of biogas plants is constrained by the availability of the feedstock within a certain distance from the biogas plant, and is typically in the range of 250 kWe (kilowatt-electric (kWe): one thousand watts of electric capacity) to 5 MWe (megawatt-electric) (IEA, 2012).

2.1.2 Thermochemical processing

2.1.2.1 Biomass combustion

Biomass combustion of solid, gaseous and liquid biomass resources is the most important option for bioenergy production. Biomass combustion occurs at both small-scale combustion and at large-scale combustion for heat, electricity or Combined Heat and Power (CHP) applications. Biomass combustion is a mature, commercial technology for heat and power production (TRL 8 - 9). Biomass combustion in a steam boiler is a well-established technology to generate electricity using Grate Boilers (GB), Bubbling Fluidised Bed Combustion (BFBC) or Circulating Fluidised Bed Combustion (CFBC) boilers, coupled with steam turbines. Grate boiler coupled with steam turbine system is the standard and simpler technology for small to medium-scale (1 to 10 MWe) power production, with low investment and operating costs. Fluidised bed technologies (Bubbling Fluidised Bed Combustion - BFBC and Circulating Fluidised Bed Combustion - CFBC boilers) are commercial technologies that ensure high efficiency, low emissions and high fuel flexibility (biomass type, moisture content, i.e., quantity of water contained in a material) with higher capital and operating costs (IEA Bioenergy, 2009; IEA-ETSAP and IRENA, 2015). The high fraction of alkali and chlorine as well as heavy metals in the biomass ash poses high risks of fouling, slagging and corrosion of boiler heating surfaces (Basu, 2018). Advanced controlled systems with automatic fuel feeders can reduce Particulate Matter (PM) and pollutant emissions to very low levels, even at small scale.

Biomass combustion and heat and power production is based on steam turbines (for plants above 2 MWe), Organic Rankine Cycles (ORC), steam engines (200 kWe - 6 MWe) and Stirling engines (below 100 kWe). The scale of operation is an important factor for technical and economic performances, with specific capital and operating costs increasing as plant capacity decreases. New plants with large capacities and advanced steam parameters offer high efficiency. Power production efficiencies using biomass and steam turbines range from 24-38% for plants between 10-50 MW and 32-42% for plants with a capacity above 50 MW for steam-turbine combined with advanced fluidised bed combustion technology (IEA-ETSAP and IRENA, 2015; IPCC et al., 2012; IEA, 2012). Stirling engines are promising applications of small scale electricity and heat production from biomass using external combustion engines. The heat is not supplied in the cycle by the internal combustion but transferred from outside through a heat exchanger. Electric efficiency can reach 12% to 15% (IEA Bioenergy, 2009; Obernberger and Thek, 2008). Cogeneration is an effective way to significantly increase the overall efficiency of a power plant (and hence its competitiveness), and when a good match exists between heat production and demand. Cogeneration plants offer typical overall efficiencies in the range of 80% to 90%.

Small-scale combustion occurs in stoves and small boilers for traditional heating in the residential sector or for industrial heat production. Biomass heating is a mature, commercial-scale technology and it is competitive with heat produced from fossil fuels. Small scale heating refers generally to traditional heating systems that rely on biomass combustion in stoves with a capacity between 5 and 15 kW, using wood logs, have low efficiency (10 - 30%) and high emissions of air pollutants (especially particulate matter). Modern biomass technologies with boilers using wood logs, wood chips, or pellet burning are available, with automatic feeding systems and advanced control systems, high efficiencies (90%) and low emission systems, but at higher cost. Small-scale automated heating boilers with high efficiency are used for central heating and are equipped with a water heat exchanger and connected to a heating water circuit based on wood chips or wood pellets. Biomass heat can also be produced in large scale cogeneration power plants, supplying heat from industry or from district heating network at high overall efficiencies of around 80 - 90% (IEA, 2012). The deployment of biomass CHP plants are also limited by the local heat demand and by its seasonal variation.

2.1.2.2 Pyrolysis

Pyrolysis is the thermochemical conversion of biomass into bio-oils (pyrolysis oils), gases and a solid product (biochar) in the absence of oxygen at lower temperatures than combustion or gasification, ranging between 450 – 600 ºC (typically 500 ºC) (Basu, 2018; Bridgwater, 2018). Pyrolysis produces different outputs with variable properties depending on the type of process adopted. The relative quantities of the products and their composition is strongly influenced by the pyrolysis temperature, the heating rate, and the residence time of the feedstock (period of time during which feedstock remains in a particular area or in a particular part of a system). Pyrolysis can also be used as a pre-treatment step for gasification and biofuels production.

Pyrolysis process can be categorised as slow, fast pyrolysis or flash pyrolysis, distinguished by different residence times in the reactor. High pyrolysis temperature and longer residence time increase the biomass conversion to gas while lower temperature and longer residence time favour the production of biochar. The proportions of each phase and product composition depend on the process design, the chemical conditions, and temperature and reaction rate (the rate is proportional to the concentration of the reactants) within the pyrolysis reactor. The resulting biochar and gases are generally used within the process to provide the process heat requirements. Fast pyrolysis is employed to maximise the bio-oil yield, while slow pyrolysis is used to maximise the biochar production (Table 3).

Table 3. Pyrolysis processes and main products

Method	Temperature Range	Residence Time	Heating rate	Main Products
Slow Pyrolysis	450 – 550 ºC	30 min	0.1–10°C/s	biochar gases bio-oil
Fast Pyrolysis	450 – 550 ºC	1 – 3 sec	10-200 °C/s	bio-oil gases biochar
Flash Pyrolysis	700 – 1000 ºC	< 1 sec	> 1000°C/s	bio-oil gases

Source: (International Renewable Energy Agency, 2024)

Fast pyrolysis has been developed in recent years as a fast and flexible method to produce high value bio-oil from biomass that can be used as intermediate energy carrier and as renewable liquid fuel replacing non-renewable fossil fuels for various applications. Fast pyrolysis produces mostly high-value bio-oil (40-60% bio oils), along with small amounts of biochar (10-15% biochar) and gases (15-35% gases), such as hydrogen, methane, carbon monoxide, and carbon dioxide. Catalytic Fast Pyrolysis (CFP) employs various catalysts that promote cracking, dehydration, deoxygenation reactions to produce a bio-oil with lower oxygen levels, increased higher heating value, and higher hydrocarbon contents (mostly aromatics and olefins). Catalysts may be deactivated via coking and condensation of poly-aromatics. The by-products obtained (char and gases) are used within the process to provide the process heat required (Basu, 2018; Bridgwater, 2018; Matayeva et al., 2019). Bio-oil can be a substitute for fuel oil or diesel for heat and power production, in many applications including boilers, engines and turbines, especially in small scale, and CHP applications.

Slow pyrolysis at moderate temperatures (450 – 550 °C) and long residence times (30 min) and low heating rates (~10 °C/s) favours the production of bio-char, while fast pyrolysis, at moderate temperatures (450 – 550 °C), short residence times (1-3 s) and high heating rates (100 °C/s) favours the production of bio-oil. Biochar from slow pyrolysis has also the potential to be used as soil improver or as activated carbon. Flash pyrolysis is an extremely rapid thermal decomposition pyrolysis with a high heating rate (>500 ºC/s), high reaction temperatures (700–1000 ºC), and shorter residence time than fast pyrolysis, to produce high yields of bio-oil relative to gas and biochar, with low water content and conversion efficiencies, a ratio between the useful output of an energy conversion and the input, of up to 70%. The yields of the products are: 60-80% gases; 10-20% bio-oil; and 10-15% biochar (Basu, 2018; Matayeva et al., 2019).

Pyrolysis can be performed in various types of reactors including fluidised-bed (fluidised bed and circulating fluidised bed reactors), ablative reactors, rotating cone or Auger (screw) reactors. The most common reactors used for slow pyrolysis, are drum, rotatory kilns, and screw/Auger reactors. Fast pyrolysis systems use fluidised bed, rotating cones, entrained flow, vacuum, and ablative reactors. Flash pyrolysis uses fluidised bed, circulating fluidised bed reactors or downer reactors (Basu, 2018; Bridgwater, 2018; Matayeva et al., 2019). Pyrolysis is adequate for small decentralised fast pyrolysis plants of 50,000 to 250,000 tonnes or 1 to 3 MWe per year for production of bio-oil liquids to be transported to a central processing plant. Multiple small modules can be employed for building large plants. Biomass pyrolysis has been successfully demonstrated at small-scale, and several large pilot plants or demonstration projects (up to 200 ton/day biomass) are in operation. Pyrolysis and bio-oil upgrading technology is not yet commercially available, although considerable experience has been gained and several pilot plants and demonstration projects are in operation, with technology reaching TRL 5-7, demonstration at commercial scale

2.1.2.3 Hydrothermal processing

Hydrothermal processing is a thermochemical process that involves thermal degradation of wet biomass at low temperature and high pressure using liquid water as conversion medium. The process converts biomass into a solid (hydrochar), a liquid (bio-oil or bio-crude), or a gas (e.g., hydrogen, methane), depending on the process parameters (Basu, 2018; Reißmann, Thrän, and Bezama, 2018; Kumar, Olajire Oyedun, and Kumar, 2018). Hydrothermal processing has an advantage that comes from its great flexibility towards the use of not only dry but also wet biomass, requiring no feedstock drying. Different hydrothermal processes occur depending on pressure, temperature and residence time: Hydrothermal Carbonisation (HTC), Hydrothermal Liquefaction (HTL) and Hydrothermal Gasification (HTG) (Reißmann, Thrän, and Bezama, 2018). The nature and yield of products from hydrothermal technologies depends on factors such as the feedstock type, catalyst, and process conditions (temperature, pressure). Hydrothermal processes (HTP) appear to be a promising technology platform for processing wet biomass and residues. the typical parameters for the main types of hydrothermal processing. Table 4

Table 4. HTP processes and parameters

HTP type	Temperature	Pressure
HTC – Hydrothermal Carbonisation	180–250 °C	2–10 MPa
HTL – Hydrothermal Liquefaction	300–350 °C	10-25 MPa
HTG – Hydrothermal Gasification		
Catalytic/low-temperature	350-450 °C	25-40 MPa
Non-catalytic/high-temperature	>500 °C	25-40 MPa

Source: (Reißmann, Thrän, and Bezama, 2018; Kumar, Olajire Oyedun, and Kumar, 2018)

HydroThermal Carbonisation (HTC), also called hydrothermal torrefaction, converts biomass into a value-added product (hydrochar) at a relatively low temperature (180–250 °C) and pressure (2–10 MPa) in a relatively short (5 min) residence time. The resulting product, a solid hydrochar or biochar, an energy dense product with high mass yields varying from 35% to 60% can be used as a solid biofuel, fertiliser and soil conditioner (chemicals having the ability to stabilise soil aggregates and to improve soil structure or tilth). This option is effective for thermal treatment of very wet biomass feedstock as it avoids the energy intensive process of drying of biomass.

HydroThermal Gasification (HTG) is a process for the production of gases by treating biomass in liquid water at high temperature (above 350 °C) and high pressure (25-40 MPa). The gas produced is rich in hydrogen or methane, depending on the reaction conditions. Temperature has a high influence on the nature and type of reaction, while pressure has only minor direct influence. HTG can be conducted in subcritical water or supercritical water conditions. Subcritical gasification typically requires the use of catalyst (nickel, palladium, platinum, rhodium, ruthenium, etc.). Catalytic gasification of biomass occurs at 350–450 °C and produces methane and carbon dioxide in the presence of a catalyst promoting CO_2 hydrogenation (methanation) to methane. Gasification at a lower temperature carried out by catalyst offers higher energy efficiency and improves the yield and quality of the output. Supercritical Water Gasification (SCWG) uses water at a supercritical state in the range of 600–700 °C to generate mainly hydrogen and carbon dioxide with/without a catalyst. The gases resulting from hydrothermal gasification include H_2, CO, CH_4 and CO_2, with small amounts of C_2H_4 and C_2H_6. (Reißmann, Thrän, and Bezama, 2018; Kumar, Olajire Oyedun, and Kumar, 2018). In comparison to conventional thermal gasification, supercritical water gasification brings several advantages that include higher thermal efficiency for very wet biomass, production of a hydrogen-rich gas with low CO and low tar in one step (Basu, 2018).

HydroThermal Liquefaction (HTL), also called hydrous pyrolysis, is direct thermochemical conversion process of wet biomass into a bio-oil (bio-crude) at high temperature (300–350 °C) and pressure (10-25 MPa). Water serves as both reactant and catalyst. HydroThermal Liquefaction is in particular suitable for the production of bio-crude from biomass. Hydrothermal liquefaction produces, along with bio-crude, a CO_2 rich-gas and solid by-products (char). Biomass derived bio-crude has high heating value (30–37 MJ/kg), low oxygen content and low moisture content, depending on the type of biomass feedstock and the operating conditions: temperature, solvent type, catalyst, residence time and biomass-to-solvent ratio. The bio-oil yield is highest at around 300°C and decreases with the increase of temperature and solid char production increases with temperature. The liquid bio-crude produced has lower oxygen content than pyrolysis oil and higher heating value. The composition and yield of bio-crude are influenced primarily by temperature and biomass type as well as by particle size and reaction time. The use of catalysts in hydrothermal liquefaction can reduce the reaction temperature, enhance reaction kinetics, increase the yield of desired liquid products and reduce char and tar formation (Dimitriadis and Bezergianni, 2017; Gollakota, Kishore, and Gu, 2018; Kumar, Olajire Oyedun, and Kumar, 2018).

Hydrothermal processing is overall now advancing from lab-pilot scale (TRL 4-5) to pilot-industrial scale (TRL of 5-6) with some projects closer to demonstration. There is a wide range of potential process designs and the optimal process parameters still need to be established. There are also several technological gaps for the commercialisation of hydrothermal processing, including the lack of a deep knowledge about the chemical pathways, reactor design for process development and optimisation, the need for advanced materials to avoid corrosion in the extreme environment (high pressure and environment) and the high capital costs (costs of fixed assets).

2.1.2.4 Biomass gasification

Gasification is a thermo-chemical conversion process of biomass into a fuel gas (syngas), at high temperature (700-1500 °C), by partial oxidation with limited oxygen. The syngas is a gas mixture of carbon monoxide, hydrogen, methane and carbon dioxide as well as light hydrocarbons (ethane and propane), traces of ammonia, hydrogen sulphide, and hydrogen halides, condensable gas (tar and water vapours) and particulate matter (char and ash). The gasification process includes the following steps: i) preheating and drying; ii) thermal decomposition; iii) partial combustion of some gases and char; iv) gasification of char and gaseous components (Basu, 2018). Direct gasification utilises the exothermic oxidation reactions from thermally degrading biomass inside the reactor, while indirect gasification requires an external source of energy. At indirect gasification, the heat source can be ensured through the separation of the gasification and combustion processes in different reactors, or by a novel technology, microwave heating instead of traditional heating methods, ensuring better heating rates compared to the conventional process. Indirect gasification allows the production of a N_2-free gas without the need for an air separation unit, making it suitable for synthesis applications.

Gasification is a highly versatile process, being able to convert any biomass feedstock into fuel gas. There is a wide range of possible configurations for biomass gasification, depending on the oxidation agent (air, oxygen or steam), process heating (direct or indirect), pressure level (atmospheric pressure or elevated pressure), or reactor type (moving bed, fluidised bed or entrained flow, up-draught and down-draught reactors). The selection of the most appropriate gasification process depends on the properties of the feedstock used, the final applications of gas and other factors. Fluidised bed gasifiers are more tolerant to feedstock properties and require less pre-treatment than entrained flow gasifiers, but produce more tars and light hydrocarbon gases, which need more complex gas purification systems (Obernberger and Thek, 2008). Fluidised-bed gasifiers typically operate in the temperature range of 800–1000°C. Entrained-flow gasifiers typically operate at 1400°C and high pressure (20–70 bar), using oxygen as the most common gasification medium. Extremely high temperatures (~ 4000 °C) during plasma gasification allow the complete dissociation of the feedstock into syngas and complete breakdown of tars and other gas contaminants. Plasma promotes the decomposition of hydrocarbons and tars and enhances the formation of combustible gases such as hydrogen and carbon monoxide. This technology is particularly promising for waste gasification (industrial or municipal waste, hazardous wastes, tyres etc.) producing a chemically inert slag itself that is safe to handle. The application of catalytic gasification has shown promising results in tar mitigation in syngas as well as enhanced high hydrogen and syngas production compared to without catalyst (Basu, 2018; Obernberger and Thek, 2008).

The composition of the gas produced in a gasifier depends on the gasification agent, temperature, pressure, heating rate and feedstock characteristics (composition, water content, particle size) and the gasifying agent used. Oxygen gasification offers a product gas with the highest heating value (value (12–28 MJ/m^3) and increased carbon-based compounds such as CO and CO_2 in the product gas. Air-based gasifiers typically produce a gas with lowest heating value (due to the dilution), a high nitrogen content and a low energy content (4 - 7 MJ/m^3). Steam gasifiers produce a product gas with higher hydrogen concentration and higher energy content (10-18 MJ/m^3) due to water gas shift reaction (Basu, 2018; Mott MacDonald, 2011; IRENA, 2012; Molino, Chianese, and Musmarra, 2016). Biomass gasification produces a syngas, Synthetic Natural Gas (SNG), that can be used to produce heat and power directly in internal combustion engines, boilers and fuel cells, or to be used for the production of methanol and other chemicals, or for the synthesis of Fischer-Tropsch hydrocarbons. Nowadays, biomass gasification is mainly used for heat and power production at small- and medium-scale plants. Syngas is in engines operating at electrical conversion efficiencies between 30 - 35%, in gas turbines (up to 40% efficiency), in gas and steam turbine combined cycles (up to 42%), or in fuel cells (50 - 55%) (IEA Bioenergy, 2009).

Typical gasification plant capacities range from a few hundred kW for heat production, and from 100 kW to 1 MWe for CHP with a gas engine, and up to 10 MW for gas turbines systems operating at higher efficiency than a steam cycle. At larger scales (>30 MWe), gasification-based systems can be coupled with a gas turbine with heat recovery and a steam turbine (combined cycle) in a Biomass Integrated Gasification Combined Cycle (BIGCC) technology, thus offering higher efficiency of 40 - 50% for 30-100 MW plant capacity. Although several projects were implemented worldwide, biomass gasification is still at demonstration stage, reaching TRL 6-8. Further technology development requires demonstration at scale and proof of reliable, continuous and long-term operation.

2.1.3 Intermediate bioenergy carriers

2.1.3.1 Biomass Pre-treatment

Biomass has a highly variable composition, high-moisture content and low energy density. These characteristics imply that significantly larger volume of biomass needs to be handled. It makes transportation, handling, and storage of biomass difficult. Biomass pre-treatment provides an appropriate feedstock from raw biomass, which is adequate for feeding in the thermal processes downstream. Pre-treatment is designed to modify the physical characteristics of biomass, in terms of size and moisture content, through several processes that includes material separation, feedstock drying, chipping and grinding (process by which particles are reduced in size mechanically) operations to modify the physical-chemical properties of the biomass feedstock. Changing the properties of the feedstock is vital for thermal processing, in particular for the conversion reactor, to optimise the plant operation and maximise product yield, typical operations are:

- removal of undesired materials (e.g., impurities, non-combustible materials)
- feedstock chipping and grinding
- feedstock drying
- pelletising, briquetting
- torrefaction

Many pre-treatment options are available, depending on the processes downstream, such as thermochemical processing (combustion, gasification, pyrolysis), or biochemical processing (anaerobic digestion, etc.). Table 5

Table 5. Solid energy carriers and coal comparison

	Wood chip	Wood Pellets	Torrefied Pellets	Coal
Moisture (%)	30-55	7-10	1-10	10-15
Net Calorific Value (MJ/kg)	7-12	15-17	17-24	23-28
Volatile Matter (% mass Dry Basis)	70-84	75-84	55-80	15-30
Fixed Carbon (% mass Dry Basis)	16-25	16-25	22-35	50-55
Bulk Density (t/m3)	0.20-0.30	0.55-0.65	0.55-0.80	0.80-0.85
Energy density (GJ/m3)	1.34-3.6	8-11	12-19	18-24

Source: (International Renewable Energy Agency, 2024)

Biomass densification

Biomass densification is a process to create compact biomass fuel with uniformly sized solid particles such as pellets and briquettes with higher energy density. This process strongly depends on the particle size, moisture content, and process parameters. This enables the production of intermediate bioenergy carriers that can be traded globally on a commodity market. The pelletisation, a process of compressing or moulding a material into the shape of a pellet, torrefied biomass brings additional advantages for transport, handling and storage, in comparison to torrefied biomass chips as intermediate bioenergy carriers. The torrefied biomass provides additional advantages for the different downstream processes such as gasification (reducing tar formation due to its high heating value and low volatiles content) and pyrolysis (reducing the water, acid, and oxygen contents of bio-oils) (Wei Hsin, Jianghong, and Bi, 2015; Eseyin, Steele, and Pittman, 2015; IRENA, 2019).

Pelletising

The biomass pelletisation process consists of several steps including feedstock pre-treatment, pelletisation and post-treatment. A pellet is a small, rounded, spherical or cylindrical mass, which is created either directly by pressing or by adding a small amount of binder. The raw materials / feedstocks used are forest residues, sawdust, wood shavings, wood wastes, agricultural residues such as straw, switchgrass, etc. (IRENA, 2019). The moisture content in biomass can be quite high and is usually up to 50%–60%, but should be reduced to 10 to 15%. Rotary drum dryers are the most common equipment used for this purpose. Superheated steam dryers, flash dryers, spouted bed dryers and belt dryers can also be used. Drying increases the efficiency of biomass and significantly reduces smoke during combustion. The feedstock should not be too dry, as a small amount of moisture helps in binding the biomass particles. The drying process is the most energy-intensive process and accounts for about 70% of the total energy used in the pelletisation process. Before feeding the biomass to the pellet mills, the biomass should be reduced to small particles no larger more than 3 mm. If the pellet size is too large or too small, it affects the quality of the pellets and consequently increases energy consumption. Therefore, the particles should of correct size, the reduction process is carried out by grinding using a hammer mill equipped with a sieve of size 3.2 to 6.4 mm. If the feedstock is relatively large, it passes through a chipper before grinding. The biomass is then pressed against a heated metal plate (known as die) using a roller. The die consists of holes of fixed diameter through which the biomass passes under high pressure. Due to the high pressure, frictional forces increase, leading to a considerable rise in temperature. High temperature causes the lignin and resins present in biomass to soften which acts as a binding agent between the biomass fibres, so that the biomass particles fuse to form pellets. The rate of production and electrical energy used in the pelletisation of biomass are strongly correlated to the raw material type and processing conditions, such as moisture content and feed size. The average energy required to pelletise biomass is roughly between 16 kWh/t and 49 kWh/t. During pelletisation, a large fraction of the process energy is used to make the biomass flow into the inlets of the press channels. Binders or lubricants may be added in some cases to produce higher quality pellets. Binders increase the pellet density and durability. Wood contains natural resins which act as a binder. Similarly, sawdust contains lignin which holds the pellet together. However, agricultural residues do not contain many resins or lignin, and so a stabilising agent needs to be added in this case. Distillers dry grains or potato starch are some commonly used binders. The use of natural additives depends on biomass composition and the mass proportion between cellulose, hemicelluloses, lignin and inorganics. Due to the friction generated in the die, excess heat is developed. Thus, the pellets are very soft and hot (about 70 to 90 °C) and need to be cooled and dried before storage or packaging. The pellets may then be passed through a vibrating screen to remove fine materials. This ensures that the fuel is clean and dust free. The pellets are packed into bags using an overhead hopper and a conveyor belt. Pellets can be stored in elevated storage bins or ground level silos. The packaging should be such that the pellets are protected from moisture and pollutants. According to Bioenergy Europe Statistical report 2024, global pellet production still grows, with an increase of 13% from 2020 to 2022. The EU reached 20.7 million tonnes of production, making it the world's major pellet producer. Germany is still the largest pellet producer within the EU. Regarding consumption, pellet use in 2022 increased by 13% globally compared to 2020, reaching 43 million tonnes. The EU remains the largest global pellet consumer. The residential and commercial segments were led by Germany and Italy, which remains the world's largest pellet users for the residential sector, with a total consumption of 7 million tonnes.

Torrefaction

Torrefaction is a thermochemical upgrading process consisting of thermal decomposition of biomass in the absence of oxygen at atmospheric pressure and temperatures typically ranging between 250-300ºC, leading to the release of moisture and partial release of volatile compounds. The objective of torrefaction is to increase the energy density of biomass by increasing its carbon content while decreasing its oxygen and hydrogen content. This produces a high-quality solid biofuel (energy carrier) with higher heating value or energy density, lower moisture content, good hydrophobic behaviour, improved grindability (energy expended to grind the fuel to a required degree of fineness) and reactivity and more uniform properties. It provides a commodity that could be also traded easier, improving the transport and storage characteristics. Biomass torrefaction is used as a pre-treatment step for biomass conversion techniques such as combustion and gasification. Dry torrefaction, through a hot inert gas or by indirect heating is a common process; wet torrefaction (called hydrothermal torrefaction or carbonisation) involves biomass heating in hot compressed water (Wei Hsin, Jianghong, and Bi, 2015; Eseyin, Steele, and Pittman, 2015; IRENA, 2019).

The heating rate in torrefaction must be slow to enable maximisation of solid yield. Thermal cracking of cellulose causing tar formation starts at temperature 300–320 °C that limits the torrefaction temperature at maximum 300°C. Torrefaction can be classified into light, mild and severe torrefaction processes. The heating value of the torrefied biomass increases from 19 MJ/kg to 21-23 MJ/kg for torrefied wood or even to 30 MJ/kg in the case of complete devolatisation, resulting charcoal. The torrefaction degree depends typically on the time that a (dry) biomass particle resides in the torrefaction reactor and on the temperature inside the reactor. The energy required for the drying and torrefaction process is delivered by the combustion of torrefaction gas, or from additional auxiliary fuel.

A typical torrefaction plant includes several units such as dryer, torrefaction reactors and cooler. Different reactor technologies are available for torrefaction, including convective bed reactors (fixed, moving, entrained), rotating drum reactor, screw or stationary shaft fluidised-bed reactor or microwave reactors. The selection of technology needs to be done based on the characteristics of the feedstock, or alternatively, the feedstock needs to be pre-processed (Basu, 2018; Cremers et al., 2015; Sarker et al., 2021). The control of the temperature profile and residence time of biomass in the reactor is crucial for an efficient process and optimal product quality. Ensuring product quality and consistency is a challenge, due to uneven biomass quality (particle size and composition), heat transfer rate, temperature, and residence time, requiring process optimisation.

Torrefaction improves biomass properties and decreases the costs for handling, storage and transport. Torrefaction of agro-residues appears to be more complicated due to the challenging variable physical and chemical characteristics. The torrefaction process results in feedstock and energy losses and increased cost. Biomass torrefaction has been proven at pilot scale and a number of demonstration and (semi)commercial facilities are in operation. Torrefaction is not yet fully commercially available and further development of torrefaction technology is needed to overcome certain technical and commercial challenges. The first demonstration projects are in operation (e.g., Andritz-ECN, at Stenderup in Denmark, Andritz ACB in Frohnleiten in Austria, Stramproy at Steenwijk in Nederland, Topell at Duiven in Nederland, etc.).

2.1.3.2 Biogas upgrading to biomethane

The biogas upgrading to biomethane involves cleaning the biogas to remove unwanted contaminants, removing carbon dioxide, cooling or drying, and compressing it to the required pressure. There is currently a clear trend towards biogas upgrading to biomethane. Biomethane can be used to replace natural gas, as a fuel in Natural Gas Vehicles (NGV) or for the injection into the natural gas grid for further use in all sectors of the economy. Biomethane can also be used as a feedstock and as an alternative for natural gas to produce a range of bio-based chemicals. While the biogas production stagnated over the past decade, biomethane production is growing at an increasing rate. Compared to on-site conversion of biogas to heat and/or electricity, the upgrading of biogas to biomethane allows for more flexible use and benefits from the natural gas and refuelling infrastructure.

Biogas upgrading entails the removal of carbon dioxide to increase the energy density as well as the removal of water, hydrogen sulphide and other contaminants to avoid corrosion or other problems in downstream applications. There are several technologies available for upgrading biogas to biomethane (Nguyen et al., 2021; van Foreest, 2012; Thrän et al., 2014; Martín-Hernández, Guerras, and Martín, 2020; Khan et al., 2021):

- **Pressurised Water Scrubbing,** where carbon dioxide from biogas is dissolved in water at low temperatures and high pressures (5-10 bar) and thus separates from the methane molecules. The dissolved carbon dioxide is released from water in a desorption vessel at lower (atmospheric) pressure.
- **Pressure Swing Adsorption,** where carbon dioxide is separated from the methane molecules by adsorption on solid surface (such as activated carbon or molecular sieves - zeolites) under elevated pressure (3-10 bar). The carbon dioxide is afterwards recovered as concentrated gas from the solid surface by reducing the pressure;.
- **Physical Absorption** dissolves the carbon dioxide is absorbed in a liquid under high pressure (5-10 bar) and flashed out in the low pressure flash tank.
- **Chemical Absorption**, where carbon dioxide from biogas dissolves into a chemical solvent (such as amines, sodium hydroxide, potassium hydroxide) at atmospheric pressure. The resultant rich amine is then regenerated by increasing temperature (heating to about 160°C), releasing carbon dioxide.
- **Membrane Separation**, where a permeable membrane separates carbon dioxide and methane molecules based on their different physical characteristics at high pressure (5 – 20 bar).
- **Cryogenic Upgrading**, which uses the different boiling points of various gases, particularly for the separation of carbon dioxide and methane. Methane remain in gaseous form and thus the liquid carbon dioxide stream can be easily separated.
- **Vacuum Swing Adsorption** involves CO_2 removal with an adsorbent; after the adsorbent's saturation, regeneration is carried out by decreasing pressure. For CO_2 separation, VSA is more efficient because generated biogas by anaerobic digestion is just slightly higher than atmospheric pressure.
- **Temperature Swing Adsorption,** an adsorber and a desorber, respectively, in the low temperatures and higher temperatures, are included within the nonstop TSA inoverhauling biogas. Within the previous, the CO2 of the pretreated biogas stream is retained specifically by the strong sorbent (substance possessing the characteristic ability of absorption or adsorption) fabric.
- **Biological Technologies** is based on microorganisms' capability to turn CO2 from an anaerobic digester (closed container where anaerobic biodigestion takes place) into CH_4 through autochthonous methanogenic archaea activity The technology works on the concept of recycling fluid slime from the assimilation chamber

to the column of desorption, where the counter stream of O_2 and N_2 is subjected to the desorption of CO_2 broken up within the slime.

- **Carbon Capture and Storage,** the strategy of capturing and putting away CO_2 using a carbon mineralisation process.

Several biogas upgrading technologies operate commercially, including membrane separation, water/chemical scrubbing (removal of solid, liquid and/or gaseous compounds from a gas stream by transferring them to a scrubbing liquid) and Pressure Swing Adsorption (PSA). In 2022 in the EU, most of the biomethane plants use membrane separation (51%), followed by water scrubbing (14%), and chemical absorption (12%) (European Biogas Association, 2023). Cryogenic separation might be of growing importance in case of higher use of biomethane as liquefied natural gas (LNG), benefitting from the integration of methane separation with liquefaction units for the methane (Thrän et al., 2014).

2.1.3.3 Syngas upgrade to synthetic natural gas

The composition of syngas depends on various factors, including the type of the gasifier (fixed bed, fluidised bed, and entrained bed) and operating condition (temperature, pressure), gasification medium (air, oxygen steam), and catalysts. Gasification gas contains a range of contaminants, such as tars, sulphur, chlorine compounds, alkali metals, heavy metals and particulates. The contaminants generally need to be removed, since they can impact the operation of downstream processes. Tar and particulate matter result in chocking, corrosion, and erosion of the downstream equipment. The other gases such as ammonia, hydrogen sulfides, and hydrogen halides can contribute to corrosion and air pollution. Therefore, gas cleaning and conditioning is a crucial step in biomass gasification facilities. The use of syngas in Fisher Tropsch (FT) process for fuels requires extensive cleaning of produced gas to prevent poisoning of catalysts (reduction of the effectiveness of a catalyst in a chemical reaction).

The gas cleaning method can be divided into primary methods (situ cleaning) and secondary methods (post cleaning). Primary methods include proper selection of gasifier design, operating conditions (temperature, pressure), gasifying agent and the use of sorbents or additives. Higher air ratio and gasification temperature lead to the reduction of the tar and ammonia production, but reduce the quality of gas. Secondary methods for gas cleaning consist in hot gas cleaning (above 400°C) and cold gas cleaning at low temperature (<250°C). Hot gas cleaning offer higher energy efficiency and employs physical separation (cyclone and filters) for separating impurities from the syngas, along with catalytic conversion for reduction of tar and other contaminants. Hot gas cleaning technologies could be used for sulphur removal through physical or chemical adsorption, ammonia removal through selective catalytic oxidation or thermal catalytic decomposition with Nickel-based catalysts, alkali (condensation) and alkali and chlorine (solid adsorption). The hot gas cleaning technologies could remove tars through thermal, catalytic cracking, plasma and physical separation and particulate matter through barrier filtration, inertial and electrostatic separation (Acharya, 2018).

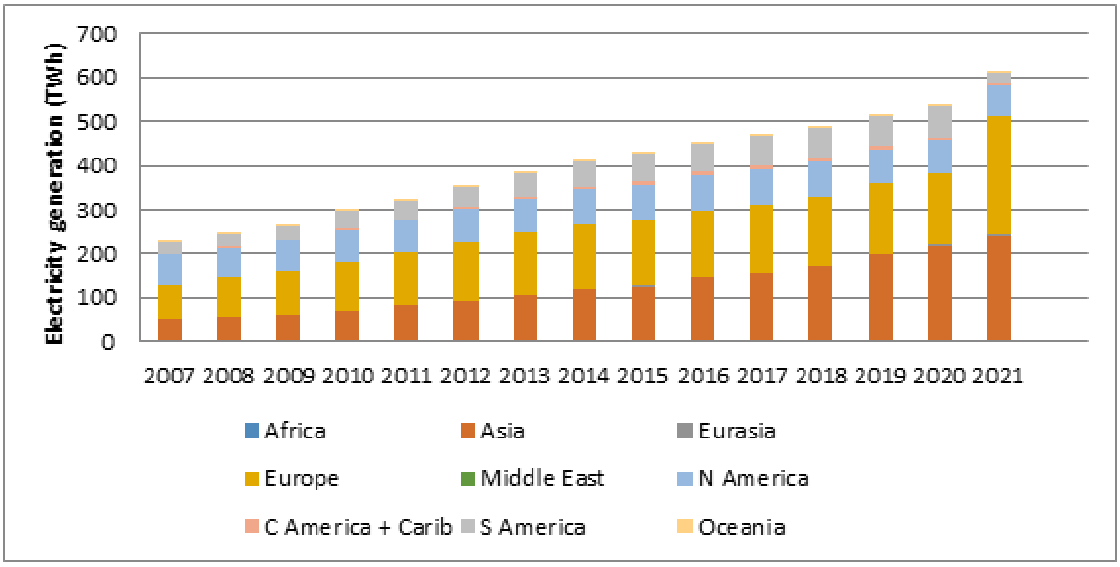
Cold gas clean-up processes entails dry cleaning or wet processes. Cold gas cleaning methods are used largely for small-scale applications. Cold gas cleaning has the disadvantage that lowers the thermal efficiency of the process. Dry cleaning entails the use of filters (fabric filters, sand bed filters), cyclones, and electrostatic precipitators. Wet methods use water or liquid absorbent with wet scrubbers, spray towers or Venturi scrubbers (Basu, 2018; IEA Bioenergy, 2009; Acharya, 2018). Water discharge from wet scrubber, heavily contaminated, requires chemical and/or biological waste water treatments in order to be recirculated or discharged (Mott MacDonald, 2011).

2.2 Production and Installed Capacity

Global bioelectricity production

Bioelectricity production increased globally from 229 TWh in 2007 to 614 TWh in 2021. The share of biomass electricity production in total renewable electricity production increased for the period 2007-2021 from 6.8 % to 7.8 % [International Renewable Energy Agency, 2024] Europe is the leading region on bioelectricity production, followed closely by Asia. Asia underwent the highest growth rate between 2007 and 2021. The next most important region, North America, is far behind in terms bioelectricity production with 71 TWh as shown in Figure 2

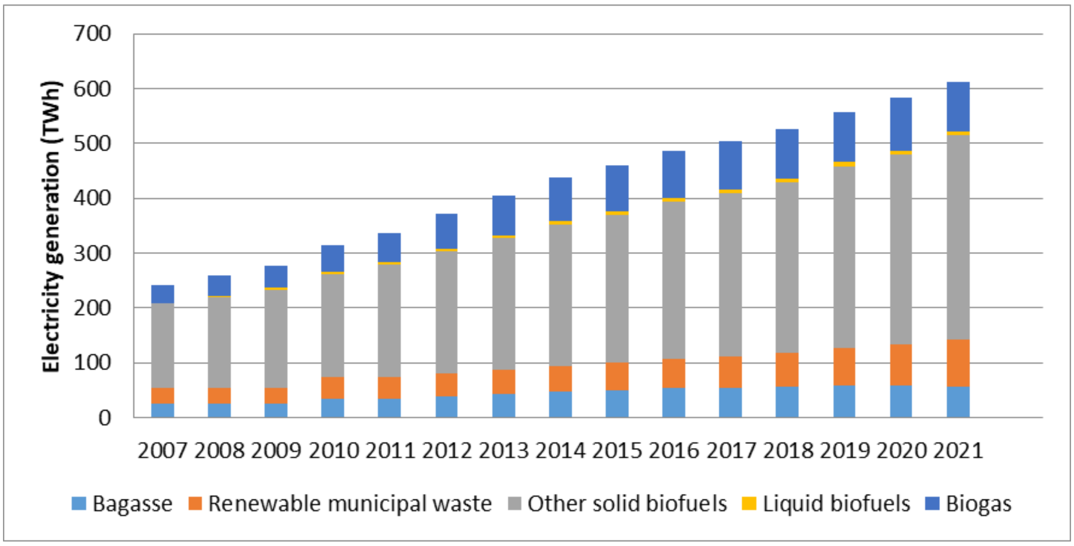
Figure 2. Evolution of Bioelectricity production in the world by regions



Source: (International Renewable Energy Agency, 2024)

Solid biomass was the main feedstock for bioelectricity production from 2007 to 2021. Over the period, electricity production from solid biomass increased from 181 TWh to 370 TWh. Biogas gained in importance as second after solid biomass with 92 TWh electricity produced in 2021 mainly in the EU and partially lower production in Asia and North America. Another feedstock used for the production of electricity from biomass is municipal renewable waste (portion of municipal waste which is of biological origin) that reached 86 TWh in 2021, mainly in Asia and the EU. Bagasse (dry pulpy residue after the extraction of juice from sugar cane) is used to produce electricity mainly in South America, with minor use in other regions of the world, taking advantage of the sugarcane production. (Figure 3)

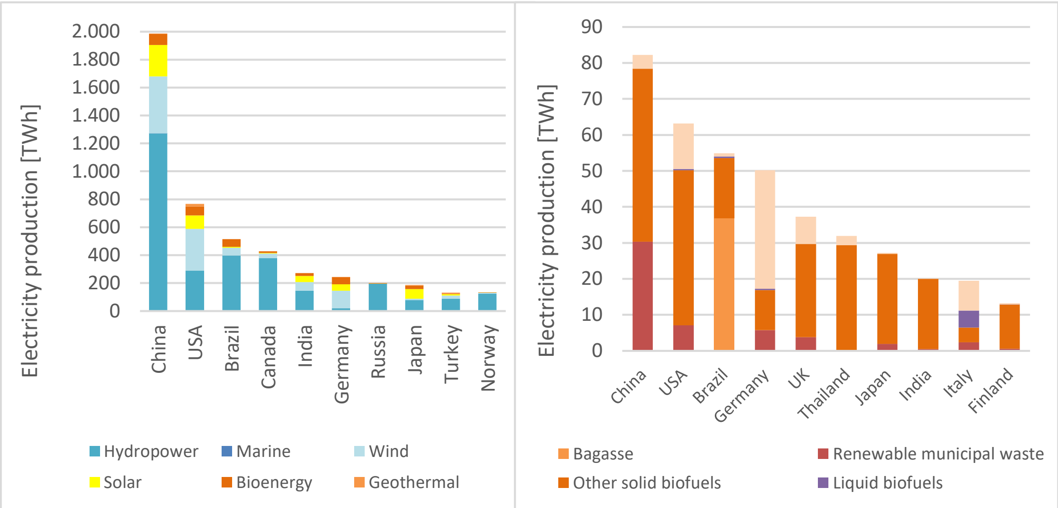
Figure 3. Evolution of bioelectricity production in the world by source



Source: (International Renewable Energy Agency, 2024)

Bioelectricity is part of renewable electricity production mix to varying degrees on several continents. Leading countries in the production of renewable electricity in 2021 include China, the Hydro is the most important source in China, Brazil, Canada, and Russia. Wind represents a major source in China, US, Germany. Solar electricity contributes significantly in China, the US, India, Germany, and Japan. Bioelectricity production provides a relatively small contribution, mostly in China, the US, Brazil, Germany, the UK and others (see Figure 4 – left panel). The most important source of bioelectricity is solid biomass in China, Brazil, Thailand, Japan, (see Figure 4– right panel). Renewable municipal waste is highly important in China, but also in the US, Germany, the UK, and Italy. Biogas dominates biomass electricity production in Germany, and also has a large share of electricity production in the US, Italy and the UK. Bagasse is the most important feedstock for bioelectricity

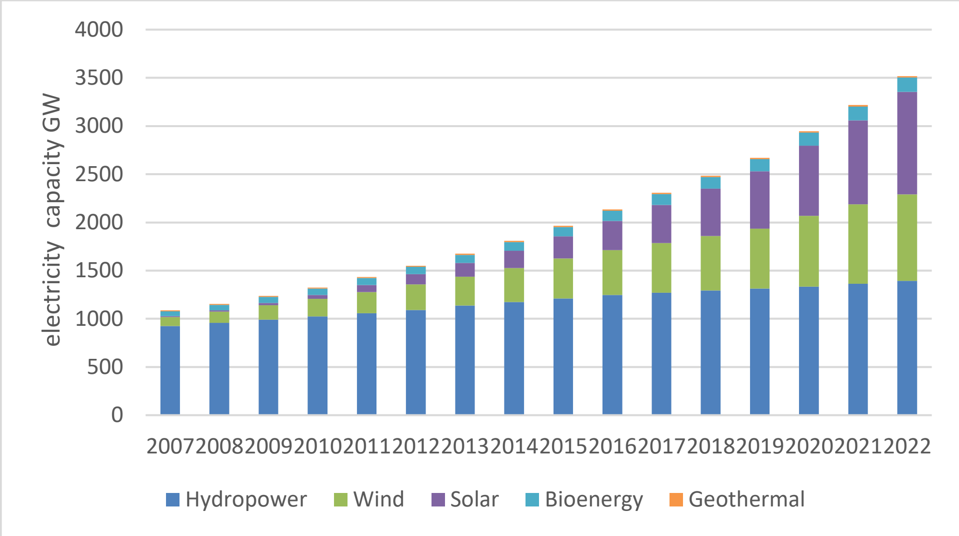
Figure 4. Leading countries in renewable electricity (left) and bioelectricity production (right) in 2021



Source: (International Renewable Energy Agency, 2024)

Global installed renewable electricity capacity increased from 993 GW in 2007 to 3381 GW in 2022, more than tripling over the period (Figure 5). Hydropower plants account for the largest share of installed capacity with 1,393 GW in 2022, experiencing slow growth, especially compared to other renewables. The second renewable energy in terms of installed capacity is solar, reaching 1,062 GWp in 2022 worldwide, the highest increase since 2007. Bioenergy electricity capacity increased significantly, tripling between 2007 and 2022 from 41 GW in 2007 to 151 GW in 2022 (Figure 6). While installed bioelectricity looks small compared to wind and power, it retains the advantage of being non-intermittent, and having a higher capacity factor (hours of electricity production per year).

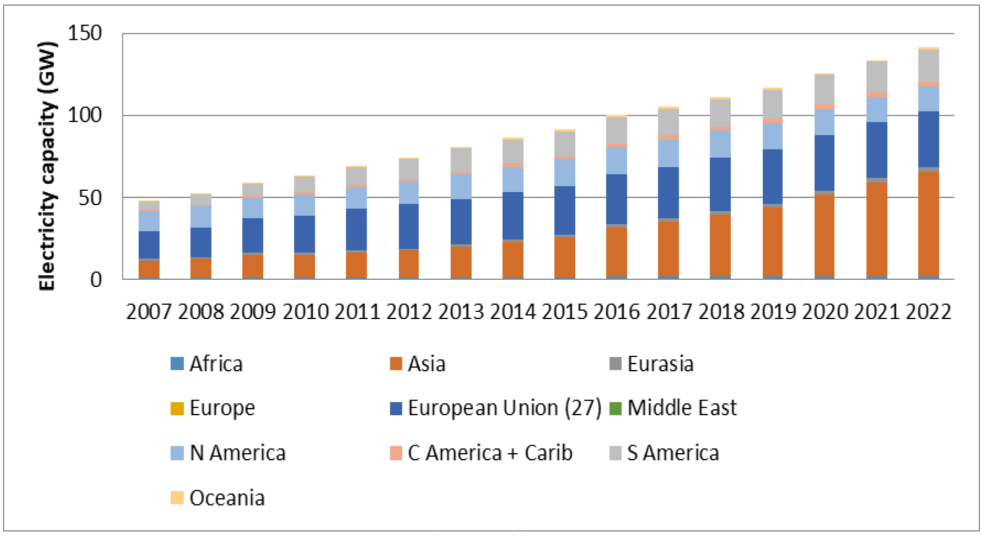
Figure 5. Evolution of bioelectricity and renewable energy capacity in the world, 2007-2022



Source: *(International Renewable Energy Agency, 2024)*

Asia had the highest bioelectricity capacity in 2022 and had the highest growth rate since 2007 compared to other world regions. The EU is the second world region in terms of biomass electricity and the second in terms of growth rate, followed by South America.

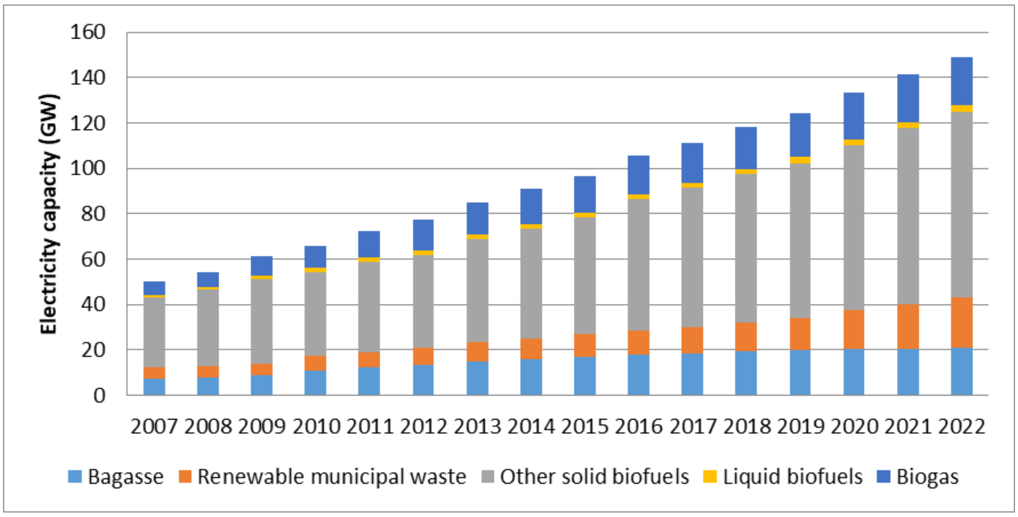
Figure 6. Evolution of bioelectricity capacity in the world by regions, 2007-2022



Source: (International Renewable Energy Agency, 2024)

The largest capacity of bioelectricity plants comes from solid biomass, followed by biogas plants, bagasse plants. The highest increase in biomass plants is for solid biomass, reaching 103 GW in 2022, followed by biogas plant with an increase from 6 GW to 21 GW and bagasse with an increase from 7 GW to 21 GW over the same time period. (Figure 7)

Figure 7. Evolution of bioelectricity capacity in the world by source, 2007-2022

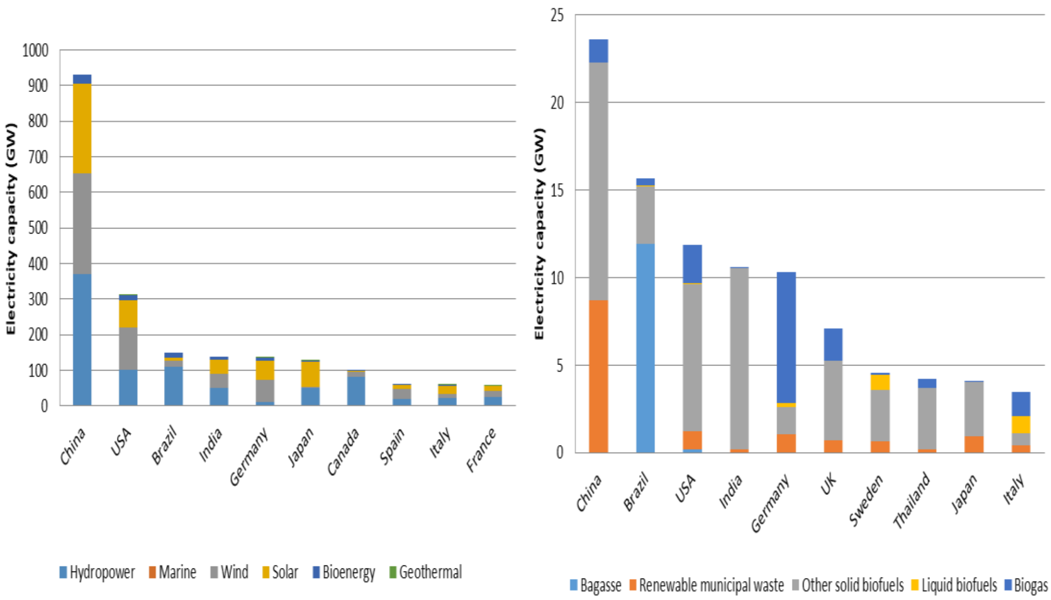


Source: (International Renewable Energy Agency, 2024)

The leading countries in renewable electricity capacity include China, followed by far by the US, Brazil, India Germany, etc. (Figure 8). The most important source include hydropower in China, Brazil, Canada, the US, etc. Wind power capacity is the highest in China (282 GW), followed by the US (118 GW), Germany. Solar electricity capacity is also the highest in China (282 GW), followed by the US, Japan, Germany.

In comparison, the capacity of electricity from biomass is much lower. The leading countries in biomass electricity capacity include China (23 GW), Brazil (16 GW), the US (12 GW), India (11 GW). Solid biomass capacity is the highest in China (14 GW), India (10 GW), the US (9 GW), the UK (5 GW). Renewable municipal waste power plants are very important in China (9 GW), with much lower electricity capacity in the US, Germany, the UK, etc. Bagasse power plants are mostly important for electricity in Brazil with a capacity of 12 GW.

Figure 8. Global leaders in renewable electricity and bioelectricity capacity in 2022



Source: (International Renewable Energy Agency, 2024)

EU bioenergy

Bioenergy production

Bioenergy is the main renewable energy source used in the EU. Energy production from all renewables, i.e., hydropower, solar wind, geothermal, heat pumps, marine energy and bioenergy, shows a significant and continuous progress, from 200 Mtoe in 2014 to surpass 250 Mtoe in 2022, Figure 9. Bioenergy electricity and heating followed a similar trend increasing from 110 Mtoe in 2014 to 126 Mtoe in 2022.

The share of bioenergy in renewable energy supply in the EU slightly decreased from 51 % in 2014 to 47 % in 2022 and appears, that the bioenergy growth trend seems to be levelling out over the last decade. The cause may be uncertainties in support policies, concerns about the sustainability of bioenergy, relatively low energy prices until the unprovoked and unjustified Russian military aggression against Ukraine (Communication REPowerEU Plan, 2022), and priority electrification based on Wind and Solar.

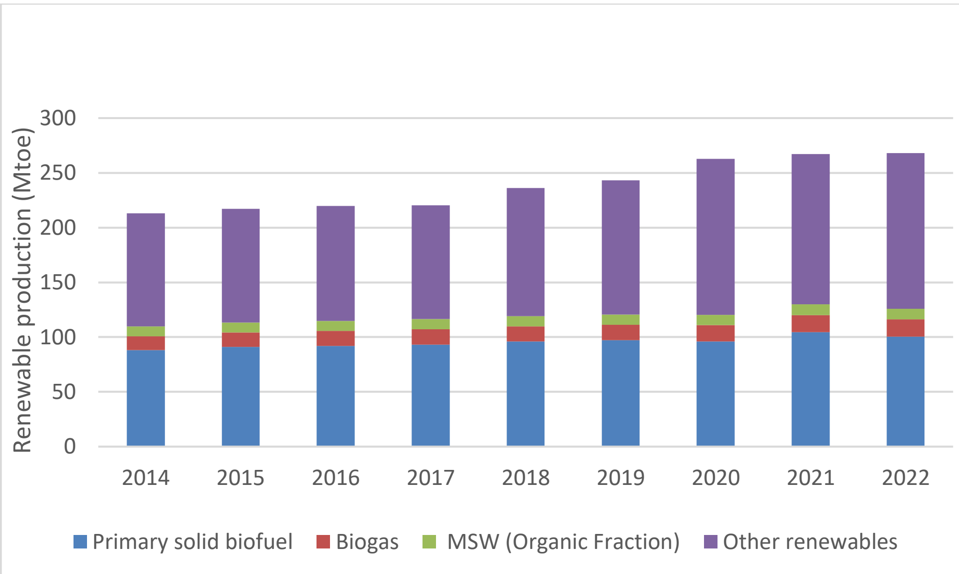
Also in the EU, bioenergy is produced from a wide range of feedstocks, such as biomass from agriculture (crop residues, bagasse, animal waste, energy crops, etc.), biomass from forests (primary woody biomass such as fuelwood and logging residues, secondary sources such as by-products of wood processing, black liquor from the pulp and paper industry, and post-consumer wood), and other types of biological waste (food waste, food industry waste, organic fraction of municipal solid waste, etc.) (Scarlat et al., 2019).

The main feedstocks used for bioenergy production in the EU are solid biofuels, municipal renewable waste, biogas and liquid biofuels (Figure 9). Solid biofuels are the most common biomass feedstock used in the EU, increasing from 88 Mtoe in 2014 to 100 Mtoe in 2022. Solid biofuels include a range of primary wood from forests (fuelwood, logging residues), and forestry waste and residues (bark, sawdust, shavings, chips) and agriculture (straw, husks, nut shells, etc.), black liquor, etc., as well as waste (used and contaminated wood, etc.).

For bioenergy production from forest biomass, the main feedstock comes from the use of by-products (49%), followed by primary wood from forests (37%), which includes logging residues and other undefined category (14%).

The contribution of biogas using agricultural residues such as manure, energy crops, biowaste, sewage sludge of from landfill gas recovery shows a significant increase from 13 Mtoe to 16 Mtoe during this period. Another component of biomass feedstock, renewable municipal waste, is also increasingly being used for energy recovery, although with a progress at lower rates that remain around 10 Mtoe. (Figure 9).

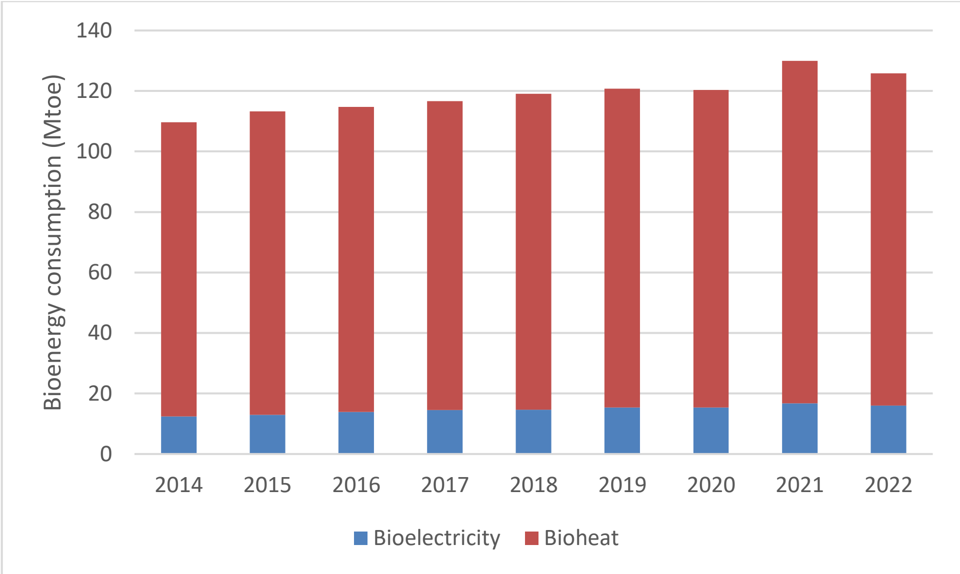
Figure 9. Evolution of bioenergy and renewable energy production in the EU



Source: (Eurostat, 2024)

The main uses of biomass is for electricity production and heating (Figure 10). Biomass heat represents around 88 % of bioenergy consumption.

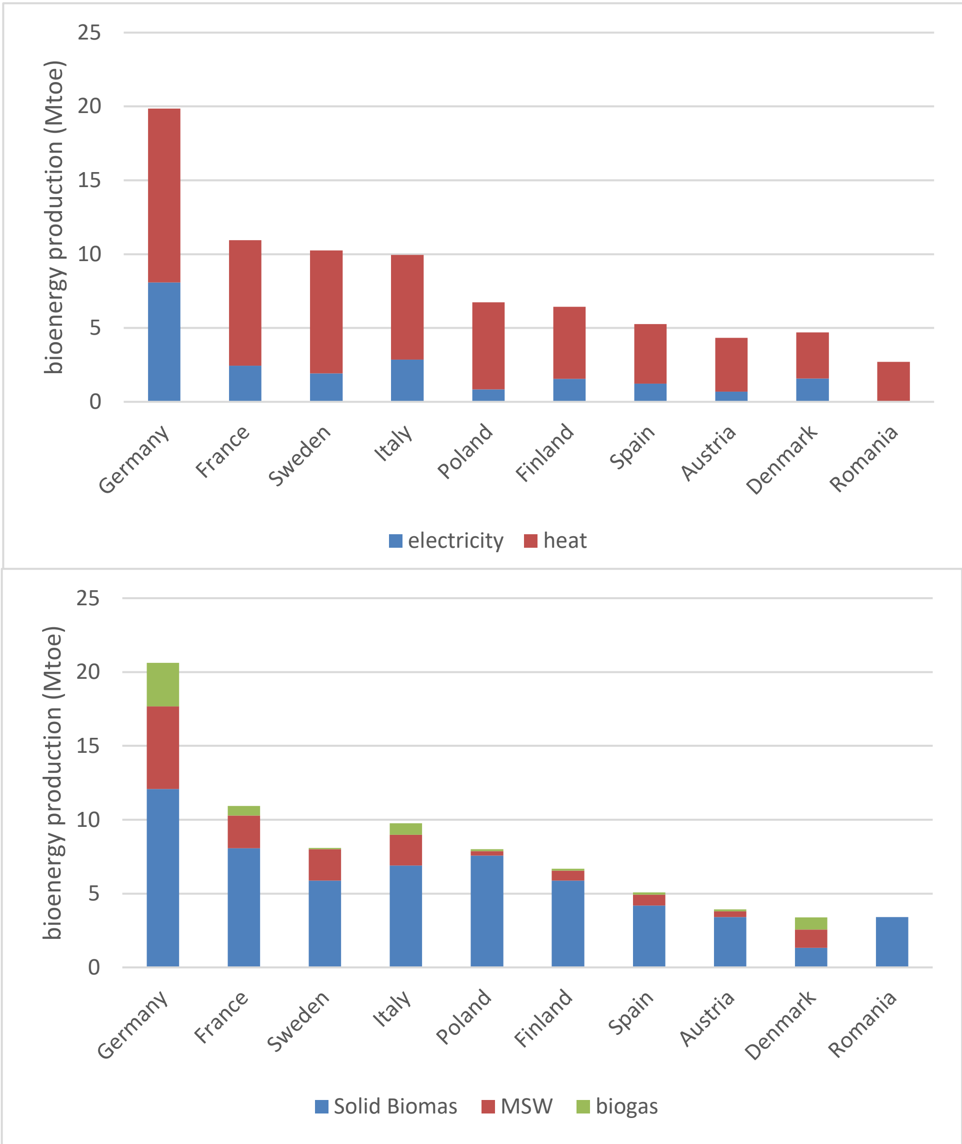
Figure 10. Evolution of bioenergy consumption for electricity and heat in the EU



Source: (Eurostat, 2024)

Figure 11 shows the contribution of bioenergy (electricity, heating) in the Member States of the EU in 2022. The leading Member States (MS) both in bioenergy and renewable energy supply include Germany, France, Italy, Poland, Finland, Spain, Austria, Denmark and Romania. Most bioenergy comes as heat in all leading MS. Electricity from biomass also plays an important role in Germany, as does biogas. Solid biomass is the main source for bioenergy production in all MS.

Figure 11. Leading EU Member States on bioenergy production in 2022



Source: (Eurostat, 2024)

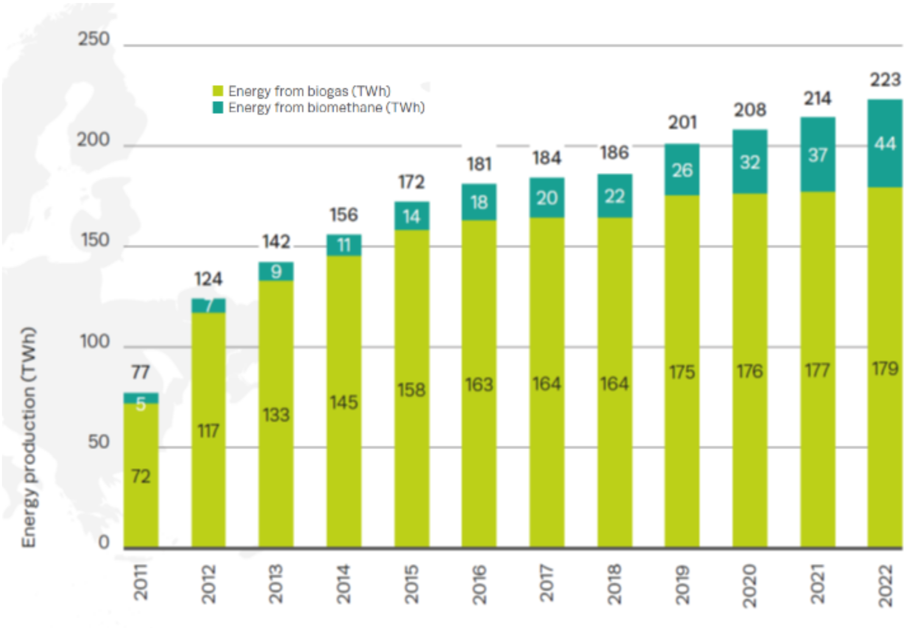
Biogas

Biogas production has seen an impressive growth in Europe, from just 72TWh in 2011 to 179 TWh in 2022 (EBA, 2023; EUROSTAT, 2024). Biomethane production is gaining momentum and more than quadrupled from 11 GWh in 2014 to 44 GWh in 2022. Biogas is most commonly used to produce electricity and heat.

Biomethane can replace conventional fuels and especially natural gas for the production of heat and electricity and for the use of biomethane in transport. Existing biogas plants are being converted to biomethane plants that could be injected into natural gas grids and used as transport fuel in natural gas vehicles.

Figure 12 shows the overall growth in biogas and biomethane production, as well as the increasing proportion of biogas upgraded to biomethane. The combined biogas and biomethane, in 2022, amounted to 223 TWh.

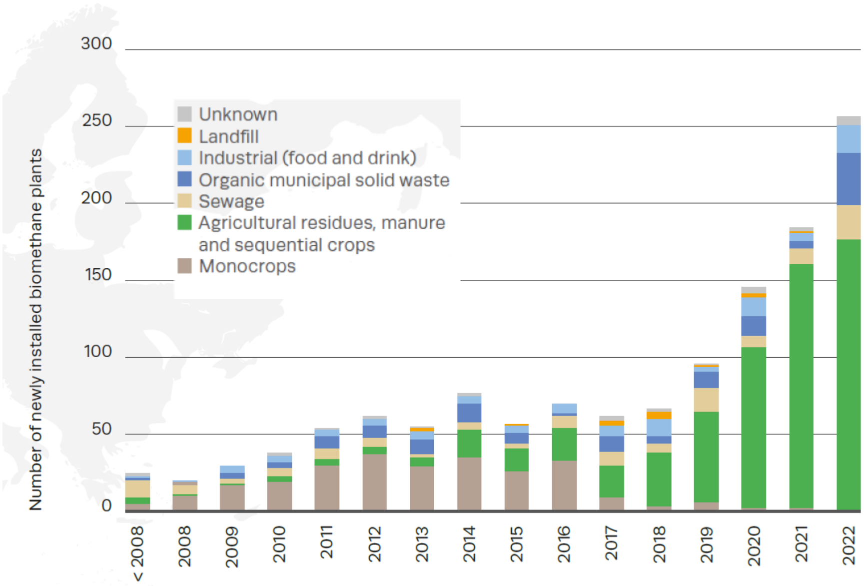
Figure 12. Evolution of biogas and biomethane production in Europe in TWh



Source : (European Biogas Association (EBA), 2023; Eurostat, 2024)

At the same time, the predominant feedstock used for biomethane production is shifting to organic industrial waste and municipal solid waste. (Figure 13)

Figure 13. Biogas and Biomethane feedstock in Europe, 2008-2022

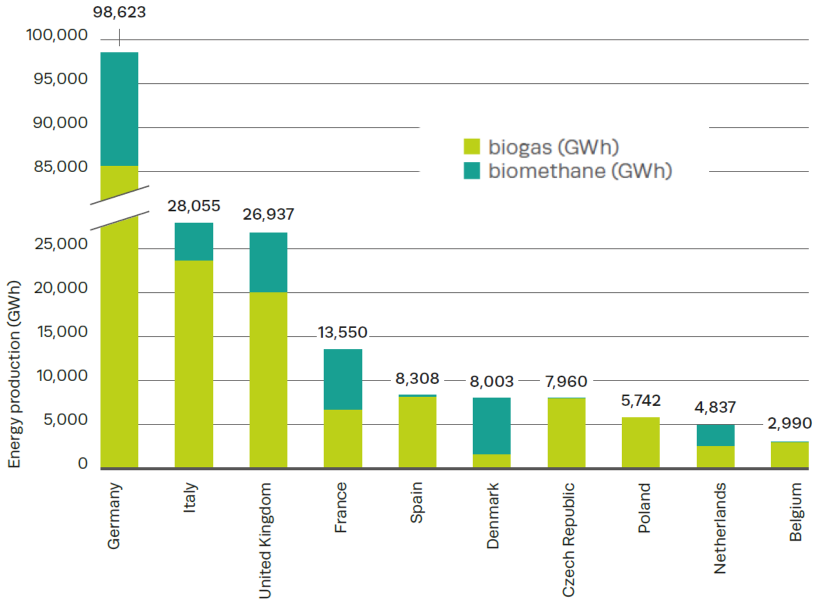


Source: (European Biogas Association, 2023)

Regarding the feedstock used for biogas production, the most impressive increase, from 0.9 billion Nm^3 biomethane equivalent in 2005 to 14.3 billion normal cubic meter (Nm^3) in 2020 comes from biogas from anaerobic fermentation of agriculture waste and residues, livestock manure, organic waste, food waste or other industrial residues. The production of biogas from landfill gas recovery or biogas from sewage gas increased slightly.

Looking at the distribution of biogas supply in different Member States, (Figure 14), and Germany was the leading Member State in 2022, accounting for about 53 % of EU biogas production 98623 GWh. Other Member States with a high biogas deployment are Italy, France, Spain and Denmark.

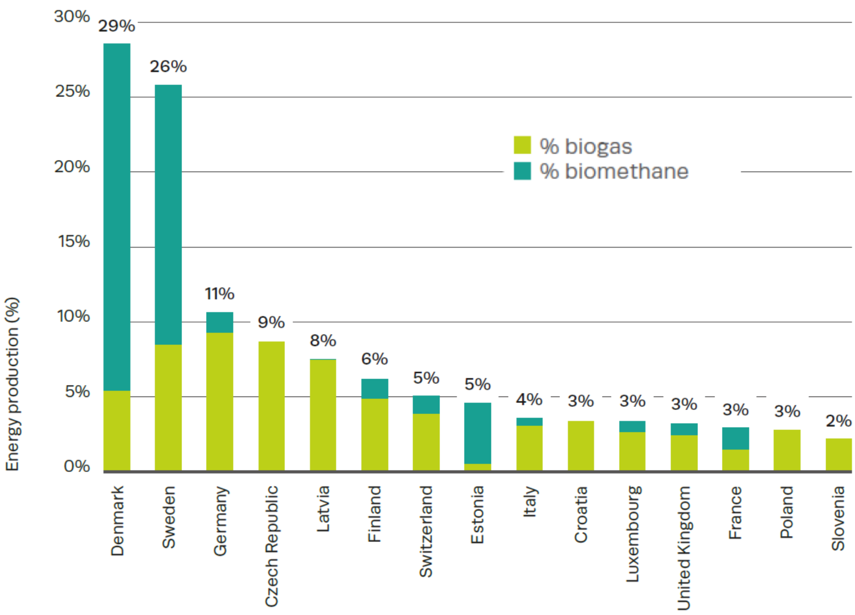
Figure 14. Biogas production in Europe in 2022



Source: (Eurostat, 2024; European Biogas Association, 2023)

Compared to the use of natural gas in different Member States, biogas has a significant contribution especially in Denmark (29 %), Sweden (26 %), and Germany (11 %). (Figure 15)

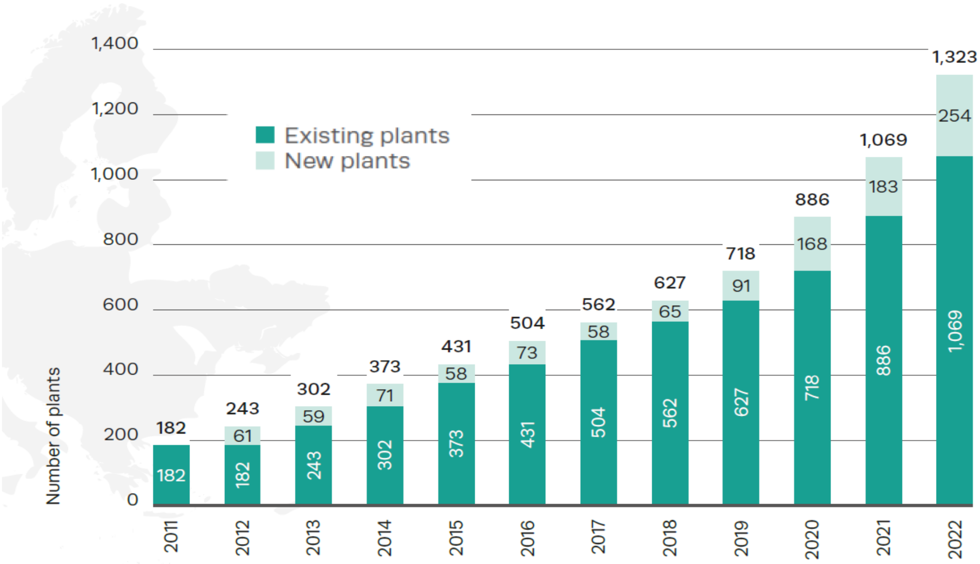
Figure 15. Share of Biomethane, Biogas production vs Natural Gas consumption in Europe, 2022



Source: (Eurostat, 2024; European Biogas Association, 2023)

The number of new biomethane added plants has increased rapidly since 2019, with 254 additions in 2022. (Figure 16).

Figure 16. Biomethane plants in Europe

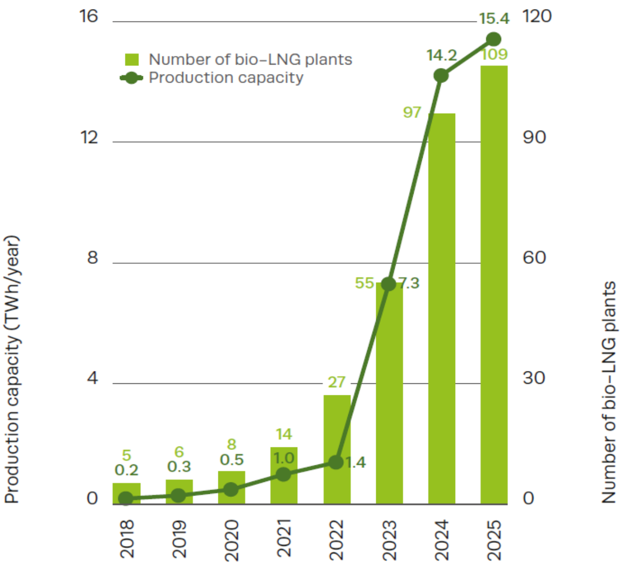


Source: EBA, (European Biogas Association, 2023)

Bio-LNG

According to EBA (European Biogas Association, 2023), there were 27 active Bio-LNG (bio- liquefied natural gas) plants active in Europe by the end of 2022, and this numbes increased sharply in 2023 (+ 28 plants) and is expected to also increase in 2024 (+ 47 plants) and 2025 (+ 11 plants), with production capacity starting at 1.4 TWh in 2022 and an estimated total production capacity of 15.4 TWh in 2025. (Figure 17)

Figure 17. Bio-LNG capacity in Europe

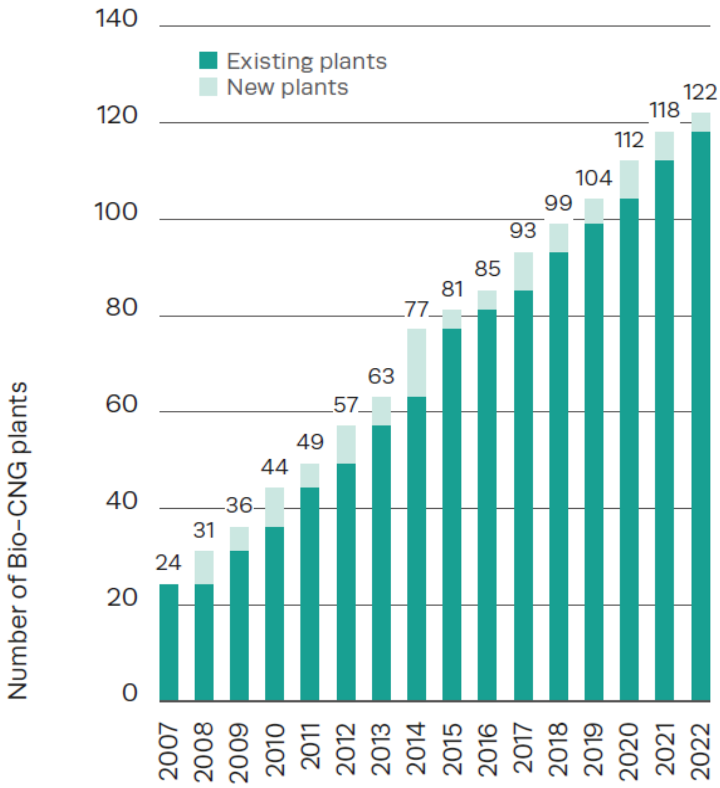


Source: (European Biogas Association, 2023)

Bio-CNG

(EBA,2023) reported that of the 1,222 biomethane plants active in Europe by the end of August 2022, 122 plants are known to compress biomethane on-site to produce Bio-CNG (Bio-Compressed Natural Gas), (Figure 18), this solution has a particular interest in countries with a less developed network Nat-Gas grid.

Figure 18. Number of Bio-CNG plants in Europe



Source: (European Biogas Association, 2023)

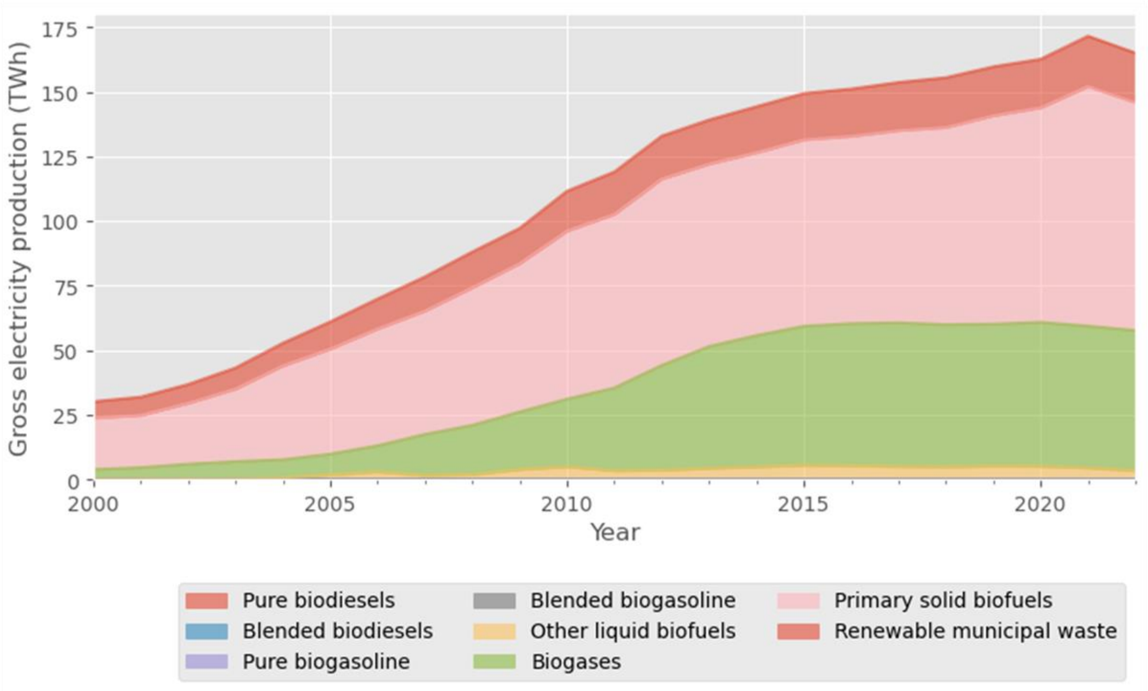
Bio-LNG and Bio-CNG refuelling stations were already in operation in Europe, in August 2022 the EBA report stated that there were 4,181 CNG filling stations and 576 LNG (liquefied natural gas) filling stations. The EU AFIR (Alternative Fuel Infrastructure Regulation) (European Union, 2023) states that, by 31 December 2024, Member States shall ensure that an appropriate number of publicly accessible refuelling points for liquefied methane are deployed, at least along the TEN-T core network in order to enable heavy-duty motor vehicles using liquefied methane to circulate in the EU, where there is demand, as long as the costs are disproportionate to the benefits, including environmental benefits.

Bio-Electricity

Bioelectricity production has increased significantly in the EU, from 30 TWh in 2000 to almost 175 TWh in 2021, before falling slightly to 166 TWh in 2022. The annual growth rate of bioelectricity production has been decreasing in recent years. Increasing from 41 TWh in 2005 to 93 TWh in 2021 and decreasing to 88 TWh in 2022, solid biomass is the main contributor to biomass electricity production, with a share falling from almost 66% in 2000 to just over 52 % in 2022, due to the strong growth of biogas electricity and the use of renewable waste. Significant progress has been made in biogas electricity from 8 TWh in 2005 to 54 TWh in 2022.

The share of biogas electricity increased significantly from 13 % in 2005 to 32 % of total biomass electricity production in 2022. Electricity production from municipal renewable waste also increased from 11 TWh in 2005 to 19 TWh in 2022, with a share decreasing from 17 % to 11 % in 2022 due to higher growth in electricity production from solid biomass and biogas. (Figure 19)

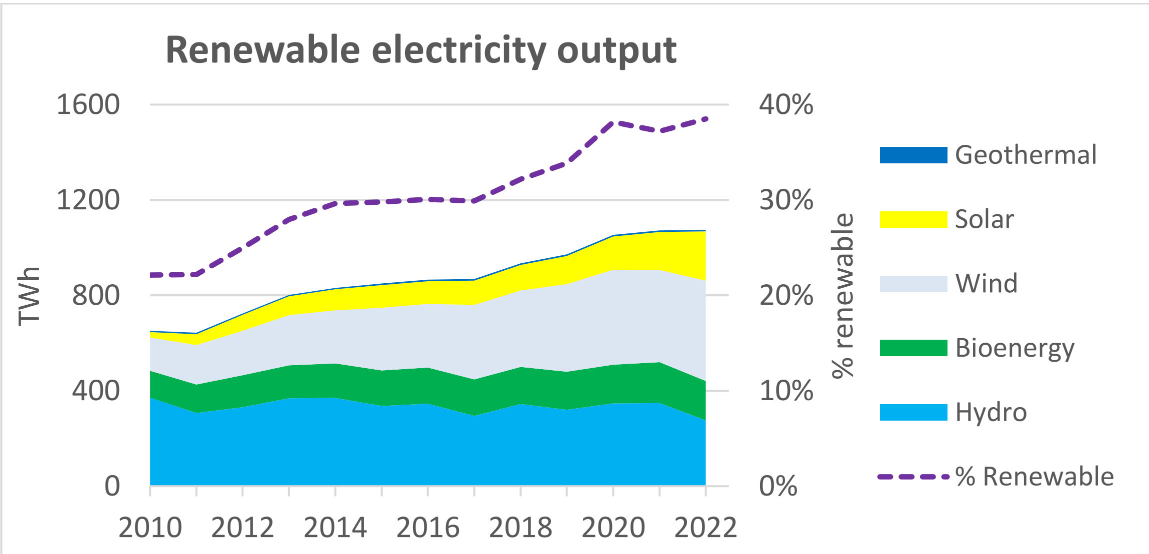
Figure 19. Evolution of bioelectricity production in the EU



Source: (Eurostat, 2024)

In connection with the increase in electricity production from renewables in the EU from 650 TWh in 2010 to 1162 TWh in 2022, the contribution of electricity from biomass decreased from 17 % to 15.6 % in the same period. (Figure 20)

Figure 20. Evolution of the production of electricity from biomass and all renewables in the EU



Source: (Eurostat, 2024)

Bioelectricity production looks very diverse in different Member States, see Figure 21. The leading countries in bioelectricity production in 2022 were Germany, followed by Italy, and Sweden. An important aspect is the high share of biogas in electricity production in Germany, with a share of 66 % of electricity from biomass and a significant share of biogas in electricity production of more than more than 40 % in Italy, while Sweden relies mostly on solid biomass. (Figure 21)

Figure 21. Leading EU Member States in bioelectricity production in 2022

Source: (Eurostat, 2024)

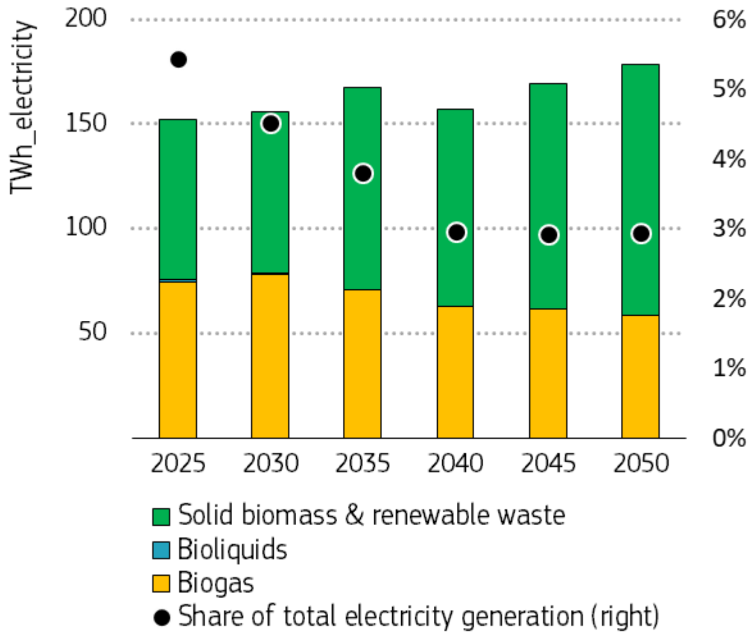
Within the CETO 2024 exercise, JRC employed the POTEnCIA model to develop the POTEnCIA CETO 2024 Scenario, a technology-oriented scenario exploring the potential role of clean energy technologies, including bioenergy for electricity generation and for centralised heat generation (e.g. in district heating (DH) networks), in achieving climate neutrality by 2050. A more detailed description of the POTEnCIA model and scenario is given in Annex 3."

This section reports the results of the *POTEnCIA CETO 2024 Scenario* for electricity generation from bioenergy in the EU, while the next section reports the results for centralised heat generation. The resulting use of bioenergy for electricity and centralised heat generation is the result of a direct competition with other alternative fuels and technologies, based on assumed techno-economic projections, to meet the overall GHG reduction target.

Figure 22 shows that the electricity generation from bio sources increases slightly in absolute numbers until 2050 while its relative share in total electricity generation decreases due to significant deployment of wind and PV capacities. In 2025, the generation from bio sources is covered approximately half by solid biomass and renewable waste and half by biogas (total 150 TWh), with a negligible contribution from bioliquids, which reduces to zero from 2030 onwards.

From 2030 to 2050, the contribution to electricity generation from solid biomass and renewable waste progressively increases while the contribution from biogas decreases, as it is progressively upgraded and used in other sectors in the form of biomethane. Electricity generation from bio sources accounts for 178 TWh in 205. In the *POTEnCIA CETO 2024 Scenario*, the importance of bioenergy with carbon capture and storage (BECCS) increases steadily towards 2050. Through BECCS applications (mainly CHP plants), the power sector reaches emissions net neutrality in the 2040s and becomes an emission net negative sector by 2050.

Figure 22. Electricity generation from bio sources in the EU (primary axis, stacked bars) and share in total electricity generation (secondary axis, black dots)



Source: POTEnCIA Model

The fate of electricity from bioenergy subsidies in the European Union is uncertain, as the EU's renewable energy policy has shifted towards a more market-based approach using bio-feedstock for sustainable biofuels production. Despite the EU's Renewable Energy Directive sets a target on renewables in the gross final energy consumption, it does not specify what should be the fraction covered by bioenergy. As a result, today the subsidised bioelectricity share ranges from 2% (France, Lithuania, Portugal, and Romania) to over 30% (Ireland, UK) in 2017, indicating the dominant role of support schemes for fostering the use of biomass in the power sector in these countries (Wu and Pfenninger, 2023). However, some countries have seen a sharp drop in supported share by around half in the studied period, such as Sweden, Portugal, and Estonia. The use of bioelectricity in the future will likely depend on the development of a clear and harmonised definition of "sustainable bioenergy" and the efficient allocation of scarce sustainable bioenergy. As reported in the “Assessment of progress towards the objectives of the Energy Union and Climate Action” (European Commission, 2023), reporting the National Energy and Climate Plans (NECP), each EU Member State will have different plans towards 2030 about the use of sustainable biomass for bioenergy (including both electricity and heat).

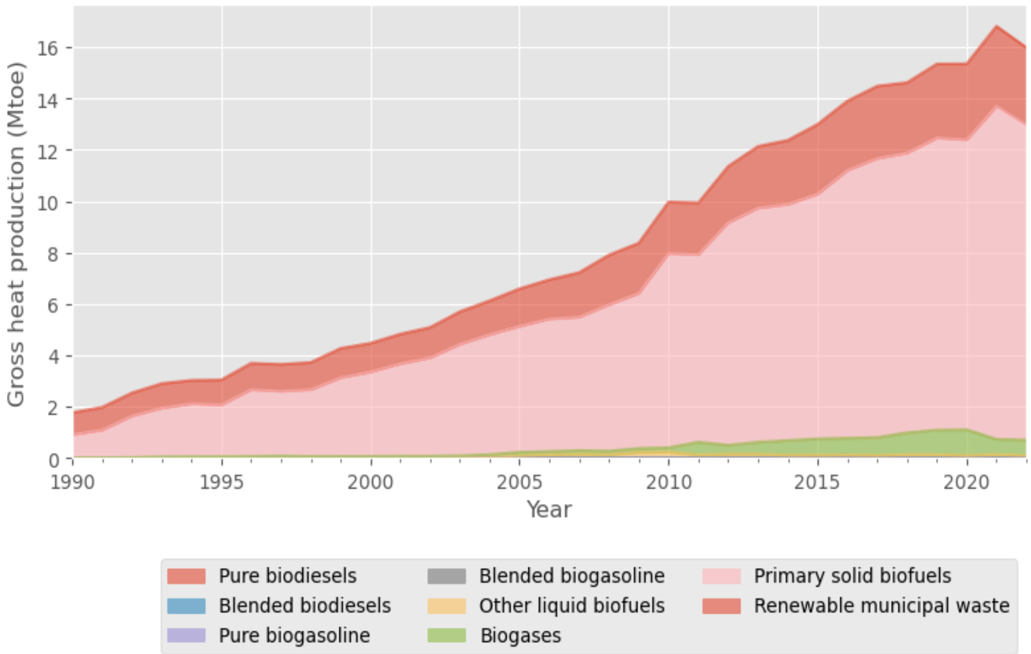
Bio-Heat

Biomass is the largest contributor to renewable direct heating and cooling. While heating produced from biomass grew from 6.2 Mtoe tomore than 16 Mtoe between 2005 and 2021, its share in heating from renewables fell slightly from 94 % in 2005 to 80 % in 2021 due to higher growth in other renewables. (Figure 23)

The main contributor of biomass in renewable heating sources is solid biomass (forest and agricultural residues, wood pellets and various waste, including municipal solid waste).

Although the use of solid biomass for heating increased, its share of biomass heating decreased from 87 % in 2005 to about 76 % in 2022. There has also been a good increase in the use of municipal renewable waste in connection with the use of waste in cogeneration power plants producing combined heat and power. A significant increase in relative terms came from the use of biogas from a contribution of 1 % in 2005 to 5 % in 2022. This is caused by the increasing use of waste heat in biogas plants enabling additional revenue streams, which is in many cases supported by EU measures to foster CHP biogas plants.

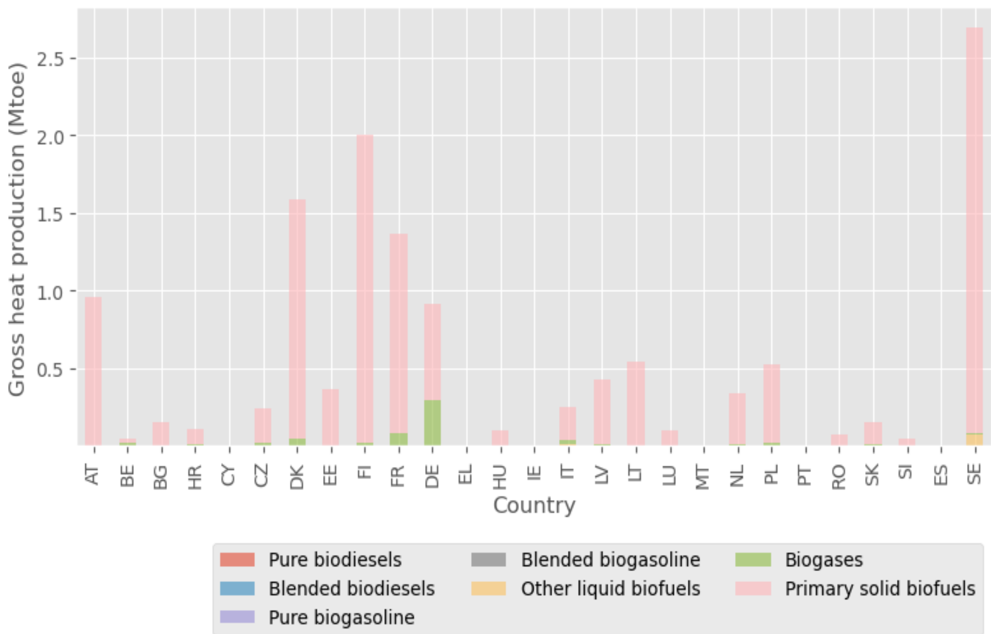
Figure 23. Evolution of gross heat production from biomass in the EU



Source: (Eurostat, 2024)

Figure 24 shows the leading Member States in gross heat biomass production in 2022. An evaluation of the data shows large differences between Member States with Sweden leading, followed by Finland and Denmark. Solid biomass is by far the dominant source for heating from renewables in most Member States.

Figure 24. Leading EU Member States in biomass gross heat production in 2022

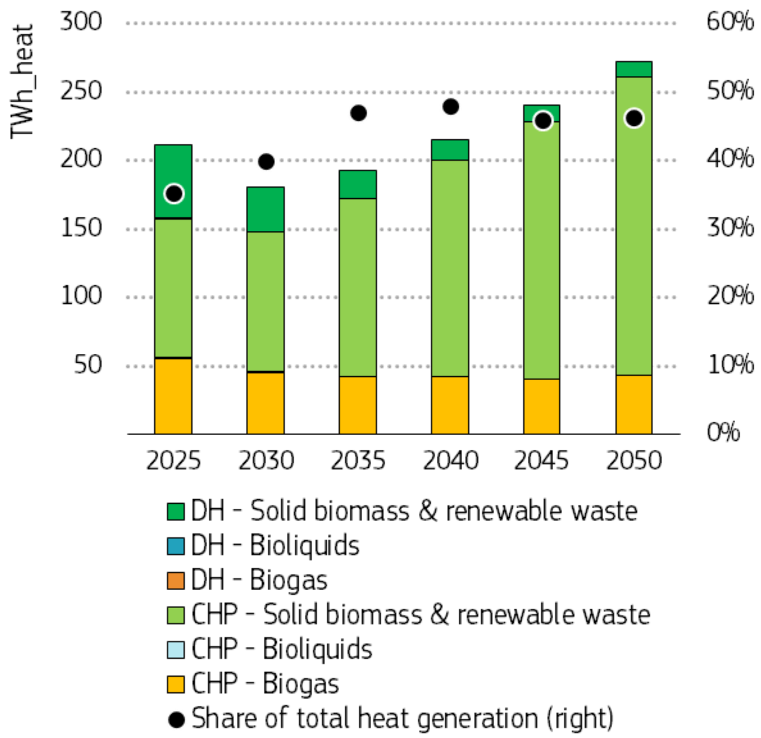


Source: (Eurostat, 2024)

Figure 25 shows the results from the *POTEnCIA CETO 2024 Scenario* for centralised heat generation from bioenergy for the EU up to 2050. Despite a slight decrease in the midterm, heat generation from bio sources increases from around 210 TWh in 2025 to 270 TWh in 2050.

The share of heat generation from bio sources in total generation increases over the years, starting from 35% in 2025 to then stabilize to around 46% after 2035. The generation is dominated by CHP plants using solid biomass and renewable waste (on an increasing trend) and biogas (on a slightly decreasing trend also due to competing uses in other sectors). A progressively decreasing contribution is provided by DH plants (large boilers) fueled with solid biomass and renewable waste.

Figure 25. Centralised heat generation from bio sources in the EU (primary axis, stacked bars) and share in total heat generation (secondary axis, black dots



Source: POTEnCIA Model

2.3 Technology Costs

The economic viability of bioenergy is highly sensitive to feedstock price, process configuration and plant size. While higher capacity plants are more economical, their maximum capacity is limited by the availability of feedstocks. The combined production of electricity and hear represents a good option for improving the overall efficiency of biogas plants, if the heat could be used locally or through heat distribution. The anaerobic digestion by-product, digestate (solid material remaining after the anaerobic digestion of a biodegradable feedstock), can be used as fertiliser, just like manure with the same nutrient content. This brings additional economic benefits by reducing the use of chemical fertilisers on farms, reducing nutrient runoff and preventing methane emissions.

Economics

The key to deploying bioenergy production is the availability and reliability of sustainable feedstock. Bioenergy production can be competitive under certain circumstances, especially when feedstock are available at low cost. Economies of scale are significant for biomass plants, although the overall size of biomass plants is limited by biomass availability, high biomass feedstock transportation costs and logistical issues.

The report “International financial corporation World Bank Group” provides the CAPEX, OPEX for bioenergy steam cycle, Organic Rankine Cycle (ORC) and biogas in relation to plant size. Table 6 shows the main data.

Table 6. CAPEX & OPEX Bioenergy technologies

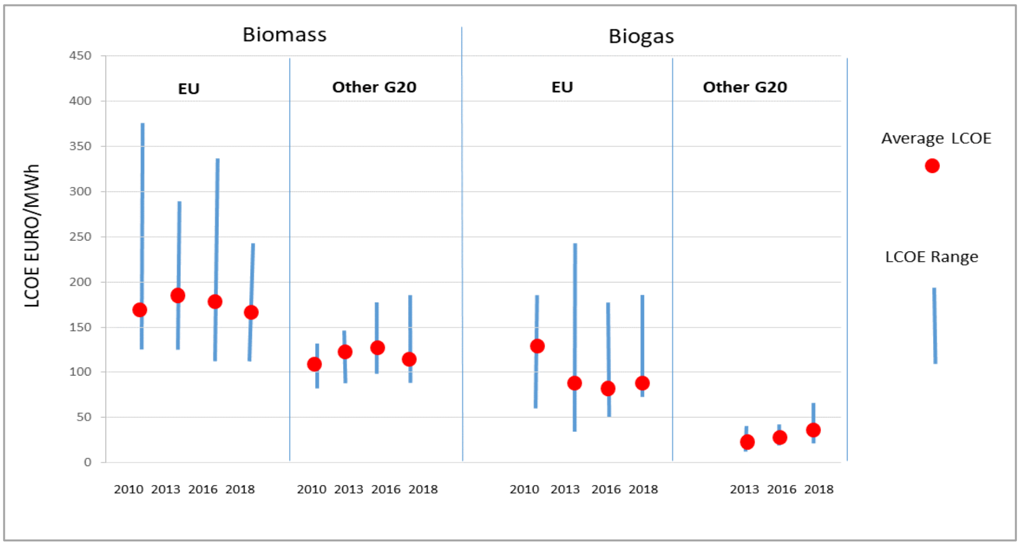
Typical Investment Costs (CAPEX) Bioenergy on a European Basis			
Plant Size (MWe)	Steam Cycle CAPEX (€/kW)	ORC CAPEX (€/kW)	Biogas CAPEX (€/kW)
1–5	3800–7000	2300–6000	2600–5000
5–10	3000–6000	1500–3800	n.a.
10–40	2300–4600	n.a.	n.a.

Typical Operation and Maintenance Costs (OPEX) Bioenergy on a European Basis			
Plant Technology	Plant Size (MWe)	OPEX Fixed Costs per Year (% of CAPEX)	OPEX Variable Costs (€/MWh)
Steam boiler and turbine	1–5 5–10 10–40	3–6% 3–6% 3–6%	2–5 2–2 2–5
ORC	1–5 5–10	2–3% 1.5–2%	3.5–7.5 3.5–7.50
Biogas	1–5 5–10	Included in variable costs	15–30

Source: International finance corporation World Bank group

According to the report EU EC Study on energy costs, taxes and the impact of government interventions on investments in the energy sector, the Levelised Cost Of Electricity (LCOE) of solid biomass-fired power plants (power plants that produce electricity and heat by burning biomass in a boiler) has fallen by 20% since 2008 to an average of €160/MWh (in 2018, LCOEs ranged between €108 - €225/MWh). This trend is due to the recent reduction in wood costs that started in 2014 and, more importantly, the reduction in CAPEX levels, which averaged €4,100/kW in 2008 and fell to €2,700/kW in 2018. With fuel costs around 30% lower than in the EU countries and the UK, non-EU G20 LCOEs ranged between €94-174/MWh in 2018. During this period, LCOE rates remained rather stable in most countries. (Figure 26)

Figure 26. LCOE on Bioelectricity from solid Biomass and Biogas

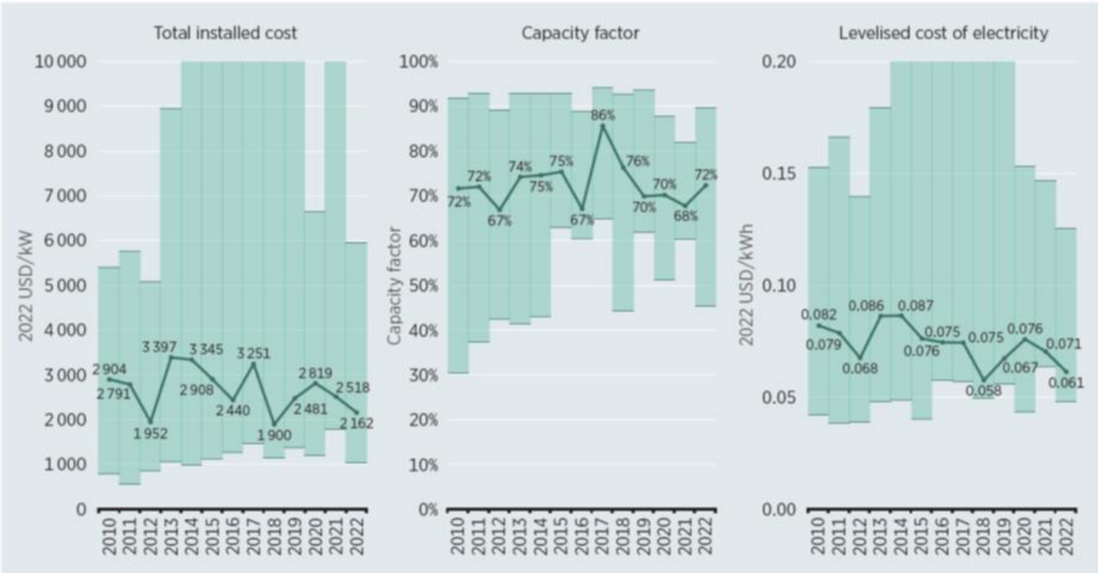


Source: DG Energy, Study on energy costs, taxes and the impact of government interventions on investments in the energy sector

In 2018, LCOEs for electricity from biogas-fired plants in the EU Member States ranged between €64-180/MWh. These rates are much higher than in other parts of the world, mainly due to the scale of the power plant projects. The EU data collection includes projects with installed capacities below 2 MW, registering CAPEX levels (in 2018) ranging from €1,700/kW to €15,000/kW (around €5,000/kW for most projects). Overall, costs have dropped by over 30% since 2008.

In a recent study, IRENA confirmed the wide range of variability at global level in terms of installation costs, capacity factor (ratio between the average generated power in a given period and the installed (rated) power) and estimated the LCOE for bioenergy production at an average of 61 USD/MWh (the latest reference year is 2022 and both criteria used together are feedstock typology and plant size, (Figure 27).

Figure 27. Global Bioenergy capacity factors and costs 2022



Source: (IRENA, 2023)

The projected CAPEX and OPEX costs of bioenergy in the EU Reference Scenario[1] are summarised in Table 7.

Table 7. Bioenergy technologies CAPEX and OPEX

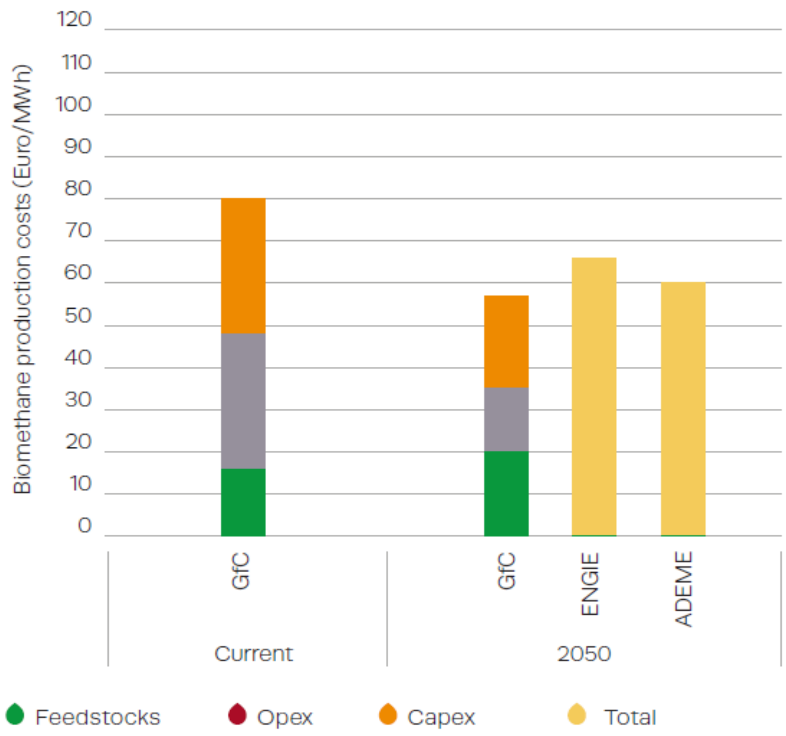
	Overnight Investment Costs in a greenfield site, excluding financial costs during construction time				Fixed Operation and Maintenance costs, annually			
	EUR/kW				EUR/kW			
Technology	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Steam turbine biomass solid conventional	2000	1800	1700	1700	47.5	40.1	39.2	38.4
Steam turbine biomass solid conventional w. CCS	4050	3675	3305	3205	81.5	69.1	63.0	61.4
Biogas plant with heat recovery	500	465	458	450	28.8	24.3	23.8	23.3
Small waste burning plant	1650	1615	1608	1600	52.3	44.5	41.8	39.2
Biomass gasification CC	2650	2405	2353	2300	27.1	22.9	22.4	21.9

Source: EC Scenario

[1] The EU Reference Scenario (*DG Energy, Study on energy costs, taxes and the impact of government interventions on investments in the energy sector*) is one of the European Commission's key analysis tools in the areas of energy, transport and climate action;

According to EBA 2023 report, the current cost of biomethane production is estimated at an average of around 80 €/MWh. This includes feedstock costs (16 €/MWh), CAPEX (32 €/MWh) and OPEX (32 €/MWh). When biomethane is produced, it must be injected into the gas grid at an estimated cost of about 5% of the cost of biomethane production (3 – 4 €/MWh). Alternatively, liquefaction has an average estimated cost of around 12 €/MWh. (Figure 28)

Figure 28. Biomethane production cost in Europe. Current (2022) and expected in 2050



Source: (European Biogas Association, 2023)

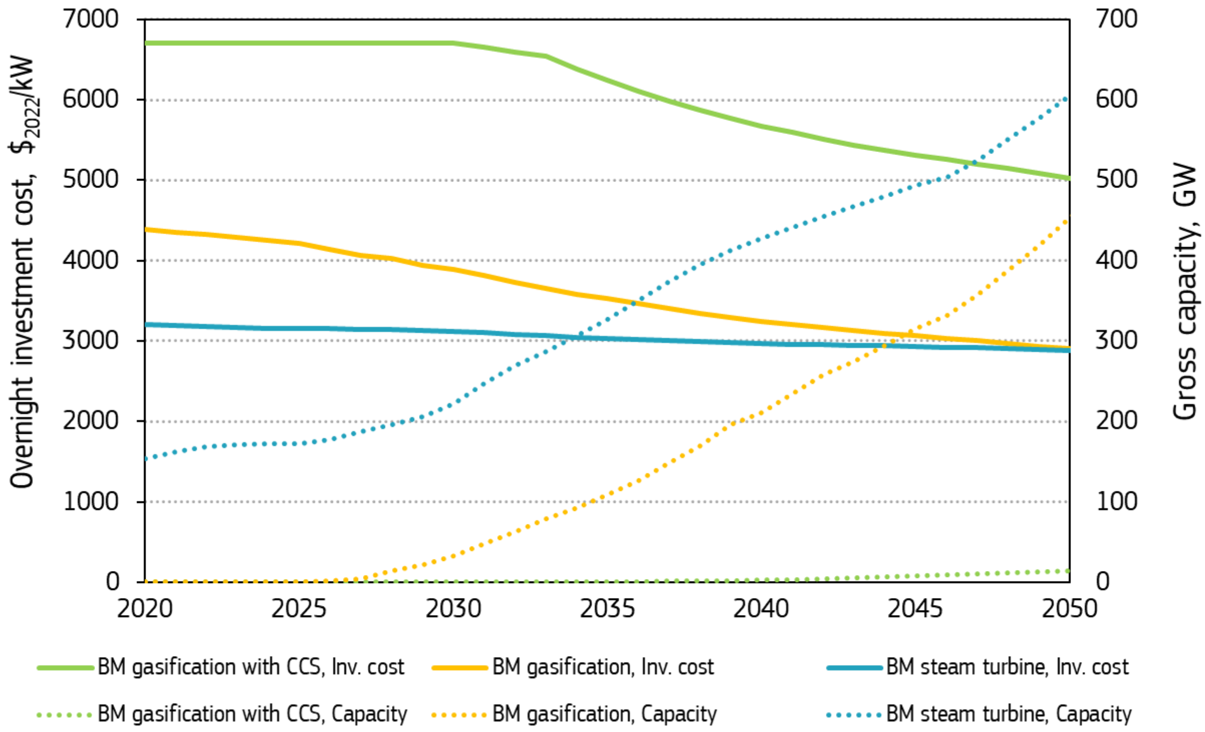
The Global CETO 2°C scenario based on the POLES-JRC model (details available in Annex 3) envisages a future where concerted efforts to limit global temperature increase to 2°C yield transformative impacts on the production and economic viability of clean energy technologies.

Figure 29 shows the development of global generation capacities and overnight investment cost per kW until 2050 for biomass (BM) powered steam turbine (fully commercial technology) and biomass gasification with and without CCS (both emerging technology) projected by the Global CETO 2°C scenario.

While the capacities for biomasss powered steam turbine increase substantially over the coming decades (600 GW by 2050), their investment costs rather stagnate due to the maturity of the technology. Conversely, for biomass gasification technologies, investment costs decrease significantly as endogenous learning for this emerging technology has a considerable impact.

This reduction in cost facilitates the expansion of the biomass gasification capacities, reaching about 450 GW of installed capacity in 2050. However, CCS biomass gasification does not experience significant growth due to the discouragingly high investment cost.

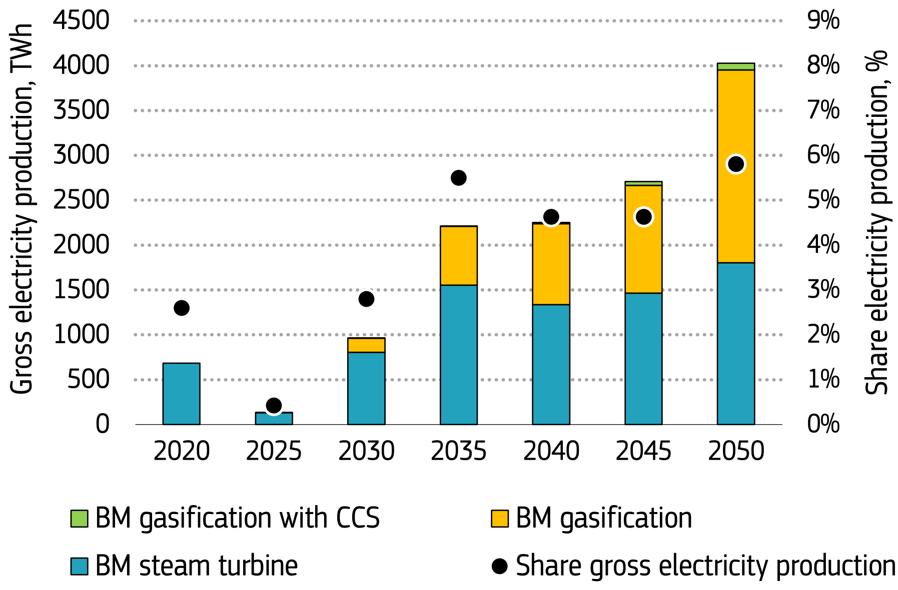
Figure 29. Global production capacity and overnight investment cost for biomass (BM) power generation technologies



Source: JRC-POLES model

As illustrated in Figure 30, biomass power generation increases in the coming decades and accounts in 2050 for about 6% of global electricity production according to the Global CETO 2°C scenario 2024. Most of the biomass power generation by 2050 (about 4000 TWh) is produced by biomass gasification without CCS followed closely by electricity produced with biomass powered steam turbine plants.

Figure 30. Global electricity production and share in total electricity production for biomass (BM) power generation technologies



Source: POTENnCIA Model

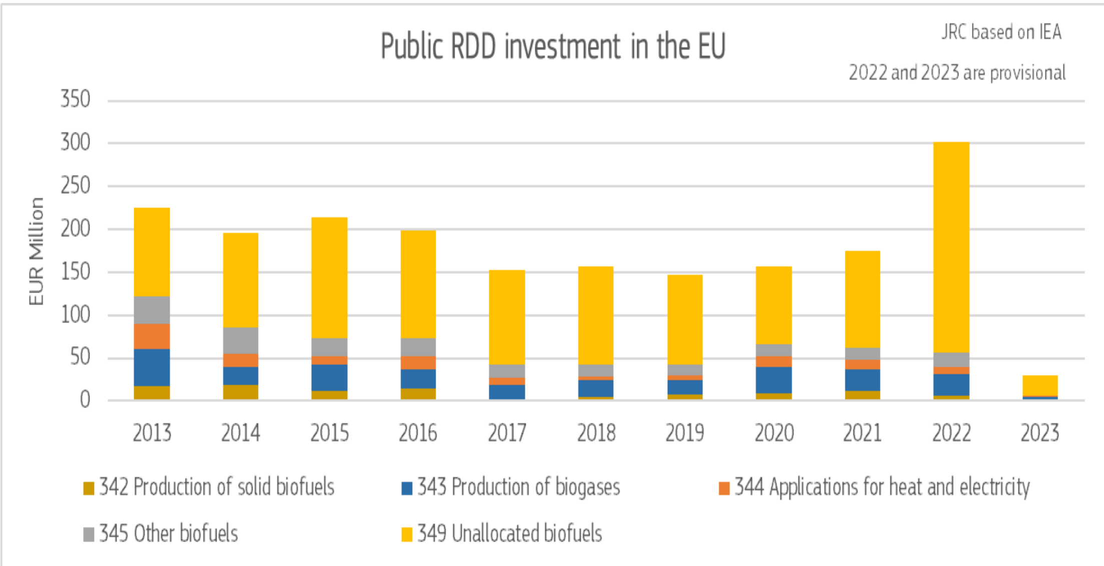
In the last years, several institutions provided estimates on what will be the scenario of bioenergy towards 2030 and beyond. For instance, IEA Net Zero scenario for 2050 (IEA, 2021) considers in large part the contribution of bioenergy to decarbonize various sectors. They reported that 40% of bioenergy used today is for the traditional use of biomass in cooking, which will be rapidly phased out in their scenarios. Modern forms of solid biomass, which can be used to reduce emissions in both the electricity and industry sectors, will rise from 32 EJ in 2020 to 55 EJ in 2030 and 75 EJ in 2050, offsetting a large portion of a drop in coal demand.

The specific share of bioenergy on each country's in the World energy mix will depend on the level of poverty, resources availability, economic development and decarbonization targets. Bioenergy will remain a fundamental source of energy for specific applications such, as remote areas, where other renewables are not available. While other renewables will be essential for achieving climate neutrality, especially in hard-to-abate sectors, bioenergy remains part of a broader set of solutions that include decentralized district heating, private heating in remote areas, etc. Moreover, it will be challenging to evaluate the availability and price of biomass, biowastes and bioresidues for bioenergy production considering the dynamic market uptake of advanced biofuels. The transition to the sustainable use of biomass for bioenergy will require coordinated effort among national governments and companies.

2.4 Public RD&D Funding and Investment

Based on the codification of the IEA (IEA, 2024) Energy Technology RDD (Research, Development and Demonstration) budget from codes 342 to 345 and 349, the Joint Research Centre of the European Commission found that public RDD investments in solid biofuels and biogas averaged around €50 million per year from 2020 to 2021. The main share of investment, which reached a peak of €300 million in 2022, is referred to unallocated biofuels. Unallocated biofuels refer to techniques, processes, equipment and systems related to biofuels that cannot be allocated to one specific area of category 34 and where it is not possible to estimate the split between two or more of the sub-categories. Total investment is showed in Figure 31

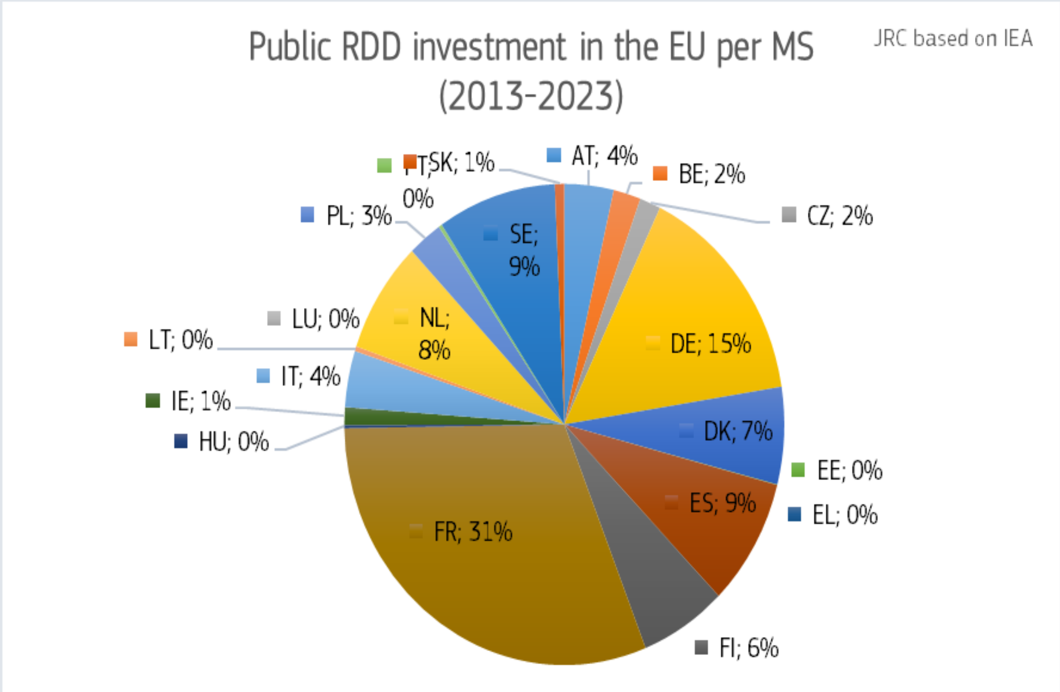
Figure 31. Investments in public RDD Biomass projects



Source: JRC elaboration on IEA

From 2013 to 2023, on bioenergy projects, France received 31% of RDD funding followed by Germany with 15%. (Figure 32)

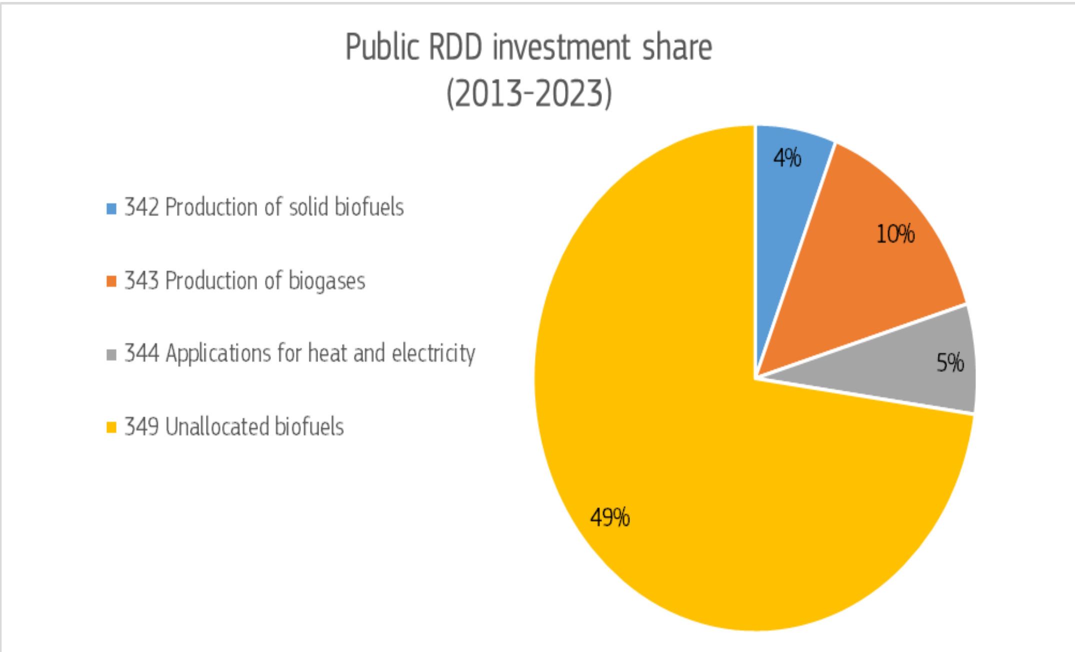
Figure 32. Share of RDD funding received by EU Member States for Bioenergy projects



Source: JRC elaboration

As for the share of financed projects in the field of bioenergy, 49 % are unallocated biofuels. Biogas makes up 10% of total share. (Figure 33)

Figure 33. Share of RDD Bioenergy projects (2013-2023)

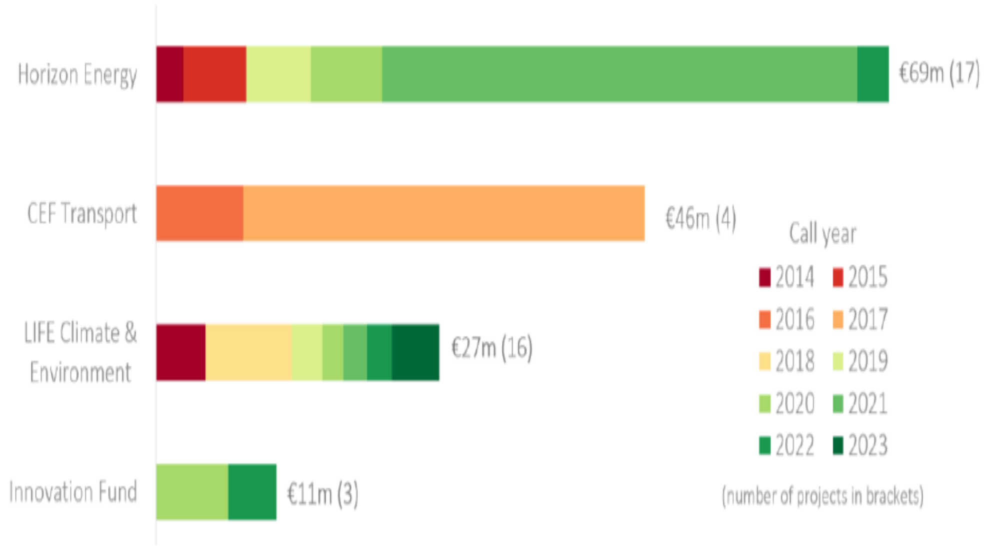


Source: JRC elaboration on IEA

Regarding Biomethane, see Figure 34, there are 40 completed and ongoing actions managed by CINEA (European Climate Infrastructure and Environment Executive Agency, 2024) supporting the sector by using the following funds:

- Horizon energy (17): 9 ongoing and 8 completed (2 RIAs, 4 IAs, 11 CSAs)
- LIFE (16): 10 ongoing and 6 completed (8 LIFE Climate, 8 LIFE Environment)
- CEF-Transport3 (4): 2 ongoing and 2 completed
- Innovation Fund: 3 ongoing (Small-scale)

Figure 34. Public R&I EU on Biomethane



Source: CINEA Report

The portfolio includes 40 projects involving 191 individual participations from 36 countries. The participation of the private sector is significant, receiving 83% of the funding, while public entities receive 17%.

2.5 Private RD&I Funding

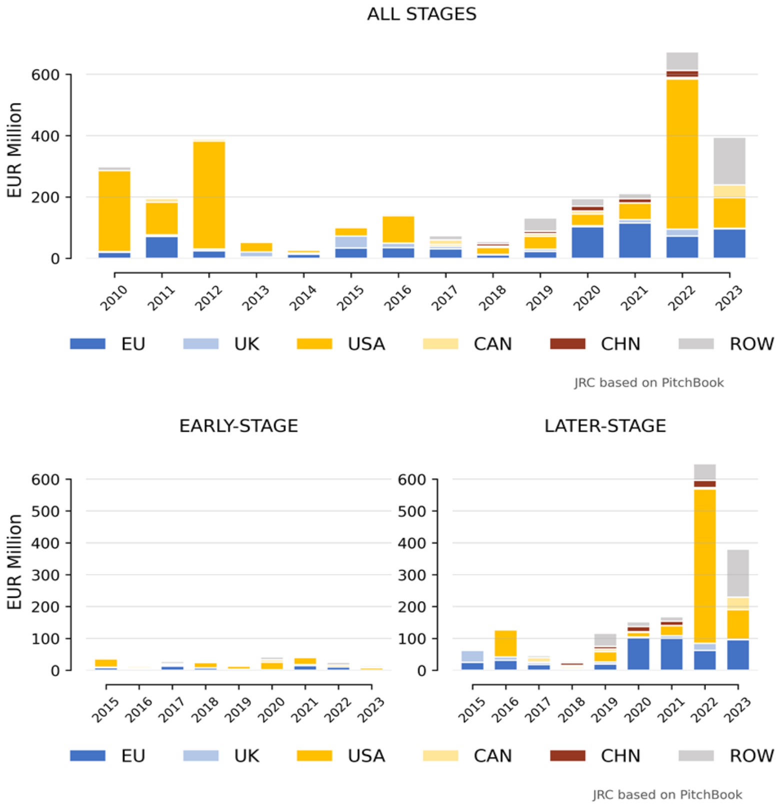
Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. Early and late stage indicators that aggregate different types of equity investments in selected companies and at different stages of their growth journey. We only include pre-venture capital companies (that have received Angel or Seed funding, or are less than 2 years old and have not received funding) and venture capital companies (companies that have been part of a venture capital's portfolio at some point)

Investments reflect investments in all active companies in a given period, regardless of their current status (defunct, publicly held, privately held with VC backing, merged or acquired, no longer actively tracked in the data source. Early stage investments include: Grants, Angel & Seed (i.e., Pre-Seed, accelerator/Incubator, Angel and Seed) and Early stage VC. Later stage investments include: Late Stage VC (and undisclosed series), Small M&A and Growth Private Equity. Small M&A refers to the acquisition by an operating company of a non-control stake in a pre-venture or VC company. Investments in later stages do not include: buyout Private Equity and public investment.

Those selections include all identified companies for each technology, regardless of their current operational status or whether they have relevant investments or patent activities in the current period. For example, VC companies may e.g., currently be start-ups, may have been start-ups or larger SMEs that grew into larger private companies, went public or were acquired by larger companies. They may also currently be out of business.

After nearly quadrupling in 2022 compared to the previous year, global VC investment in bioenergy firms reached an all-time high of €752.1 million, before falling to less than € 400 million in 2023. Consequently, global VC investment in the period 2018-2023 exceeded € 1.60 billion, surpassing the investment made during the previous 6-year period (2012-2017) for the first time. (Figure 35)

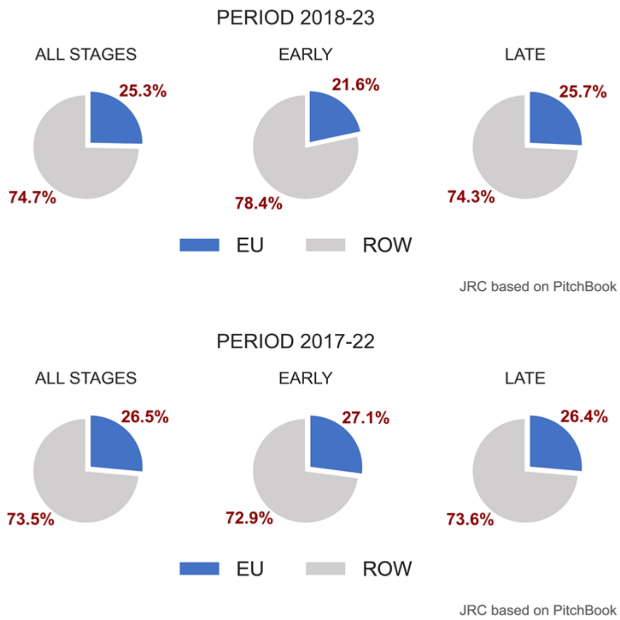
Figure 35. Venture Capitalist investment in Bioenergy, the EU vs Rest of the world (RoW)



Source: JRC elaboration

The EU number of deals accounts for just over one quarter of global VC investment in the period 2018-23. (Figure 36)

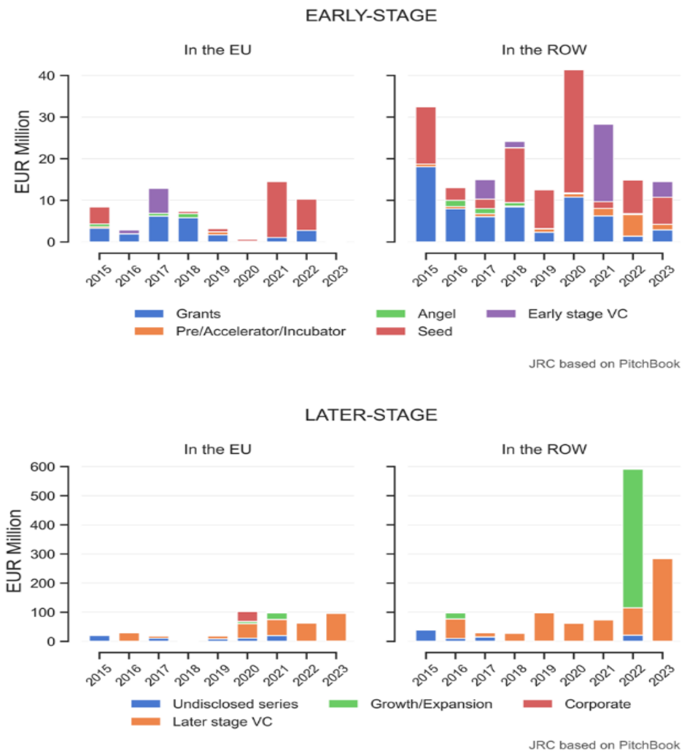
Figure 36. Venture Capital investment share EU vs Rest of the world (RoW), number of deals 2018-2023



Source: JRC elaboration

Grants and seed were the most financed mode use for the early stage in the EU as of 2021, while later stage VC predominates in both the EU and the US, with the exception of large growth/expansion investments made in the US in 2022. (Figure 37)

Figure 37. Venture Capital investment by stages and regions



Source: JRC elaboration

2.6 Patenting trends

To assess the technical progress achieved in the field of bioenergy technologies, the analysis focused on the world distribution of patent filings for the period 2009 to 2020 extracted from the PATSTAT database. In order to estimate the share of total inventions, a fractional count should be adopted, where inventions designated by more than one code contribute the equal fraction to all included codes (classes).

Biomass-related patents for the heat and power sector and biogas are identified using the relevant code families of the Cooperative Patent Classification (CPC), for technologies or applications for climate change mitigation or adaptation, reduction of greenhouse gases emissions related to energy production, transmission or distribution. The Y codes are designed to facilitate the identification of inventions related to renewable energy and climate mitigation technologies. Within this classification is a set of technical classes of inventions that may be related to biomass technologies, patent families code Y02E related to the energy production, transmission or distribution, and code Y02E 50, which includes CPC classes referred to as ‘technologies for the production of fuel of non-fossil origin’. Y02E 50/30 ‘fuel from waste’ where they intersect with C12M 21/04 ‘digester from manure’ or C12P 7/10 ‘bioreactors’.

The classes included in this analysis often refer to “biofuels”, but this does not mean biofuels for transport, but actually biomass fuels as bioenergy carriers. This could overlap with biofuels for transport, but it is not possible to distinguish between the end uses of these products, as for example pyrolysis products or methane from anaerobic digestion may have different uses in transport or heat and power production. The relevant patents are grouped into the following patent classes:

CPC: Y02E 50/30 ‘Fuel from waste’

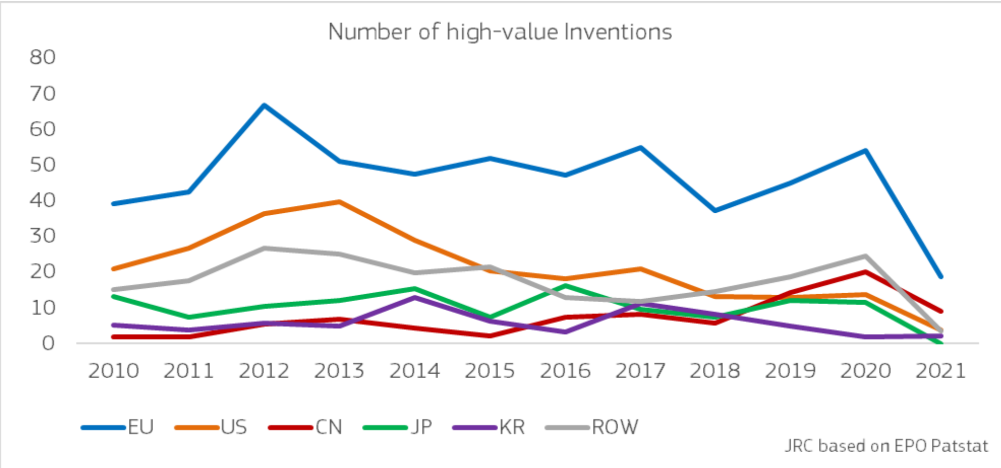
Intersection with:

C12M21/04 'digesters for manure'

C12M21/00 'bioreactor or fermenters'

In order to achieve a representative classification, the three patent categories have been grouped with the following terminology. Patent families (or inventions) measure the inventive activity. Patent families include all documents related to a particular invention (e.g., applications to multiple authorities), thus preventing multiple counting. Each applicant and relevant technology is assigned a family fraction. High-value inventions (or high-value patent families) refer to patent families that include patent applications filed with more than one patent office. Granted patent families represent the share of granted applications in one family. The share is then linked to the fractional counts in the family. From 2010 to 2021, the EU maintained leading position in high-value inventions with 40 to 70 patents per year, (Figure 38)

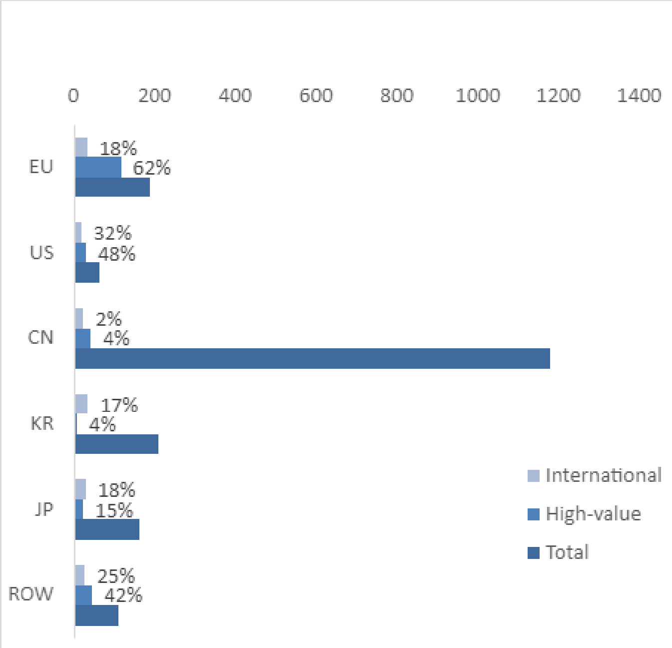
Figure 38. Bioenergy and Biogas Number of High Value Inventions



Source: JRC elaboration

Over the triennium from 2019 the 2021, the EU had a 62% share of high-value patents out of an EU total of 190 patents applications, while China applied for a total 1,179 patents with only 44 high-value patents. (Figure 39)

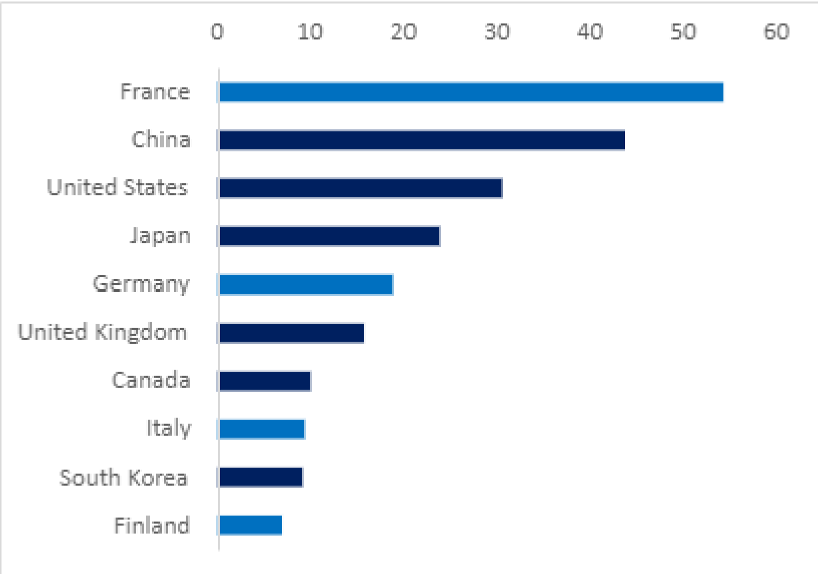
Figure 39. Number of invention and share 2019-2021



Source: JRC elaboration

For the 2019-2021 triennium, at country level, the leading EU Member States were France and Germany with 54 and 19 high-value patents, respectively. (Figure 40)

Figure 40. Bioenergy High Value Inventions top 10



Source: JRC elaboration

French company Lair Liquide leads the world's top 10 entities for 2019-2021 with 13 high-value inventions, as reported in Table 8.

Table 8. High Value Inventions top 10 entities

High-value inventions - Global Top 10 entities (2019-2021)	
Row Labels	High-value
Lair Liquide Societe Anonyme Pour Letude Et Lexploitation Des Procedes Georges Claude (FR)	13
Mitsubishi Heavy Industries Ltd (JP)	5
Suez Groupe (FR)	4
Velocys Technologies Ltd (UK)	4
Valmet Oy (FI)	3
Indian Oil Corporation Limited (IN)	2
Ecogensus Llc (US)	2
Abundia Biomass To Liquids Limited (UK)	2
Eastman Chemical Company (US)	2
Planet Biogas Group Gmbh (DE)	2

Source: JRC elaboration

Granted inventions fell in the 2019-2021 triennium from a total of 23 in 2019 to 8.1 in 2021, with China leading the category with a share of 40% in 2019 and 86% in 2021, (Table 9).

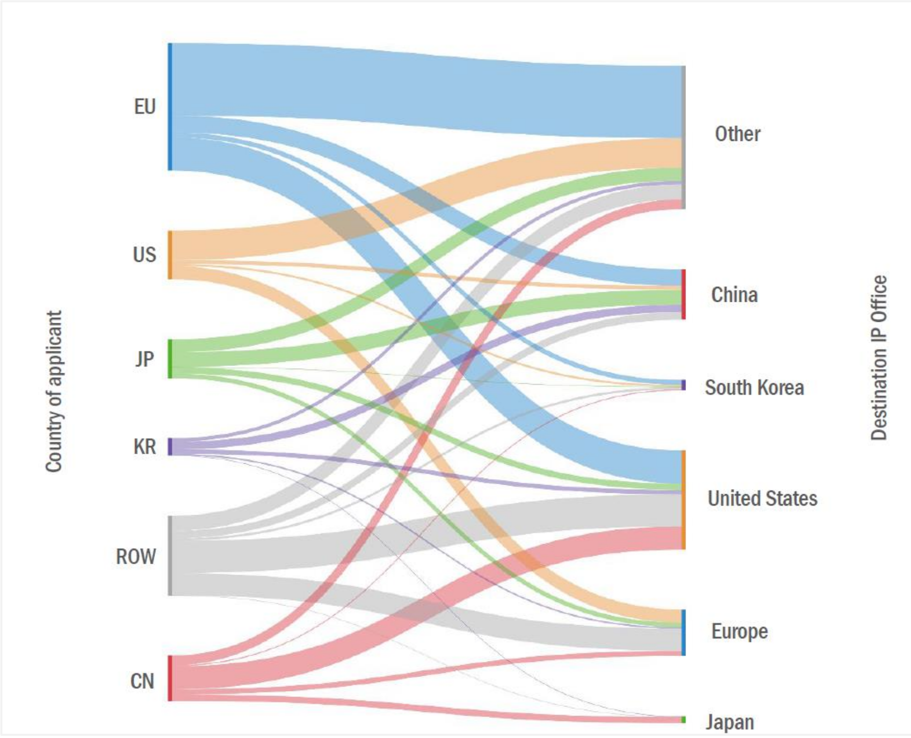
Table 9. Inventions granted

World_player	2019	2020	2021
EU (European Union)	4.9	5.7	0.0
CN (China)	9.1	18.9	7.0
JP (Japan)		0.0	
KR (South Korea)	6.8	2.0	0.1
US (United States)	1.0	0.0	0.0
ROW (Rest of world)	1.2	0.2	1.0
	23	26.8	8.1

Source: JRC elaboration

The flow of inventions (or destination of patent families) indicates where (in which national patent office) the inventions are filed. This can be used to analyse the international flow of inventions, the directional streams between geographical areas, when considering the cumulative number of inventions from 2019 to 2021, it can be observed that EU inventions flowed mainly to other countries, the US and China. The total stream flow is shown in Figure 41.

Figure 41. Total Inventions stream from 2019-2021



Source: JRC elaboration

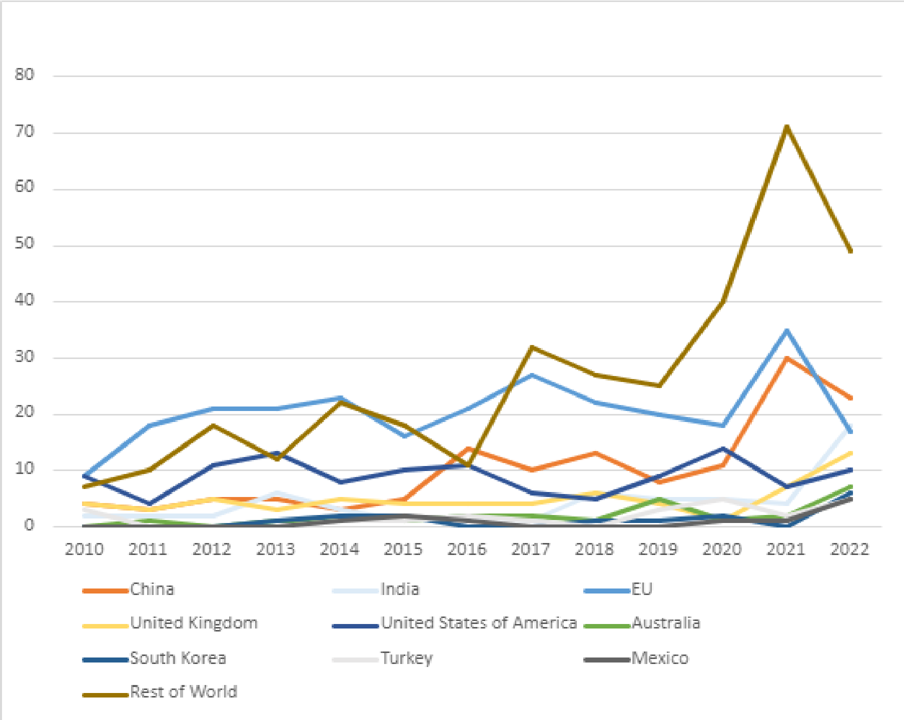
2.7 Scientific publication trends

The analysis on bibliometric trends of scientific publications was carried out by the JRC TIM based on the Scopus database. Two main categories of publications were considered for the Bioenergy Heat & Power, namely feedstock and processes.

The strings used to retrieve the biomass feedstock consisted of algae; waste; straw; animal manure; sewage sludge; forestry residues; wood residue; wood pellet; forestry waste; used cooking oil; animal fat; organic waste; black liquor; sawdust. These strings were linked to the following sectors: biomass heat production; biomass power production. A total of 675 articles (2010-2022) were obtained for the biomass feedstock for Heat & Power.

The strings used to retrieve biomass processes were: biomass heat production; biomass power production;; biomass CHP production; biomass pelletisation; torrefaction; pyrolysis; briquetting; wood chipping; anaerobic digestion; biogas upgrading; boilers; stoves; hydrothermal processing; fluidised bed combustion; fluidized bed combustion. In terms of scientific publications on biomass feedstocks for Heat & Power, the “Rest of the World” has been leading in recent years, reaching 70 publications in 2021, with the EU leading the way with an average of around 20 articles per year since 2012, parallel to China with 30 articles in 2021. (Figure 42)

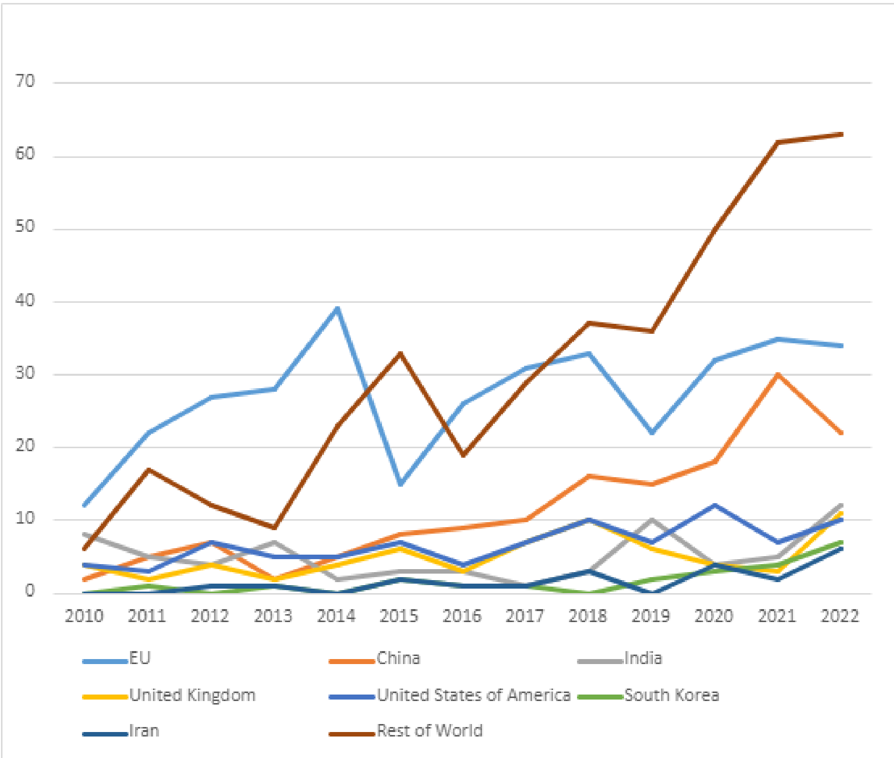
Figure 42. Scientific publication Biomass Feedstock, 2000-2022



Source: JRC elaboration

For Biomass Heat & Power processes, a total of 1122 articles (2010-2022) were retrieved The EU led the ranking until 2017, after which the EU remained second to "Rest of the World" with more than 30 publications in 2022. (Figure 43)

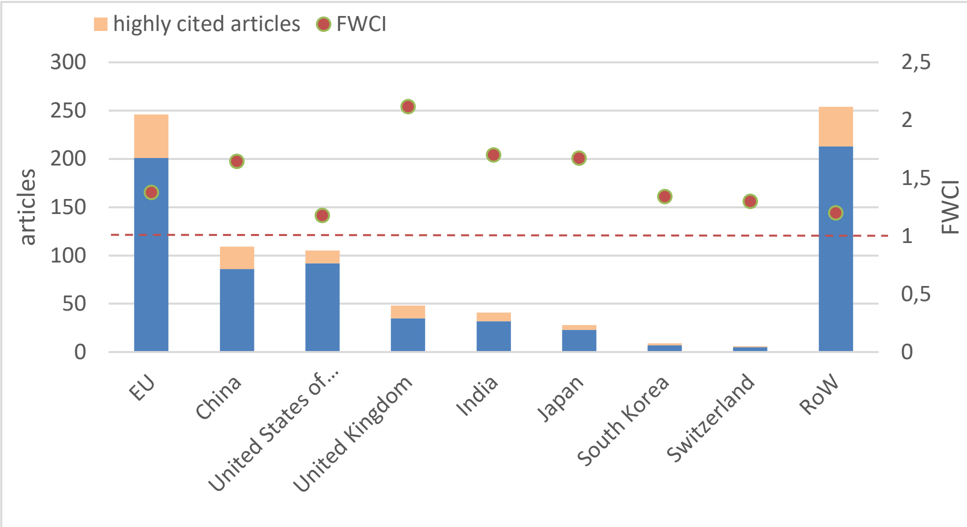
Figure 43. Scientific publication Biomass Processes, 2010-2022



Source: JRC elaboration

In terms of citations of scientific articles on biomass feedstock, in 2012-2022 the EU has 42 highly cited papers, with Field Weighted Citation Impact (FWCI) of 1.3 above dashed line representing FWCI 1. (Figure 44).

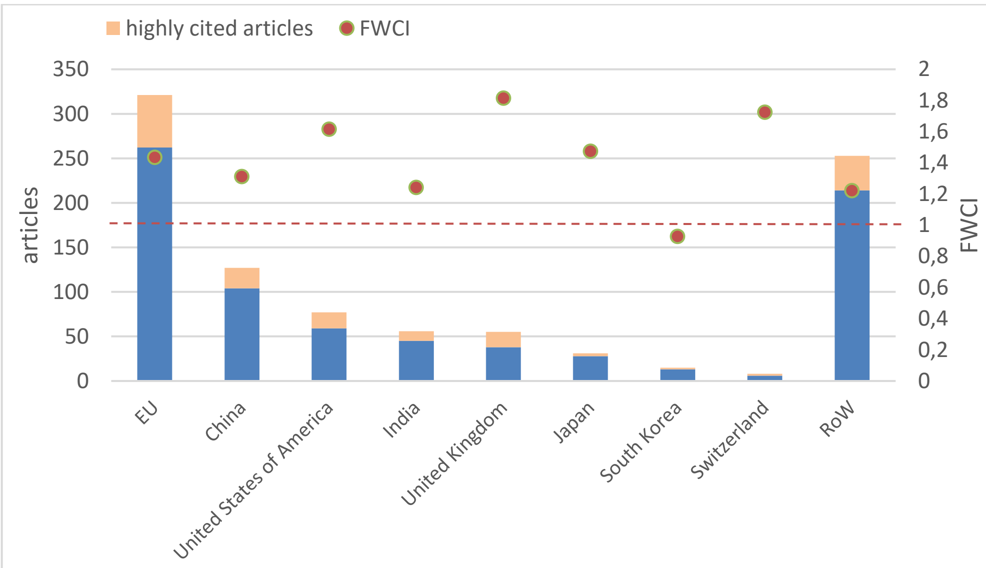
Figure 44. Highly cited scientific publication Biomass feedstock, 2012-2022



Source: JRC elaboration

In terms of scientific articles citations on biomass processes, in 2012-2022 the EU has 45 highly cited papers, Field Weighted Citation Impact at 1.4, above dashed line representing FWCI 1. (Figure 45)

Figure 45. Highly cited scientific publication Biomass processes, 2012-2022



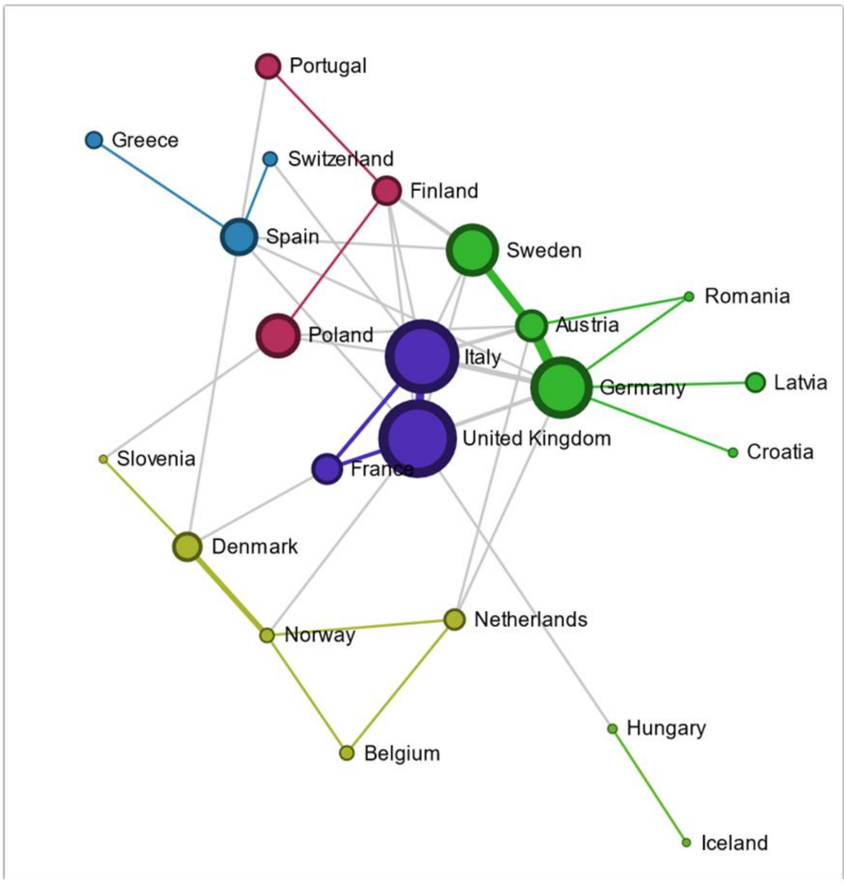
Source: JRC elaboration

Looking at the collaboration network related to Biomass Heat & Power scientific publications from 2010 to 2022, we can see a strong relationship between the EU and the "Rest of the World" (ROW). (Figure 46). At the EU level, the biomass collaboration network, from 2010 to 2022 related to Biomass Heat & Power scientific publications, sees strong links between Italy and the UK, and between Germany, Sweden and Austria. (Figure 47)

Figure 46. Collaboration network scientific publication Biomass H&P worldwide, 2010-2022

Source: JRC elaboration

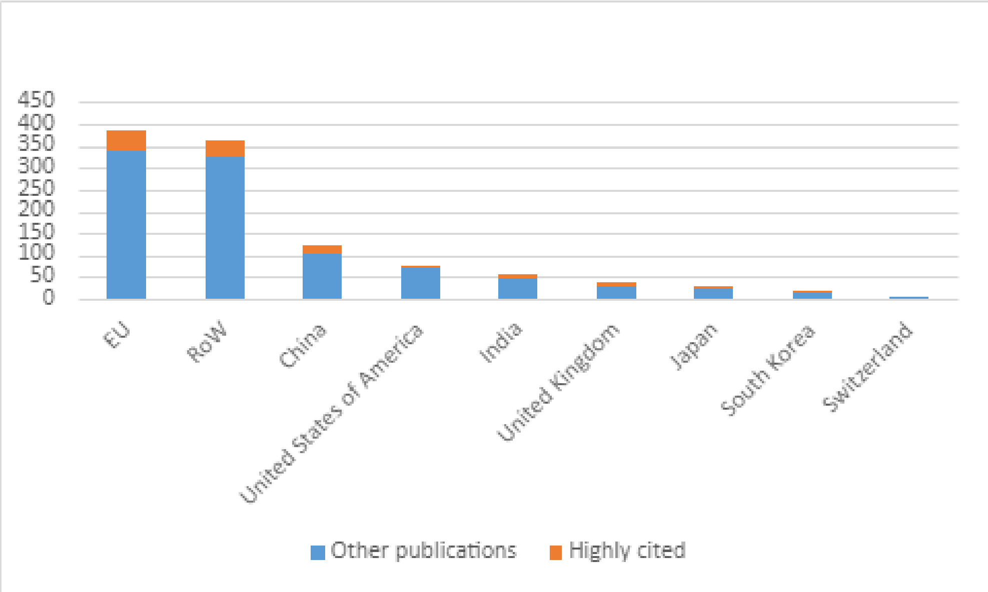
Figure 47. Collaboration network scientific publication Biomass H&P in Europe, 2010-2022



Source: JRC elaboration

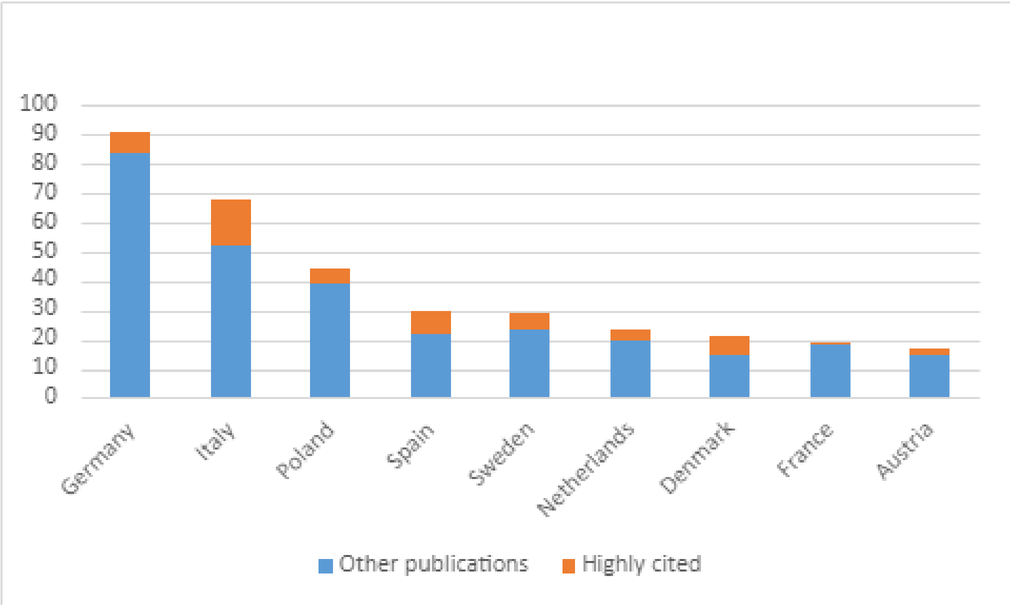
Globally, the EU leads in scientific publications on biogas with 385 articles, of which 47 were highly cited, in the period 2010-2022. (Figure 48). At the EU level, Germany produced 91 scientific papers on biogas in the period 2010-2022, 7 were highly cited. (Figure 49)

Figure 48. Scientific publication on Biogas, 2010-2022



Source: JRC elaboration

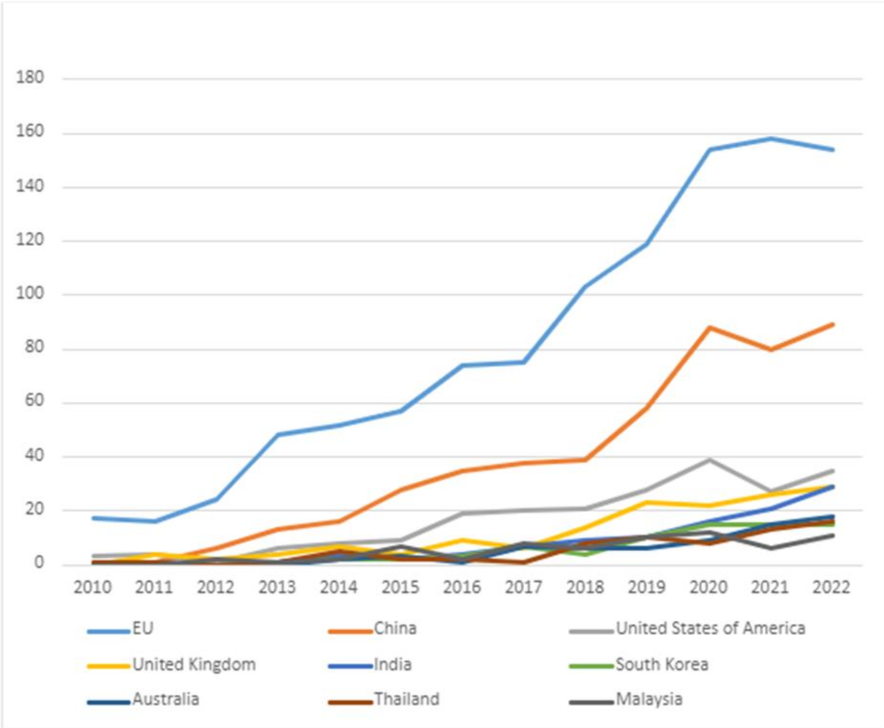
Figure 49. Scientific publication on Biogas in Europe, 2010-2022



Source: JRC elaboration

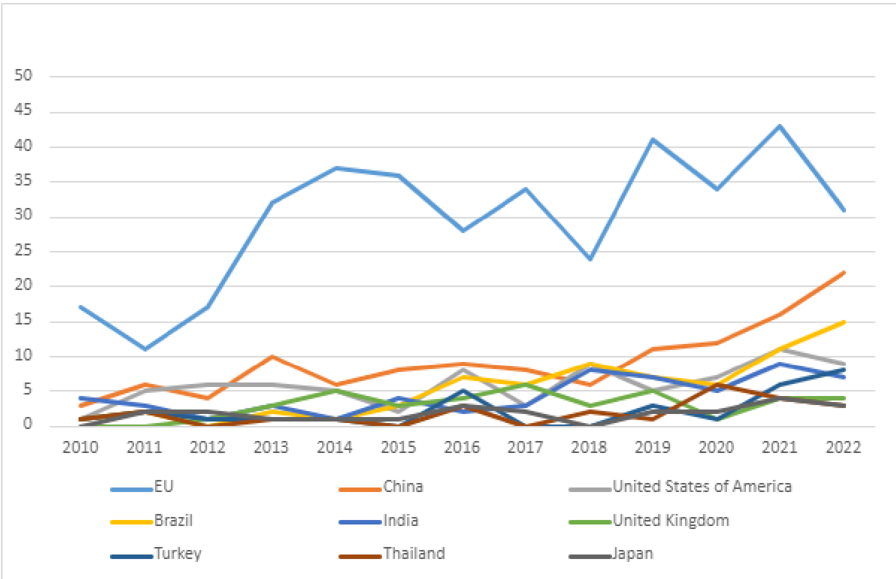
Globally, the EU has led biomethane publications for the past 12 years, growing steadily increase to reach 160 publications in 2021. (Figure 50). Regarding biogas, while the EU always leads in the number of publications with an up-down trend, China steadily increased its publications after 2019. (Figure 51)

Figure 50. Global trend in scientific publications on Biomethane, 2010-2022



Source: JRC elaboration

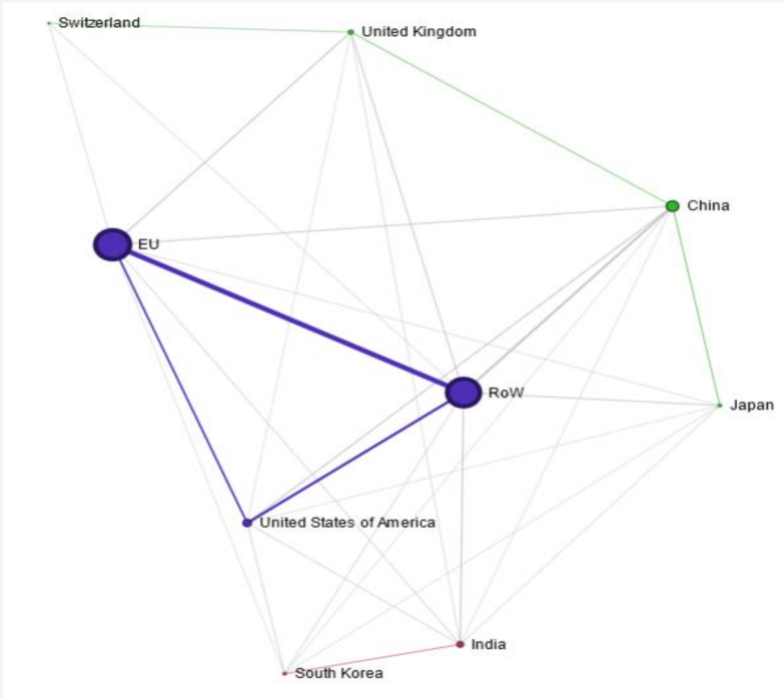
Figure 51. Global trends in scientific publications on Biogas, 2010-2022



Source: JRC elaboration

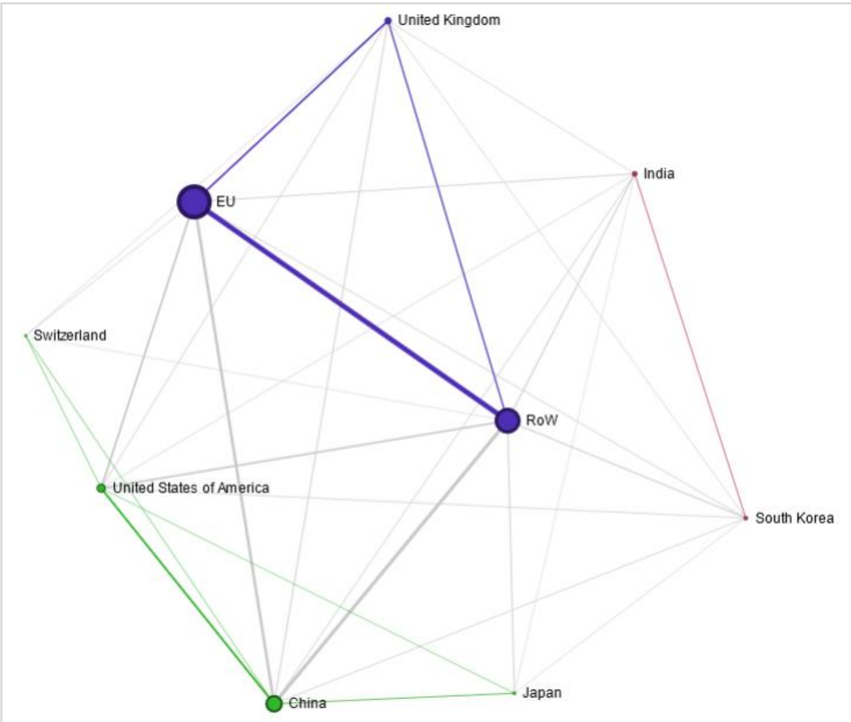
At the global level, a strong scientific network on biogas is observed between the EU, RoW (Rest of the World) and the USA in the period 2010-2021. Figure 52. At the global level, a strong scientific network on biomethane is observed between the EU, RoW (Rest of the World) and the UK in the period 2010-2022. (Figure 53)

Figure 52. Biogas Scientific Network 2010-2022



Source: JRC elaboration

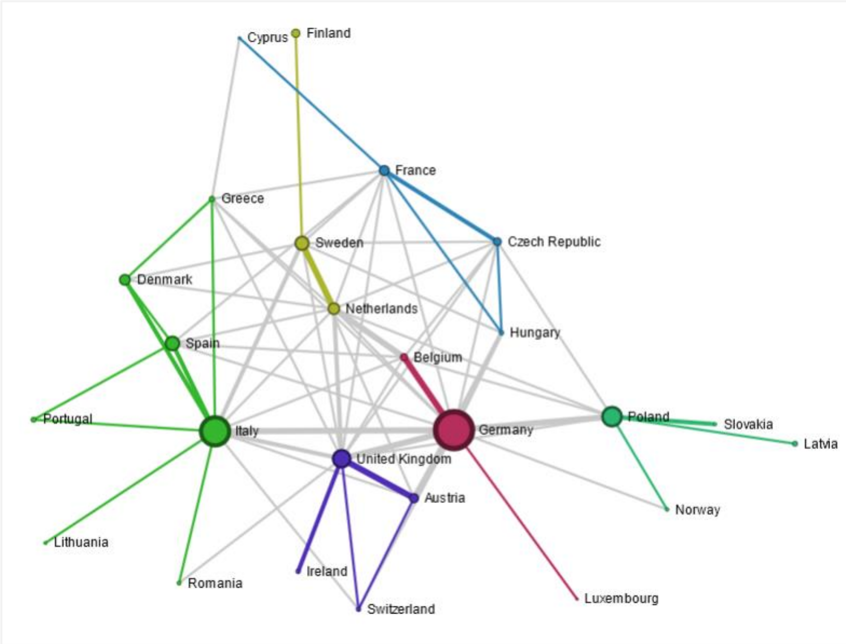
Figure 53. Global Biogas Scientific Network 2010-2022



Source: JRC elaboration

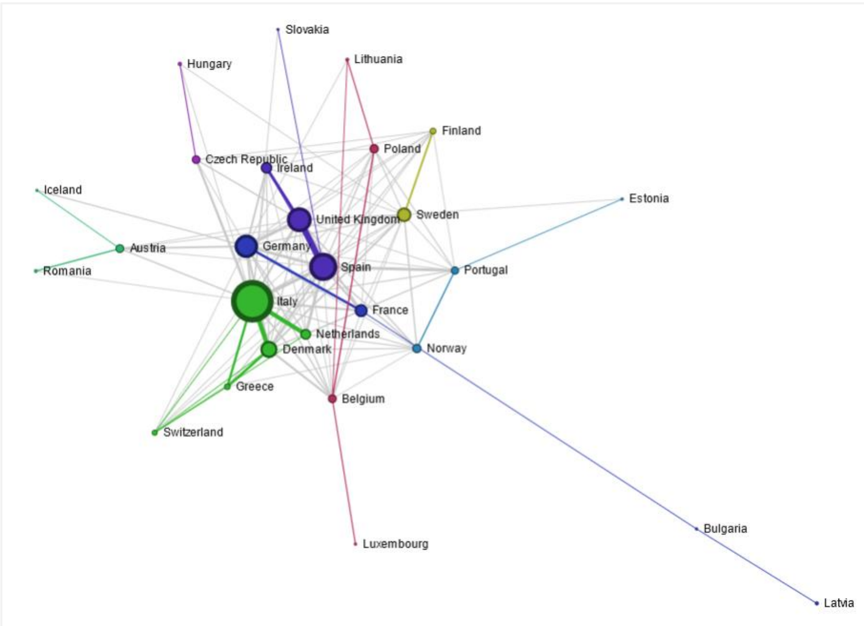
At the EU level, a strong scientific network on biogas is observed between Germany, Belgium and Italy, Spain and Denmark during the 2010-2022 period. (Figure 54). At the EU level, a strong scientific network on biomethane is observed between Germany, France, Spain and the UK, and Italy with Denmark and the Netherland in the period 2010-2022. (Figure 55)

Figure 54. European Biogas Scientific Network 2010-2022



Source: JRC elaboration

Figure 55. European Biomethane Scientific Network 2010-2022



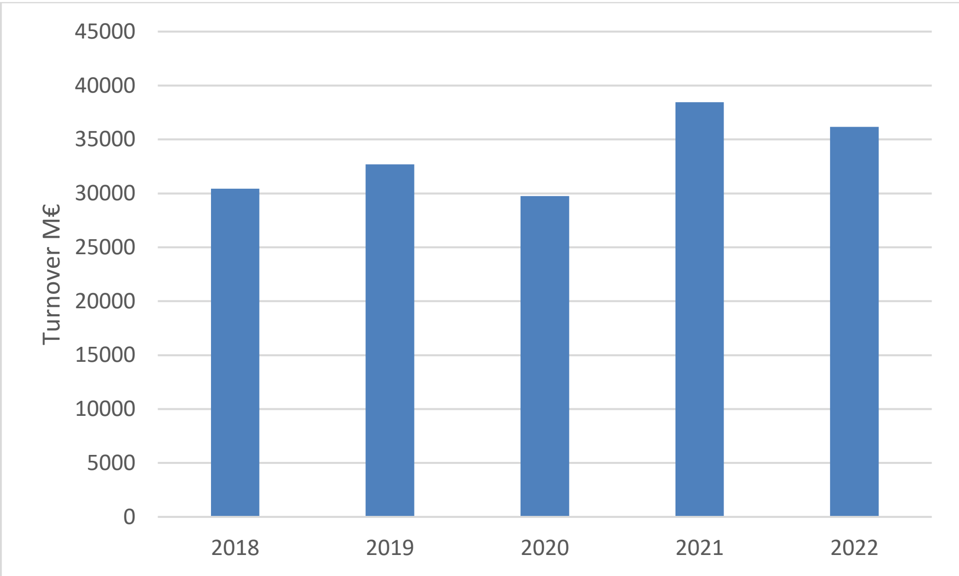
Source: JRC elaboration

3 Value Chain Analysis

3.1 Turnover

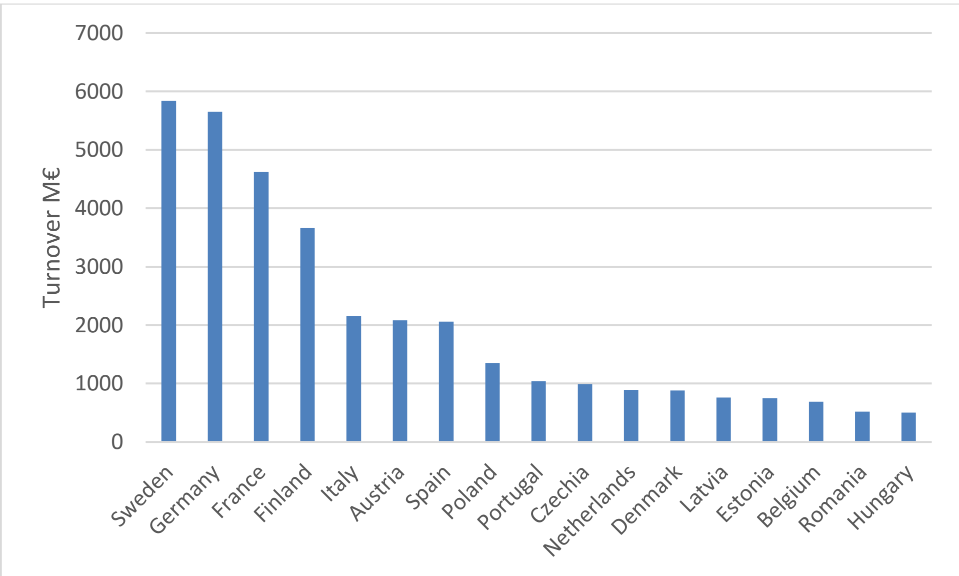
Turnover in the context of structural business statistics comprises the totals invoiced by the observation unit: this corresponds to the total value of market sales of goods and services to third parties. After being stable at around €30,000 million between 2018 and 2020, the turnover related to solid biomass in the EU increased to €38,450 million in 2021 and slightly decreased in 2022.(Figure 56). At EU Member State level, concerning the year 2022, Sweden had almost €6,000 million turnover, followed by Germany and France. (Figure 57)

Figure 56. Turnover of Solid Biomass to Energy, EU 2018-2022



Source: EurObserv'ER online database

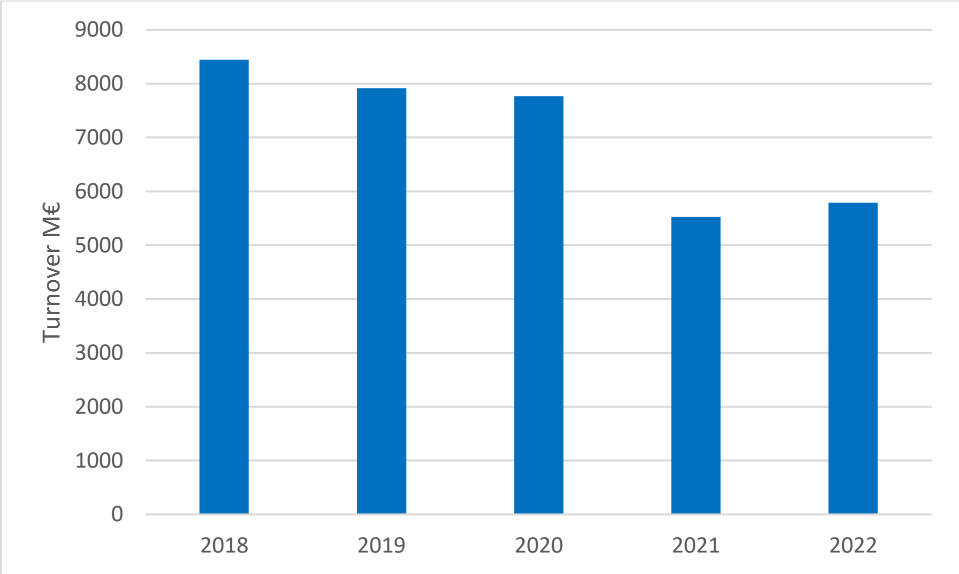
Figure 57. Turnover of Solid Biomass to Energy, EU Member States 2022



Source: EurObserv'ER online database

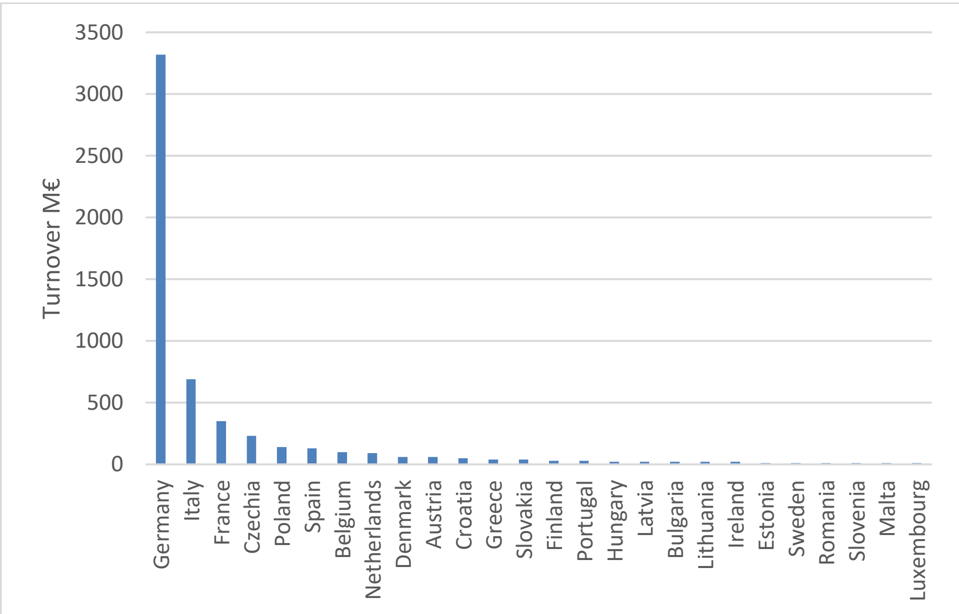
EurObserv'ER online database provides turnover data for the biogas sector, the highest value was reached in 2018 with €8,448 million, on averaged above €7,000 million from 2019 to 2020 and then falling to €5,790 million in 2022. (Figure 58)Germany was by far the leading country in the EU with a turnover of almost € 3,180 million from biogas, followed by Italy with € 890 million. (Figure 59)

Figure 58. Turnover of Biogas, EU 2018-2022



Source: EurObserv'ER online database

Figure 59. Turnover of Biogas, EU Member States 2022

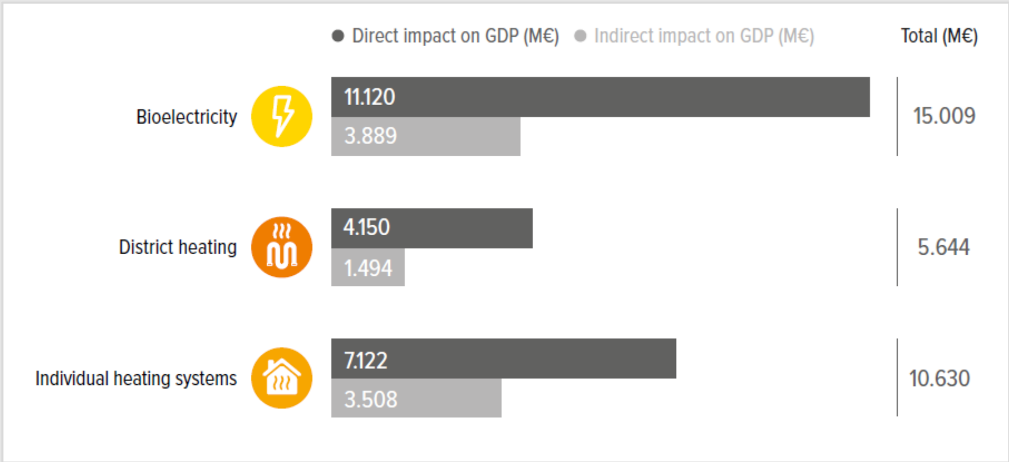


Source: EurObserv'ER online database

3.2 Gross value added

Deloitte (Deloitte, 2022) estimated the contribution of the bioenergy sector to the EU economy using three approaches recognised by the European System of National and Regional Accounts (ESNRA). Deloitte collected data (added value, expenditure, jobs) from published financial statements on EU companies active in the bioenergy industry, with also seeking additional information on players in the bioenergy industry. In addition, Deloitte calculated the indirect impacts of the bioenergy sector on other sectors of the economy using an input-output methodology. The Deloitte report puts the impact of the Heat & Power bioenergy sector on GDP in 2019 at around €31,282, representing 0.23% of the EU 27 GDP, the direct impact was €22,392 million, while the indirect impact was €8,890 million. (Figure 60)

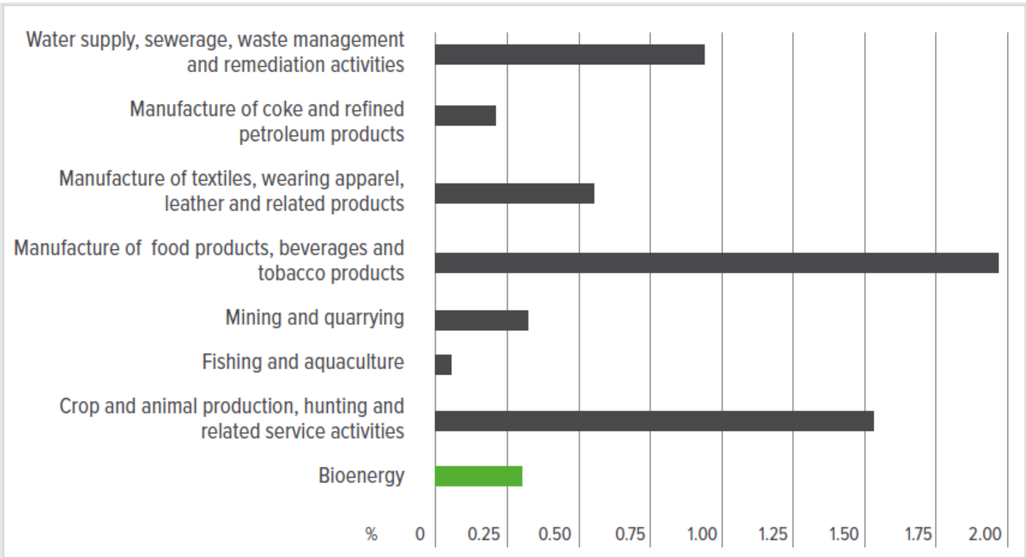
Figure 60. Bioenergy GDP Impact, EU 2019



Source: Deloitte

It is estimated that each additional Million Tons of oil Equivalent (Mtoe) of biomass for energy would have an impact of €359 million in terms of GDP. When comparing the GDP contribution of all bioenergy including transport biofuel for to other sectors, at EU level the GDP impact in 2019 was comparable to mining and quarrying and higher than the oil refining sector. Figure 61

Figure 61. Bioenergy GDP Impact share vs other sectors, EU 2019



Source: Deloitte

In 2019, according to a report by Deloitte in the EU, 70% of bioelectricity came from cogeneration (CHP), hile 30% came from bioelectricity-only power while solid biomass and biogas accounted for 84% of fuel input. Operation and maintenance had the main impact on the contribution to GDP with € 6,791 million out of a total of € 11,120 million in 2019.Table 10

Table 10. Bioenergy GDP Impact along Bioelectricity production chain, EU 2019

Bioelectricity EU			
Impact on GDP (million €)	**Direct**	**Indirect**	**Total**
Equipment manufacturing	216	3,889	**15,009**
Construction	445		
Supply of feedstock	3,668		
Operation and maintenance	6,791		
Total	**11,120**		

Source: Deloitte

According to (Deloitte, 2022), in 2019, District Heating Solutions companies in the EU operated both with cogeneration (CHP) and heat only, with fossils fuels as the fuel were still the predominant source with a share of 72%, while biomass accounted for 97% of the 28% share of renewables Equipment with € 1,297 million and operation and maintenance with € 1,766 million had the main direct impact on GDP, which was € 4,150 million. (Table 11)

Table 11. Bioenergy GDP Impact along biomass District heating production chain, EU 2019

Biomass District Heating EU			
Impact on GDP (million €)	**Direct**	**Indirect**	**Total**
Equipment manufacturing	1,297	1,494	**5,644**
Construction	715		
Supply of feedstock	363		
Operation and maintenance	1,766		
Total	**4,150**		

Source: Deloitte

The Bioenergy Europe report states for the EU 27 bio heat consumption of 41,527 ktoe for residential purposed (boiler and stove) in 2019, the fuel used is mainly pellets and wood, it represents almost 50% of bio heat consumption. The supply of feedstock of € 4,895 million directly affected more GDP, which was € 7,122 million. (Table 12)

Table 12. Bioenergy GDP Impact along biomass residential Bioheat production chain, EU 2019

Biomass Residential Heat EU			
Impact on GDP (million €)	**Direct**	**Indirect**	**Total**
Equipment manufacturing	1,548	3,508	**10,630**
Construction	434		
Supply of feedstock	4,895		
Operation and maintenance	244		
Total	**7,122**		

Source: Deloitte

3.3 Environmental and socio-economic sustainability

The different dimensions of sustainability of bioenergy are described as harmonized tables throughout the different CETO reports, and attached as annex 2 in this report.

3.4 Role of Companies in the EU

The European biomass industry is a leader biomass energy, especially solid biomass and biogas. The European biomass heat industry deals with small-scale heat production (domestic stove boilers using solid biomass such as wood pellets, fuelwood woodchips, etc.) to medium and large-scale. Although support is declining, the EU remains the world's most important market for biomass power plants.

This section provides a non-exhaustive overview of the major players in the bioenergy field, including the companies in the production of equipment and the development of bioenergy technologies. The information comes from the publicly available information of the companies' web sites. The companies are transitioning away from coal and other fossil fuels to invest in low-carbon and renewable energies, which requires substantial capital and technological advancements. The complexity of converting various biomass feedstock into high-quality biofuels and chemicals presents technical challenges. The logistics of sourcing and transporting biomass materials, such as wood chips and agricultural residues, can be complicated and costly. The companies are united by their commitment to sustainability and innovation in biomass energy, particularly in solid biomass and biogas. Companies such as Alstom, Ameresco, ANDRITZ, and Babcock & Wilcox are engaged in designing, manufacturing, and supplying components and systems for biomass power production. Companies such as BTG, Drax, and Fortum are focused on converting biomass into various forms of renewable energy, including bio-oil and biogas.

Alstom

The activities Alstom Power Systems include the design, manufacture, service and supply of products and systems (gas, nuclear, hydro, wind and biomass) for power production and industrial markets. Alstom Power Systems supplies components including boilers and emission control equipment, steam turbines and gas turbines, wind turbines, generators, air quality control systems and monitoring and control systems for power plants and related products. Following the sale of the company's power and transmission business to GE, they were integrated into GE Power & Water.

Ameresco

Ameresco Inc. is a supplier of renewable energy and energy efficiency solutions, active in the development, construction and operation of biomass power plants. Ameresco's service activities include the design, development, engineering and installation of projects that reduce the energy and operation and maintenance costs of power plants. Ameresco provides solutions from the modernisaton of energy infrastructure such as distributed generation power plants and onsite cogeneration to the development, construction and operation of renewable power plants. Ameresco builds power and cogeneration facilities for renewable waste to produce power and heat from large biomass power plants, as well as smaller on-site biomass cogeneration and distributed generation plants, as well as methane digester facilities.

ANDRITZ

ANDRITZ Feed and Biofuel is one of the world's leading suppliers of technology and services for the animal feed and biofuel industry. ANDRITZ offers a wide range of equipment and complete plant solutions to produce high-quality feed and biomass products. ANDRITZ has proven experience in the design and construction of feed and biomass facilities, including engineering, installation, start-up, and commissioning, as well as spare parts and service. ANDRITZ offers a range of pelletising, grinding, mixing and screening equipment for the processing of dry materials and to produce pellets from biomass, solid biofuel, and waste pellets.

Babcock & Wilcox

Babcock & Wilcox Enterprises Inc. is a global leader in advanced energy and environmental technologies and services for the energy, renewables and industrial markets. The company is a supplier of energy services and products such as biomass-fired boilers, biomass gasification, boiler pressure parts and field engineering services. Babcock & Wilcox technologies include pre-treatment technologies, vibrating grate, burners, stokers, bubbling, circulating fluidised-bed and stoker boilers, gasifiers, black liquor recovery boilers. Historically, the company is mainly known for steam boilers, biomass to energy, emission control equipment, waste-to-energy equipment, boiler cleaning equipment, ash handling and Transportation.

BTG

BTG Biomass Technology Group BV specialises in the conversion of biomass into fuels, energy and biological feedstocks. BTS is a leading fast pyrolysis technology provider, supplying production plants that convert sustainable biomass residues into Fast Pyrolysis Bio-Oil (FPBO) that can replace fossil fuels. BTG-Bioliquids supplies Fast Pyrolysis Bio-Oil -plants that operate only on biomass residues, such as sawdust, sunflower husk, roadside grass and straw. BTG-neXt offers technology to produce drop-in biofuels that can be used in transport without the need to invest in new engines or systems, such as advanced marine biofuels for aviation and road transport.

Drax

Drax Group plc is an electricity production company. The company operates three main business activities: wood pellet production, biomass processing for electricity production; flexible, low carbon and renewable energy production; and sale of energy and services to corporate customers. The company focuses on electricity production, producing flexible, low carbon and renewable electricity, as well as providing grid system support services from a portfolio of biomass, hydro, gas and coal technologies. The company plans to invest in improving the performance of its biomass business unit. Drax Group plc plans to carry out R&D activities to develop new types of biomass that can be burned efficiently.

ENGIE

Engie SA was formerly known as GDF SUEZ S.A. ENGIE operates in the production and distribution of electricity, natural gas, nuclear, renewable energy and energy services. It engages in the production and sale of energy through nuclear, thermal, and biomass sources; and seawater desalination activities, and also offers energy, hydraulics, and infrastructure engineering services. ENGIE decided to stop new investments in coal-fired power plants and invest in projects that support low carbon, renewable energies (solar, wind, geothermal, biomass, hydro), nuclear, and energy services such as heating and cooling networks and decentralised energy technology.

ENVIVA

Enviva is a producer of sustainable wood pellets, a renewable alternative to coal. Wood-based bioenergy is part of a comprehensive renewables strategy to reduce carbon emissions and limit dependence on fossil fuels.

NextFuel AB

NextFuel AB developed a highly scalable technology to convert fast-growing grasses and other types of crops into a substitute for coal (briquettes). NextFuel AB provides torrefaction technology that processes a variety of biomass feedstocks in addition to wood, including fast-growing, abundant, carbon-rich plants such as elephant grass and bagasse (waste from sugarcane). The patented NextFuel™ torrefaction reactor, based on the rotary drum principle, provides high flexibility and processes energy crops such as various species of elephant grass, agricultural waste such as bagasse and paddy straw, and forestry waste such as wood residues and low quality wood.

Fortum

Fortum is a leading energy company developing and offering services for the power production industry and solutions in the field of electricity, heating, cooling, and also efficient use of resources. Fortum's business activities cover the production and sale of electricity and heat, waste-to-energy solutions and circular economy. The City Solutions division includes heating, cooling, waste-to-energy, biomass, and other circular economy solutions, as well as solar power production. Fortum has expanded its waste-to-energy and biomass-fired heat and electricity capacity and recycling and waste solutions. Fortum Otso bio-oil is produced from wood-based feedstock (forest residues, wood chips or sawdust) by fast pyrolysis, it can replace heavy or light fuel oil, e.g., in heating plants and industrial steam production.

Green Fuel Nordic

Green Fuel Nordic Oy is a biorefining company based on the use of innovative, commercially used pyrolysis technology in the production of advanced bio-oil. Green Fuel Nordic biorefinery uses renewable wood-based material to produce advanced bio-oil based on fast pyrolysis, where pre-treated biomass is converted into bio-oil. Pyrolysis technology also allows the use of for by-products from the rest of sawmill and pulp industry as a resource. Bio-oil can be directly used as an industrial resource in the production of electricity and heat, as a substitute for light and heavy fuel oil and gas, and to power diesel engines of ships.

Nature Energy

Nature Energy, Denmark's largest producer of biogas and Europe's leading producer of green gas to the grid from farm and food waste. Nature Energy (former Naturgas Fyn) owns and operates seven large-scale biogas plants and currently has a production capacity of more than 100 million m^3 (approx. 5 % of green gas in the European gas network). Nature Energy acquired Xergi from Schouw & Co. in 2018 and Hedeselskabet, one of Europe's leading suppliers of turnkey biogas plants. Xergi has more than 30 years of experience in the design and construction of biogas plants worldwide.

Ørsted A/S

Ørsted A/S (DONG Energy) is an energy company based in Fredericia, Denmark, which develops, constructs and operates offshore and onshore wind farms, bioenergy plants and innovative waste-to-energy solutions. DONG Energy produces and supplies heat and electricity from thermal and biomass power stations to business and residential customers. Bioenergy plants from Ørsted use residues from forestry and agriculture such as straw, wood pellets and wood chips from wood residues and waste, mainly tree tops, branches and sawdust from sawmills as well as low quality roundwood to produce electricity and district heating. The most recent focus includes the industrial biogas production from industrial waste streams (insulin and enzyme production at Novo Nordisk and Novozymes).

Sekab

Sekab is a green chemical company for the production of chemicals and fuels. Sekab conducts research and development of new opportunities for sustainable products. Sekab developed processes and technologies that enable the production of bioproducts and advanced biofuels. CelluAPP® technology makes it possible to process various biomass feedstocks into environmentally friendly, high-quality and marketable chemical products and feedstocks such as biogas, cellulosic sugars, ethanol and lignin. The technology of SEKAB mainly of four steps: pre-treatment, enzymatic hydrolysis, fermentation and distillation.

UPM is a world leader in the use of biomass for the production of pulp and paper, biomaterials, biofuels and bioenergy and the second largest electricity producer of electricity in Finland. UPM invested in replacing power plants that use renewable fuels such as bark, forest residues, fibre residues and solid residues, bark and black liquor from the pulping process. UPM Biofuels produces innovative, advanced biofuels for transport and for petrochemical applications. UPM Lappeenranta Biorefinery started commercial production in 2015 of 120 million litres of renewable wood-based diesel from crude tall oil (UPM BioVerno).

Valmet

Valmet is a leading global developer and supplier of process technologies, automation and services for the pulp, paper and energy industries. VALMET provides energy solutions based on biomass, waste or a mixture of different fuels (biomass to energy, waste to energy, multifuel solutions and for combined heat and power production (CHP) based on different fuels. VALMET is a leading supplier of boilers and gasification technologies that offer a choice of solutions for flexible energy production. Valmet offers complete power plants for small and medium scale with comprehensive air emission control systems.

Vattenfall

Vattenfall AB is a state-owned company for the production and distribution of electricity and heat from coal, natural gas, nuclear, wind, hydro, solar, biomass and waste. Vattenfall AB invests in renewable sources and develops modern energy systems to reduce carbon emissions from its operations. Vattenfall operates over 15 biomass plants using wood chips, forest residues and sawmill by-products, landscape protection material and compost residues. The Vattenfall subsidiary Energy Crops GmbH operates over 2,000 hectares of energy wood plantations, which provide fuel supply of heating facilities in Berlin.

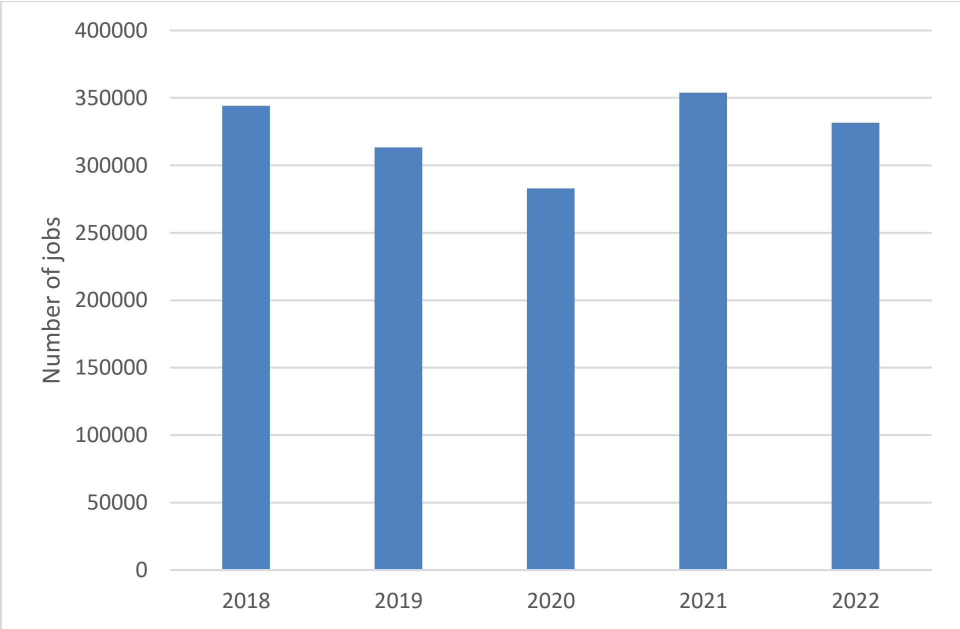
3.5 Employment

Data on Jobs in EurObserv'ER online database includes both direct and indirect employment. Direct employment includes renewable energy sources equipment, manufacturing, renewable energy plants construction, engineering and management, operation and maintenance, biomass supply and exploitation.

Indirect employment refers to secondary (additional) activities, such as transport and other services, manufacturing, renewable energy plants construction, engineering and management, operation and maintenance, biomass supply and exploitation.

According to EurObserv'ER online database, the number of employees in the solid biomass sector (direct and indirect) in the EU reached 283,000 in 2020, regained 332,000 employees in 2022 (Figure 62).

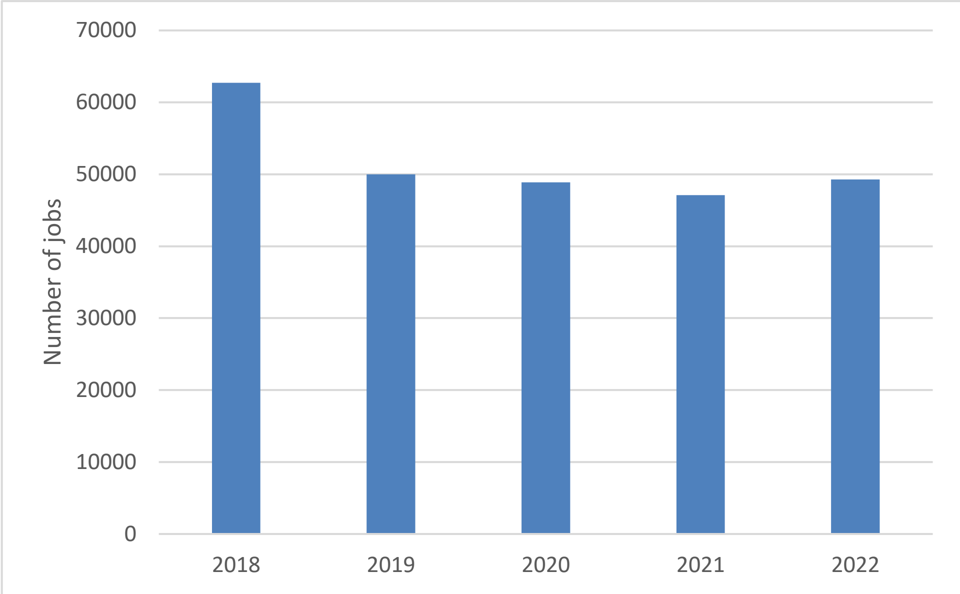
Figure 62. Number of jobs solid Biomass (direct and indirect), EU 2018-2022



Source: EurObserv'ER online database

EurObserv'ER online database also trucks the number of employees in the biogas sector in the EU (direct and indirect), the number of jobs peaked at 62,700 employees in 2018, and decreased in subsequent years dropping to 49,300 employees in 2022. (Figure 63)

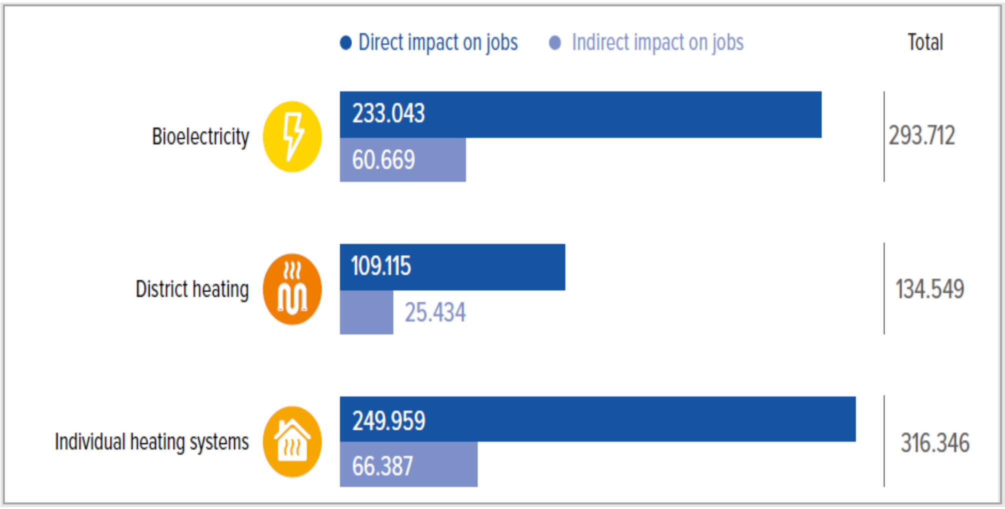
Figure 63. Number of jobs Biogas (direct and indirect), EU 2018-2022



Source: EurObserv'ER online database

According to the Deloitte report, EU 2019, the employment impact of bioenergy heat and power reached 744,608 FTE (Full-Time Equivalent), with 592,118 direct jobs and 152,490 indirect job. (Figure 64)

Figure 64. Bioenergy direct and indirect impact on jobs, EU 2019



Source: Deloitte

Overall, the biomass to energy sector requires mainly jobs in construction and the production of equipment related to the installation of new plants, while the operation and maintenance of power plants requires permanent jobs. In particular, the collection, processing and transport of biomass before its final use is needed compared to other renewable energy sources (solar, wind, geothermal, hydro). The feedstock supply is the sector, in the chain, with a major contribution as there are 153,000 direct jobs out of 233,043 total direct jobs. (Table 13)

Table 13. Bioelectricity direct and indirect impact on jobs, EU 2019

Bioelectricity EU			
Impact on Jobs	**Direct**	**Indirect**	**Total**
Equipment manufacturing	5,818	**60,669**	**293,172**
Construction	4,682		
Supply of feedstock	15,3047		
Operation and maintenance	69,544		
Total	**233,043**		

Source: Deloitte

District heating in the EU works both with cogeneration of heat and electricity (CHP) and heat only-plant: in this sector direct jobs are mainly influenced by equipment manufacturing and operation and maintenance with 34,880 and 47,165 respectively. (Table 14)

Table 14. Biomass district heating direct and indirect impact on jobs, EU 2019

Biomass District Heating EU			
Impact on Jobs	**Direct**	**Indirect**	**Total**
Equipment manufacturing	34,880	25,434	**134,549**
Construction	10,088		
Supply of feedstock	16,981		
Operation and maintenance	47,165		
Total	**109,115**		

Source: Deloitte

For residential use (boiler and stove), the fuel used is mainly pellets and wood. It represents almost 50% of bio heat consumption. The sector "supply of feedstock" with 210,511 direct jobs, has by far the highest share of employees in the supply chain, (Table 15)

Table 15. Biomass residential heat, direct and indirect impact on jobs, EU 2019

Biomass Residential Heat EU			
Impact on Jobs	**Direct**	**Indirect**	**Total**
Equipment manufacturing	26,390	66,387	**316,346**
Construction	8,390		
Supply of feedstock	210,511		
Operation and maintenance	4,669		
Total	**249,959**		

Source: Deloitte

3.6 Energy intensity and labour productivity

Regarding biogas and biomethane, the EBA 2023 report (European Biogas Association, 2023) considers different studies due to the inclusion of several sectors such as agriculture, waste management, water treatment, logistics, etc. The evaluation of job impact requires assumptions. Depending on the methodology, which is not harmonised among different references, the total employment ratevaries between 0.56 and 1.92 jobs/GWh. The number of direct jobs varies between 0.07 and 1.18 jobs/GWh and the number of indirect jobs between 0.22 and 1.56 jobs/GWh. The average employment rate is calculated at 1.09 jobs created per GWh of biogas and biomethane produced. From these jobs, 0.32 are direct jobs and 0.77 indirect jobs. In Europe, in 2022, a total of 179 TWh of biogas and 44 TWh of biomethane was produced. Using the above indicators, more than 265,000 jobs are estimated in the biogas and biomethane sector across Europe, of which approximately 71,000 jobs are direct jobs and 171,000 indirect jobs.

3.7 EU Value Production Data

The trade statistics were produced using the Comext Eurostat' reference database for detailed statistics on international trade in goods. It provides access on recent and historical data for the EU and its individual Member States, but also covers a significant number of non-EU countries.

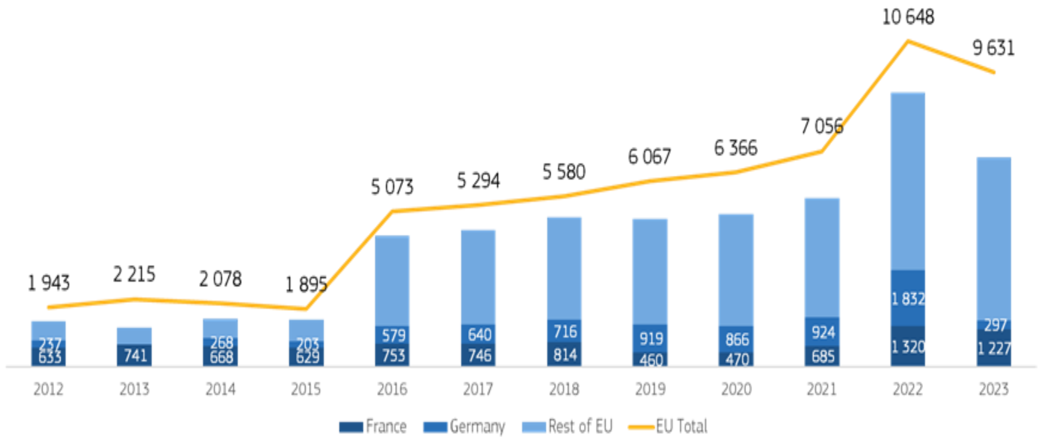
Prodcom provides statistics on the production of manufactured goods carried out by enterprises in the national territory of reporting countries. The purpose of Prodcom statistics is to provide a complete picture of the development of industrial production at EU level for a given product or for an industry in a comparable way across countries.

The Comext codes included for bioenergy statistics are listed in the following table:

Prodcom	Description	Alias
10622000	Residues of starch manufacture and similar residues	starch residue
10812000	Beet-pulp, bagasse and other sugar manufacturing waste (including defecation scum and filter press residues)	bagasse
16102503	Coniferous wood in chips or particles	wood chips conf
16102505	Non-coniferous wood in chips or particles	wood chips
16291500	Pellets and briquettes of pressed and agglomerated wood and of wood waste and scrap	pellets
20147200	Wood charcoal whether or not agglomerated (including shell or nut charcoal)	charcoal

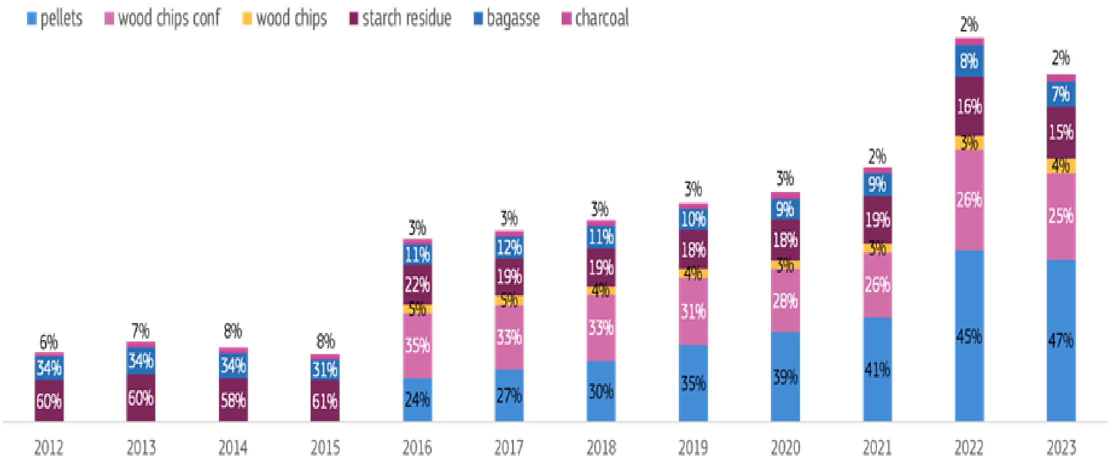
The value of energy carriers produced in the EU Member States steadily increased from EU €5,073 million in 2016 to €10,648 million in 2022, before decreasing by 10% in 2023. The combined value produced in Germany and France in the last 3 years represents one quarter of the total EU production. (Figure 65), pellets and wood chips account for 47% and 25% share respectively in 2023, it represents more than 70% of the value produced in the EU. (Figure 66)

Figure 65. Biomass carrier production value, M€, EU 2012-2023



Source: JRC elaboration on Comext Eurostat's DB

Figure 66. EU biomass commodities production share, 2012-2023



Source: JRC elaboration on Comext Eurostat's DB

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

The leading EU countries in the production of electricity from biomass in 2022 were Germany, Italy, Finland, and Sweden. Solid biomass was the main feedstock for bioelectricity production in 2022 in several Member States such as Finland, Sweden and Poland, while in other Member States, such as Italy and France, different feedstock contribute to biomass electricity production to varying degrees. An important aspect to note is the high share of biogas in electricity production in Germany, with a share of 76 % of electricity from biomass, and a significant share of biogas in electricity production in Italy, which is more than 40 %.

For Biomass Heating gross production, Sweden, Finland are the main contributors. By far biomass is the dominant source for renewable heating in most EU Member States, followed by heat pumps, which have a higher share in France, Italy and Sweden. Looking at feedstock, solid biomass plays the main role with a good contribution of biogas in Germany, France and Italy.

Looking at the distribution of biogas supplies to different Member States, the leading Member State in 2022 was Germany that had a contribution of about 44 % into the biogas production at the EU level with 99 GWh. Other leading Member States include Italy, France, and Spain. Biogas production from anaerobic digestion plants dominates in most countries, especially in Germany Italy, France, etc. However, biogas from landfill gas recovery dominates in other Member States, including Spain, Greece, Portugal and Ireland. Biogas production from anaerobic digestion of sewage sludge from wastewater treatment plants also has an important contribution in Germany, Poland, Spain and Sweden. Compared to the use of natural gas in various Member States, biogas has a significant contribution, especially in Denmark (29%), Sweden (26%), Germany (11%), the Czech Republic (9%) and Latvia (8%).

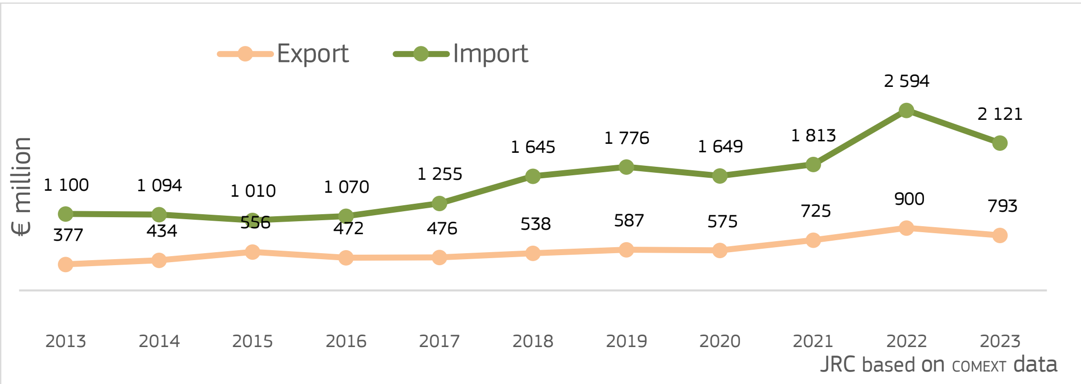
The value of bioenergy energy carriers and feedstock produced in EU countries steadily increases from € 5,073 million in 2016 to € 10,640 million in 2022, the combined value produced in Germany and France, acummulated over the last 3 years, represents one quarter of EU production.

For the triennium 2021-2023, in terms of solid bioenergy carriers and feedstocks, Latvia with almost € 2,000 million and Germany with € 1,600 million lead the top 5 EU exports, mostly delivered to other EU countries.

4.2 Trade (Import/export) and trade balance

Considering the EU Member States as a group, they more than double the value of imports from extra-EU countries from € 1,010 million in 2015 to € 2,589 million in 2022. The exports from EU to extra-EU countries averaged €500 million between 2015 and 2020, before peaking at € 900 million in 2022. In 2023, the value of extra-EU imports of biomass energy carriers and biomass decreased by 18%, compared to 2022, to €2.1 billion. The extra-EU exports decreased by 12% to €0.793 billion in 2023. (Figure 67)

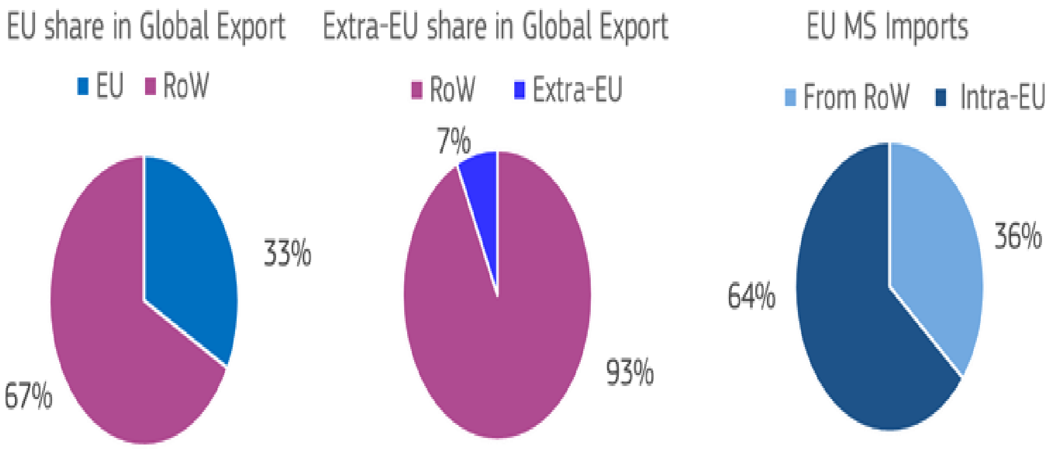
Figure 67. Biomass energy carrier and feedstock trade



Source: JRC elaboration from n Eurostat's DB

In the period 2021 to 2023, EU accounted for 33% of global exports, while the extra-EU share (excluding intra-EU trade) was only 7%. The EU covered 64% of its import needs through trade among its Member States. (Figure 68)

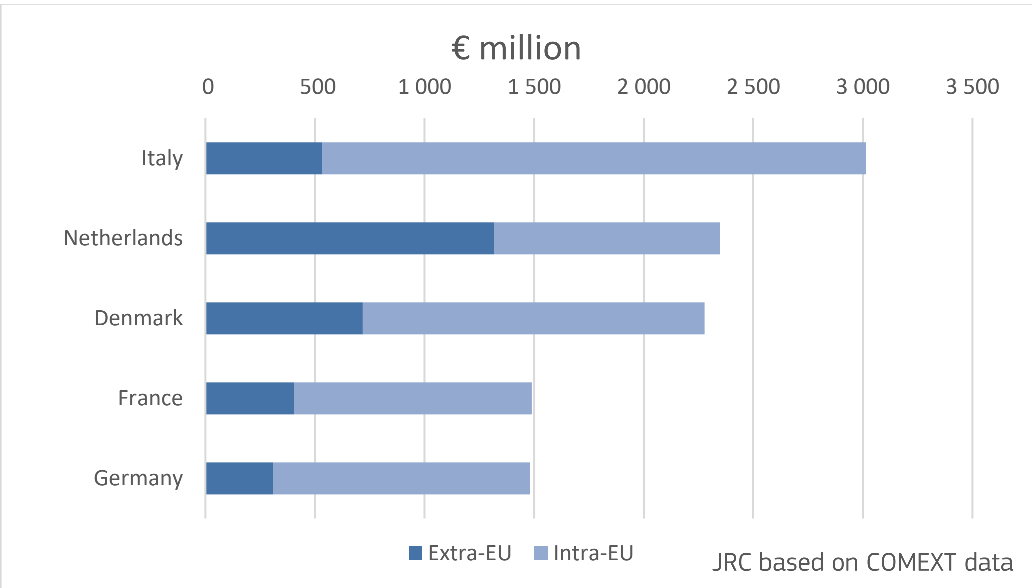
Figure 68. EU share in global export (left), extra-EU share in global export (middle) and EU imports (right), 2021-2023



Source: JRC elaboration on Comext Eurostat's DB

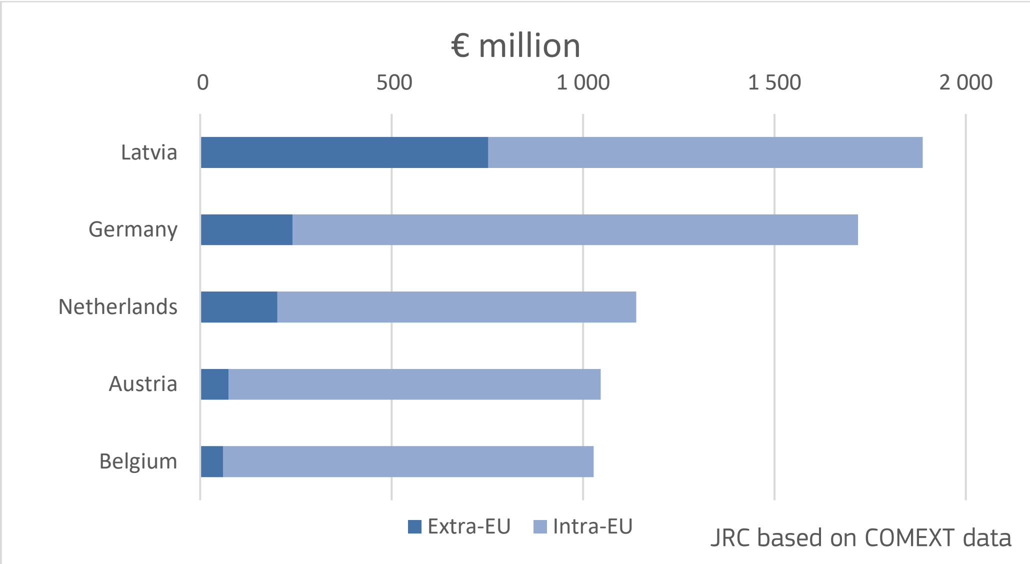
For the triennium 2021 to 2023, the top 3 EU importers are Italy, Denmark and the Netherland. Together they imported more than €7000 million worth of biomass annually. Italy and Denmark imported mostly Intra-EU. Figure 69. For the triennium 2021 to 2023, Latvia leads with almost €2,000 million and Germany with more than € 1,500 million among the top 5 EU exporters, mostly to the Intra-EU Market. (Figure 70)

Figure 69. Biomass energy carrier and feedstocks trade EU top 5 importers 2021-2023



Source: JRC elaboration on Comext Eurostat's DB

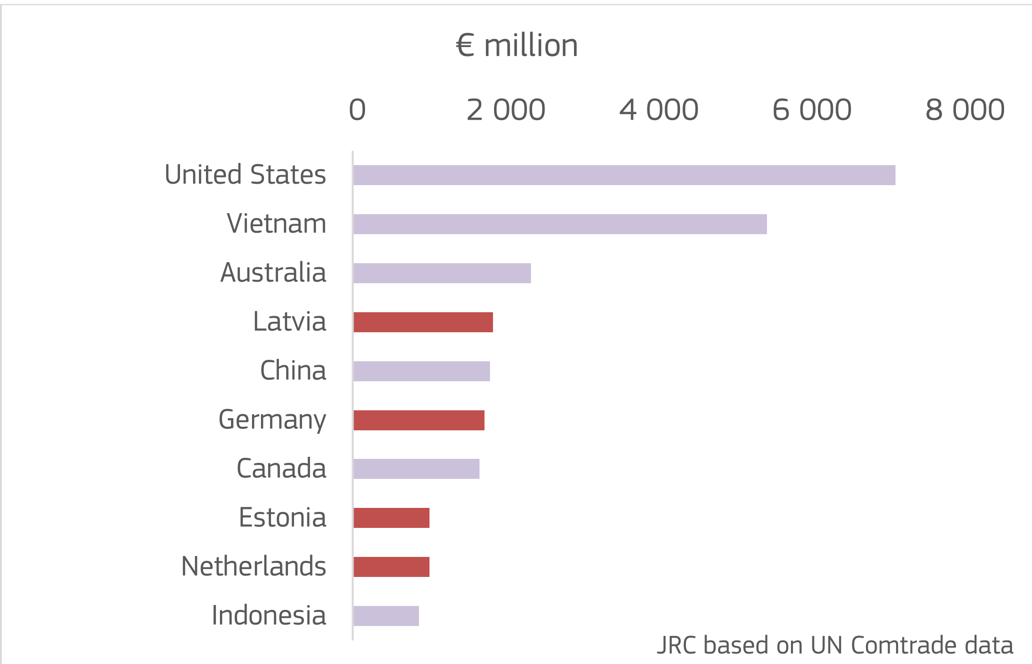
Figure 70. Biomass energy carrier and feedstock trade EU top 5 exporters 2021-2023



Source: JRC elaboration on Comext Eurostat's DB

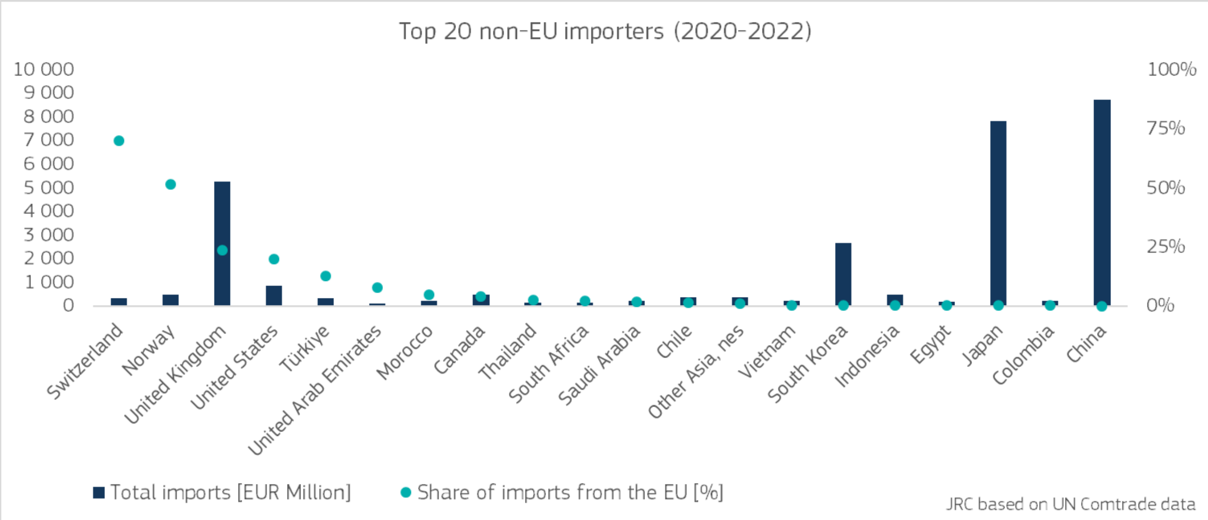
The US leads the world's top 10 exporters with more than € 7,000 million exported during the triennium 2021-2023. (Figure 71). Japan, China and the UK are the top 3 non-EU importers. Only the UK relies on the EU for 25% of its imports, which amounted to € 5,000 million over the triennium 2020 to 2022. (Figure 72)

Figure 71. Biomass energy carrier and feedstock top 10 exporters to EU, 2021-2023



Source: JRC elaboration on Comext Eurostat's DB

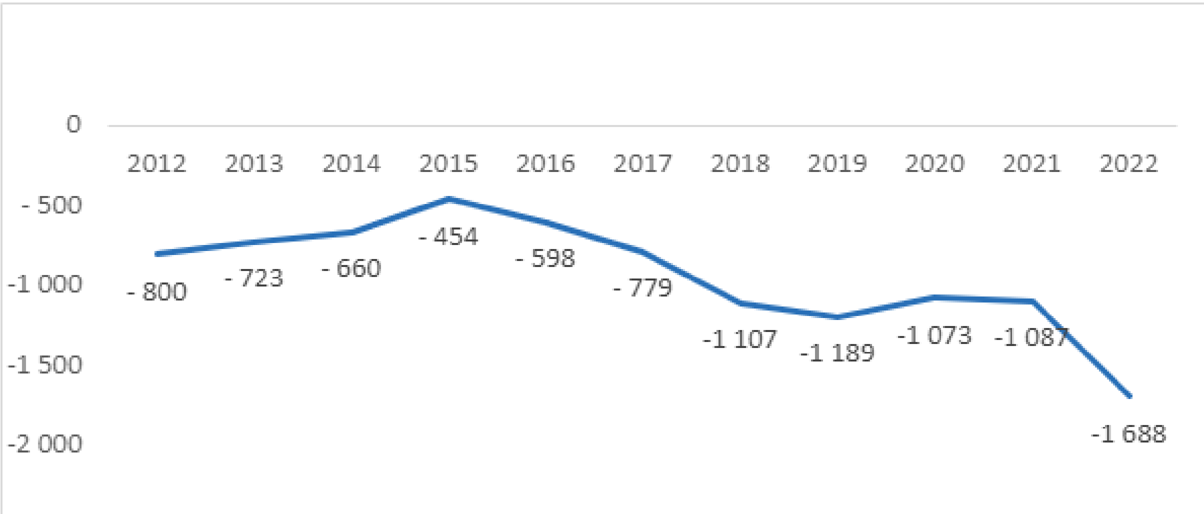
Figure 72. Biomass energy carrier and feedstock top 20 non-EU importers



Source: JRC elaboration on Comext Eurostat's DB

EU trade feedstock for bioenergy has been trending increasingly negative in the last years, from negative € -454 million in 2015 to negative € –1,688 million in 2022. (Figure 73)

Figure 73. Biomass energy carrier and feedstock extra-EU Trade Balance, 2012-2022



Source: JRC elaboration on Comext Eurostat's DB

4.3 Resource efficiency and dependency in relation to EU competitiveness

Most estimates suggest that biomass is likely to be sufficient to play a significant role in the global energy supply system until 2050 (Scarlat and Dallemand, 2019). Biomass availability for energy use is a key issue for bioenergy deployment. Various feedstock can contribute to meeting the bioenergy demand, including energy crops, residues from agriculture and forestry, organic waste from households and industry, as well as algae and aquatic biomass. As bioenergy would not require large imports of various materials, the bioenergy deployment would also reduce the material dependence of the EU. Several studies showed that the domestic available biomass in the EU could be sufficient to meet the EU energy and climate targets for bioenergy for 2030 and 2050. The amount of biomass potential available will depend on the ability to mobilise additional untapped potential and on additional more stringent sustainability criteria.

According to RED II, the EU Member States should consider the availability of sustainable biomass when developing support schemes and respect the principles of the circular economy and the waste hierarchy (in line with Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives) to avoid unnecessary distortions of raw materials markets. The increased competition between food, feed and fibre, wood products or new bio-based materials and bioenergy needs to be properly addressed. It will allow the use of biomass to be prioritised according to the societal needs. The multiple use of biomass (food, feed, fiber, biomaterials and bioenergy) entails a combination of several applications in a cascade of uses based on the prioritization of biomass use. When prioritizing the use of biomass, a number of factors could be considered, such as the economic or social value of biomass products, efficiency of biomass conversion, reduction of greenhouse gas emissions, etc.

According to the REDII and RED III requirements, biomass should be converted into electricity and heat in an efficient way to maximise energy security and greenhouse gas emissions savings, reduce emissions of air pollutants and minimise pressure on limited biomass resources. The electricity production from biomass fuels higher capacity installations should be done using highly efficient combined heat and power cogeneration. The electricity-only plants must achieve the Best Available Techniques energy efficiency level defined in Commission Implementing Decision (EU) 2017/1442 of 31 July 2017 establishing best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for large combustion plants. Electricity produced in power plants with a thermal input (the rated thermal input is the calorific value of the fuel supplied per unit of time to the combustion unit to operate at the rated power established in an administrative decision) above 100 MW should be done by high-efficiency cogeneration or, for electricity-only installations, by achieving a net electrical efficiency of at least 36%. Member States may apply higher energy efficiency requirements to installations with lower rated thermal input.

Bioenergy can also play a key role in short-term in decarbonizing the economy towards a low-carbon economy, while increasing energy security and energy diversification and negative emissions. Bioenergy provides flexible, low-carbon power production that can be used to balance the grid and is a key enabler for a high share of variable renewables, such as wind and solar in electricity grids. Biomethane can be used in conjunction with gas storage as energy storage solution increasing energy security and balancing the gas grid.

According to the Communication from the Commission REPowerEU Plan of 18 May 2022, bioenergy from sustainable sourcing will ensure sustainable energy production that can contribute to the REPowerEU objectives by prioritising the use of non-recyclable biomass waste and agricultural and forest residues. In particular, biomethane can contribute in the short term to the goals of the REPowerEU Plan, which aims to reduce the EU's dependence on imported fossil fuels and diversify its energy supply. In conditions of high energy prices, bioenergy, including biomethane production, can become cost-effective. Today, the EU has a leading role in bioenergy production and further development can ensure EU’s technological leadership in new emerging technologies and a key role in the transition toward a low-carbon economy.

5 Conclusions

Bioenergy is on of the pivotal elements in the European Union's (EU) strategy to decarbonise the economy, enhance energy security, and promote sustainable development. The EU has established itself as a global leader in bioenergy production, with substantial contributions from solid biomass, biogas, and liquid biofuels. In 2022, bioenergy accounted for 47% of the EU's renewable energy supply, underscoring its critical role in the renewable energy mix.

The primary feedstock for bioenergy, biomass, is derived from various sources, including energy crops, agricultural and forestry residues, organic waste from households and industry, and algae. The availability of sustainable biomass is a key factor in the successful deployment of bioenergy technologies.

Bioenergy technologies are versatile and available at various scales, from small to large, allowing for substantial contributions to energy diversification and security. This reduces dependency on fossil fuels. Technologies such as anaerobic digestion and biomass upgrading have reached commercial scale (Technology Readiness Level 9), while other processes like pyrolysis, gasification, and hydrothermal liquefaction range from pilot scale (TRL 5) to pre-commercial (TRL 7).

Despite these strengths, the bioenergy sector faces several challenges. Competition with alternative uses of feedstocks and land, complex and costly logistics for collection, transport, and storage, and the economic viability that depends on the availability of low-cost feedstock are significant issues. Small-scale combustion in residential areas can significantly impact air quality. Intensified management practices may negatively affect ecosystems and biodiversity. The EU's trade balance for bioenergy feedstock has been trending increasingly negative, indicating a growing dependency on imports.

For the EU, in the POTEnCIA CETO 2024 Scenario, electricity generation from bioenergy increases from 150 TWh in 2025 to about 180 TWh in 2050, though in the same period its share in total electricity generation decreases from 5.5% to 3% due to the large increase of total generation. Centralised heat generation from bioenergy increases from about 210 TWh to 270 TWh by 2050 (reaching around 50% of the total generation). The results of POLES-JRC showed an increase of biomass gasification installations at global level with a relative decrease of overnight investment cost of this technology.

To address these challenges, the EU strongly promotes further research to improve the economic and environmental performance of bioenergy technologies, ensuring their reliability and long-term operation. Continued investment in research, development, and demonstration projects is essential to advancing bioenergy technologies and achieving the EU's energy and climate targets. Research can help develop new processes, improve existing ones, and explore innovative applications of bioenergy, contributing to the overall sustainability and competitiveness of the sector.

The combined production of electricity and heat (CHP) represents a good option for improving the overall efficiency of biogas plants. The anaerobic digestion by-product, digestate, can be used as fertiliser, providing additional economic benefits by reducing the use of chemical fertilisers and preventing methane emissions.

The EU's robust patenting activity and leadership in scientific publications on bioenergy technologies underscore its strength in this field. The EU encourages collaboration between Member States and stakeholders to enhance the competitiveness and sustainability of the bioenergy sector. Promoting best practices and reducing negative impacts are crucial for the sector's growth and sustainability.

Bioenergy is one of the cornerstones of the EU's strategy to achieve a low-carbon economy and enhance energy security. The EU must navigate the identified challenges to fully realise the potential of bioenergy in contributing to a sustainable and diversified energy future. Continued investment in research, development, and demonstration projects, along with strong collaboration networks within the EU, will be crucial for the continued development and success of the bioenergy sector.

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List of abbreviations and definitions

AD	Anaerobic Digestion
Bcm	Billion cubic metres
BIG-GT	Biomass Integrated Gas Turbine
Bm^3	Billion cubic metres
BtL	Biomass to Liquid
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CETO	Clean Energy Technology Observatory
CFBC	Circulating Fluidised Bed Combustion
CHP	Combined Heat and Power
CPC	Coordinated Patent Classification
DH	District Heating
FBC	Fluidised Bed Combustion
FT	Fischer-Tropsch
FWCI	Field Weighted Citation Impact
GDP	Gross DomesticPproduct
GHG	GreenHouse Gas
GW	Gigawatts
GWp	Gigawatt-peak
H&P	Heat and Power
HTC	HydroThermal Carbonisation
HTG	Hydrothermal Gasification
HTL	HydroThermal Liquefaction
IEA	International Energy Agency
IED	Industrial Emissions Directive
ILUC	Indirect Land Use Change
IPC	International Patent Classification
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
Jobs/GWh	Jobs / gigawatt hours
JRC	The European Commission's Joint Research Centre
LCA	Life Cycle Analysis
LCEO	Low Carbon Energy Observatory
LCOE	Levelised Cost Of Electricity
LFG	LandFill Gas

LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MJ/kg	Megajoules per Kilogram
MS	The Member States of the European Union
MSW	Municipal Solid WasteMtoe
OPEX	Operational Expenditure
PWS	Pressurised Water Scrubbing
PSA	Pressure Swing Adsorption
RDD	Research, Development and Demonstration
RED II	Renewable Energy Directive; Directive (EU) 2018/2001 European Parliament and of the Council 11 December 2018 on the promotion of the use of energy from renewable sources (recast)
R&D	Research and Development
R&I	Research and Innovation
RES	Renewable Energy Sources
SCR	Selective Catalytic Reduction
SET Plan	Strategic Energy Technology Plan
SNG	Synthetic Natural Gas
Toe	Tonnes of oil equivalent
TRL	Technology Readiness Level
TWh	Terawatt-hour
VC	Venture capital
We	Watt-electric
Wh/t	Watthours per tonne

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Annexes

Annex 1 Summary Table for the CETO Indicators

Theme	Indicator
Technology maturity status, development and trends	Technology readiness level
	Installed capacity & energy production
	Technology costs
	Public and private RD&I funding
	Patenting trends
	Scientific publication trends
	Assessment of R&I project developments
Value chain analysis	Turnover
	Gross Value Added
	Environmental and socio-economic sustainability
	EU companies and roles
	Employment
	Energy intensity and labour productivity
	EU industrial production
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections
	EU market share vs third countries share, including EU market leaders and global market leaders
	EU trade (imports, exports) and trade balance
	Resource efficiency and dependencies (in relation EU competiveness)

Annex 2 Sustainability Assessment Framework

Parameter/Indicator	Input
Environmental	
LCA standards, PEFCR or best practice, LCI databases	Life Cycle Assessments (LCA) are commonly used to quantify the GHG emissions savings of bioenergy, by comparing the bioenergy system with a reference (fossil) energy system following a life cycle approach. The utilization of by-products that can displace other materials, having GHG and energy implications, must also be considered in the analysis. The RED II 2018/2001 established the methodology for the calculation of greenhouse gas emissions from the production and use of biomass fuels before conversion into electricity, heating and cooling based on a life cycle approach. This includes all emissions from the extraction or cultivation of raw materials, emissions from processing, transport and distribution and emissions from carbon stock changes caused by direct land-use change. REDII set the typical and default values of greenhouse gas emissions savings for biomass fuels. Several LCA models are available for GHG emission estimation, such as Biograce, E3 Database in Europe, the Argonne National Laboratory GREET model in the US and the GHGenius model in Canada. LCA requires large amounts of data on a specific product or service for assessing the complete supply chain. The wide range of results of LCA studies occurred depending on the data that are generally valid for certain regions and conditions. Several LCA databases for the GHG and energy balance of bioenergy systems are available worldwide, such as ECOINVENT, ELCD (European reference Life Cycle Database), GEMIS (Global Emission Model for Integrated Systems), CPM LCA Database or US Life Cycle Inventory Database (LCI) from NREL (Scarlat and Dallemand, 2018). Sustainability criteria RED II established the sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids and biomass fuels. The standard ISO 13065:2015 on Sustainability criteria for bioenergy provides a practical framework to facilitate the assessment of environmental, social and economic aspects and the evaluation and comparability of bioenergy production and products, supply chains and applications. ISO 13065 provides sustainability principles, criteria and measurable indicators to provide objective information for assessing sustainability. ISO

	13065:2015 specifies principles, criteria and indicators for the bioenergy supply chain to facilitate assessment of environmental, social and economic aspects of sustainability.
GHG emissions	The RED III extended the sustainability criteria to solid and liquid and gaseous biomass. Biomass fuels shall fulfil the sustainability and greenhouse gas emissionssaving criteria if used: • in the case of solid biomass fuels, in installations producing electricity, heating and cooling with a total rated thermal input equal to or exceeding 7.5 MW, (initially 20 MW) • in the case of gaseous biomass fuels, in installations producing electricity, heating and cooling with a total rated thermal input equal to or exceeding 2 MW, • in the case of installations producing gaseous biomass fuels with the following average biomethane flow rate: o above 200 m3 methane equivalent/h measured at standard conditions of temperature and pressure, o if biogas is composed of a mixture of methane and non-combustible other gases, for the methane flow rate, the threshold set out in point, recalculated proportionally to the volumetric share of methane in the mixture. The calculation of the GHG emissions has been performed by the JRC (Prussi et al., 2020) for a large number of bioenergy pathways. The GHG emissions for a selection of bioenergy pathways is presented in the next: GHG footprint for electricity generation g CO_{2eq}/MJ biogas from municipal waste, large power plant: 13.5 - 15.9 g CO_{2eq}/MJ biogas from wet manure, local (closed storage): (-247.1) - (-233.3) g CO_{2eq}/MJ farmed wood, 200 MW gasification: 15.9 - 17.3 g CO_{2eq}/MJ farmed wood, conventional power: 25.7 - 27.9 g CO_{2eq}/MJ waste wood, 200 MW gasification: 10.9 - 12.1 g CO_{2eq}/MJ waste wood, conventional power: 18.4 - 19.9 g CO_{2eq}/MJ GHG footprint for heat generation heat from biogas (municipal waste, closed storage): 8.2 - 9.5 g CO_{2eq}/MJ heat from biogas (wet manure, closed storage): (-104.2) – (-102.9) g CO_{2eq}/MJ heat from farmed wood, industrial: 7.1 - 7.4 g CO_{2eq}/MJ heat from waste wood, industrial: 4.5 - 4.6 g CO_{2eq}/MJ

	GHG footprint for electricity generation in CHP electricity from farmed wood, CHP: 5.4 - 7.6 g CO_{2eq}/MJ electricity from waste wood, CHP: 2.8 - 3.7 g CO_{2eq}/MJ electricity from biogas from silage maize: 75.0-84.0 g CO_{2eq}/MJ electricity from biogas from biowaste: 19.3 - 43.9 g CO_{2eq}/MJ electricity from biogas from manure: (-267.2) - (-230.6) g CO_{2eq}/MJ GHG footprint for heat generation in CHP heat from farmed wood, CHP: 1.5 - 2.5 g CO_{2eq}/MJ heat from waste wood, CHP: 0.5 - 1.0 g CO_{2eq}/MJ Bioenergy with Carbon Capture and Storage (BECCS) is the industrial option available today enabling achieving negative carbon dioxide emissions, when using sustainable biomass (Creutzig et al., 2015; Clery and Rackley, 2023; IEA Bioenergy). According to IEA, the deployment BECCS is essential to reach net-zero emissions by 2050, offsetting emissions from sectors (such as industry or transport) where their mittigation is very difficult (IEA, 2021).
Energy balance	JRC performed the balance of the energy expended in different bioenergy pathways (Prussi et al., 2020). The energy expended ratio is given for a selection of bioenergy pathways is presented in the next: Energy expended (MJ/MJ final fuel) electricity generation -biogas from municipal waste, large power plant: 2.27 - 2.46 MJ/MJ final fuel -biogas from wet manure, local (closed storage): 4.76 - 5.08 MJ/MJ final fuel -farmed wood, 200 MW gasification: 1.58 - 1.80 MJ/MJ final fuel -farmed wood, conventional power: 2.83 - 3.24 MJ/MJ final fuel -waste wood, 200 MW gasification: 1.45 - 1.68 MJ/MJ final fuel -waste wood, conventional power: 2.64 - 3.01 MJ/MJ final fuel heat generation -heat from biogas (municipal waste, closed storage): 0.82 - 0.92 MJ/MJ fuel

	-heat from biogas (wet manure, closed storage): 1.67 - 1.71 MJ/MJ final fuel -heat from farmed wood, industrial: 0.38 - 0.47 MJ/MJ final fuel -heat from waste wood, industrial: 0.32 - 0.40 MJ/MJ final fuel electricity generation in CHP -electricity from farmed wood, CHP: 0.38 - 1.00 MJ/MJ final fuel -electricity from waste wood, CHP: 0.35 - 0.90 MJ/MJ final fuel heat generation in CHP -heat from farmed wood, CHP: (-0.47) – (-0.18) MJ/MJ final fuel -heat from waste wood, CHP: (-0.47) – (-0.20) MJ/MJ final fuel
Ecosystem and biodiversity impact	The major issue related to the use of biomass crops for energy is that they compete for water, land and nutrients with food and feed crops, and that they could cause land use changes. Habitat loss due to the conversion of natural landscapes for biofuel production is one of the major pathways for biodiversity loss (Ale et al, 2019). Excessive crop residues and forest residue extraction might lead to ecosystem degradation and loss of biodiversity through the reduction of soil organic matter , nutrient availability, decreased dead wood, increased erosion risks. The application of Sustainable Forest Management practices, together with guidelines for sustainable extraction rates can alleviate to some extent certain negative impacts (IEA Bioenergy). The use of perennial energy crops can have a positive impact on biodiversity, increase carbon stock, improve soil quality, and reduce soil erosion especially when grown on marginal[2] and degraded land (IEA Bioenergy: ExCo, 2016; Irena, IEA Bioenergy, and FAO, 2018; Gerwin et al., 2018; Vera et al., 2022; IEA Bioenergy; Agostini et al., 2021; Scarlat and Dallemand, 2018). There are significant trade-offs and synergies between bioenergy and food production, water, ecosystems, that can produce multiple benefits, if properly planned and managed (Dauber et al., 2012; Dauber and Miyake, 2016; Creutzig et al., 2015; Englund et al., 2020; Englund et al., 2023). In a number pathways, bioenergy affects negatively ecosystem

[2] Marginal lands are intended as lands facing natural constraints, where competition with food production is likely to be avoided when used. They are characterised by severe biophysical soil constraints (low fertility, poor drainage, shallowness, salinity, steepness of terrain and unfavourable climatic conditions) and socio-economic constraints. Several EU projects addressed the issue of marginal lands, including MAGIC, Seemla, MUSIC, BIOPLAT EU, S2biom, GOLD, etc., to identify and assess the potential of marginal lands for bioenergy. FAO-CGIAR defined marginal land as: "*Land having limitations which in aggregate are severe for sustained application of a given use. Increased inputs to maintain productivity or benefits will be only marginally justified. Limited options for diversification without the use of inputs. With inappropriate management, risks of irreversible degradation*" (FAO CGIAR, 2000).

	health and biodiversity, and should therefore be avoided (Vera et al., 2022; Welfle et al., 2023). RED II established the sustainability and the greenhouse gas emissions saving criteria for the energy from biofuels, bioliquids and biomass fuels. Similar to biofuel feedstocks, biomass for heat and power should not be sourced from land converted from forest or other areas of high biodiversity or high carbon stock. Biofuels, bioliquids and biomass fuels produced from waste and residues, other than agricultural and forestry residues, are required to fulfil only the greenhouse gas emissions saving criteria. Secondary agri, industrial and wood residues include residues from the wood processing industry, are utilised in the wood industry, while the remaining part is already used for energy generation with no impact on ecosystems and biodiversity. The RED II excludes several land categories, with recognised *high biodiversity value*, from being used for biofuels, bioliquids and biomass fuels production: a) primary forests and other wooded land; b) highly biodiverse forests and other wooded land; d) areas designated for nature protection or for the protection of rare, threatened or endangered ecosystems or species; c) highly biodiverse grassland, either natural or non-natural. Biofuels, bioliquids and biomass fuels shall not be made from material from peatland and land with *high carbon stock*, such as: a) wetlands; b) continuously forested areas; c) land covered by trees higher than 5 m and a canopy cover between 10% and 30%. Biofuels, bioliquids and biomass fuels produced from forest biomass shall meet the following criteria: (a) national or sub-national laws or (b) management systems are in place ensuring: (i) legality of harvesting operations; (ii) forest regeneration of harvested areas; (iii) protection of designated areas; (iv) maintenance of soil quality and biodiversity; and (v) maintenance or improvement of long-term production capacity of the forest. ILUC Implementing regulation - 2022/996 with Auditing of natural and non-natural highly-biodiverse grassland
Water use	Water is used at different stages of energy production: fuel production, power plant construction and operation. Water requirements vary depending on fuel used, type of cooling systems, plant location or climate conditions. In the case of bioenergy, water is used for biomass growth and for power plant construction and operation. Water consumption for biomass growth can be substantial, up to 100 times greater than operational cooling system needs. Water use for biomass feedstock

	Differences among biomass feedstock are large, depending on the type of biomass feedstock used, the agricultural system and climatic conditions and if biomass crops or waste and residues are used. In the case of the waste and residues, the water consumption can be very low, because the water consumption is allocated between the main crop and crop residues (Gerbens-Leenes, Hoekstra, and van der Meer, 2009; Mathioudakis et al., 2017). -crop residues: 8-10 m^3/GJ -firewood: 21-73 m^3/GJ -energy crops: 20-64 m^3 /GJ The use of agro or forestry residues and industry process by-products can decrease the water consumption per bioenergy output substantially. Water use for power plant operation Most of the water used during power plant operation comes from the cooling systems this depends on fuel type, cooling system and technology. Cooling of power plants dominates the total water consumption and withdrawal depending highly on the type of cooling system installed. Cooling systems use fresh or saline water and include recirculating systems (evaporative cooling towers), once-through cooling systems (open loop cooling), air-cooled condensing (dry cooling), hybrid wet and dry cooling systems (hybrid cooling), and pond cooling systems (Macknick et al., 2012). -steam turbine with cooling tower: 2.095 (1.818-3.653) m^3/MWh -steam turbine with pond: 1.476 (1.136-1.817 m^3/MWh) -steam turbine once-through: 1.136 m^3/MWh -gas turbine, internal combustion engine: 0.189 (0.189-1.288) m^3/MWh -biogas dry: 0.132 m^3/MWh Water use for power plant construction Water use for power plant construction is negligible in most thermoelectric technologies (except for CSP plants) compared to water use during power plant operations (Macknick et al., 2012). Biomass: -steam turbine: 0.0039 (0.0012-0.0986) m^3/MWh -gas turbine: 0.0039 (0.0012-0.0986) m^3/MWh -internal combustion engine 0.0039 (0.0012-0.0986) m^3/MWh
Air quality	Biomass combustion emit various air pollutants that include nitrous oxides, carbon monoxide, particulate matter (PM), black carbon, as well as

	polyaromatic hydrocarbons (PAHs) (Booth, 2018). Air emissions vary according to the technology used, operation and the biomass characteristics. The emissions of PM as well as black carbon and PAHs from biomass combustion at small scale in the residential sector are of the greatest concern for local air quality specially for small scale applications. New developed technologies enable the reduction of pollutant emissions to very low levels below the emission limits (Obernberger et al., 2017; Schwarzer et al., 2022). In practice, the domestic combustion of biomass, not subject to sustainability criteria, is a source of major concern in terms of air pollution especially amongst the poorest people who are likely not to rely modern bioenergy, but on less efficient boilers and no control over air pollutant emissions.He The regulatory regimes for biomass plants, and the control of emissions depends on the size of the installation: a) For large scale installations (above 50 MWth capacity): Regulation through the Industrial Emissions Directive (IED, 2010/75/EU); b) For medium to large scale installations (1 - 50 MWth) capacity, the Directive (EU) 2015/2193 Medium Combustion Plant Directive with emissions limits for sulphur dioxide (SO_2), nitrogen oxides (NO_X) and dust. For combustion plants that apply to electricity generation, domestic or residential heating and cooling, providing heat or steam for industrial processes. The Eco-design Directive provides the rules for improving the environmental performance of products and sets out minimum mandatory requirements for the energy efficiency for smaller appliances (heaters and boilers <1 MWth).
Land use	Land use / land use change Increased demand of biomass for energy could lead to both direct and indirect land use change. Direct land use change accounts for changes associated with the expansion of biomass production on cropland, the displacement of food or feed crops and the possible conversion of other land use types into cropland. The increased demand of biomass might have multiple effects: crop area expansion; multiple cropping and yield increase through agriculture intensification. Land use change can have a positive or a negative impact. If high soil carbon stocks land (e.g. grassland, forest land) is converted into cropland, this might lead to high carbon emissions. When marginal or degraded land, with low carbon stock is used, or when perennial energy crops are established on cropland, this leads to an increase in the carbon stock (Hiederer et al., 2010),. To limit certain negative impacts, the EU-RED excludes several land categories, with recognised high biodiversity value and land with high carbon stock, from being used

	for biomass fuels production. However high-biodiversity land is not defined in RED, and the implementation of this provision is open to interpretation. Wastes and residues from agriculture and by-products from the forest sector, or the use of agricultural or industry waste can be important sources for bioenergy with no land use impacts. Indirect land use change Indirect Land Use Change (ILUC) includes the change in land use outside the production area. Since ILUC is not empirically observable, the estimates are determined mostly through modelling and few studies have been conducted to find evidence of ILUC in historical data. Since the ILUC impact cannot be unequivocally determined with an adequate level of precision, criteria were developed to mitigate the risk for ILUC. The highest risks of ILUC have been identified for the feedstock (used for all purposes) for which a significant expansion of the production area into land with high-carbon stock was observed. In order to mitigate ILUC, the ILUC Directive 2015/1513 and the RED II limited the share of high ILUC-risk biofuels produced from food and feed crops and reduced the share of high ILUC-risk biofuels, bioliquids or biomass fuels down to zero in 2030. Low ILUC-risk biofuels, bioliquids and biomass fuels are exempt from the specific and gradually decreasing limit. Low ILUC-risk biofuels, bioliquids and biomass fuels are fuels produced from feedstock within schemes which avoid displacement effects through improved agricultural practices as well as through the cultivation of crops on areas which were previously not used for cultivation of crops.
Soil health	The use of agri, forestry residues or waste offers good opportunities for bioenergy production with low or no land use competition. In the past, most of the crop residues were not collected from land and burned in the fields. During the last years, crop residue burning in the field has been banned for air quality protection reasons. Biomass left on land is an important source of organic carbon in soil and play a key role for the maintenance of soil organic matter balance, the improvement of soil structure and nutrients in soil. Excessive residue removal from the field can reduce the carbon input into soil, soil organic carbon, which may reduce the long-term productive capacity of the soils. The fate of soil organic carbon in soil depends on the biomass input, the farming practices (tillage, crop rotation, nutrients input, etc.), soil characteristics (soil texture and structure) and climate (moisture, temperature). Some management practices can offset soil carbon

	losses due to residue removal, such as the use of cover crops, no-tillage, crop rotation and the application of digestate, compost or biochar. Bioenergy perennial crops (energy grasses, short rotation coppice, etc.) can reduce water and wind erosion, improve soil and water quality through riparian buffers and windbreaks, and provide a substantial carbon sequestration potential for cropland when introducing annual crops grass rotation, etc. (Englund et al., 2020; Agostini et al., 2021). In particular, the addition of biochar can promote long-term carbon sequestration in soil.
Hazardous materials	The various bioenergy technologies do not use hazardous materials for the manufacture of various components (boilers, reactors, steam turbines, gas turbines, tubes, compressors, fans, etc.).
Economic	
LCC standards or best practices	
Cost of energy	See 2.3 Technology Cost – Present and Potential Future Trends
Critical raw materials	Materials for various bioenergy technologies include stainless steels and nickel–chromium alloys, depending on operating conditions (pressure, temperature) and working environment. The choice of materials takes into account characteristics at high temperature, surface degradation through deposition, erosion, or corrosion due to various impurities, water vapour oxidation, hydrogen embrittlement etc. Reaching high efficiency is limited by the steam parameters (temperature, pressure) related to the need for the use of higher-grade materials (adequate strength at higher temperature and pressure) and corrosive and abrasive environment. Certain catalysts are needed in relatively small quantities to enhance the yield of desired products or selectivity by promoting various reactions in gasification, hydrothermal liquefaction, gas cleaning, gas shift reactions, cracking reactions, etc., depending on the process and operating parameters. A range of catalysts can be used, including natural catalyst (dolomite, olivine, zeolite, etc.), alkali and alkaline earth metals and stable metal catalysts. Naturally occurring catalysts are inexpensive and are readily available. Metal catalysts (Ni, Ru, Pd, Pt, Rh, Zn, Cu, Al, Co, Cr, Fe based catalysts etc.) show better performance but are costly and can suffer from fouling, poisoning and catalyst deactivation in various environments.

Resource efficiency and recycling	Resource efficiency emerged to develop a resource-efficient, to achieve sustainable growth and to decouple economic growth from resource and energy use. REDII provides that biomass should be converted into electricity and heat in an efficient way to maximise energy security and greenhouse gas emissions savings, to limit emissions of air pollutants and minimise the pressure on limited biomass resources. RED II also provides for some requirements for the efficient use of biomass fuels. Electricity production from biomass fuels produced in installations with a thermal input range 50-100 MW should be done, with high-efficiency cogeneration. Electricity-only plants must achieve energy efficiency level of the Best Available Techniques defined in Commission Implementing Decision (EU) 2017/1442. Electricity produced in plants with a thermal input above 100 MW should be done by high-efficiency cogeneration or, for electricity-only installations, achieving a net-electrical efficiency of at least 36%. MS may apply higher energy efficiency requirements to installations with lower rated thermal input. The multiple uses of biomass (food, feed, fibre, biomaterials and bioenergy) entails a combination of several applications in a cascade of uses, based on the prioritization of biomass use. A number of factors could be considered in the prioritisation of biomass use, such as the economic or social value of biomass products, the conversion efficiency of biomass, in addition to the GHG emission reduction performances and the environmental impacts, etc. According to RED II, when developing support schemes, Member States should consider the availability of sustainable biomass and respect the principles of the circular economy and of the waste hierarchy (in line with Directive 2008/98/EC) to avoid unnecessary distortions of raw materials markets.
Industry viability and expansion potential	Yes, see markets section
Trade impacts	Yes, see markets section
Market demand	Yes, see markets section
Technology lock-in/innovation lock-out	There is no considerable risk of technology lock-in as the bioenergy will be able to enable the integration of the variable renewable electricity in the electricity grid.
Tech-specific permitting requirements	The rules for permitting are very complex and lengthy, representing important barriers for renewable energy deployment and include environmental and building permits. The duration, complexity and the steps for the permit-granting procedures varies largely between different

	renewable energy technologies and MS, from 6 weeks up to 24 months. A Commission recommendation was adopted in May 2022 for accelerating permitting for renewable energy projects to ensure that projects are approved in a simpler and faster way (max two years, for projects outside renewables go-to areas), streamlining the different steps of the permit-granting processes and providing a specific framework for permit-granting procedures. Bioenergy is today the most regulated energy sector when it comes to environmental protection under the RED. Economic operators must comply with additional requirements in comparison to other renewable energy installations, irrespective of the place of origin of biomass. Economic operators must provide evidence that energy from biofuels, bioliquids and biomass fuels fulfil the sustainability and the greenhouse gas emissions saving criteria, in accordance with a scheme recognised by the Commission. Biomass fuels shall fulfil the sustainability and greenhouse gas emissions saving criteria if used in installations Biomass fuels shall fulfil the sustainability and greenhouse gas emissionssaving criteria if used: • in the case of solid biomass fuels, in installations producing electricity, heating and cooling with a total rated thermal input equal to or exceeding 7.5 MW, (initially 20 MW) • in the case of gaseous biomass fuels, in installations producing electricity, heating and cooling with a total rated thermal input equal to or exceeding 2 MW, • in the case of installations producing gaseous biomass fuels with the following average biomethane flow rate: o above 200 m3 methane equivalent/h measured at standard conditions of temperature and pressure, o if biogas is composed of a mixture of methane and non-combustible other gases, for the methane flow rate, the threshold set out in point, recalculated proportionally to the volumetric share of methane in the mixture
Sustainability certification schemes	Voluntary schemes and national certification schemes of EU MS can ensure that biofuels, bioliquids and biomass fuels are sustainably produced, by verifying that they comply with the sustainability criteria set by the RED. Several voluntary schemes take into account additional sustainability aspects, as compared to the minimum RED mandatory sustainability criteria, such as soil, water, air protection and social criteria. The EU sustainability criteria are extended to cover biomass for heating and cooling and power generation in the revised Directive (EU) 2018/2001. The EU Member States are responsible for checking compliance with the sustainability criteria, while the European Commission can recognise the compliant voluntary sustainability certification schemes. The

	European Commission has formally recognized 13 voluntary schemes under REDII (June 2022).
Social	
S-LCA standard or best practice	Not available
Health	Air pollution has now been identified as the most significant environmental risk to human health. Biofuel combustion emits nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), and other hazardous air pollutants. Like other combustion fuels, air pollution from burning biomass can cause various human health impacts. The emissions of particulate matter (including black carbon) and polyaromatic hydrocarbons (PAHs) from biomass combustion at small scale in the residential sector are of the greatest concern. The use of biomass for heating and cooking, as traditional bioenergy, can have severe impact on indoor and local air quality and health that can be mitigated through the use of modern heating systems. The use of various waste for energy or fuels has to protect the environment, reduce methane emissions and protect human health from the harmful effects of waste in accordance with contribute to the objectives of the Waste Framework Directive 2008/98/EC (WFD) and protect human health from the harmful effects of waste in accordance with contribute to the objectives of the Waste Framework Directive 2008/98/EC (WFD).
Public acceptance	Public acceptance is essential for successful development and take up of bioenergy. The debate around the sustainability concerns of bioenergy and biofuels raised questions on the real benefits and negative impacts on biodiversity, competition for food and feed and land use and led to decreased social acceptance. The public needs to be informed and confident that bioenergy is environmentally and socially beneficial and all the trade-offs are considered (IEA Bioenergy, 2009; Welfle et al., 2023). Public awareness and knowledge on the real benefits and the negative impacts, as well as on the best uses of biomass can lead to the promotion of best practices and reduction of negative impacts and can contribute to social acceptance of bioenergy .. However, “each application must be judged on its own specific circumstances, and generalisations regarding the sustainability of bioenergy feedstocks, fuels and technologies have limited value and can be misleading” (IEA, 2018).
Education opportunities and needs	Biomass energy is highly complex field, having multiple trade-offs and synergies with agricultural production, forestry and environmental preservation as well as technological development.

	Biomass production for bioenergy and biofuels can contribute to improve the competitiveness of agriculture and forestry, ensure EU technological leadership, and diversify the rural economy and to support rural development. The need for further R&D for the development of various bioenergy technologies also requires the need for education programs on technologies that convert biomass into bioenergy, intermediate energy carriers and biofuels as well as environmental sciences. Education opportunities concern the development of new processes, improvement of process performances, process control, process integration and optimisation, opportunities for development of new analysis and testing methods, development of new materials.
Employment and conditions	For employment data see section 3.5
Contribution to GDP	see VC analysis section
Rural development impact	Bioenergy ensures significant positive impact on sustainable rural development Bioenergy production provides job opportunities along the supply chain, including skilled labour that can be a driver of agriculture, forestry and industrial development in rural areas. Biomass production for bioenergy provides opportunities to promote sustainable agriculture and forestry, to improve agricultural practices, supply chain logistics and local infrastructure that are beneficial for food production. Positive effects of bioenergy production include new income-generating opportunities in rural areas, enhanced economic security of rural communities by supporting economic activities and economic growth (Scarlat and Dallemand, 2018).
Industrial transition impact	Today, bioenergy plays an important role in climate change mitigation, representing about 60 % of the renewable energy used in the EU. Bioenergy biofuels can play on short term to the decarbonisation of the economy, to the increase of the energy security and in the transition toward a low carbon economy. Bioenergy provides flexible low carbon power generation that can be used to balance the grid and is a key element enabling high shares of variable renewable energies, such as wind and solar, in the electricity grids. Bioenergy can contribute on short term on the decarbonisation of industry; for example, biochar can be used as a substitute for coke in steel industry as chemical-reducing agent for the reduction of iron oxides, as catalyst for industrial applications. Biomethane can contribute on short term to the decarbonisation of the gas grids, increasing the share of renewable energy in the natural gas grid. Biomethane be used in connection with gas storage as energy storage solution

	enhancing energy security and can be used to meet the electricity demand and balance the grid. Bioenergy with Carbon Capture and Storage (BECCS) is now the only commercially available industrial-scale option that can achieve negative CO_2 emissions (Clery and Rackley, 2023; Creutzig et al., 2015), with significantly reduced emissions can be achieved through the production of biochar as carbon storage on land and as a soil amendment.
Affordable energy access (SDG7)	Sustainable energy is a key enabler for sustainable development. Energy poverty in a wide context is related to the access and affordability of energy. The use of biomass can make a significant contribution to the achievement of the sustainable development goals, in particular on the 2030 goal to ensure universal access to affordable, reliable, sustainable and modern energy for all (SDG7). Modern bioenergy is expected to increase globally and to play an important role in the future sustainable energy supply, fostering sustainable and clean energy (Fritsche, Cowie, and Johnson, 2017; Scarlat and Dallemand, 2018).
Safety and (cyber)security	Not relevant to specific technology.
Energy security	Bioenergy is a key element in the electricity system, increasing the diversity of energy supply for balancing the electricity grid and enabling higher shares of renewable energies, such as wind and solar. Improved access to reliable and affordable energy, including through the use of bioenergy, offers opportunities for economic activities and growth. Local modern bioenergy enhances energy access for energy-deprived and remote communities. Bioenergy can contribute to the energy security since biomass power plants can be used as a base-load or for grid balancing, having certain flexibility capability in operation. Biomethane can increase the share of renewable energy in the natural gas grid and then be used in connection with gas storage to compensate for variable renewables. Biomethane can be produced through methanation when there is excess variable renewable production. Biogas injection into the gas grid can exploit the large storage capacity of the gas systems connected to the gas storage facilities, enhancing energy security. Biomethane can be used in a number of end-use applications (heat, power and transport fuel) thus increasing energy security.
Food security	The most significant concerns for the use of biomass for bioenergy include the risks of increased competition between food and non-food uses of biomass. RED strictly limits the use of biofuels and bioliquids, as well as of biomass fuels

	consumed in transport, where produced from food and feed crops, in order to reduce the impact on food availability and food security. Food security, according to FAO, has multiple dimensions: availability, accessibility, stability and utilization. The competition between food and non-food uses may put at risk local food supplies and food security, while bringing little benefits for local population other than additional income (Fritsche, Cowie, and Johnson, 2017; Osseweijer et al., 2015; FAO, 2017). The use of agricultural, forestry residues and industry waste for bioenergy, and the use of marginal, abandoned or degraded land for biomass feedstock production can minimize food-bioenergy competition (Fritsche, Cowie, and Johnson, 2017; Irena, IEA Bioenergy, and FAO, 2018). Positive effects of bioenergy production include enhanced economic conditions of rural communities, new job opportunities, increasing overall food availability, food accessibility and affordability (IEA Bioenergy: ExCo, 2016). Bioenergy can increase food security through improved farming practices, improved infrastructure and investments leading to increased crop productivity and food production.
Responsible material sourcing	Responsible sourcing has become a topic of interest to address sustainability risks in the global mineral supply chains. Several responsible sourcing initiatives exist for various materials, most of them aligned with the OECD guidance for responsible supply chains of minerals from conflict-affected and high-risk areas. The OECD Guidance focuses on issues of human rights, forced and child labour, occupational health and safety, human well-being and legality of operations. The EU Regulation (EU) 2017/821) established the requirements for supply chain due diligence obligations for materials originating from conflict-affected and high-risk areas. Responsible consumption and production is addressed by the SDG 12 *Ensure sustainable consumption and production patterns* that aims to ensure responsible consumption and production in the world, by ensuring efficient and sustainable use of natural resources by 2030. Some companies have taken voluntary commitment for responsible sourcing into account social and environmental considerations in their supply chains and their products. Sustainability assessment, using a variety of standards and frameworks, has also become a more common practice at the corporate level and plays a prominent role for responsible sourcing. For bioenergy and advanced biofuels, voluntary schemes and national certification schemes were developed to ensure that biofuels, bioliquids and biomass fuels comply with the sustainability criteria set by the renewable energy directive.

	Voluntary schemes generally consider additional soil, water, air protection and social criteria. Regulation (EU) 2017/821 has low relevance for bioenergy and advanced biofuels requiring higher grade steel and certain metal catalysts needed in relatively small quantities.

Annex 3 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 3.1 POTEnCIA Model

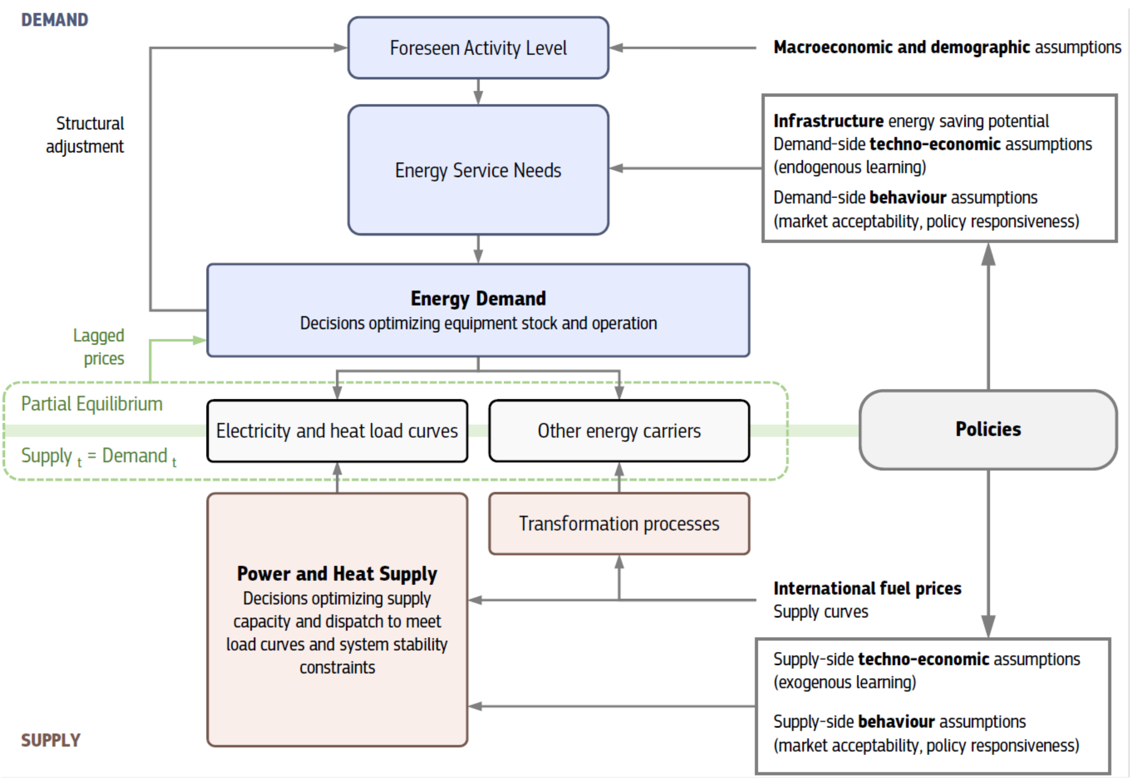
AN 3.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (**Figure 74**; detailed in (Mantzos et al., 2017; Mantzos et al., 2019) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 74. The POTEnCIA model at a glance



Source: JRC adapted from (Mantzos et al., 2019)

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES; (Rózsai et al., 2024)).

AN 3.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 Scenario* will be available in the forthcoming report (Neuwahl et al., 2024).

AN 3.2 POLES-JRC model

AN 3.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

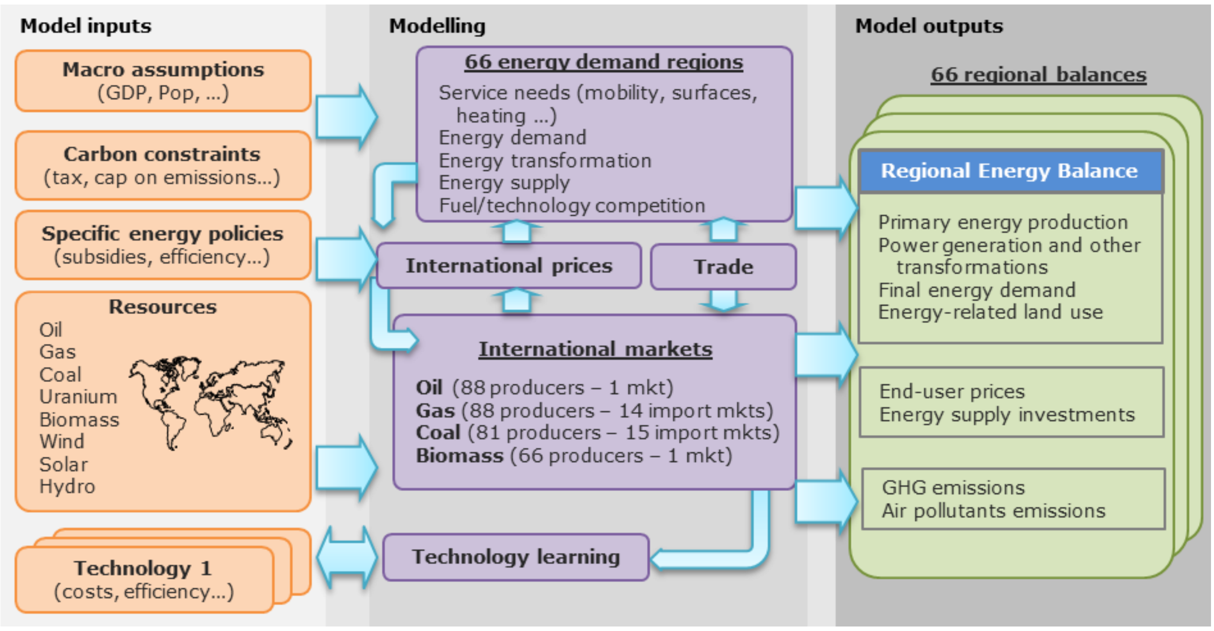
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in (Despres et al., 2018).

Figure 75. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

AN 3.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand
Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning
Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characeristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar. wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

AN 3.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2024* and its specific POLES-JRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" (Schmitz et al., 2024).

The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[3]:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.

[3] A description of the *Global CETO 2°C scenario 2023* can be found in Annex 3 of (Chatzipanagi et al., 2023).

- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

AN 3.3 Distinctions for the CETO 2024 Scenarios - POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The *Global CETO 2°C scenario 2024* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.

The POTEnCIA CETO 2024 scenario is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

Annex 4 PRODCOM Trade coding

HS code	Description	Alias
180200	Cocoa shells, husks, skins and other cocoa waste	cocoa shells
230310	Residues of starch manufacture and similar residues	starch residue
230320	Beet-pulp, bagasse and other waste of sugar manufacture	bagasse
440111	Fuel wood, in logs, billets, twigs, faggots or similar forms, coniferous	wood fuel
440112	Fuel wood, in logs, billets, twigs, faggots or similar forms, non-coniferous	
440121	Coniferous wood in chips or particles (excl. those of a kind used principally for dyeing or tanning purposes)	wood chips
440122	Wood in chips or particles (excl. those of a kind used principally for dyeing or tanning purposes, and coniferous wood)	
440132	Wood briquettes	wood pellets
440131	Wood pellets	
440139	Sawdust and wood waste and scrap, agglomerated in logs or similar forms (excl. pellets and briquettes)	sawdust
440141	Sawdust, not agglomerated	
440149	Wood waste and scrap, not agglomerated (excl. sawdust)	
440210	Bamboo charcoal, incl. shell or nut charcoal, whether or not agglomerated (excl. used as a medicament, mixed with incense, activated bamboo charcoal and in the form of crayons)	charcoal
440220	Wood charcoal of shell or nut, whether or not agglomerated (excl. of bamboo, used as a medicament, mixed with incense, activated charcoal and in the form of crayons)	
440290	Wood charcoal, whether or not agglomerated (excl. of bamboo or shell or nut, charcoal used as a medicament, charcoal mixed with incense, activated charcoal and charcoal in the form of crayons)	

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