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BIOENERGY IN THE EUROPEAN UNION

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

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Contents

Abstract

This report presents an assessment of the state of the art of key technologies for bioenergy production. Several biomass technologies are available for heat and power production from biomass, namely combustion, anaerobic digestion, as well as intermediate energy carriers produced by torrefaction, pyrolysis, hydrothermal processing and gasification.

Anaerobic digestion is a relatively established, commercial technology, with minimal environmental impacts when using manure, food and agricultural waste or sewage sludge, around TRL 8 - 9. Combined biogas and biomethane production in 2021 amounted to 196 TWh or 18.4 bcm. There were 18,774 biogas plants and 1,067 biomethane-producing facilities in Europe at the end of 2021, It means an additional 184 biomethane plants compared to 2020, the year 2021 registered the biggest increase in biomethane plants to date. GWe. Biomass combustion of solid, gaseous and liquid 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). In the EU the total bioenergy produced from solid biomass was 69.4 Mtoe in 2021, representing around 75% of all biomass use for energy, but with an environmental impact (air pollution, biodiversity), especially when not based on non-recyclable waste and residues.

Biomass pyrolysis has been successfully demonstrated at small-scale, and several pilot plants or demonstration projects (up to 200 ton/day biomass) are in operation. Hydrothermal processing is now advancing from lab-pilot scale (TRL 4-5) to pilot-industrial scale (TRL of 5-6) with some projects closer to demonstration. Gasification is still at demonstration stage, reaching TRL 6-7. Further technology development requires demonstration at scale and proof of reliable, continuous and long-term operation.

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, recognizing 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 Generals Research and Innovation (R&I) and Energy (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 pages

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Executive Summary

This report presents an assessment of the state of the art of key technologies for heat and power from biomass, namely combustion, anaerobic digestion, as well as intermediate energy carriers produced by using processes such as pelletization, pyrolysis, hydrothermal processing and gasification. The EU (European Union) has a leading role in bioenergy production today and further development can ensure its leadership in new emerging technologies, which can have key role in the transition towards a low carbon economy.

Anaerobic digestion is an established, commercial technology for manure, food and agricultural waste or sewage sludge, Technology Readiness Level (TRL) 8 - 9. There is a large number of operational biogas plants in the EU (about 18,843 biogas plants in 2021) with a total energy production of 159 TWh, while Biomethane production was at 37 TWh with 1067 facilities at the end of 2021. The combined biogas and biomethane produced in EU in 2021 was 18,4 bm^3 with a share of 4.4 % of natural gas consumed. The EU biogas sector's turnover in 2020 was 7770 M€, with 48900 direct and indirect jobs. The labour productivity was 0.12 M€/Job and 0.30 ktoe/Job. The current biomethane production costs average around 80 €/MWh, and includes feedstock costs (16 €/MWh), CAPEX (32 €/MWh) and OPEX (32 €/MWh). When produced the Biomethane needs to be injected into the gas grid at estimated costs at about 5% of the biomethane production costs (3 – 4 €/MWh). Alternatively, liquefaction has an average estimated cost at around 12 €/MWh.For Biogas production 7% CAPEX reduction, and 15% OPEX reduction are projected for 2030.

Biomass combustion of solid, gaseous and liquid biofuels occurs at both small-scale combustion and at large-scale combustion for heat, electricity or in Combined Heat and Power (CHP) applications. This is a mature, commercial technology (TRL 8 - 9). In the EU the total bioenergy produced from solid biomass was 79 Million Tons of oil Equivalent (Mtoe) in 2020, the turnover 29750 M€, 283000 direct and indirect jobs provided, labour productivity was at 0.1 M€/Job and 0.30 ktoe/Job, while the total bioenergy intensity, which is the relation between bioenergy primary energy produced in the EU, and its impact on GDP, it is estimated at 5.2 ktoe/M€. The LCOE for electricity production from solid biomass averaged 170 Euro/MWh in 2018, with CAPEX of average 2700 /KW and OPEX at 130 €/kWh.

Biomass pyrolysis has been successfully demonstrated at small-scale, and several pilot plants or demonstration projects (up to 200 tons/day of biomass) are in operation. The technology to produce upgraded pyrolysis oil, developed originally for heat, power, and food industry applications, ranges from the initial lab demonstration stage to pilot? production TRL 3 – 7.

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

Gasification is still at industrial demonstration stage, reaching TRL 6-8. Further technology development requires demonstration at scale and proof of reliable, continuous and long-term operation, which requires innovation to integrate various components into a full scale plant and requires significant R&D before reaching full maturity.

Energy carriers: pelletization has reached a maturity state of TRL 9. In 2020 EU production was 18.1 million tonnes, making it the world's major pellet producer. Germany is still the largest producer within the EU, whilst Czechia registered a remarkable increase of 21.5% in 2020. Regarding consumption, pellet use in 2020 increased by 7% globally compared to 2019, reaching 39.8 million tonnes. The EU remains the largest global pellet consumer. The residential and commercial segments were again led by Italy, which remains the world's largest pellet user for the residential sector, with a total consumption of 3.4 million tonnes.

The EU Horizon 2020 Research Programme (H2020) had funding dedicated to bioenergy projects that amounted to 769 M€ and financed 198 projects from 2014 to 2020.

For global private sector Venture Capital (VC), the highest investment level was reached in 2012 with almost 400 M€ invested. VC investments decreased from 2016 to 2021, and for those five years averaging around 50 M€ per year, while for the triennium 2010-2012 VC investment averaged around 250 M€ per year. EU had a share of 6 % of total VC capital invested 2016-2021 but 27 % of all deals.

For patents, for 2017-2019 the EU had 68% share of high-value patents with a total of 61 patents applications, while China applied for total of 276 patents, among which only 4 are considered high-value ones.

In terms of scientific publication, for what concerns biomass feedstock for H&P, the EU has been the leading actor, averaging more than 20 articles per year from 2014 onward and matched only by China with 30 articles each in 2021. For citations on biomass feedstock scientific articles, during 2000-2021, EU has 42 highly cited papers based on Field Weighted Citation Impact (FWCI).

Considering solid bioenergy carriers**,** EU produced a value of 5084 M€ in 2016, which increased to 6 276 M€ in 2020. The EU almost doubled the value of imports from 1010 M€ in 2015 to 1 826 M€ in 2021, while exports averaged 500 M€ from 2015 to 2020 (and peaked at 721 M€ in 2021).

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. As result, the EU Renewable Energy Directive (2009/28/EC) established the sustainability and GreenHouse Gas (GHG) emissions saving criteria for biofuels, bioliquids and biomass fuels. These apply to all installations producing electricity, heating and cooling or fuels with a fuel capacity equal or above 20 MW in the case of solid biomass, and with a fuel capacity above 2 MW in the case of gaseous fuels. Bioenergy from waste and processing residues needs to meet only the GHG saving criteria.

Bioenergy pathways available in the REDII Annex VI having GHG emissions under the 80% threshold required for bioheat or bioelectricity production, are mostly the ones powered by their own produced bioheat and electricity. When fossil-based inputs and grid electricity are used as energy supply for pellets or briquettes production, system sustainability is more challenging. Moreover, transport distances of wood chips and pellets strongly affect the pathway' sustainability, so short chain bioenergy systems are preferred. As regards the direct use of agro-residues for bioenergy purposes, it is easier to remain within the sustainability thresholds since feedstock come with no emissions debit since consisting in a bio-waste. Bioenergy with Carbon Capture and Storage is another option for achieving negative CO_2 emissions, offsetting emissions from sectors where their mitigation is very difficult. .

A major issue related to the use of biomass crops for energy is that they compete for land and resources with food production and could cause land use changes, with significant impact on biodiversity, in the case of large scale monocultures. The use of residues and non-recyclable wastes should be an important source for bioenergy, with no land use impacts. The use of crop and forest residues could also have some negative impacts if not properly managed, e.g. etc. when no sufficient residues are left on land, etc. (IEA Bioenergy). Depending on the previous land use, land use change can have a negative impact (if high soil carbon stocks land is converted to cropland) or positive impact (if marginal or degraded land is used, or when perennial energy crops are set up on cropland). To limit certain negative impacts, RED II excludes several land categories with high biodiversity value and high carbon stock from receiving support for bioenergy and count against targets..

The water use for biomass feedstocks is estimated for crop residues at 8-10 m^3/GJ; firewood 21-73 m^3/GJ, and energy crops 20-64 m^3/GJ, while at plant level the water use -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.

Air pollutant emissions vary according to the technology used, operation and the characteristics of biomass. The emissions of particulates (as well as black carbon) and polyaromatic hydrocarbons from biomass combustion in the residential sector are of the greatest concern for local air quality. 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 poor who are less likely to rely on modern bioenergy and more on less efficient boilers with no control over air pollutant emissions.

To ensure the most efficient possible use of biomass, RED II requires that electricity produced in plants with a thermal input between 50-100 MW to be done with high-efficiency cogeneration; electricity-only plants must achieve energy efficiency level of the Best Available Techniques. The electricity production in installations 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%.

According to the REPowerEU plan, bioenergy from sustainable sourcing will contribute to sustainable energy production by prioritizing use of non-recyclable biomass waste and agricultural and forest residues. In particular sustainable biomethane can contribute on short term to the goals of REPowerEU of reducing the EU dependence on imported fossil fuels and to the diversification of energy supply.

Table 1. CETO SWOT analysis for the competitiveness of bioenergy.

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 feedstocks are available in large amounts for bioenergy • bioenergy easily produced in decentralized 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 feedstocks 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 of small-scale combustion in residential areas • Potential negative effects on ecosystems and biodiversity due to increased intensity of management. • Biomass energy carriers Import and Negative trade balance for the EU
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

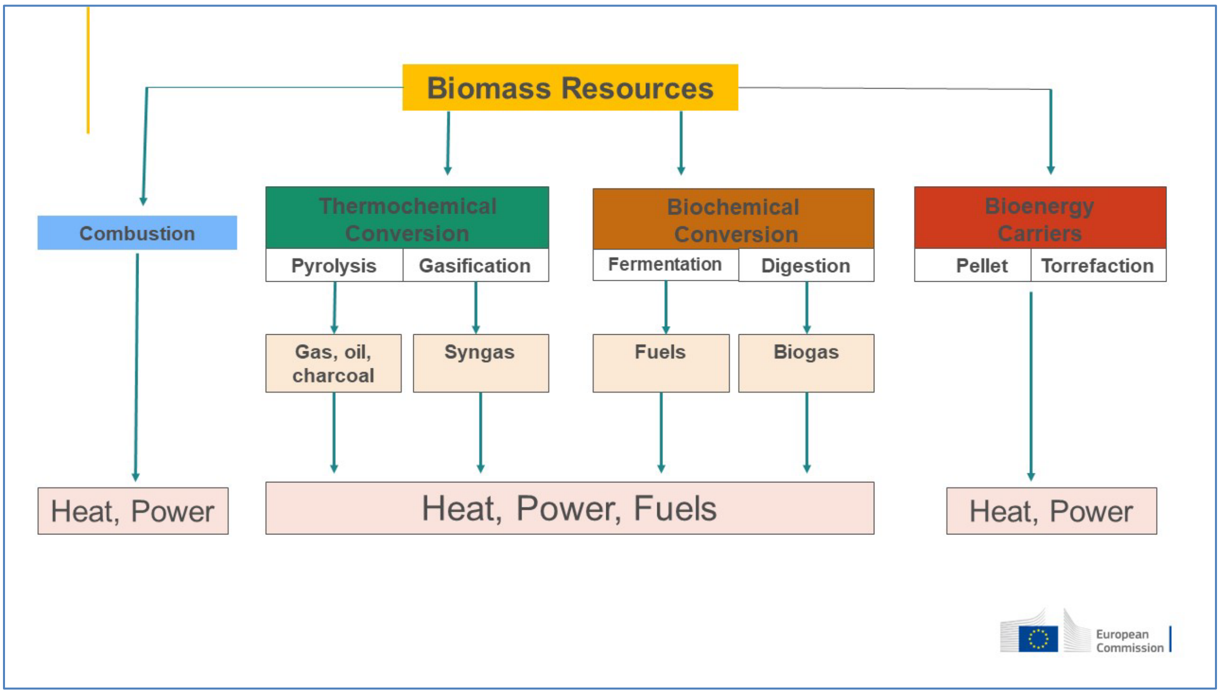
1.1 Scope and context

This report presents an assessment of the state of the art of key technologies for bioenergy production. The various biomass technologies were 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 study builds on previous Commission studies (Padella, Georgiadou, and Schleker, 2019).

The analysis focused on the main technologies that are currently used for heat and power production and intermediate energy carriers or have good prospects for entering soon on the market, including biomass combustion, anaerobic digestion, as well as torrefaction, pyrolysis, hydrothermal processing and gasification.

These various technologies, although in different stages of development, 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 that will be discussed in the report. Some technologies still require research support to improve their technical, economic and environmental performances to achieve commercial operation.

Figure 1 Biomass Heat & Power production flowchart.



Source: JRC 2023

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 divided as follows:

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

  POTEnCIA and POLES Models
- EUROSTAT and Eurobserver
- Existing scientific overviews and compilations

2 Technology status and development trends

2.1 Technology readiness level

SET Plan Action 8 Bioenergy and Renewable Fuels for Sustainable Transport, the TRL has been applied as recommended by the European Horizon 2020 Research Programme. Biomass Combustion, this indicator offers a classification related to technology readiness level:

- 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; or in space).

Anaerobic Digestion, 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) **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									
Hydro Thermal Processing									
Gasification									
Pelletization									
Torrefaction									

Source: SET Plan

2.1.1 Biochemical processing

2.1.1.1 Anaerobic digestion and biogas upgrading

Anaerobic digestion (AD) involves feedstock processing by microorganisms under anaerobic conditions to produce biogas, a mixture of methane, carbon dioxide and some minor contaminants. Anaerobic digestion includes a series of biological 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 (H2), nitrogen (N2), 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 could be used to produce electricity, heat or as vehicle fuel or 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.

The biogas plants are agriculture-based biogas plants (agricultural residues and energy crops), industrial biogas plants (food and beverage industry waste, organic municipal solid waste, and sewage sludge), and landfill gas. Anaerobic digestion can use a large variety of feedstocks (substrate) including mostly wet biomass and organic waste, such as agricultural, municipal and industrial organic residues and wastes, sewage sludge, animal fats and slaughtering residues, sewage sludge from wastewater treatment and also aqueous biomass (micro and macro algae). There is a trend for feedstock usage moving away from energy crops, towards sequential cropping, agricultural residues, organic municipal solid waste, and sewage sludge. 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 maximize the biogas yield. More difficult feedstocks (such as straw, food waste and other residues) might require additional pre-treatment to achieve higher gas yields or post-processing to remove various contaminants (Amin et al., 2017).

There are two main types of anaerobic digestion, which differ mainly based on 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 mixed with industrial and food wastes are the most common but thermophilic conditions are applied mostly in large-scale centralized 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 than mesophilic digestion, requiring lower digester volume, but entailing more expensive technology and higher energy consumption (Ricardo, 2022; Nguyen et al., 2021).

The anaerobic digestion process may operate as a wet or a dry process, depending on the water content of the material in the digester. 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). It is generally not feasible to pump dry waste, so the waste is typically moved mechanically, by screw conveyors rather than a liquid/sludge pumping. Dry anaerobic digestion plants offer several benefits, including greater flexibility in the type of feedstock, shorter retention times and lower water usage and lower capital costs.

Biogas can be used directly for electricity and heat production in electricity only plants, heat only plants or Combined Heat and Power (CHP) plants. Energy generation options with anaerobic digestion include gas engines, Stirling engines, gas turbines, and micro turbines. Anaerobic digestion plants are mostly connected to gas-fired engines for heat and power generation. The heat generated can also be used to meet the local heat demand on farm, or delivered to external users, such as for 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 to 5 MWe (IEA, 2012). Anaerobic digestion is an established, commercial technology for manure, food and agricultural waste or sewage sludge, around TRL 8 - 9.

2.1.2 Thermochemical processing

2.1.2.1 Biomass combustion

Biomass combustion of solid, gaseous and liquid biomass 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 generation, 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) 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) and 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 generation 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). Co-generation is an effective way to significantly increase the overall efficiency of a power plant (and hence its competitiveness) when a good match exists between heat production and demand. Co-generation 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 (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 co-generation 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 (for heating cooling of industrial heat) 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. Pyrolysis can also be used as a pre-treatment step for gasification and biofuels production.

Pyrolysis process can be categorized 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 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 maximize the bio-oil yield, while slow pyrolysis is used to maximize 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

Method	Temperature Range	Residence Time	Heating rate	Main Products
				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: IRENA

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, 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 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 is based on various types of reactors including fluidized-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 fluidized bed, rotating cones, entrained flow, vacuum, and ablative reactors. Flash pyrolysis uses fluidized bed, circulating fluidized 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 a great 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 Carbonization (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. Table 4, shows the typical parameters for the main types of hydrothermal processing.

Table 4. Pyrolysis processes and main products.

HTP type	Temperature	Pressure
HTC – Hydrothermal Carbonization	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 Carbonization (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, fertilizer and soil conditioner. 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. HTC 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 (biocrude) 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 biocrude from biomass. Hydrothermal liquefaction produces, along with biocrude, a CO2 rich-gas and solid by-products (char). Biomass derived biocrude 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 biocrude produced has lower oxygen content than pyrolysis oil and higher heating value. The composition and yield of biocrude 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 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 several technological gaps for the commercialisation of hydrothermal processing that include the lack of a deep knowledge about the chemical pathways, reactor design for process development and optimization, the need for advanced materials to avoid corrosion in the extreme environment (high pressure and environment) and the high-capital costs.

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 utilizes 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 N2-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). Fluidized-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 that can be used to produce heat and power directly in internal combustion engines, boilers and fuel cells, Synthetic Natural Gas (SNG) or to be used for the production of methanol or and other chemicals, or the synthesis of Fischer-Tropsch hydrocarbons. Nowadays, biomass gasification is mainly used for heat and power production at small- and medium-scale plants. Syngas 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

Chipping, grinding, drying

Biomass has a highly variable composition, high-moisture content and low energy density that makes transportation, handling, and storage of biomass difficult. These characteristics imply that significantly larger volume of biomass needs to be handled and makes transportation, handling, and storage of biomass difficult.

Biomass pre-treatment provides an appropriate feedstock from raw biomass, which is adequate for processing 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 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
- pelletizing, briquetting
- torrefaction

Many pretreatment 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: *IRENA*

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.. Pelletizing 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).

Pelletizing

The biomass pelletization process consists of multiple steps including raw material pretreatment, pelletization and post-treatment. Raw materials used are forest residues, sawdust, wood shavings, wood wastes, agricultural residues like straw, switchgrass etc (IRENA, 2019). The moisture content in biomass can be considerably high and is usually up to 50%–60% which 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 it strongly reduces smoke on combustion. The feedstock should not be over dried, 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 pelletization process. Before feeding biomass to pellet mills, the biomass should be reduced to small particles of the order of not more than 3 mm. If the pellet size is too large or too small, it affects the quality of pellet and in turn increases the energy consumption. Therefore, the particles should have proper size, the reduction process is done by grinding using a hammer mill equipped with a screen of size 3.2 to 6.4 mm. If the feedstock is quite large, it goes through a chipper before grinding. Then biomass is compressed 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 pelletization 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 pelletize biomass is roughly between 16 kWh/t and 49 kWh/t. During pelletization, 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 stabilizing 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 2021, global pellet production still grow, with an increase of 5% from 2019 to 2020. The EU reached 18.1 million tonnes of production, making it the world's major pellet producer. Germany is still the largest pellet producer within the EU, whilst Czechia registered a remarkable increase of 21.5% in 2020. Regarding consumption, pellet use has increased by 7% globally compared to 2019, reaching 39.8 million tonnes. The EU remain the largest global pellet consumer. The residential and commercial segments are once again led by Italy, which remains the world's largest pellet user for the residential sector, with a total consumption of 3.4 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 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 carbonization) 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 maximization 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 devolatization, 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 fluidized-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, it 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 to the required pressure. There is a clear trend nowadays toward biogas upgrading to biomethane with an increasing portion of biogas being upgraded. Biomethane can be used for the replacement of natural gas, as a fuel in Natural Gas Vehicles (NGV) or for the injection in 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 has stagnated over the past decade, biomethane production grows at an increasing rate. In comparison to on-site conversion of biogas into heat and/or electricity, the upgrading of biogas to biomethane allows a 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 CO2 removal with an adsorbent; after the adsorbent's saturation, regeneration is carried out by decreasing pressure. For CO2 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 fabric
- **Biological Technologies,** it is based on microorganisms' capability to turn CO2 from an anaerobic digester into CH4 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 O2 and N2 is subjected to the desorption of CO2 broken up within the slime
- **Carbon Capture and storage,** The strategy of capturing and putting away CO2 using a carbon mineralizaion process

Several biogas upgrading technologies operate commercially, including membrane separation, water/chemical scrubbing and Pressure Swing Adsorption (PSA). Most of the biomethane plants use membrane separation (47%), water scrubbing (17%), chemical absorption (12%) or pressure swing adsorption (10%), with a limited number of biomethane plants using cryogenic separation (1%) and physical absorption (2%) (European Biogas Association (EBA), 2021). Cryogenic separation might be of growing importance in case of higher use of biomethane as LNG, benefitting from the integration of methane separation with liquefaction units for the methane (Thrän et al., 2014).

Anaerobic digestion and biogas upgrading to biomethane has been successfully demonstrated. The number of biomethane plants in Europe reached 1067 in 2021 in the European countries. The production of biomethane reached 3.5 billion m^3 biomethane (37 TWh) in comparison to a total combined Biogas-Biomethane production of 18.4 billion m^3 (196 TWh) in 2021. Biomethane plants are larger in size than biogas plants, although an increasing share of smaller biomethane plants are being built (European Biogas Association (EBA), 2021). Biomethane plants can be connected to the distribution gird or the transport natural gas grid or can produce on-site biomethane without a grid connection.

2.1.3.3 Bio-oil upgrading

Bio-oils are a complex mixture of hundreds of chemicals and oxygenated hydrocarbons, with high water content (20-30%), high oxygen content (35-40%), high acidity (pH of 2-4), high viscosity and a calorific value of 16-19 MJ/kg lower than fossil oil (30 MJ/kg). The bio-oil and properties of bio-oil vary significantly, being influenced by several factors that include: feedstock properties and processing conditions: heat transfer rate, reaction time, temperature profile, and/or the use of catalysts. Direct use of bio-oil without chemical upgrading is challenging, due to its high viscosity, high water and ash contents, low heating values, solid content, chemical instability, and high corrosiveness. Besides the heat and power applications, bio-oil need to be upgraded to energy carriers and feedstock for advanced biofuels, chemical intermediates and final products. Investigations are under way to explore the possibility of mixing pyrolysis oil with conventional crude oil in existing oil refineries and co-processing bio-oil with fossil fuels in common processes in refineries (Basu, 2018; Matayeva et al., 2019; Bridgwater, 2018).

Bio-oil upgrading aims to improve bio-oil quality for the production of chemicals or hydrocarbon biofuels, involving in particular the reduction of oxygen content through deoxygenation (Bridgwater 2018a). Bio-oil upgrading is challenging because of the high oxygen and water content of bio-oils. Various upgrading techniques have been developed for bio-oil upgrading, through physical, chemical and catalytic pathways. Physical upgrading technologies include solvent extraction, to reduce its viscosity and improve the homogeneity and energy density, or emulsion to enhance its ignition properties. These physical upgrading technologies do not help eliminate undesirable compounds, such as oxygenates, from the bio-oil, with limited large-scale application.

The most important upgrading processes involves chemical upgrading through hydrocracking, hydrotreatment and hydrodeoxygenation (HDO). Hydrocracking involves cracking the heavy molecular feeds into smaller valuable products at high temperature of 300–500 ºC and pressure of 10–20 MPa, through (1) catalytic cracking of the high molecular weight compounds, and (2) hydrogenation reaction reaction of the cracked molecules. Hydrotreatment is been employed and is a well-established process in oil refineries that are often carried out at temperatures of 300–450 ºC and high hydrogen pressure up to 20 MPa. A series of reactions possibly occur in bio-oil upgrading including decarbonylation, decarboxylation, hydrodeoxygenation, hydrogenation, deoxygenation, cracking and hydrocracking. Hydrodeoxygenation (HDO) involves a combination of different reactions such as hydrogenation, hydrogenolysis, decarbonylation, and dehydration during which oxygen present in the bio-oil is removed through water formation. Catalytic Hydrodeoxygenation involves removing oxygen from a hydrocarbon by applying different catalytic reactions at pressures up to 200 bar and temperatures up to 400 ºC (Matayeva et al., 2019; Bridgwater, 2018; Attia, Farag, and Chaouki, 2020). The yield and properties of upgraded bio-oil obtained dependent on the temperature, residence time, pressure, solvent, catalyst type, and reactor configuration (Basu, 2018).

The bio-oil can be converted through gasification into a synthesis gas that is then cleaned to remove particles, tars, alkaline salts, HCl, H2S, COS, CS2, NH3, and HCN, followed by synthesis to hydrocarbons (gasoline of diesel). Many chemical pathways are possible to produce gaseous and liquid fuels and chemicals from syngas (Bridgwater 2018b). Pyrolysis and bio-oil upgrading technology is still in the pre-commercial demonstration phase, with considerable experience been gained from several pilot and demonstration plants (Meier et al., 2013).

2.1.3.4 Bio-crude upgrading to bioliquid intermediates

The liquid bio-crude or HTL oil can be used as an intermediate energy carries, bio-fuel and as a substitute for crude oil for chemical products manufacture (Kumar, Olajire Oyedun, and Kumar, 2018; Reißmann, Thrän, and Bezama, 2018). Biocrude has high viscosity, high corrosive activity, and relatively low stability requiring further upgrade. The biocrude oil contains primarily C16-C18 hydrocarbons, aromatics such as organics such as phenols, benzenes and naphthalene, other heavy components, 10-20% oxygen, 3-7% nitrogen, and up to 20% moisture content (Wan-Ting, 2017; Zhu et al., 2019; Matayeva et al., 2019). The composition and yield of biocrude is influenced primarily by temperature and biomass type. However, the composition of the biocrudes from different sources can be different and require quite different upgrading strategies (Castello, Haider, and Rosendahl, 2019). The aqueous phase can be treated via catalytic hydrothermal gasification to produce off-gas to be used for process heating or anaerobic digestion to produce methane-rich or hydrogen-rich syngas (Kumar, Olajire Oyedun, and Kumar, 2018; Dimitriadis and Bezergianni, 2017; Zhu et al., 2019).

Through separation and distillation, the oxygen content in the biocrude oil could be reduced from 10-20% oxygen to 5% and the heating values could be increased to 41-45 MJ/kg. Upgrading techniques for biocrude include steam reforming, sub/super-critical fluid (SCF) treatment, cracking (hydrocracking, zeolite cracking, thermal cracking) and hydrotreating. During upgrading, aromatics, fatty acids and other compounds in the biocrude are saturated with hydrogen, removing oxygen, nitrogen and sulfur. Cracking is one of the major processes in petroleum refining, that can be used to upgrade biocrude by fragmenting heavy molecules into lighter hydrocarbons molecules at high temperature (above 350°C) and high pressure with catalysts catalysts. Hydrotreating is also a well-established process in oil refineries, involving several reactions such as hydrodeoxygenation to remove oxygen, hydrodenitrogenation to remove nitrogen, and hydrodesulfurization to remove sulphur. During hydrotreating, aromatics, fatty acids and other compounds in the biocrude are reacted with hydrogen in the presence of a catalyst at relatively high temperatures and moderate pressures to convert aromatics and olefins into saturated hydrocarbons and increases the stability of bio-oil (Attia, Farag, and Chaouki, 2020; Hao et al., 2021; Matayeva et al., 2019).

Steam reforming is a relatively well-established technique that could be a promising method to upgrade biocrude from HTL producing a synthesis gas at high temperature (700-1000°C). The catalysts used in steam reforming can be deactivated by coking. Sub-/ Super-critical fluid (SCF) treatment involves the use of water or organic solvents that produces a similar to petroleum-based fuels, increasing heating value, reducing viscosity, decreasing oxygen and nitrogen content. Less severe upgrading, includes solvent addition, that improves the viscosity and acidity of bio-oil through esterification and transesterification, chemical extraction and emulsification (Basu, 2018)

2.1.3.5 Syngas upgrade to synthetic natural gas

The composition of syngas depends on various factors, including the type of the gasifier (fixed bed, fluidized 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 producer gas to prevent poisoning of catalysts.

The gas cleaning method can be divided into in 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 generation, 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 chemically 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 Installed Capacity and Production

Global bioenergy

Biomass electricity production has increased globally from 229 TWh in 2007 to 614 TWh in 2021, with a share in total renewable electricity production increasing from 6.8 % to 7.8 % respectively The EU is the leading region on biomass electricity production, followed closely by Asia, which however, underwent the highest growth rate between 2007 and 2021. The next most important region, North America is well behind in terms of biomass electricity production with 71 TWh, Figure 2

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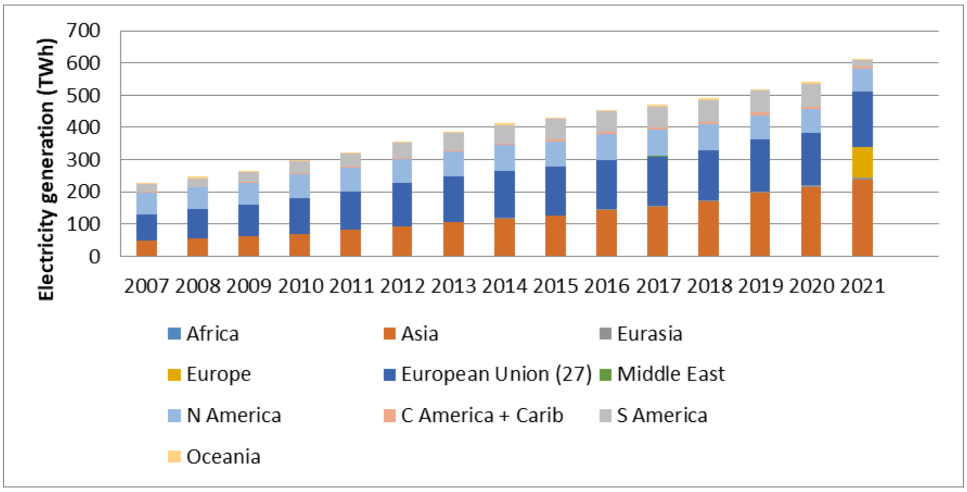
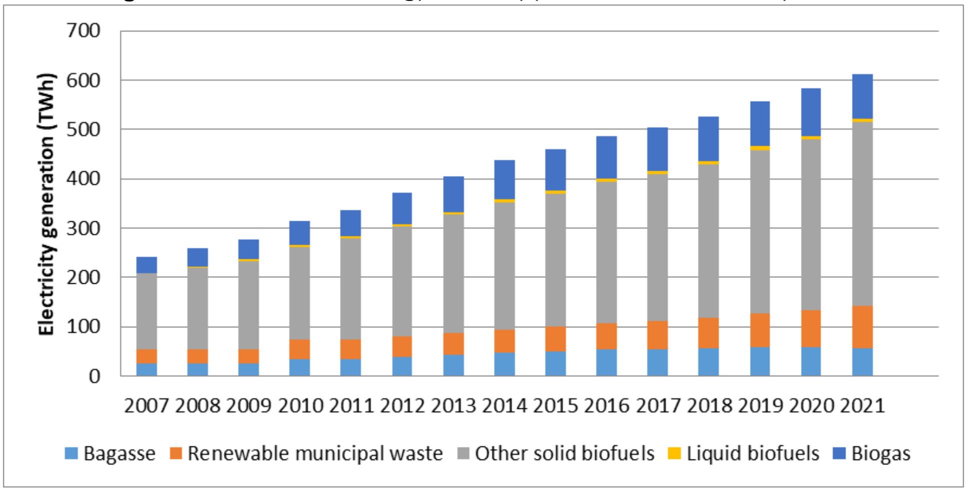
Figure 2. Evolution of bioenergy electricity production in the world by regions



Source: (IRENA, 2022)

Solid biomass has been the main feedstock for biomass electricity from 2007 to 2021, throughout this period the production of electricity from solid biomass increased from 181 TWh to 458 TWh. Biogas has also gained in importance as second after solid biomass, with 92 TWh electricity produced in 2021, mostly in the EU and some lower production in Asia and in North America. Another feedstock used for biomass electricity production is municipal renewable waste that reached 86 TWh in 2021, in particular in Asia and in the EU. Bagasse is used for electricity production mainly in South America, with some minor uses in other regions of the world, taking advantage of the sugarcane production, Figure 3

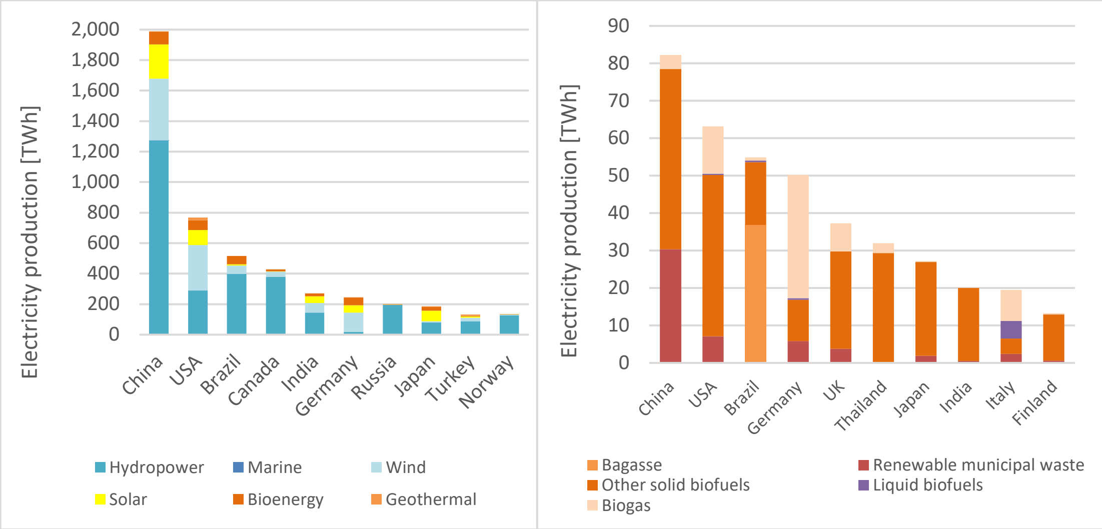
Figure 3. Evolution of bioenergy electricity production in the world by source



Source: (IRENA, 2022)

Leading countries on renewable electricity production in 2021, include China, US, Brazil, Canada, India, Germany, etc. (Figure 4). The most important source include hydro in China, Brazil, Canada, Russia. Wind represent a major source in China, US, Germany, while solar electricity delivers also an important contribution in China, US, India, Germany, Japan. Biomass electricity production provides a small contribution, mostly in China, US, Brazil, Germany, etc. Leading countries on biomass electricity production include China, US, Brazil, Germany, UK. The most important biomass source include solid biomass in China, Brazil, Thailand, Japan, etc. Renewable municipal waste is highly important in China, but also in US, Germany, UK, and Italy. Biogas dominates the biomass electricity production in Germany, having also a large contribution to electricity production in US, Italy, US and UK. Bagasse is the most important feedstock for electricity in Brazil. Biomass electricity production has a smaller share, mostly in China, US, Brazil, Germany. (Figure 4).

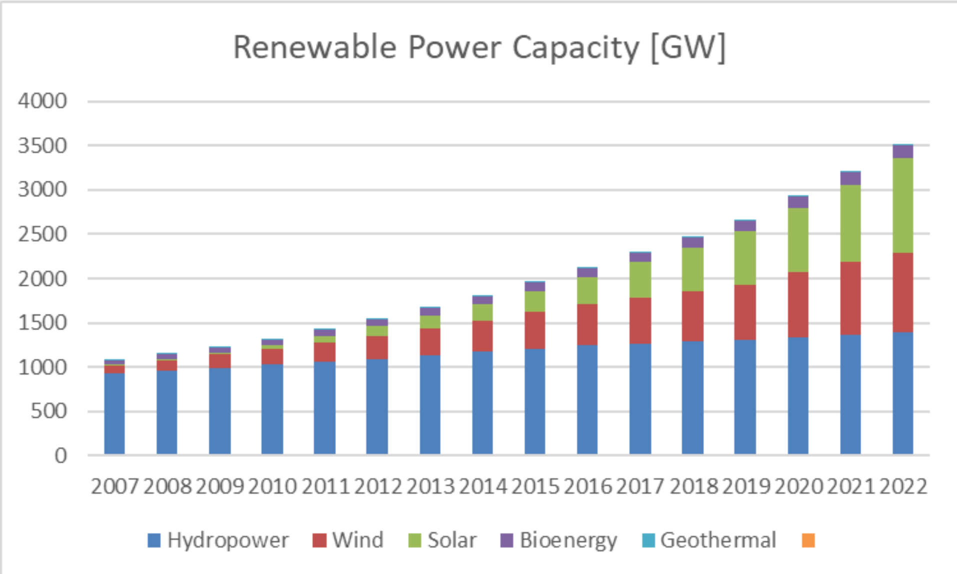
Figure 4. Leading countries on renewable electricity (left) and biomass electricity production (right) in 2021



Source: (IRENA, 2022)

The global installed renewable electricity capacity has increased from 993 GW in 2007 to 3,381 GW in 2022, that is more than three times increase over the period).Figure 5. The installed capacity of hydropower plants is the highest, with 1393 GW in 2022, undergoing a slow increase, in particular in comparison to other renewables. The second renewable energy in terms of installed capacity is solar, reaching 1062GWp in 2022 worldwide, registering the highest increase from 2007. Bioenergy electricity capacity had a significant increase, tripling between 2007 and 2022 to reach 151 GW in 2022.

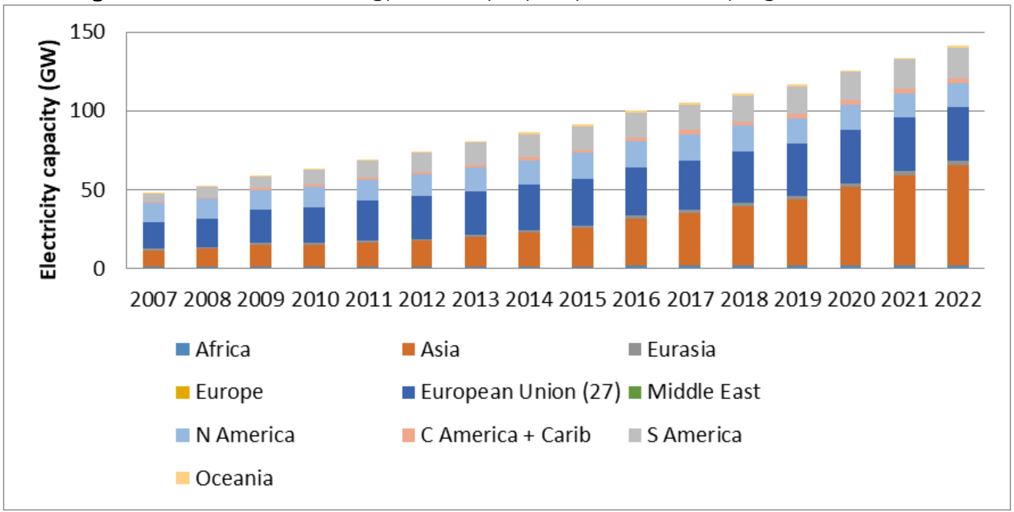
Figure 5. Evolution of bioenergy and renewable energy capacity in the world, 2007-2022



Source: (IRENA, 2022)

Total global biomass electricity capacity increased significantly worldwide, about three times, from 41 GW in 2007 to 151 GW in 2022 (Figure 6). Asia had the highest biomass electricity capacity in 2022 and had the highest growth rate since 2007, in comparison to other world regions. EU is the second world region in terms of biomass electricity and second in terms of growth rate, followed by South America and South America.

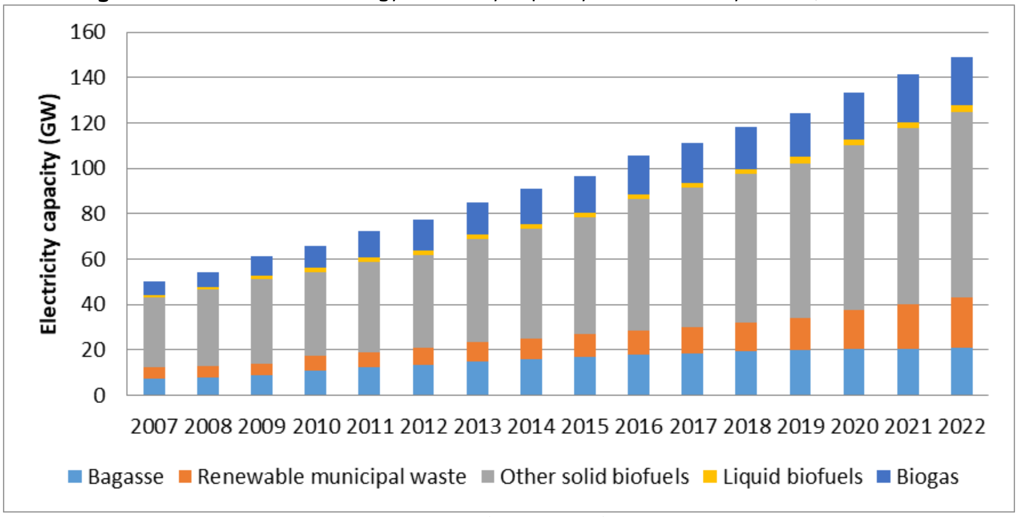
Figure 6. Evolution of bioenergy electricity capacity in the world by regions, 2007-2022



Source: (IRENA, 2022)

The highest capacity of biomass electricity plants comes from solid biomass, followed by biogas plants, bagasse and biogas plants. The highest increase in biomass plants relate to solid biomass, from 36 GW to 103 GW in 2022, followed by biogas plant, increasing from 6 GW to 21 GW and bagasse with a growth from 7 GW to 21 GW. See Figure 7

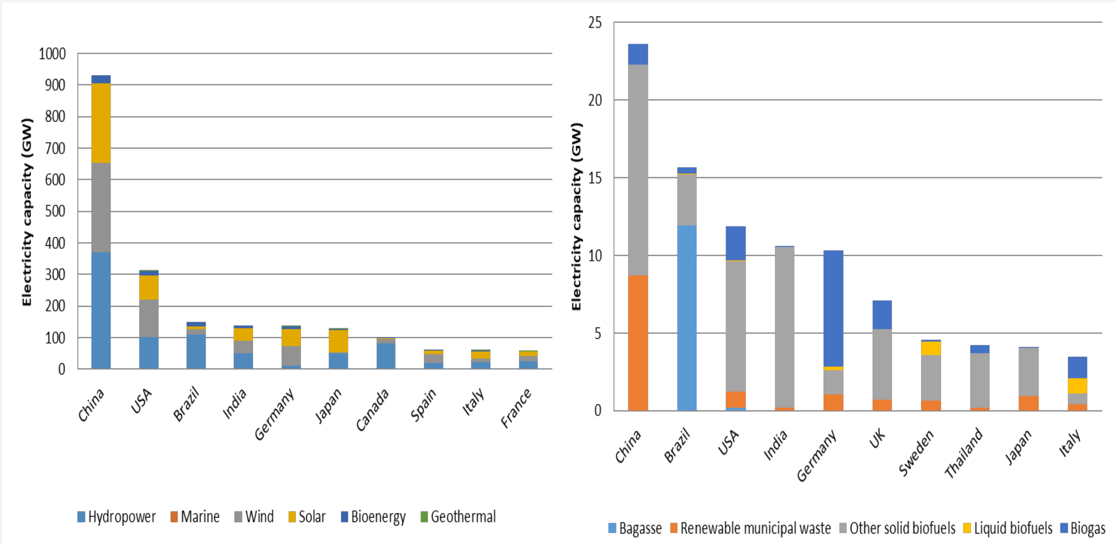
Figure 7. Evolution of bioenergy electricity capacity in the world by source, 2007-2022



Source: (IRENA, 2022)

Leading countries on renewable electricity capacity include China, followed by far by the US, Brazil, India Germany, etc. Figure 8. The most important source include hydro in China, Brazil, Canada, US, etc. Wind power capacity is the highest in China (282 GW), followed by US (118 GW), Germany. Solar electricity capacity is also the highest in China (282 GW) followed by US, Japan, Germany. In comparison Biomass electricity capacity is much lower. Leading countries on biomass electricity capacity include China (23 GW), Brazil (16 GW), US (12 GW), India (11 GW). Solid biomass capacity is the highest in China (14 GW), India (10 GW), US (9 GW), UK (5 GW). Plants using renewable municipal waste is highly important in China (9 GW), with much lower electricity capacity in US, Germany, UK, etc. Bagasse plants are mostly important for electricity in Brazil with a capacity of 12 GW.

Figure 8. Global leaders on renewable electricity and biomass electricity capacity in 2022



Source: (IRENA, 2022)

EU bioenergy

Bioenergy production

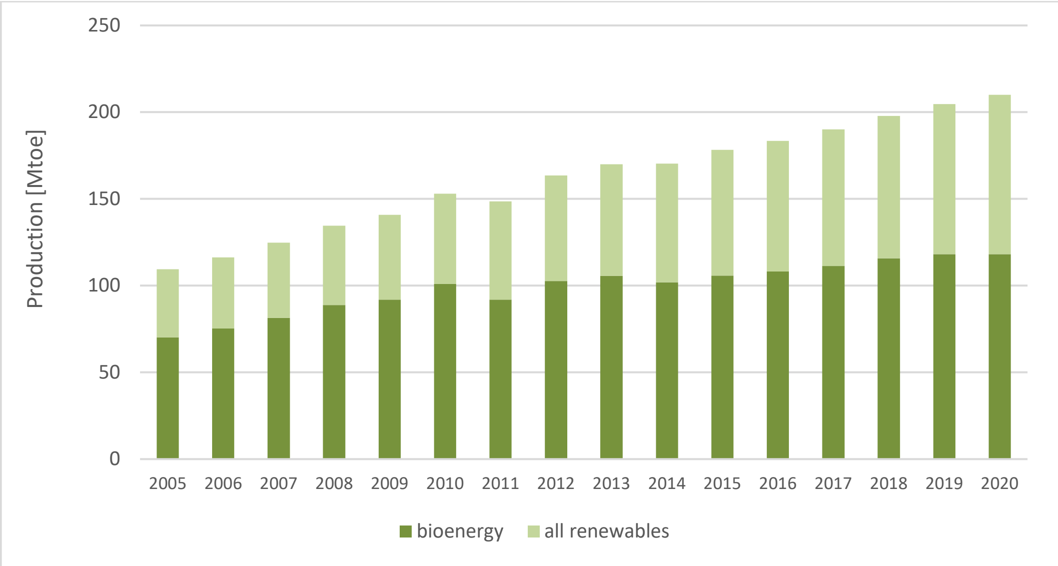
Bioenergy is the main renewable energy source used in the EU. The analysis of energy production from all renewables, i.e. hydro, solar wind, geothermal, heat pumps, marine energy and bioenergy, shows a significant and continuous progress, from 103 Mtoe in 2005 to 210 Mtoe in 2020, Figure 9. A similar trend can be noticed for the deployment of bioenergy for electricity, heating and cooling and biofuels for transport. It increased from 66 Mtoe in 2005 to 117 Mtoe in 2020. The share of bioenergy in renewable energy supply in the European Union slightly decreased from 60 % in 2005 to 56 % in 2020. The growth trend seems to be levelling out over the last decade in bioenergy due to, the uncertainties in supporting policies, the sustainability concerns of bioenergy and relatively low energy prices until the unprovoked and unjustified Russian military invasion to Ukraine.

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 like fuelwood and logging residues, secondary sources like wood processing by-products, black liquor from the pulp and paper industry, and post-consumer wood), and other types of biological waste (food waste, food industry waste, the organic fraction of municipal solid waste, etc.) (Scarlat et al., 2019). Biomass for energy includes direct supply of woody biomass (forestry residues - tops, branches, bark, stumps- landscape management residues, but also whole trees) with 32.5%, and indirect supply of wood (sawmilling residues, woodworking, furniture industry (bark, sawdust), by-products of the pulp and paper industry - black liquor, tall oil - or fuelwood, recycled and waste wood) with 28.2% agricultural biomass (equally from agricultural crops and agricultural by-products) with 27% and municipal and industrial waste with 12.4% (Scarlat et al., 2019).

The major feedstocks used for bioenergy production in the European Union are solid biofuels, municipal renewable waste, biogas and liquid biofuels (Figure 10). Solid biofuels are the most common biomass feedstock used in the European Union with an increase from 63 Mtoe in 2005 to 86 Mtoe in 2020. Solid biofuels include a range of primary wood from forests (fuelwood, logging residues), and waste and residues from forestry (bark, sawdust, shavings, chips) and agriculture (straw, husks, nut shells, etc.), black liquor, etc.) as well as waste (recovered and contaminated wood, etc.). For bioenergy production from forest biomass 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%).

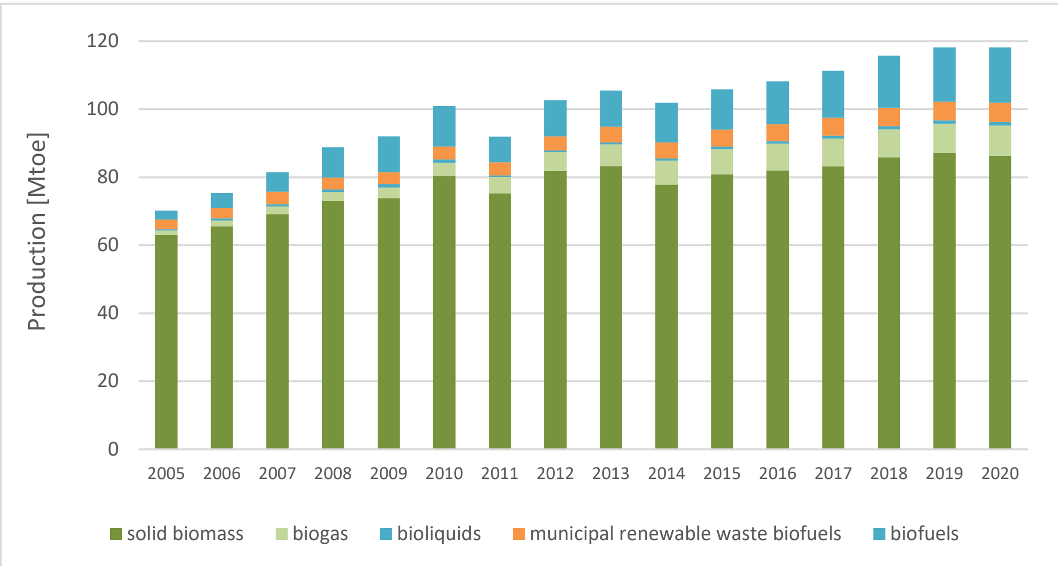
The contribution of biogas, using agricultural residues such as manure, energy crops, biowaste, sewage sludge of from landfill gas recovery, shows a significant increase in this period from 1.4 Mtoe to 8.9 Mtoe. Liquid biofuels have also seen a large growth from 2.6 Mtoe in 2005 to 12.3 Mtoe in 2020, mostly for use in the transport sector (biogasoline, biodiesel, and other biofuels) or as liquid biofuels for heat and power. Another component of biomass feedstock, renewable municipal waste is also increasingly used for energy recovery, although with a progress at lower rates, increasing from 2.8 Mtoe to 5.7 Mtoe in 2020 (Figure 10).

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



Source: (Eurostat, 2022)

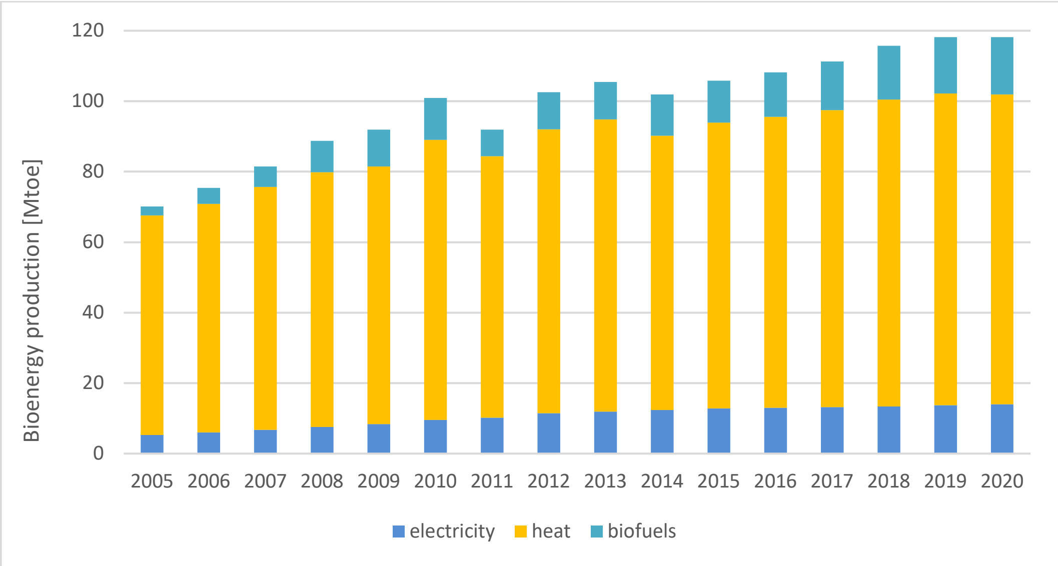
Figure 10. Evolution of bioenergy production in the EU from different feedstock



Source: (Eurostat, 2022)

The main uses of biomass is for electricity, heating and cooling and for the production of biofuels for transport. (Figure 11). Biomass heat represent the more than 75 % of bioenergy production, decreasing from 90 % in 2005. Despite of a biomass heat increase by about 50 % between 2005 and 2020, to reach 88 Mtoe in 2020, the growth rate decreased in the last years. Biomass electricity instead had a much higher increase, from 4.3 Mtoe in 2005 to 12.4 Mtoe in 2020. Similar to biomass heat, the growth rate of biomass electricity decreased significantly during the last years. In contrast biofuel production has seen a much higher increase, driven by the renewable energy mandates for the transport sector.

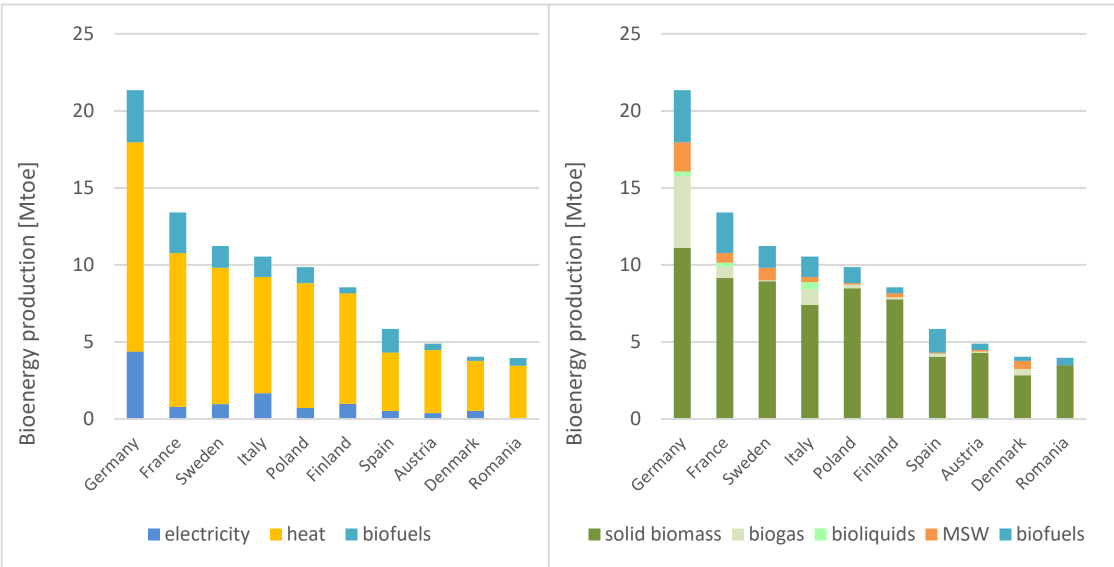
Figure 11. Evolution of bioenergy production for electricity, heat and biofuels for transport in the EU



Source: (Eurostat, 2022)

Figure 12 shows the contribution of bioenergy (electricity, heating and biofuels for transport) in the Member States of the European Union in 2020. The leading Member States both in bioenergy and renewable energy supply include Germany, France, Italy, Poland, Finland, Spain, Austria, Denmark and Romania. The majority of bioenergy comes as heat in all leading MS. Biomass electricity also plays an important role in Germany, as well as biogas. Solid biomass is the major source for bioenergy production in all MS.

Figure 12. Leading EU MS on bioenergy production in 2020

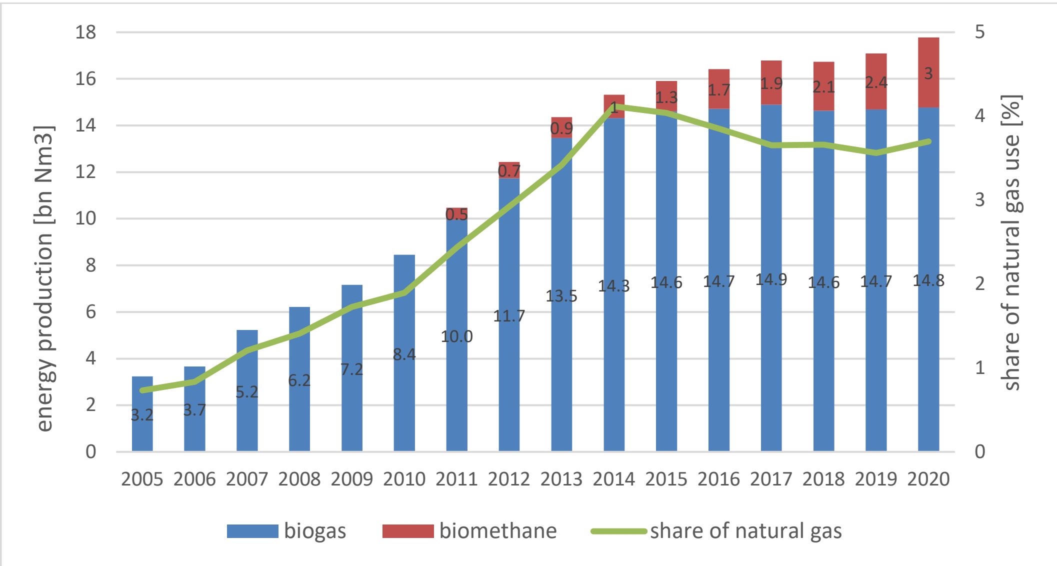


Source: (Eurostat, 2022)

Biogas

Biogas production has seen an impressive growth in the European Union, from only 3.2 billion Nm³ (Normal Cubic Meters) in 2005 to 14.3 billion Nm³ in 2014, source (EBA, EUROSTAT) The biogas industry has stagnated over the past decade due to the lack of clear policy perspectives, poor economic performances, lack of support and the debate on the use of energy crops for biogas production. Biomethane production is instead gaining momentum more than triple from 1 bcm in 2014 to 3 bcm in 2020. Biogas is most often used to produce electricity and heat. Biomethane can replace conventional fuels and in particular natural gas, for heat and power production and for the use of biomethane in transport. Biomethane production continues to grow at an increasing rate. Existing biogas plants are being converted to biomethane plants that could be injected into the natural gas grids and used as transport fuel in natural gas vehicles. Figure 13, shows the overall growth of biogas and biomethane production, as well as the increasing portion of biogas upgraded to biomethane. Combined biogas and biomethane production amounted to 18 billion Nm3 biomethane equivalent, of which about 15 billion Nm^3 is produced as biogas and 3 billion Nm^3 is produced as biomethane. In comparison, the natural gas consumption amounted to 400 billion Nm^3 in the EU in 2020. The Figure also shows the share of biogas of the total natural gas consumption in the EU that reached 3.7 % in 2020.

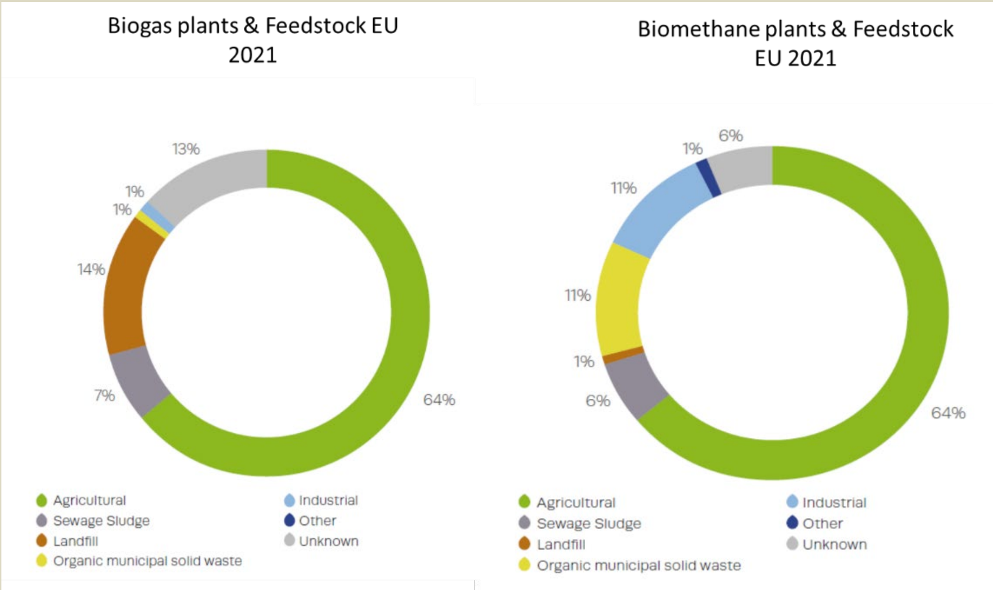
Figure 13. Evolution of biogas production in the EU



Source: (European Biogas Association (EBA), 2021; Eurostat, 2022)

While share of feedstock used for biomethane production is shifting to organic industrial waste and municipal solid waste, Figure 14.

Figure 14. Biogas and Biomethane feedstock in the EU, 2021

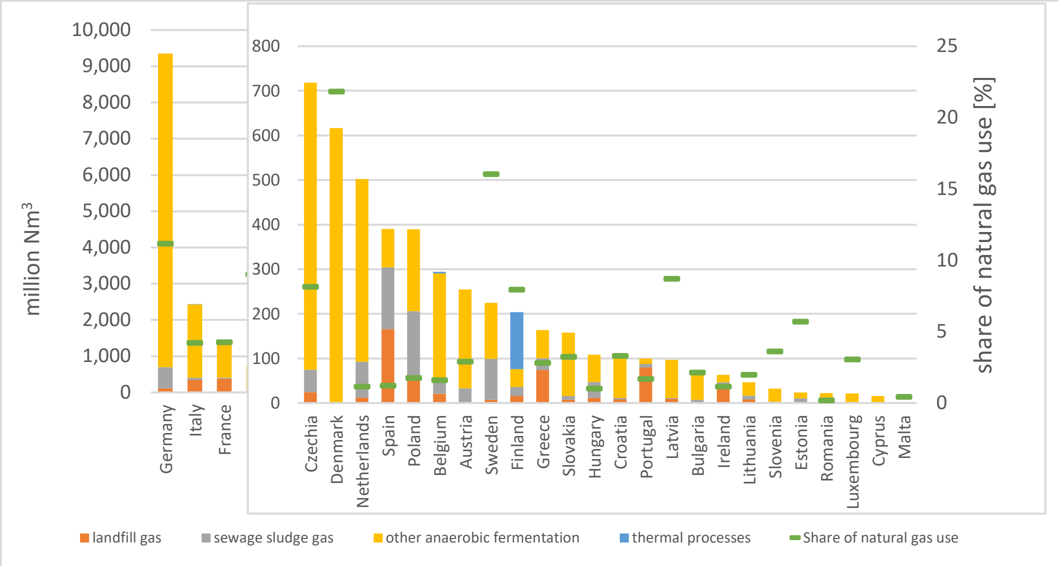


Source: (Eurostat, 2022; European Biogas Association, 2023)

The share of biogas into bioenergy supply in the European Union increased steadily from 1.7 % of bioenergy production in 2005 to almost 8% in 2020. About the feedstock used for biogas production, the most impressive increase, from 0.9 billion Nm^3 biomethane equivalent in 2005 to 14.3 billion Nm^3 in 2020, comes from biogas from anaerobic fermentation of waste and residues from agriculture, livestock manure, organic waste, food waste or other industry residues. Biogas production from landfill gas recovery or biogas from sewage gas has increased moderately. Biogas production from thermal processes has started only recently (2011) mostly in Finland, with a marginal contribution to biogas supply (140 billion Nm^3 in 2020).

Looking at the deployment of biogas supply in different Member States, Figure 15, the leading MS in 2020 was Germany that had a share of about 53 % into the biogas production at the European Union level with 9.4 billion Nm^3. Other MSs with high deployment Italy, France, Czech Republic Denmark and The Netherlands. Biogas production from anaerobic digestion plants dominates in most countries in particular in Germany Italy, France, Czech Republic, Denmark etc. Biogas from landfill gas recovery, however, dominates in other Member States, including Spain, Greece, Portugal and Ireland. Biogas production from anaerobic digestion of sewage sludge from waste water treatment plants has also an important contribution in Germany, Poland, Spain and Sweden. When comparing to the natural gas use in various MS, biogas has a significant contribution in particular in Denmark (21.8 %), Sweden (16 %), and Germany (10 %) Latvia (9%) and Czechia and Finland (8 %).

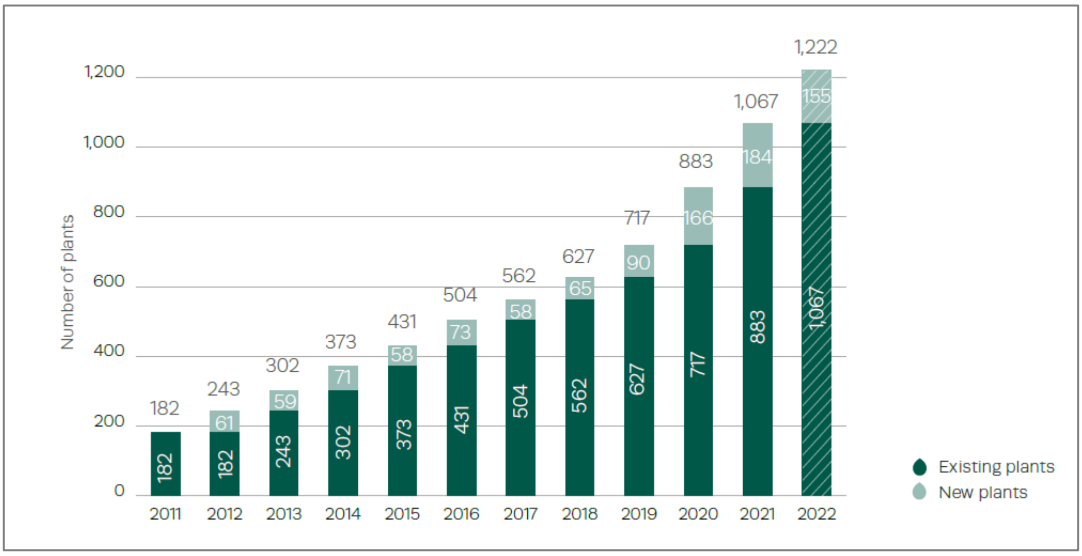
Figure 15. Biogas production in EU MS in 2020



Source: (Eurostat, 2022)

The EU is adding new biomethane plants at the ratio of about 20% annual increase in the last 3 years, see Figure 16.

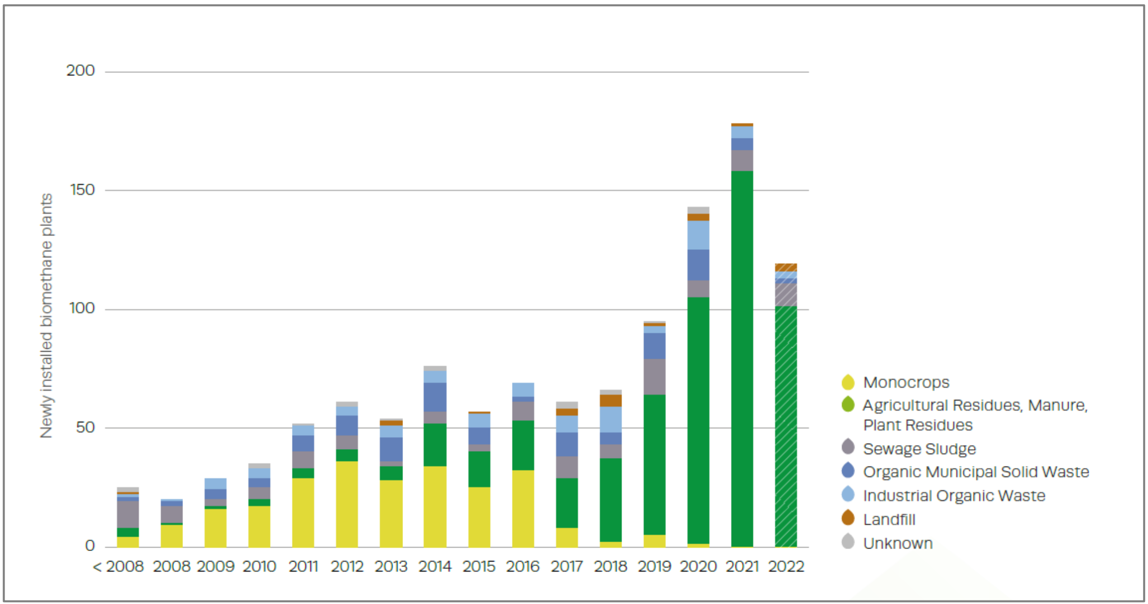
Figure 16. Number of Biomethane production plants in the EU



Source: (Eurostat, 2022; European Biogas Association, 2023)

According to Figure 17, the new built biomethane plants are using mainly Agriresidues and waste instead than crops.

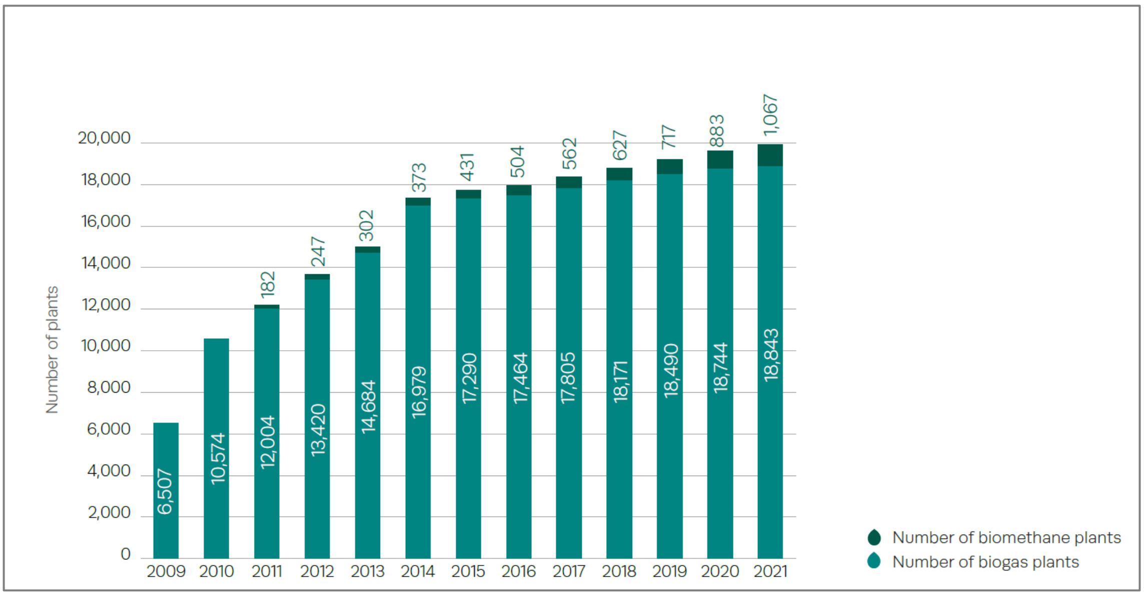
Figure 17. Newly installed plants and feedstock use



Source: (Eurostat, 2022; European Biogas Association, 2023)

The number of biogas plants in the EU, increased from 6,507 in 2009 to 18,843 in 2021. The number of biogas plants increased rapidly until 2014, followed by a soother rise in plant numbers, Figure 18

Figure 18. Biogas and biomethane plants

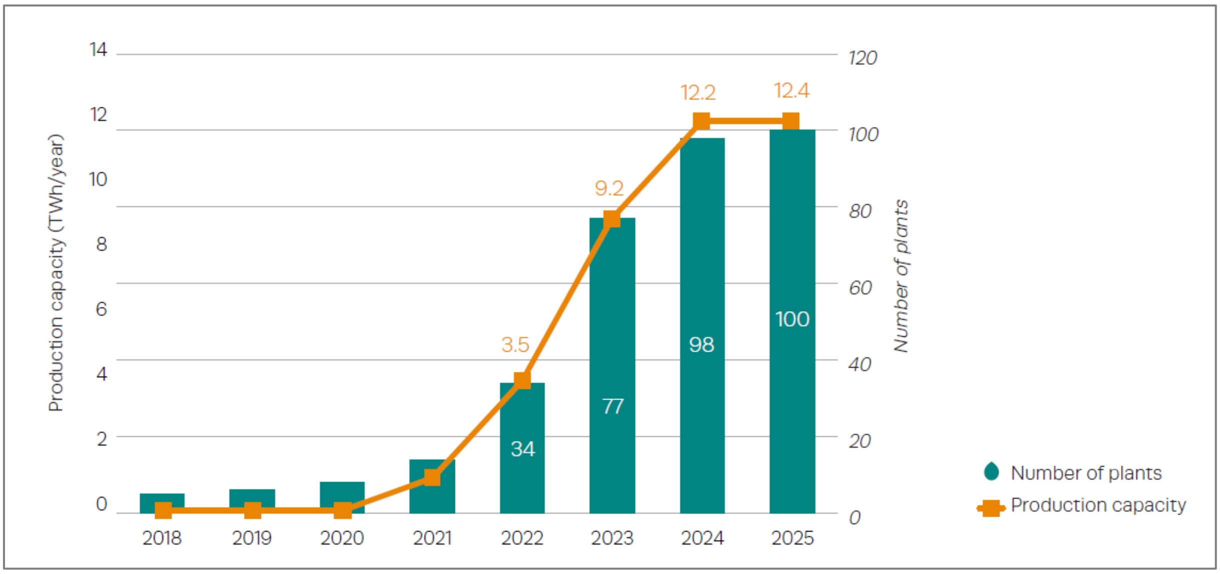


Source: EBA, (Eurostat, 2022; European Biogas Association, 2022)

Bio-LNG

According to EBA (European Biogas Association, 2022), there were 15 active Bio-LNG producing plants in Europe by the end of 2021, and this number is expected to increase sharply in the years 2022 (+ 19 plants), 2023 (+ 43 plants) and 2024 (+ 21 plants, starting for a production capacity at 3.5 TWh in 2022 and having in 2025 an estimated total production capacity at 12.4 TWh, see Figure 19.

Figure 19, Bio-LNG capacity in the EU

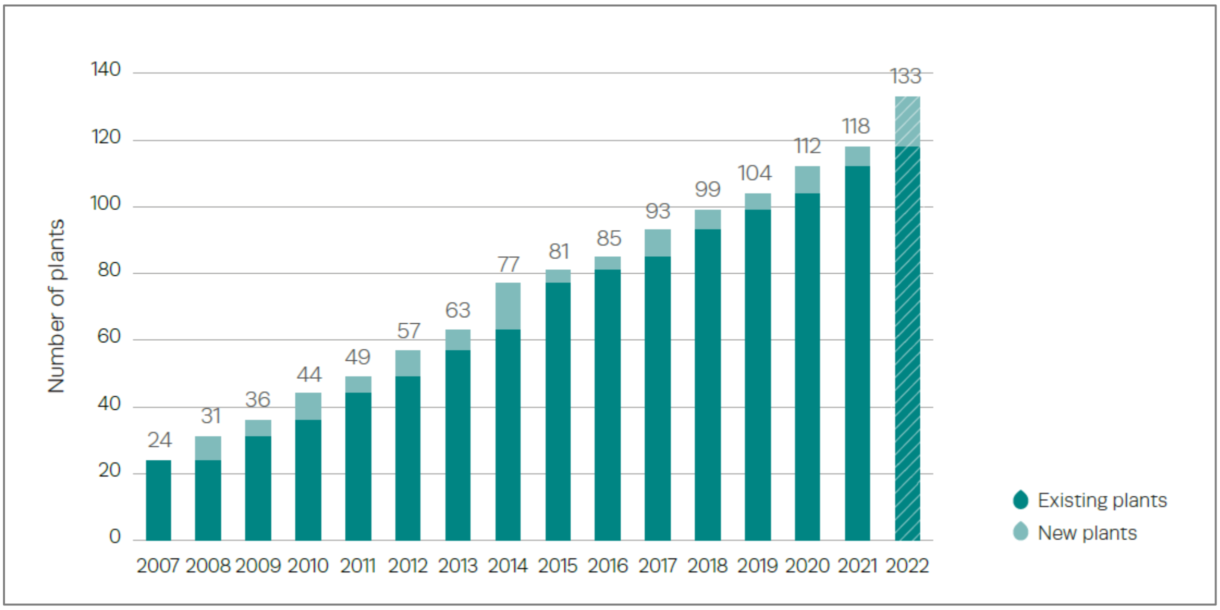


Source: (European Biogas Association, 2022)

Bio-CNG

The EBA report 2022 discovered out of the 1,222 biomethane plants active in Europe by the end of August, 133 plants are known to compress biomethane on-site to produce Bio-CNG, see Figure 20, this solutions has a particular interest in countries with less developed Nat-Gas grid.

Figure 20. Number of Bio-CNG plants in Europe



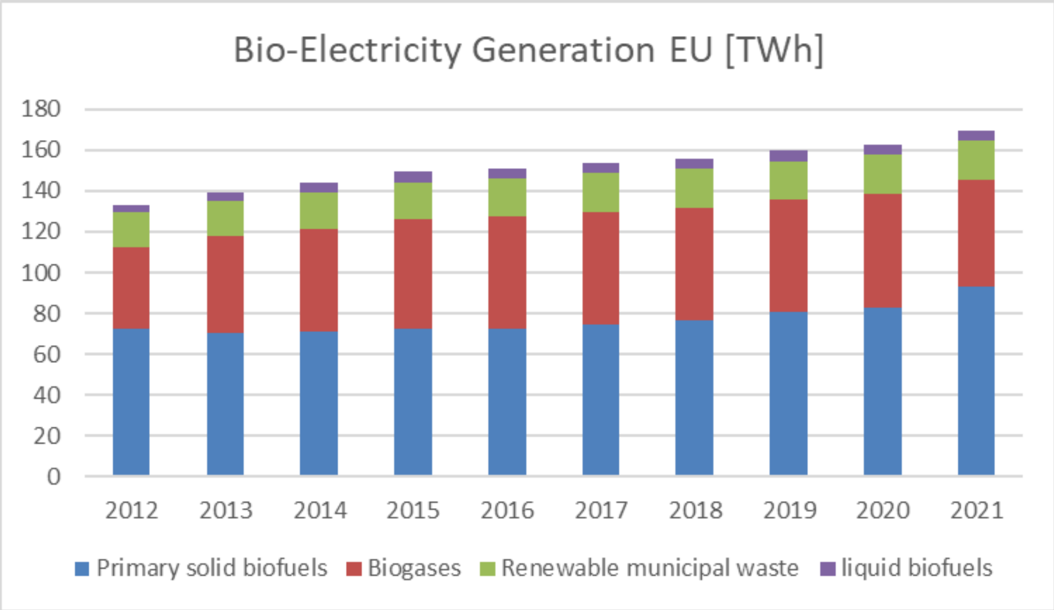
Source: (European Biogas Association, 2022)

Bio-LNG and Bio-CNG fuelling stations were already in service in Europe, in August 2022 EBA report says there were 4,181 CNG filling stations and 576 LNG filling stations

Electricity

Electricity generation from biomass has increased significantly in the European Union, from 133 TWh in 2012 to 169 TWh in 2021. The annual growth rate of electricity generation seems to be decreasing in the last years. Solid biomass, with an increase from 41 TWh in 2005 to 93 TWh in 2021, is the main contributor to biomass electricity generation, with a share decreasing from almost 66% in 2000 to just above 54 % in 2021, due to the strong growth from biogas electricity and from the use of renewable waste. Significant progress has been achieved in biogas electricity from 8 TWh in 2005 to 56 TWh in 2016. The share of biogas electricity increased significantly from 13 % in 2005 to 31 % of total biomass electricity generation in 2021. Electricity generation from municipal renewable waste has also increased from 11 TWh in 2005 to 19 TWh in 2021, with a share decreasing from 17 % to 11 % in 2021 due to higher growth from solid biomass and biogas electricity generation, see Figure 21

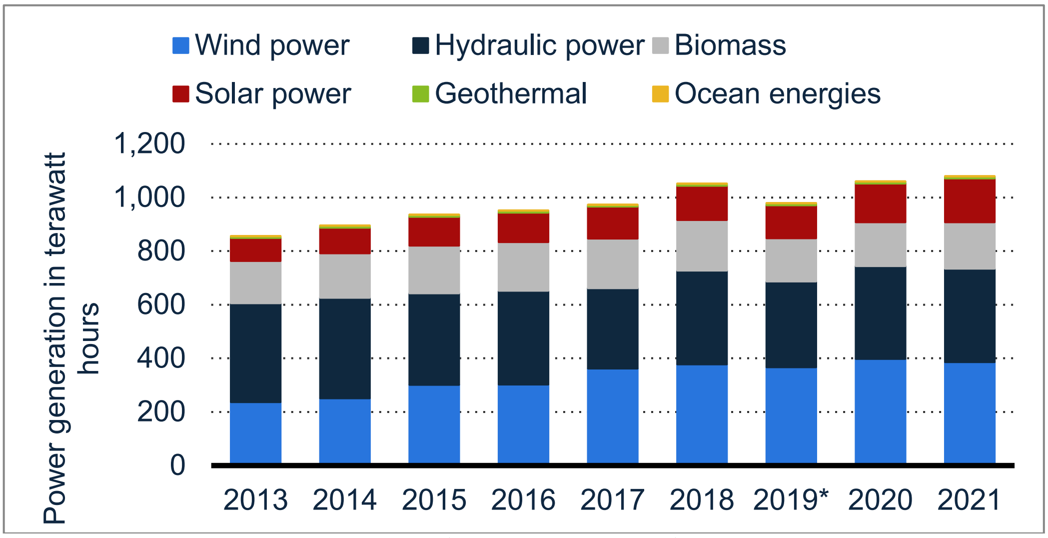
Figure 21. Evolution of biomass electricity production in the EU



Source: (Eurostat, 2022)

In the context of an increase of renewable electricity production in the EU from 476 TWh in 2005 to 1,068 TWh in 2021, the contribution of biomass electricity increased from 13 % to 16 % in the same period. In 2021 the Bioelectricity production was at around 16% share of Renewable electricity produced in the EU, see Figure 22

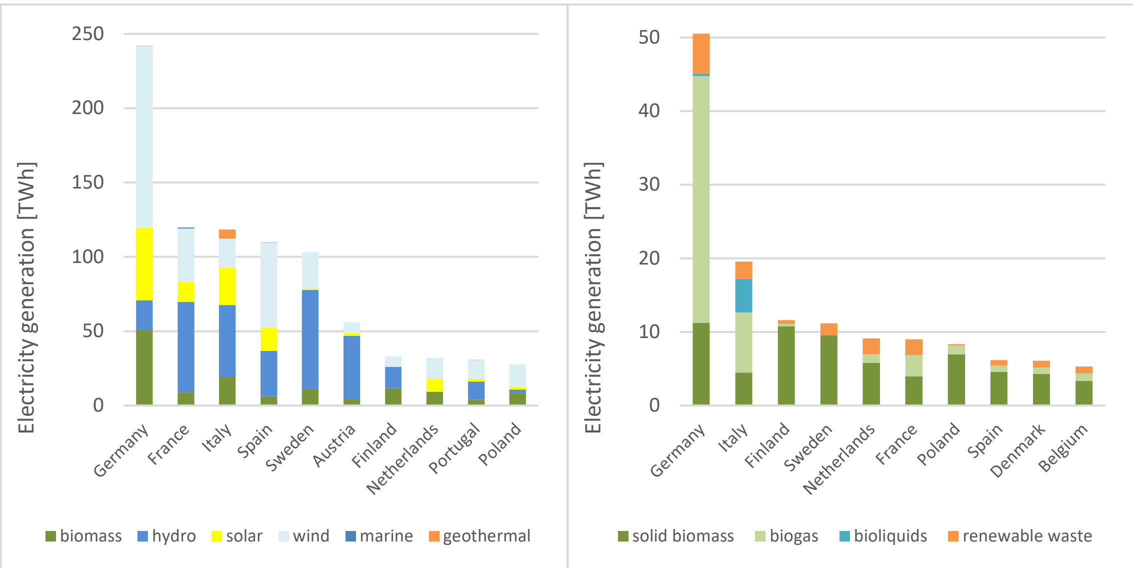
Figure 22. Evolution of the production of electricity from biomass and all renewables in the EU



Source: (Eurostat, 2022, STATISTA)

The production of renewable electricity and biomass electricity looks very diverse among different Member States, see Figure 23. The leading countries in renewable electricity generation in 2020 were Germany, France, Italy, Spain and Sweden. The major contribution to renewable electricity production comes from wind, biomass and solar in Germany, while the major contribution to renewable electricity in France comes from hydro, wind, solar and biomass in France. Biomass electricity has a lower contribution to renewable electricity in most MS. The leading countries in biomass electricity generation in 2020 were Germany, Italy, Finland, Sweden and Netherlands. Solid biomass was the main feedstock for bioelectricity in 2016 in several Member States (such as Finland, Sweden and Poland), while in other Member States, such as Italy and France, different feedstocks contribute to various extent to biomass electricity production. An important aspect to notice is the high contribution of biogas to electricity production in Germany with a share of 66 % of biomass electricity and an important biogas contribution to electricity production of more than more than 40 % in Belgium, Italy, Croatia and Latvia

Figure 23. Leading EU MS on renewable electricity and biomass electricity production in 2020

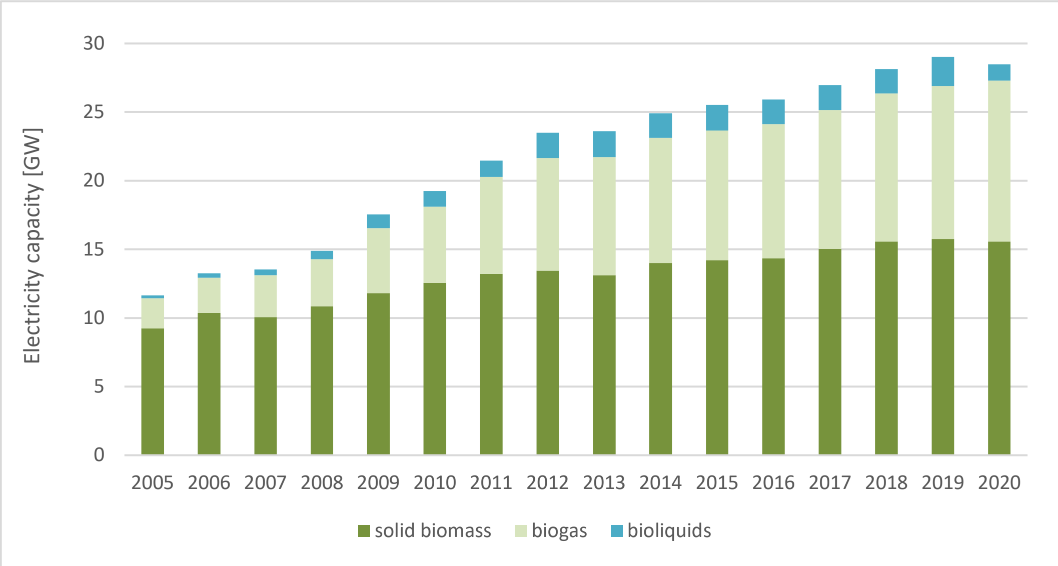


Source: (Eurostat, 2022)

EU biomass electricity capacity

The installed biomass electricity capacity in the European Union has increased from 12 GW in 2005 to 28 GW in 2020, with a decrease in the installed capacity in 2020 in comparison to 2019, **Figure 24**.

Figure 24. Evolution of biomass electricity capacity in the EU

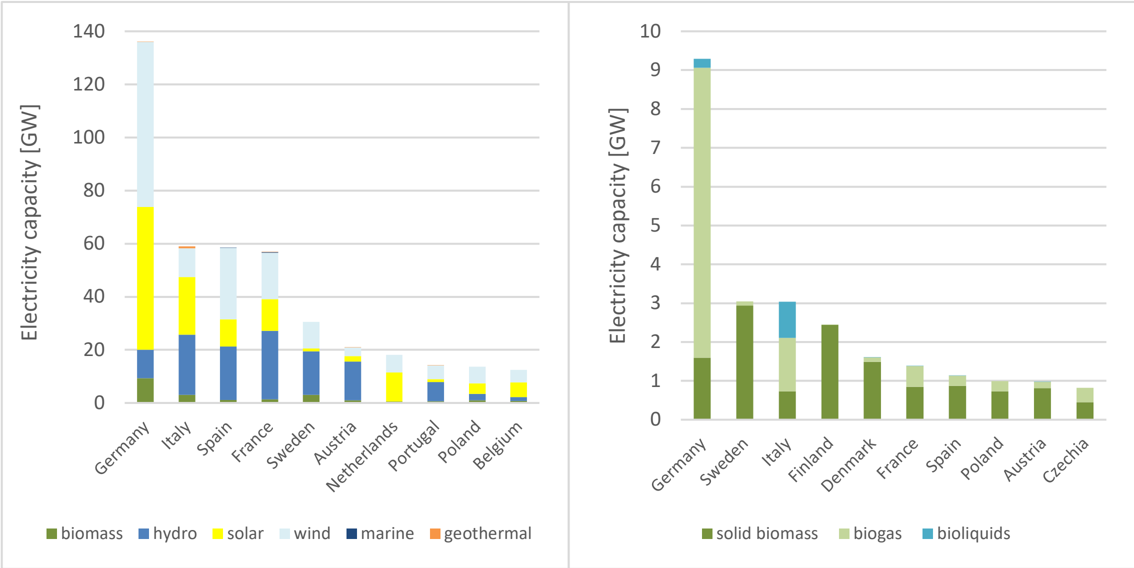


Source: (Eurostat, 2022)

The installed capacity of plants using solid biofuels increased from 9.2 GW in 2005 to 15.6 GW in 2020, showing very limited growth in the last years. In contrast, an important increase has been noticed in the installed capacity of biogas plants, with a growth from 2.2 GW to 11.7 GW. The share of biogas electricity plants in bioenergy plant capacity increased from 19 % in 2005 to 41 % in 2020. This growth seems to be levelling out in the last years. Thus, this figure shows that solid biofuels electricity plants dominated the European Union market in 2020, with 15.6 GW installed (55 % of total biomass capacity), followed by the total biogas plants with 11.7 GW installed capacity. The capacity of biomass plants based on the use of liquid biofuels is limited (1.2 GW), being used only in few MS (mostly in Italy), showing even a decrease in the last years due to the sustainability debate on the use of liquid biofuels. In 2020 Germany was the European Union leader in terms of renewable electricity capacity, in particular wind, biomass and solar,

Figure 25, the largest share of renewable electricity capacity comes from hydro, wind and solar with much smaller biomass plant capacity. Other EU Leaders in terms of installed renewable electricity capacity includes Italy, Spain, France and Sweden. The leading countries in biomass electricity capacity in 2020 were Germany, Sweden, Italy, Finland and Denmark. Biogas electricity plants had a share of 80 % in the total bioenergy capacity in Germany. Solid biomass was the main feedstock for bioelectricity production in 2020 in several Member States (such as Finland, Sweden and Denmark), while in other Member States, such as Italy and France, different feedstocks contribute to various extent to biomass electricity production. Important aspect to notice is the high share of biogas electricity capacity of biomass electricity plants of more than 40 % in Italy, Czech and The Netherlands.

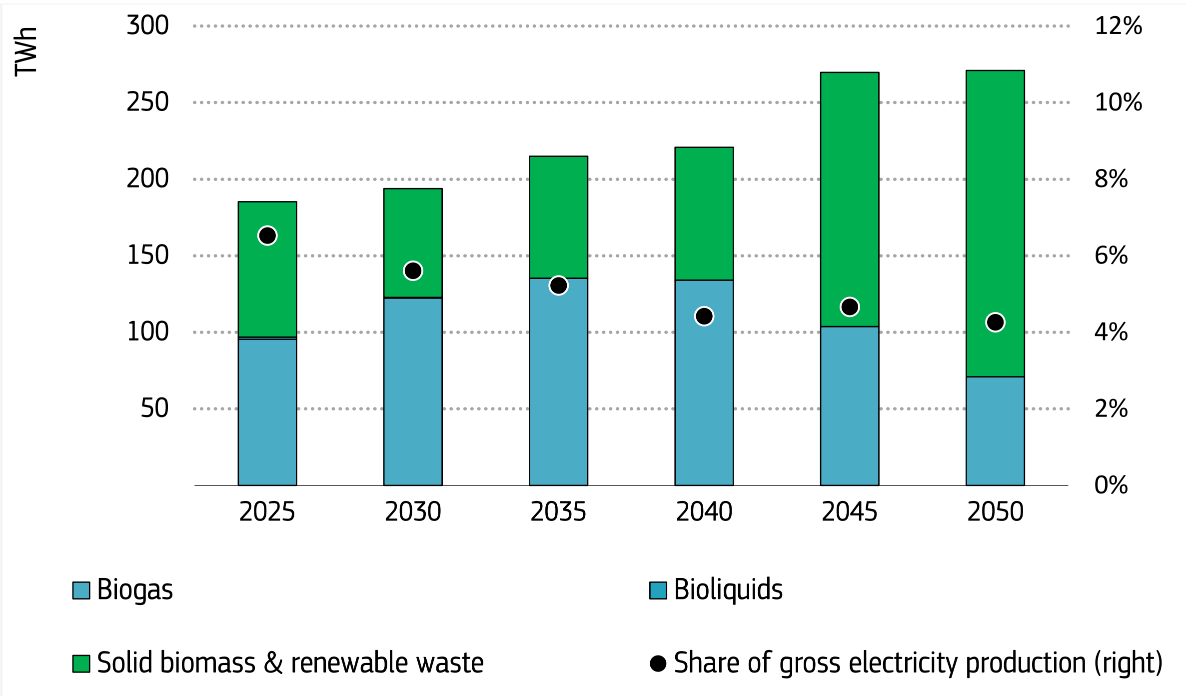
Figure 25. Leading MS in renewable electricity and biomass electricity capacity in the EU in 2020



Source: (Eurostat, 2022)

According to POLES modelling (Annex 3), the Bioelectricty production in EU will grow to more than 250 TWh in 2050, while its share for electricity mix will drop from 6.5% in 2025 to 4.3% in 2050, Figure 26

Figure 26, Bioelectricity production in the EU and share

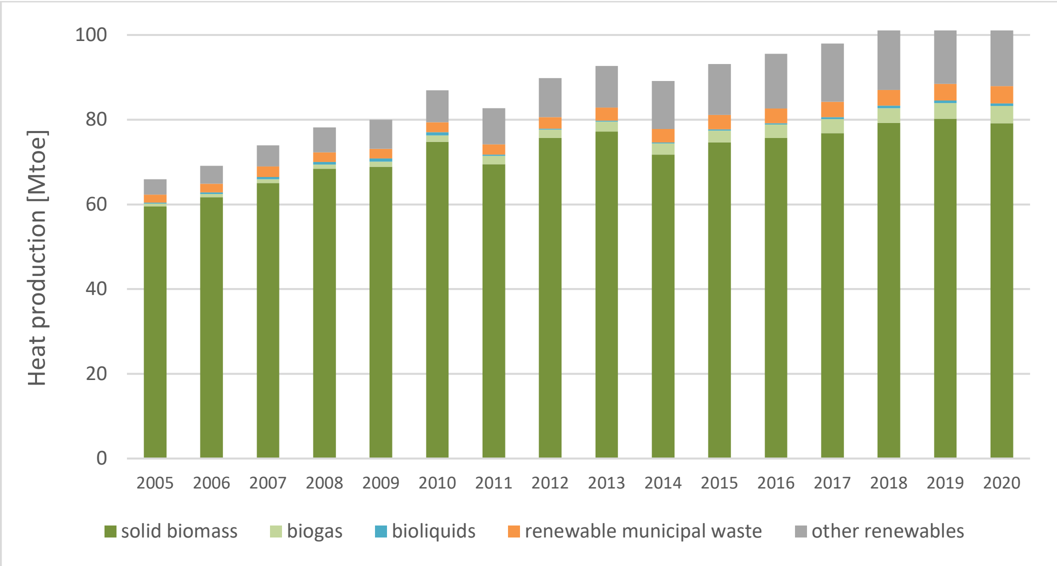


Source: POLES MODEL

Heat

Biomass is the largest contributor to renewable heating and cooling. While biomass heating grew from 62 Mtoe to 84 Mtoe between 2005 and 2020, its share in renewable heating decreased slightly from 94 % in 2005 to 80 % in 2020, due to higher growth of other renewables,The main contributor of biomass in renewable heating is solid biomass (forest and agricultural residues, wood pellets and various waste, including municipal solid waste). Although the use of solid biomass in heating increased, its share in biomass heating decreased from 97 % in 2005 to about 90 % 2020. The use of municipal renewable waste also has seen a good increase, related to the deployment of waste to energy plants producing combined heat and power. Important increase, in relative terms, came from the use of biogas from a contribution of 1 % in 2005 to 5 % in 2020. The use of heat from biogas has increased as result of the need to improve the economics of biogas plants through additional income, or measures to promote the use of heat from CHP plants in the European Union. With a slower progress in biogas heat use than in the electricity generation, the use of heat from biogas increased from 0.7 Mtoe in 2005 and 4 Mtoe in 2020.

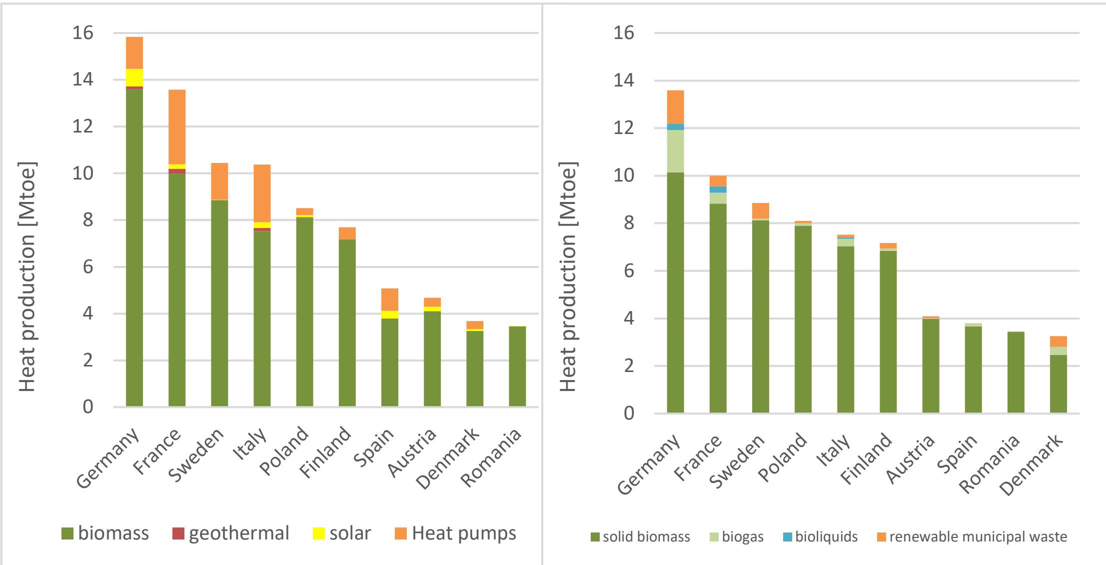
Figure 27. Evolution of the production of heat from biomass and all renewables in the EU



Source: (Eurostat, 2022)

Figure 28 shows the leading MS in the use of renewable heat and of biomass heat in 2020. The assessment of the data shows large differences across MS with Germany having the leading position on renewable heating, followed by France, Sweden, Italy, Poland and Finland. On biomass heating Germany also holds the first position followed by France, Sweden, and Poland Italy. By far biomass is the dominant source for renewable heating in most MS, followed by heat pumps, which have a higher share in France, Italy and Sweden. Looking at feedstocks, solid biomass plays main role, with a good contribution of biogas in Germany, France and Italy.

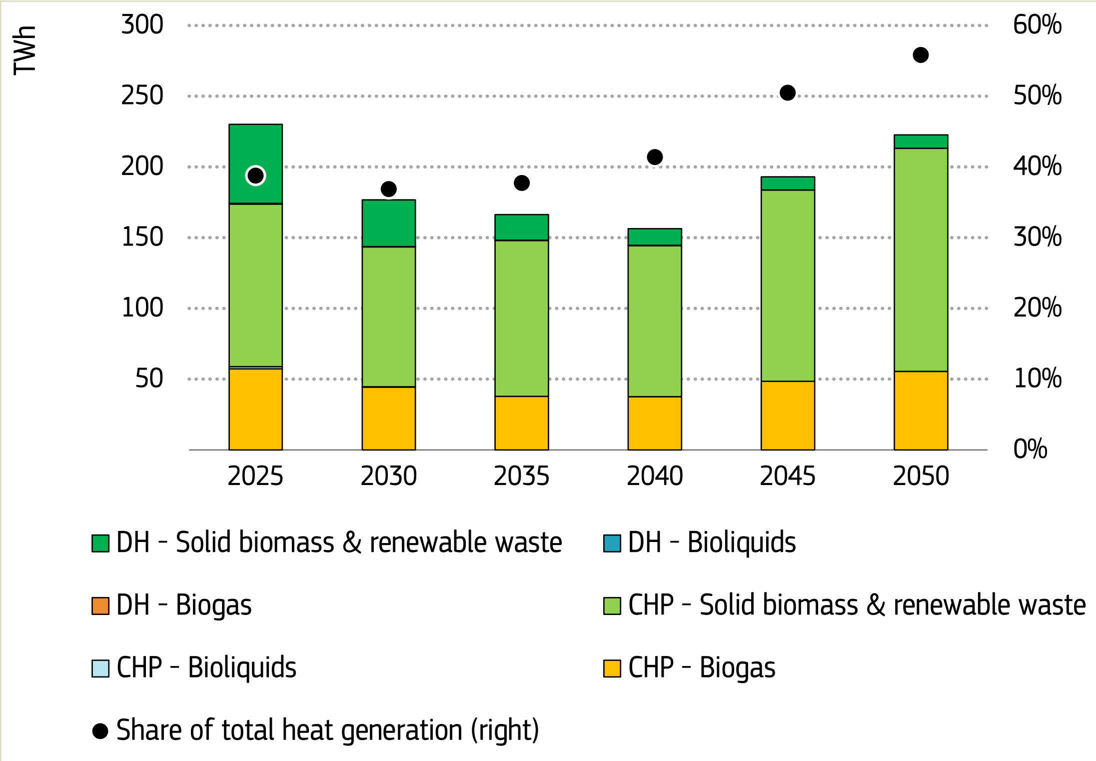
Figure 28. Leading EU MS on renewable heating (left) and biomass heating in 2020



Source: (Eurostat, 2022)

According to a POTEnCIA scenario targeting climate-neutrality in 2050 (see Annex 3) for the scenario description), despite a slight decrease across the years of heat production from bio sources (from 230 TWh in 2025 to 220 TWh in 2050), its share will increase from 39% to 56%, Figure 29

Figure 29. Heat production from bio sources in the EU (left axis) and relative share (right axis).



Source: POTENnCIA Model

Bio-LNG (Bio-Liquefied Natural Gas)

EBA 2022 Report states there were 15 active Bio-LNG producing plants in Europe by the end of 2021, and this number is expected to have added 19 Plants in 2022), for 2023 another 43 plants are under construction, and it is planned to add also 21 plants The combined Bio-LNG production capacity by 2025, considering only confirmed plants, adds up to 12.4 TWh per year.

Among the 100 Bio-LNG projects will be totally active until the year 2025, 62 plants use or will use agricultural residues as a feedstock, 16 plants are or will be using organic municipal solid waste, and 6 plants are based on industrial wastes

Bio-CNG (Bio-Compressed Natural Gas)

According to EBA Report 2022, the Bio-CNG production in Europe continues to increase constantly, out of the 1,222 biomethane plants active in Europe, by the end of August 2022, 133 plants are known to compress biomethane on-site. The on-site Bio-CNG production is particularly applied in areas where the gas network is less developed like in Sweden and Finland which in 2022 have 69 and 23 Bio-CNG plants respectively.

2.3 Technology Costs

The economic viability is highly sensitive to feedstock price, process configuration and plant size. While higher capacity plants are more economic, their capacity is limited by the feedstock availability. Combined heat and power production represents a good option to improve the overall efficiency of biogas plants if heat could be used locally or through heat distribution networks. The by-product from AD, the digestate, can be used as fertiliser, just like manure, having the same content of nutrients as manure. This brings additional economic benefits by reducing the use of chemical fertilizers in farms, and reduces nutrient runoff and avoids methane emissions. Their technical complexity and associated capital and operational costs depend on the feedstock.

Economics

The key to the deployment of bioenergy production is the availability and reliability of sustainable feedstocks. Bioenergy production can be competitive in some circumstances and when feedstock is available at low cost. The economies of scale are significant for biomass plants, although the overall size of biomass plants is limited by biomass availability, the high transportation cost for biomass feedstock and logistic issues.

The report “International financial corporation World Bank Group” provide the CAPEX, OPEX and for the Bioenergy Steam cycle, Organic Rankine Cycle (ORC) and Biogas related to the plant size. In Table 6, the main data is presented:

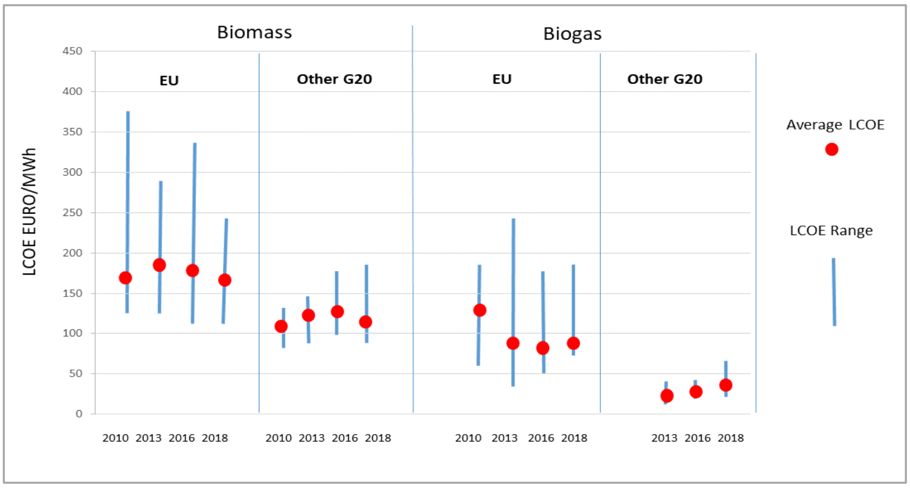
Table 6. CAPEX & OPEX Bioenergy technologies

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 LCOE of solid biomass-fired power plants have dropped by 20% since 2008 to €160/MWh on average (in 2018 LCOE ranged between €108-€225/MWh). The trend is driven by recent reductions in wood costs which started in 2014 and more importantly a reduction in CAPEX levels which were on average at €4,100/kW in 2008 and €2,700/kW in 2018. With fuel costs around 30% lower than for EU countries and the UK, LCOE in non-EU G20 countries were between €94-174/MWh in 2018. Over the period, LCOE rates remained rather stable in most countries, Figure 30.

Figure 30. LCOE on Bioelectricity from solid Biomass and Biogas

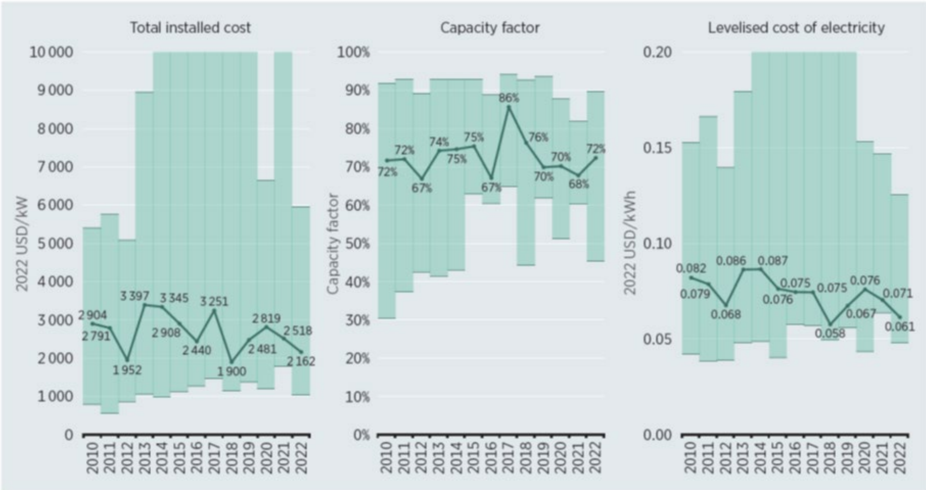


Source: DG Energy, Study on energy costs, taxes and the impact of government interventions on investments in the energy sector

LCOE for electricity from biogas-fired plants ranged between €64-180/MWh in the EU countries in 2018. These rates are much higher than those registered in other parts of the world mostly due to the scale of the power plant projects. EU data collection includes projects with installed capacities below 2 MW which register CAPEX levels (in 2018) that ranged 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 has confirmed the wide range variabilibility, al global level, about installation cost, capacity factor and LCOE for Bioenergy power production at an average of 61 $ /MWh, last reference year is 2022 and the two combined criteria used are the feedstock typology and the plant size. Figure 31

Figure 31. Global Bioenergy capacity factors and costs



Source: IRENA 2023 Power generation cost

The EU Reference Scenario is one of the European Commission's key analysis tools in the areas of energy, transport and climate action; the modelling cost assumptions concerning bioenergy are summarised in Table 7.

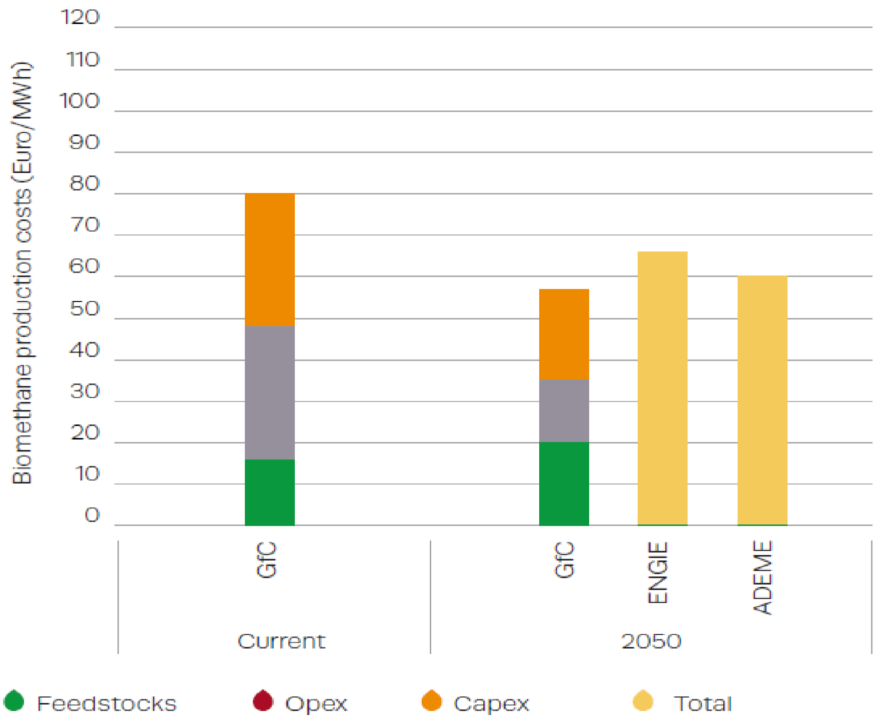
Table 7. Bioenergy technologies CAPEX and OPEX

Technology	Overnight Investment Costs in a greenfield site, excluding financial costs during construction time EUR/kW				Fixed Operation and Maintenance costs, annually EUR/kW			
	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

According to EBA report 2022, the current biomethane production costs are estimated averaging around 80 €/MWh. This includes feedstock costs at (16 €/MWh), CAPEX (32 €/MWh) and OPEX (32 €/MWh).When produced the Biomethane needs to be injected into the gas grid at estimated costs at about 5% of the biomethane production costs (3 – 4 €/MWh). Alternatively liquefaction has an average estimated cost at around 12 €/MWh.

Figure 32. Biomethane production cost Europe 2022

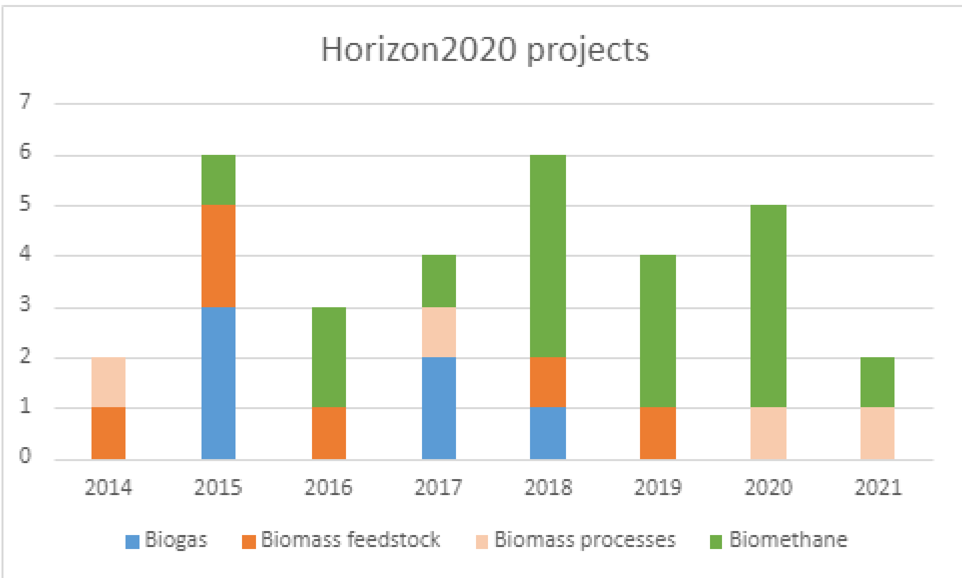


Source: (European Biogas Association, 2022)

2.4 Public RD&I Funding and Investments

Horizon 2020 was the EU's research and innovation funding programme from 2014-2020 with a budget of nearly €80 billion, retrieving data from the CORDIS database, the number of biomass projects that have received funding under the Horizon 2020 programme were in total 32, Biomethane 16, Figure 33.

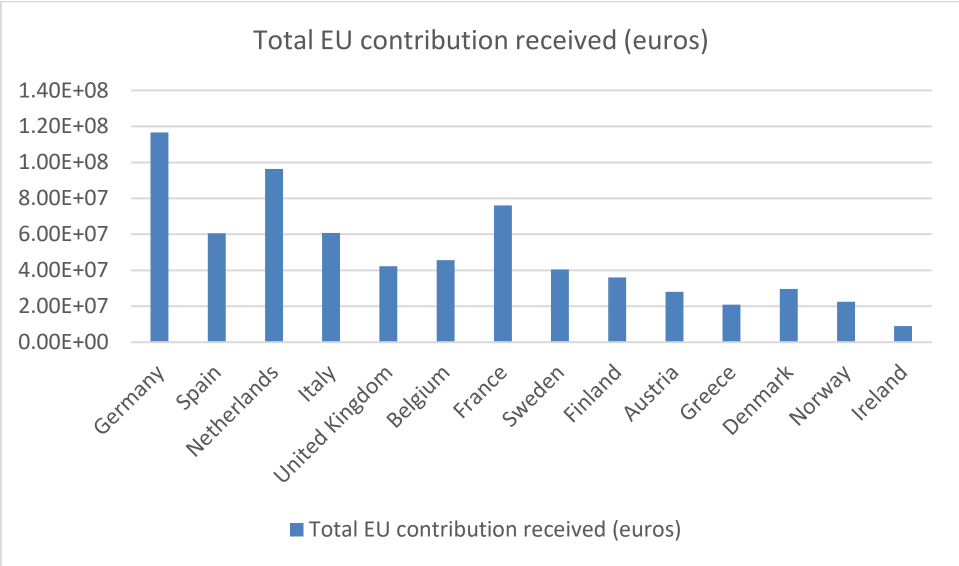
Figure 33. Number of H2020 Biomass projects.



Source: JRC 2023

From the whole duration of the H2020 programme, the funding dedicated to Bioenergy projects amounted to 769 M€, German entities received 120 M€, followed by Netherlands and France, Figure 34.

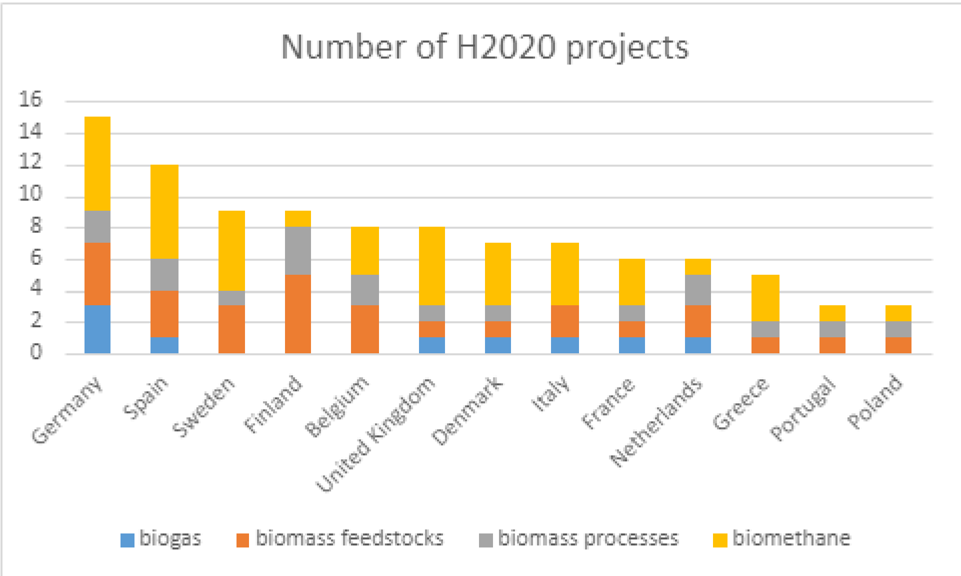
Figure 34. Number of H2020 funding received by nations on Bioenergy projects



Source: JRC 2023

Concerning the number of Horizon 2020 projects financed, German entities participated to 15 projects, followed by Spain with 12 and Sweden with 9 projects. Figure 35.

Figure 35. Number of Bioenergy projects H2020 by nations



Source: JRC 2023

The Pubblic R&I investment in the Biogas sector in EU peaked at 54 M€ in 2012, and after averaging at around yearly 20 M€ from 2017 to 2019, regained the 33 M€ in 2020, see Figure 36

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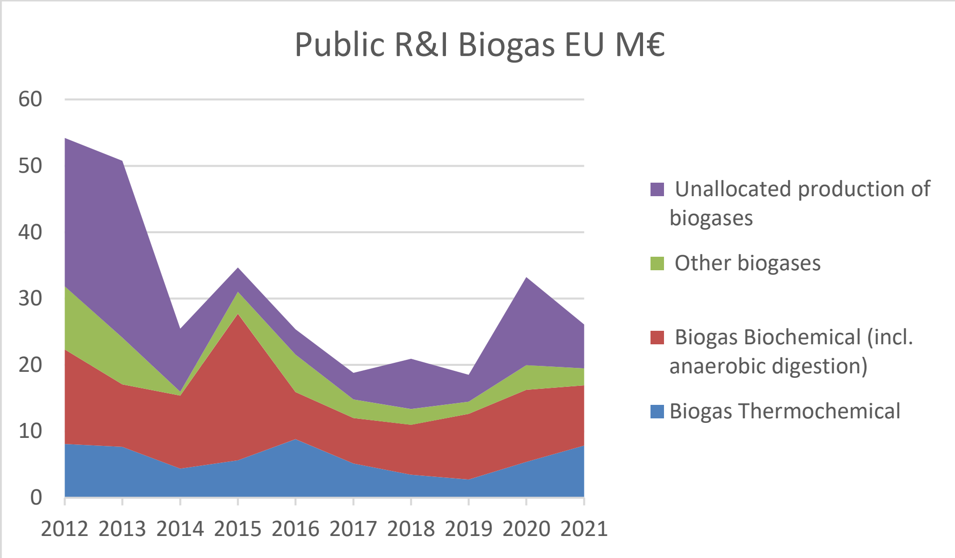
Figure 36. Public R&I EU Biogas



Source: JRC 2023

2.5 Private RD&I funding

Investments considered in this analysis are early and later stages investments in Venture Capital (VC) companies over the considered period, VC companies include Pre-Venture companies and Venture Capital companies. Pre-venture companies are companies that have received Angel or Seed funding or are less than 2 years old and have not received funding. Venture Capital companies are companies that have, at some point, been part of the portfolio of a venture capital firm.

Investments reflect investments in all active companies over that period irrespectively of their current status (defunct, publicly held, privately held with no VC backing, merged or acquired, no longer actively tracked in the data source. Early stages investments include: Grants, Angel & Seed (i.e. Pre-Seed, accelerator/Incubator, Angel and Seed) and Early stage VC. Later stages 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. Later stages investments do not include: Buyout Private Equity and Public investments.

The list of VC companies includes all the identified companies, irrespectively of their founding year, the fact that have received investments over the period or their current status. The number of VC companies corresponds to the count of active VC companies that have been founded over the period (irrespectively of the investments they have received) or have received investments over the period (irrespectively of the year they have been founded). VC companies that have not been founded or have not received investments over the period are not considered as active.

For the Bioenergy In 2022, global VC investments in bioenergy firms have quadrupled (x 4.1 as compared to 2021) and reached an all-time high of EUR 752.1 Million. Consequently, global VC investments amount to EUR 1.33 Billion over the period 2017-22 and overtook for the first time those realised during the previous 6-year period (2011-16). Figure 37

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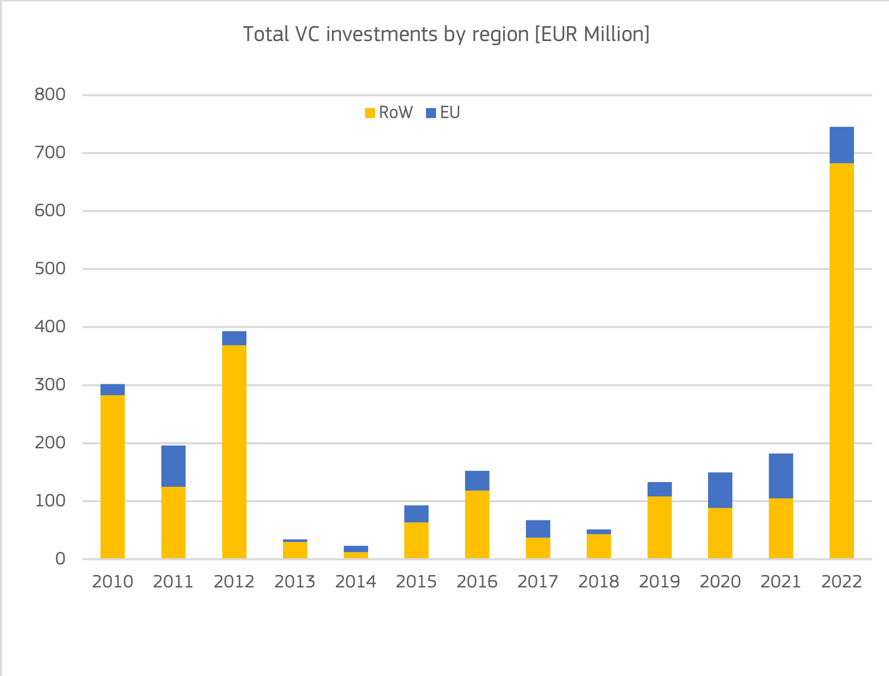
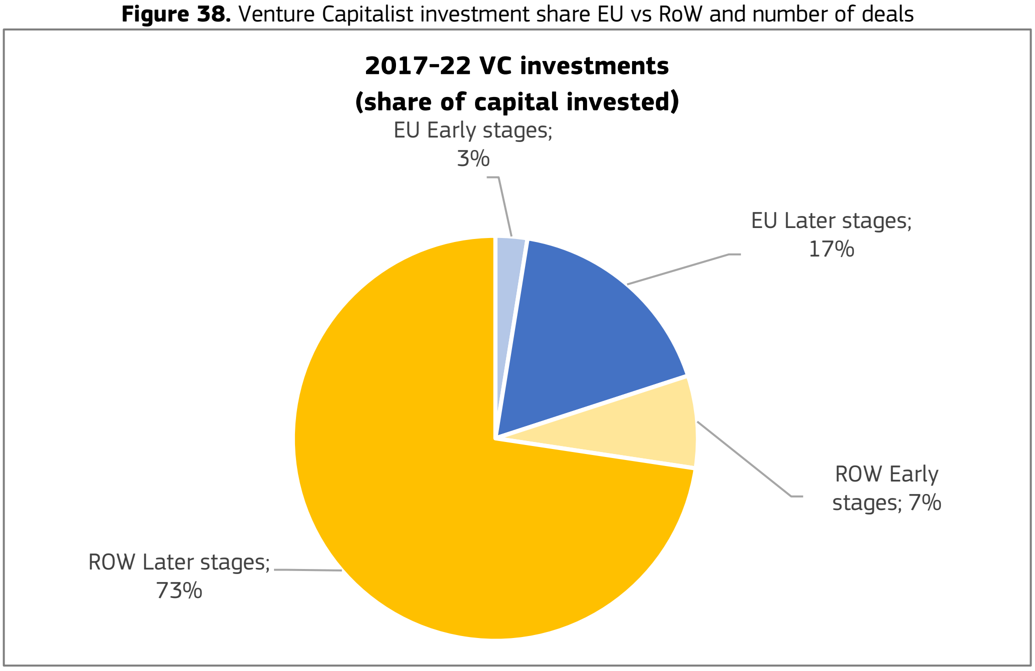
Figure 37. Venture Capitalist investment in Bioenergy, EU vs RoW



Source: JRC 2023

The EU accounts for a significant part of active innovators (45 % of VC companies across 15 Member States) and maintains a solid competitive position at both early and late stages. With almost half (49 %) of global VC investments over the period 2017-22, the US however takes a clear leadership in the investment race, both at early and late stage. The EU had a share of 20 % on global VC capital invested in the last 5 years, Figure 38.

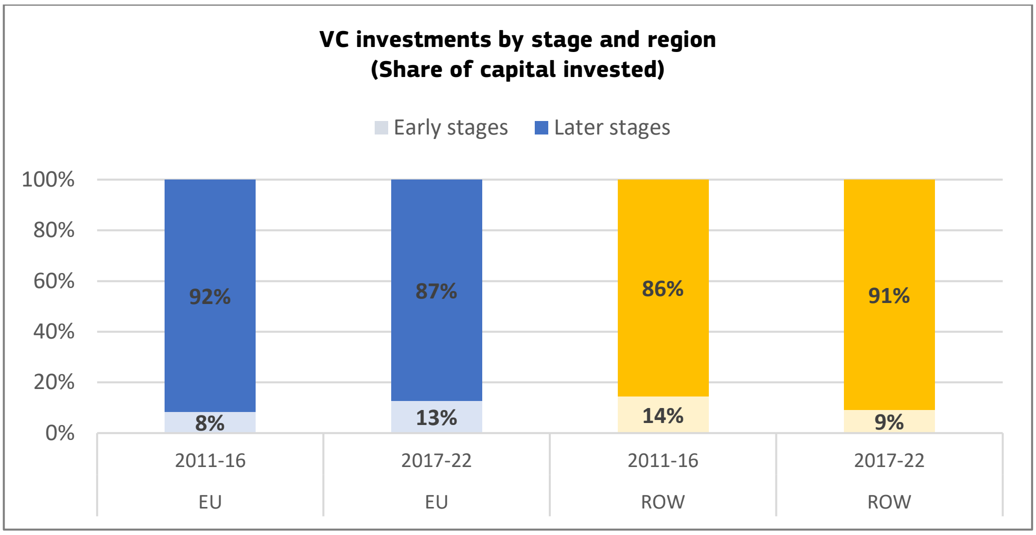
Figure 38. Venture Capitalist investment share EU vs RoW and number of deals



Source: JRC 2023

Over the 2017-22 period, early stage investments in EU companies amount to EUR 40.9 Million and account for 29.5 % of global early stage investments. The EU improves an already strong competitive position as early investments in the rest of the world decrease in 2022 (– 29.5 % as compared to 2021)An increasing trend for early stages VC investment in the EU is observed in the last 5 years as it rose from 8 % to 13% (Figure 39).

Figure 39. Venture Capitalist investment by stage and regions



Source: JRC 2023

Late stage investments in EU companies amount to EUR 227 Million over the 2017-22 period and account for 19 % of global late stage investments. In 2022, they have however decreased in the EU (13.6 % as compared to 2021) back to 2020 levels. This contrasts with the outstanding growth of late stage investments realised outside of the EU in 2022 (x 9 as compared to 2021), driven by a single large deal in the US company California Bioenergy (EUR 476.24 Million of growth equity

Grant funding in the EU amount to EUR 14.6 Million, putting the EU public effort on par with the cumulated contribution in the rest of the world. On the other hand, this means that EU early ventures rely largely on public funding (which represents 37 % of EU early stage investments over the 2017-22 period).

2.6 Patenting trends

For the assessment of the technical progress achieved in the field of bioenergy technologies, the performed analysis focused on the world distribution of patent filings for the time period between 2009 and 2020 as extracted from PATSTAT database. In order to estimate the share in total inventions a fractional count should be adopted, where inventions tagged with more than one code contribute with an equal fraction to all the codes (classes) involved.

Patents related to biomass for heat and power sector are identified by using the relevant code families of the Cooperative Patent Classification (CPC), for the technologies or applications for mitigation or adaptation against climate change, reduction of greenhouse gases emission related to energy generation, transmission or distribution. The Y codes are designed to facilitate the identification of inventions relevant to renewable energy and climate mitigation technologies. Within this classification, the set of technical classes of inventions that can be related to the biomass technologies, are patent families with code Y02E related to energy generation, transmission or distribution and the Y02E 50 code that include CPC classes referred as 'technologies for the production of fuel of non-fossil origin'. Y02E 50/30 'fuel from waste', where intersecting with (C12M 21/04 'digester from manure' OR C12P 7/10 'bioreactors').

The classes that are included in the present analysis often refer to "biofuels", but this does not mean biofuels for transport but in fact fuels from biomass, as bioenergy carriers. This could be overlapping with the biofuels for transport, but there is no possibility to differentiate between the final use of these products, as pyrolysis products or methane from anaerobic digestion can have various uses in transport or heat and power production. The relevant patents are grouped under the following classes of patents:

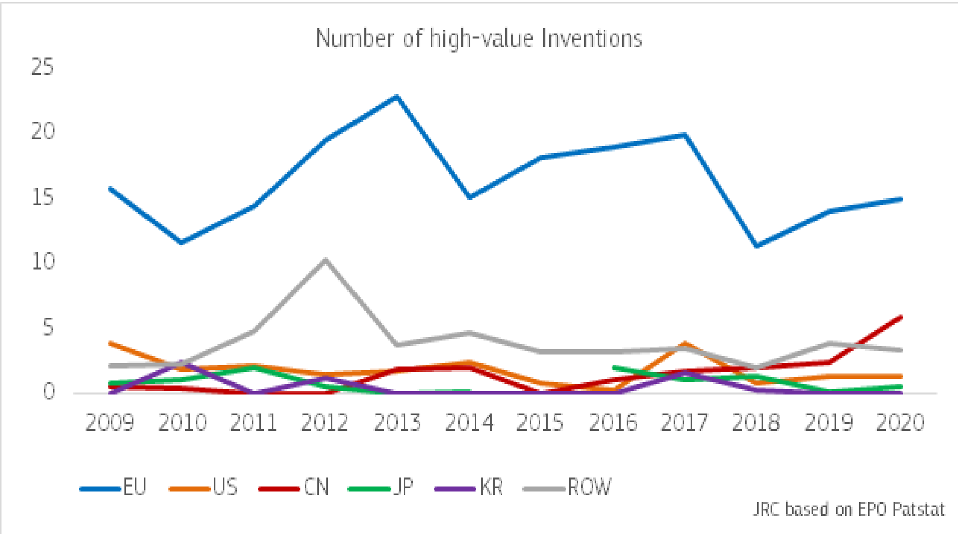
- CPC: Y02E 50/30 'Fuel from waste'
- Intersection with:
- C12M21/04 'digesters for manure'
- C12M21/00 'bioreactor or fermenters'

For having a representative classification three patent categories have been grouped with the following terminology. Patent families (or inventions) measure the inventive activity. Patent families include all documents relevant to a distinct invention (e.g. applications to multiple authorities), thus preventing multiple counting. A fraction of the family is allocated to each applicant and relevant technology. High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office. Granted patent families represent the share of granted applications in one family. The share is then associated to the fractional counts in the family.

From 2009 to 2010 the EU has kept the lead in terms of high value inventions from 10 to 23 patents per year,

Figure 40

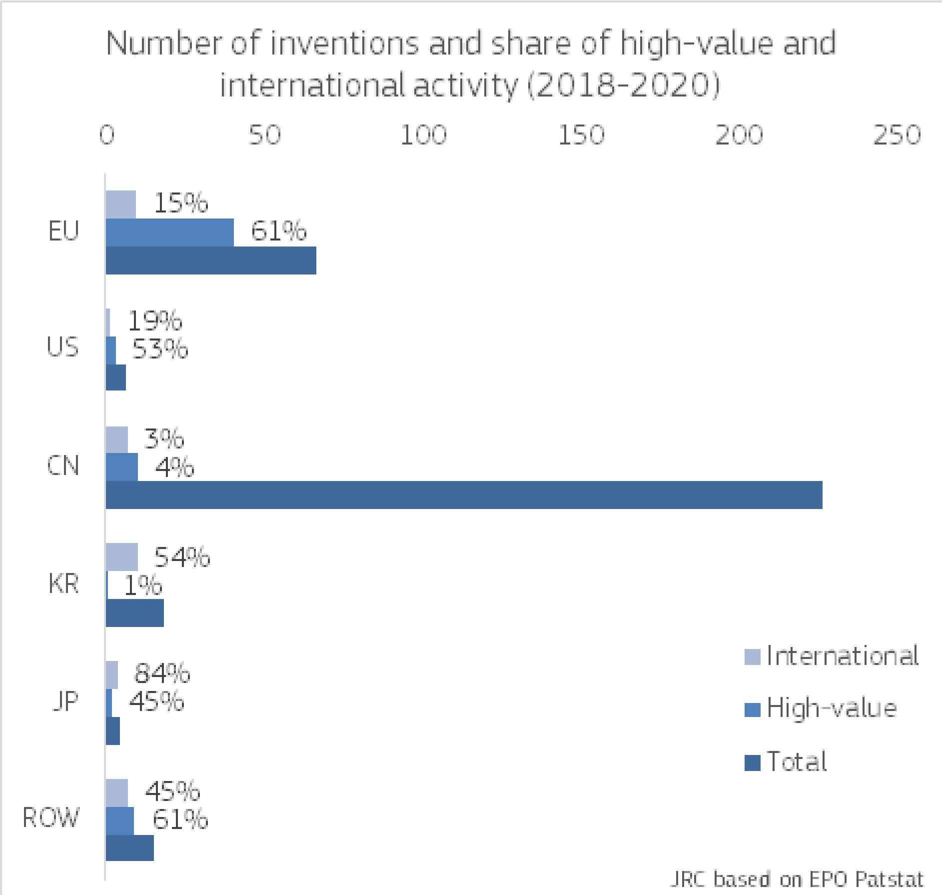
Figure 40. Bioenergy Number of High Value Inventions



Source: JRC 2023

For the triennium from 2018 the 2020, the EU had 61% share of high-value patents for a EU total of 66 patents applications, while China applied for total 226 patents with only 10 high-value, Figure 41.

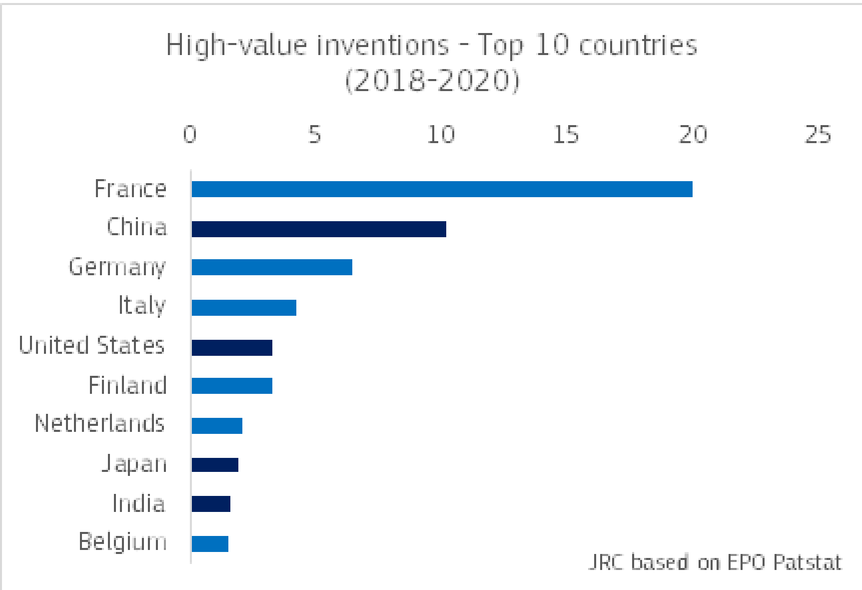
Figure 41. Number of invention and share



Source: JRC 2023

For the triennium from 2018-2020, at country level France and Germany were the EU leading countries with 20 and 6 high-value patents respectively, Figure 42.

Figure 42. Bioenergy High Value Inventions top 10



Source: JRC 2023

The French company Lair Liquide, with seven high-value inventions, leads the ranking of top 10 world entities for the 2018-2020 time period, Table 8.

Table 8. High Value Inventions top 10 entities

High-value inventions - Global Top 10 entities (2018-2020)	
Row Labels	High-value
Air Liquide Societe Anonyme Pour Letude Et Lexploitation Des Procedes Georges Claude (FR)	7
Ies Biogas S.R.L. (IT)	2
Mitsubishi Heavy Industries Ltd (JP)	2
Indian Oil Corporation Limited (IN)	1
Planet Biogas Group Gmbh (DE)	1
Goffin Energy Gmbh (DE)	1
Connected Energy Technologies Limited (UK)	1
Fliegl Agrartechnik Gmbh (DE)	1
Martin Gmbh Fur Umwelt Und Energietechnik (DE)	1
Welle Environmental Group Co Ltd (CN)	1

Source: JRC elaboration

The inventions granted decreased in the triennium 2018-2020 from total 21.8 in 2018 to 19.9 in 2020, China leads this category with share of 76% in 2018 and 75% in 2020, Table 9.

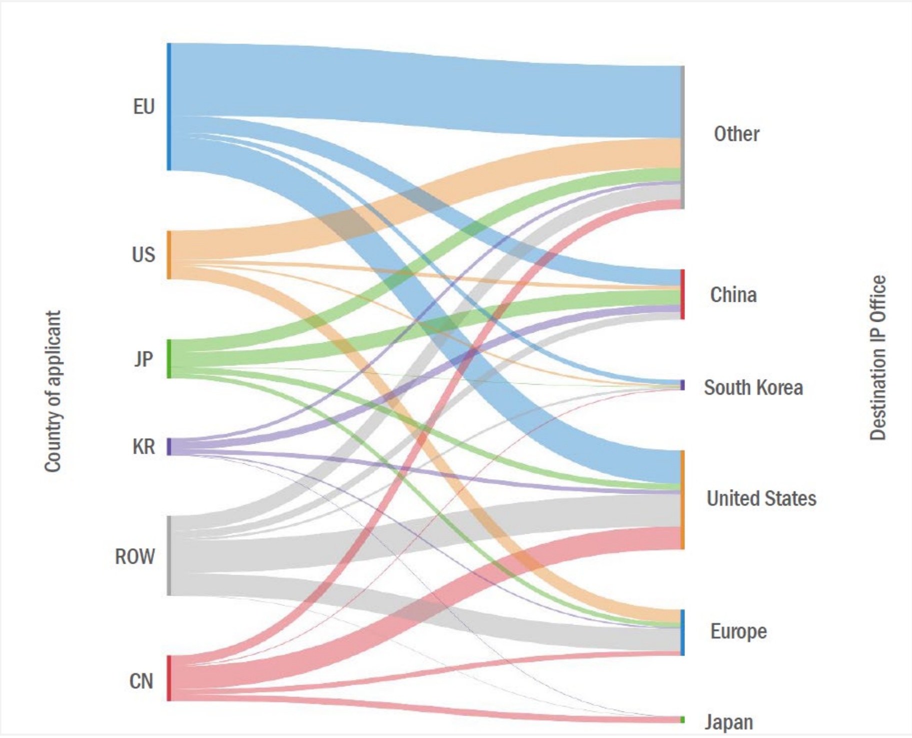
Table 9. Inventions granted 2018-2020

World_player	2018	2019	2020
EU	3.0	3.9	2.9
CN	16.7	13	15
JP	0.7	0.0	0.0
KR	0.3	6.8	2.0
US	1.1	0.3	0.0
ROW	0.0	0.1	0.0
	21.8	**25.2**	**19.9**

Source: JRC 2023

Flow of inventions (or destination of patent families) indicates where (in which national patent office) inventions are filed. This can be used to analyse the international flow of inventions, the directional streams between geographical areas, when the cumulated number of inventions from 2018 to 2020 are accounted, it is observed the EU inventions flowed mainly toward to other countries, US and China. The overall stream flow is represented in the Figure 43.

Figure 43. Total Inventions stream from 2018-2020



Source: JRC 2023

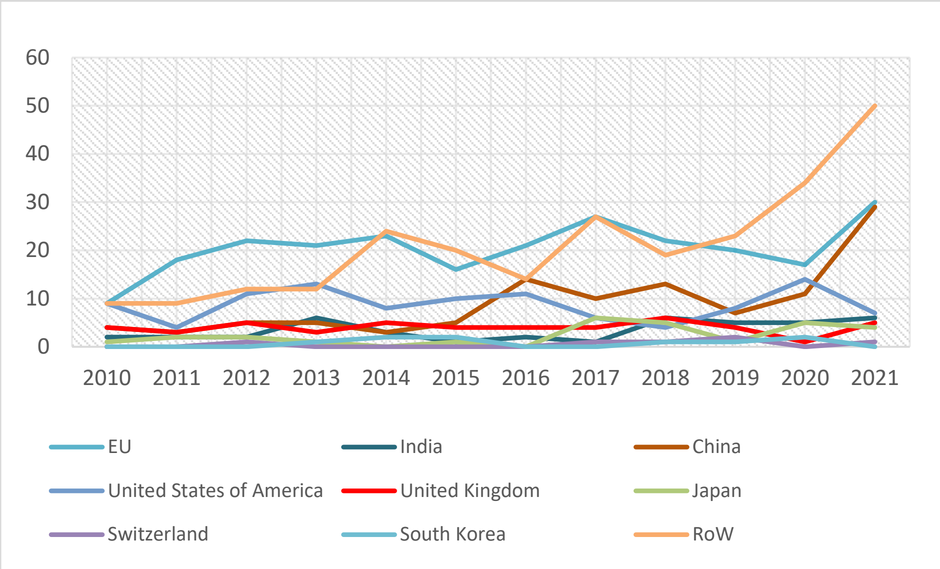
2.7 Scientific publication trends

The analysis on Bibliometric trends of scientific publications was performed by the JRC TIM based on Scopus database. For the Bioenergy Heat & Power, two main categories of publications were considered, feedstock and processes. The strings used to retrieve the biomass feedstock biomass: 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. Which were associated to sectors: Biomass heat production; biomass heat generation; biomass power production; biomass power generation; biomass electricity production; biomass electricity generation. For the Biomass for H&P – feedstock, a total of 675 articles were retrieved (2010-2021).

The strings used to retrieve the biomass processes : Biomass heat production; biomass heat generation; biomass power production; biomass power generation; biomass electricity production; biomass electricity generation; biomass heat and power; biomass CHP production; biomass CHP plant; Biomass Pelletization; torrefaction; pyrolysis; Briquetting ; wood chipping; anaerobic digestion; biogas upgrading; boilers; stoves; hydrothermal processing; fluidised bed combustion; fluidized bed combustion.

For the Biomass H&P processes a total of 769 articles were retrieved (2010-2021). For the scientific publications concerning the Biomass Feedstock for H&P, the EU has been the leading actor averaging more than 20 articles per year from 2014 onwards, outperformed by China with 30 articles in 2021, Figure 44.

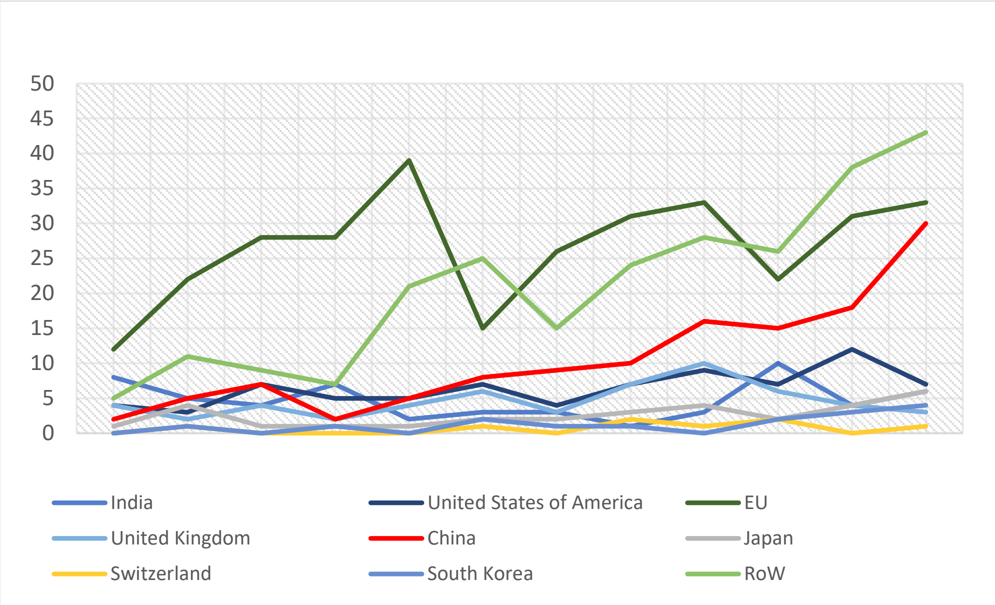
Figure 44. Scientific publication Biomass Feedstock, 2000-2021



Source: JRC 2023

Concerning the number of scientific publications, from 2000 to 2021, biomass to H&P processes, EU was leading the ranking until 2017, afterward EU remained the second behind RoW with more than 30 publications in 2021, Figure 45.

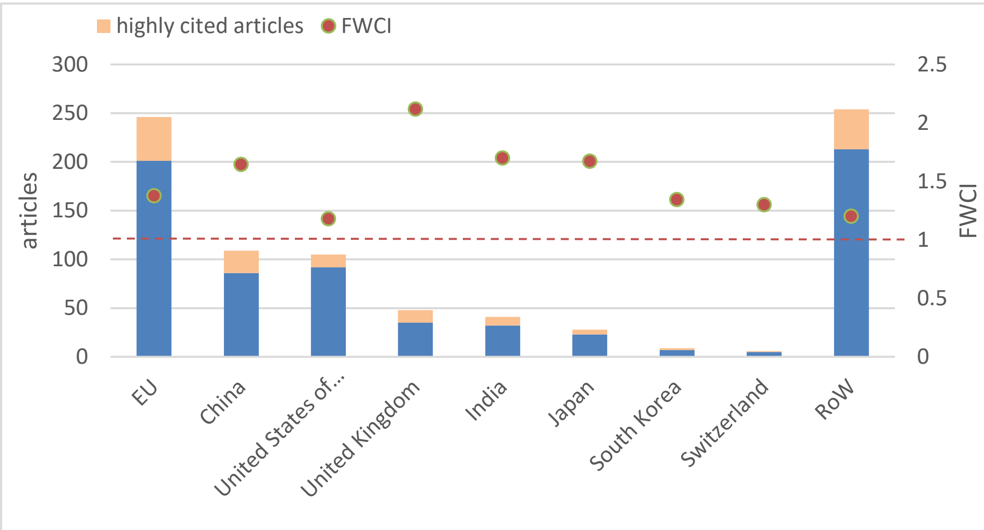
Figure 45. Scientific publication Biomass Processes, 2000-2021



Source: JRC 2023

Citations on biomass feedstock scientific articles, during 2017-2021, EU has 42 highly cited papers, with Field Weighted Citation Impact (FWCI) at 1.3, Figure 46.

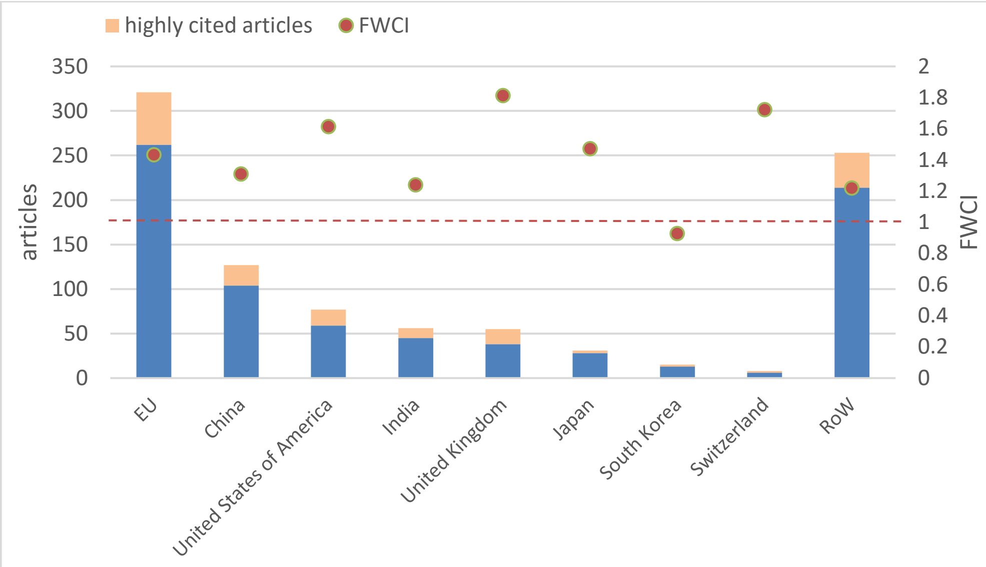
Figure 46. Highly cited scientific publication Biomass feedstock, 2017-2021



Source: JRC 2023

With regards to Citations on biomass processes scientific articles, during 2017-2021, the EU has 45 highly cited papers, Field Weighted Citation Impact at 1.4, Figure 47

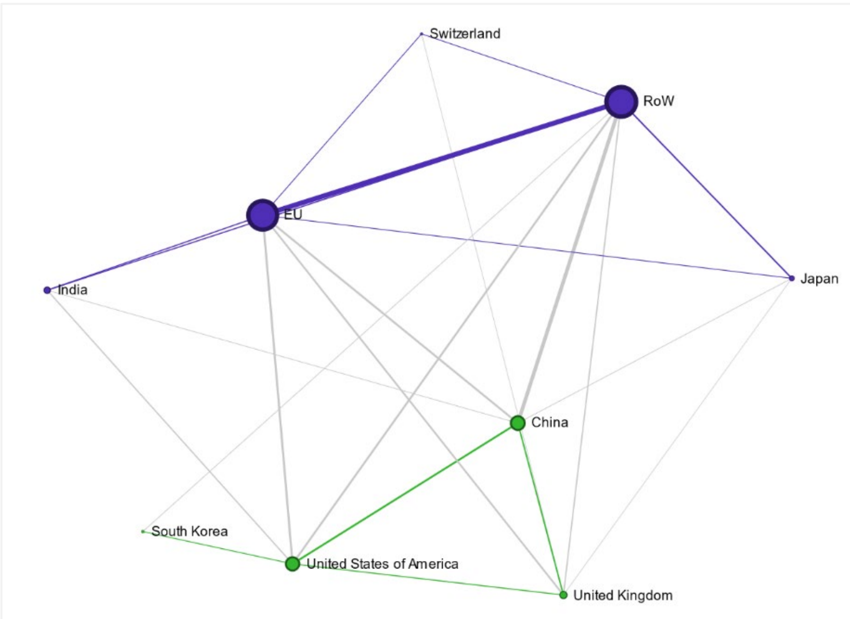
Figure 47. Highly cited scientific publication Biomass processes, 2017-2021



Source: JRC 2023

Looking at collaboration network related to Biomass H&P scientific publications, from 2010 to 2022, we can see a strong relation between EU and the RoW, Figure 48

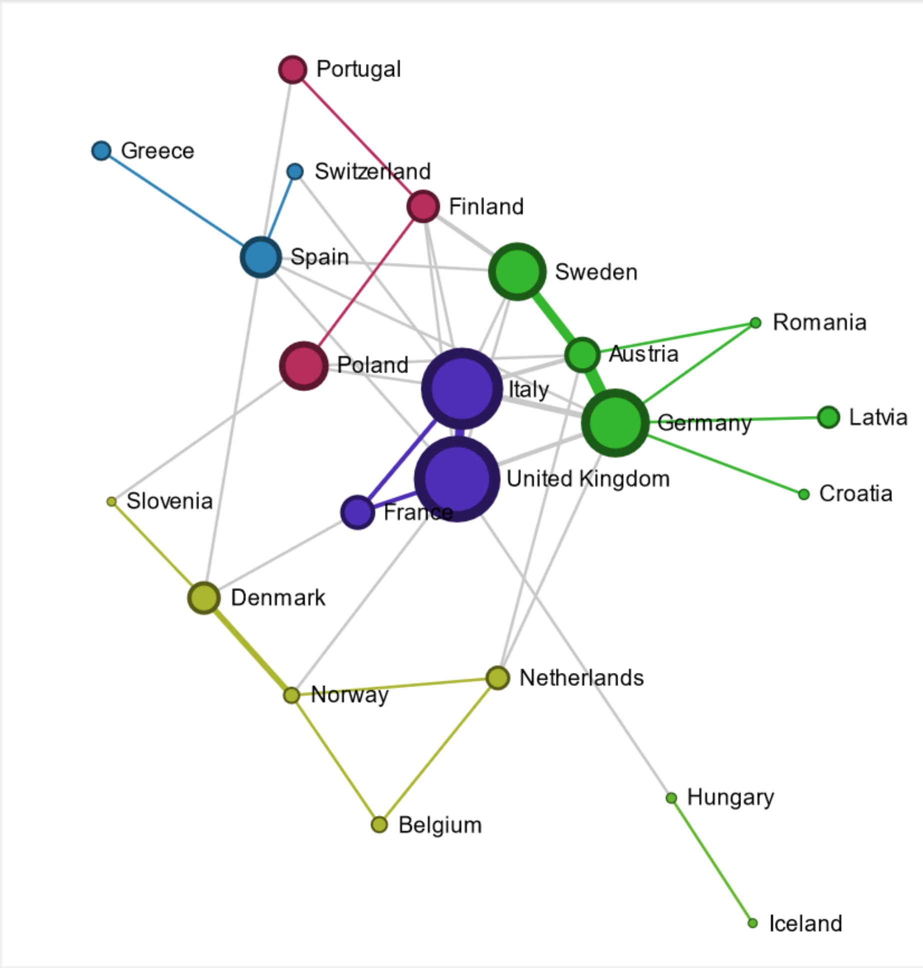
Figure 48. Collaboration network scientific publication Biomass H&P worldwide, 2010-2022



Source: JRC elaboration

At European level the collaboration network on biomass, from 2010 to2022 related to Biomass H&P scientific publications, sees strong connections between Italy and the UK, and among Germany, Sweden and Austria. Figure 49.

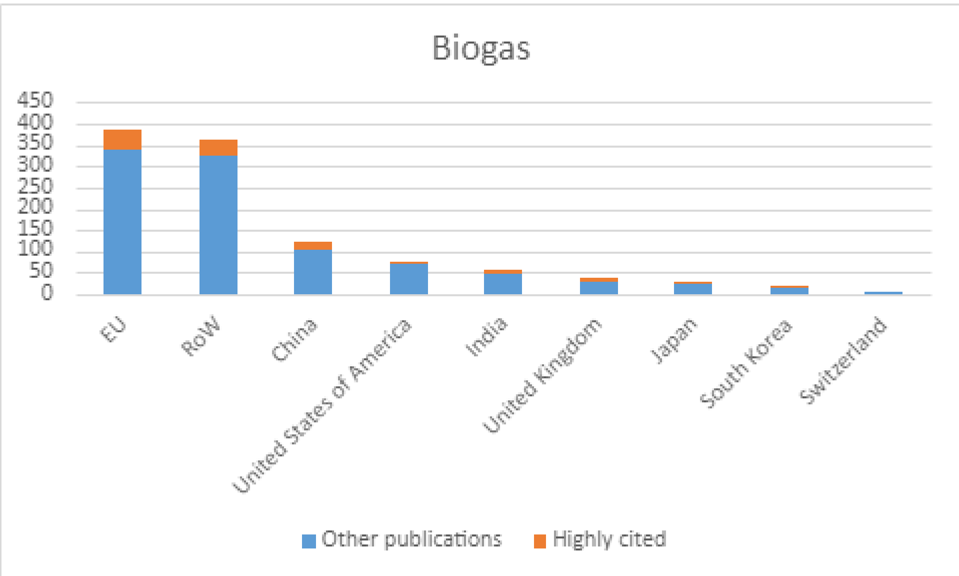
Figure 49. Collaboration network scientific publication Biomass H&P in Europe, 2010-2022



Source: JRC 2023

At the global level during the period 2010-2022 the EU leads the scientific publications on Biogas with 385 articles of which 47 were highly cited. Figure 50

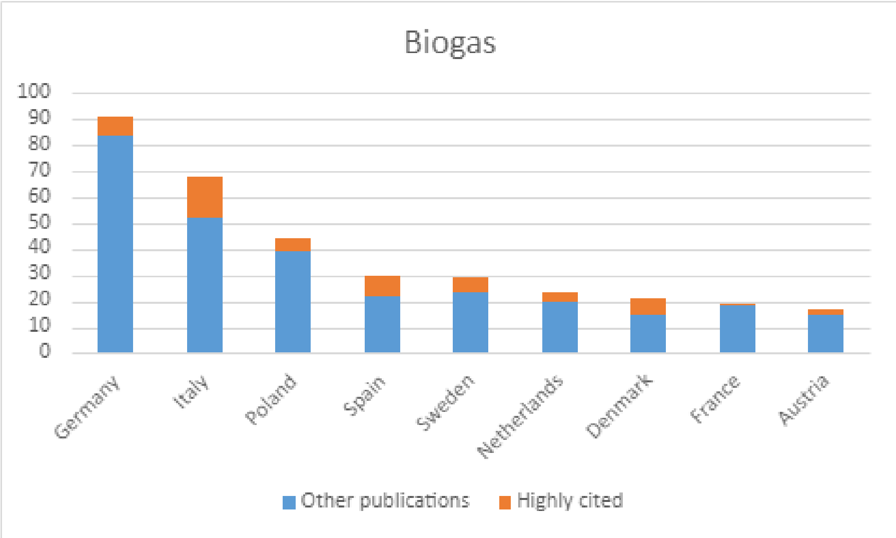
Figure 50. Scientific publication on Biogas, 2010-2022



Source: JRC 2023

At the EU level, in the period 2010-2022 Germany produced 91 scientific papers on Biogas, 7 were highly cited, Figure 51

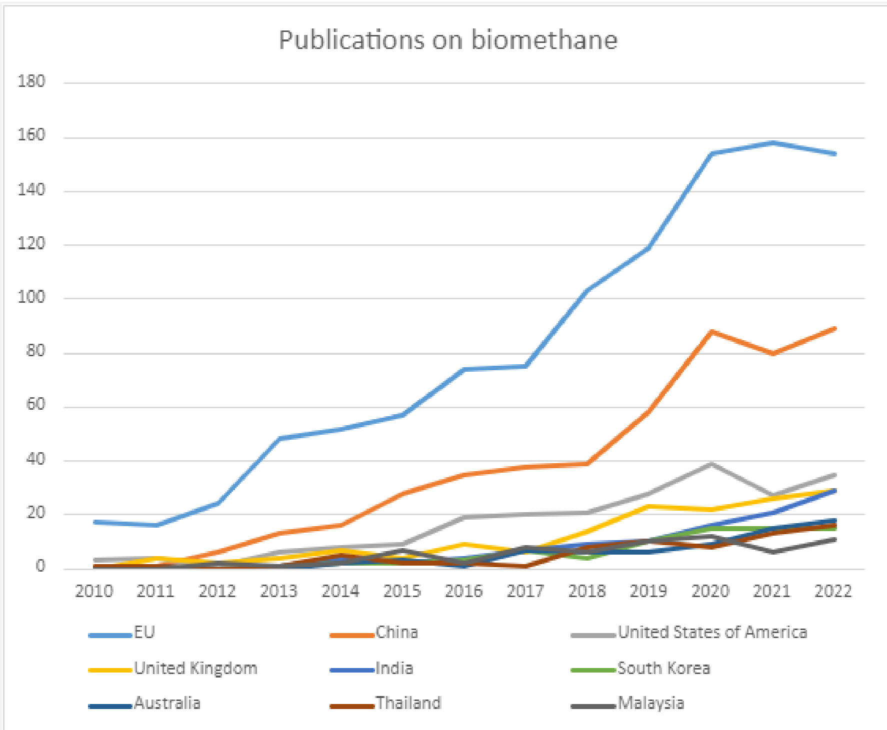
Figure 51. Scientific publication on Biogas in Europe, 2010-2022



Source: JRC 2023

At global level, the EU has been leading the Biomethane publications in the last 12 years, with steadily increase until reach 160 publication in 2021, Figure 52

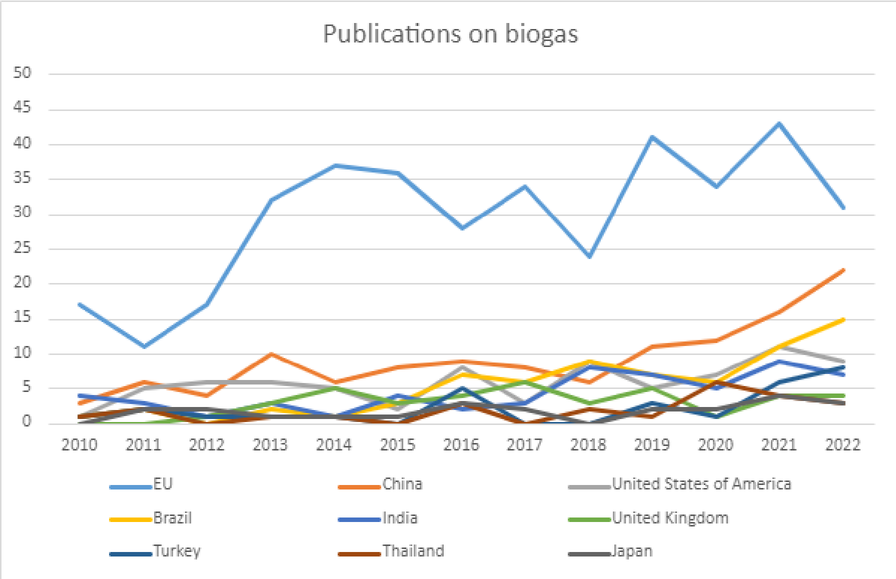
Figure 52. Global trend scientific publication on Biomethane, 2010-2022



Source: JRC 2023

For Biogas, while the EU ever leads the numbers of publications, with up-down trend, China steadily increased after 2019, Figure 53

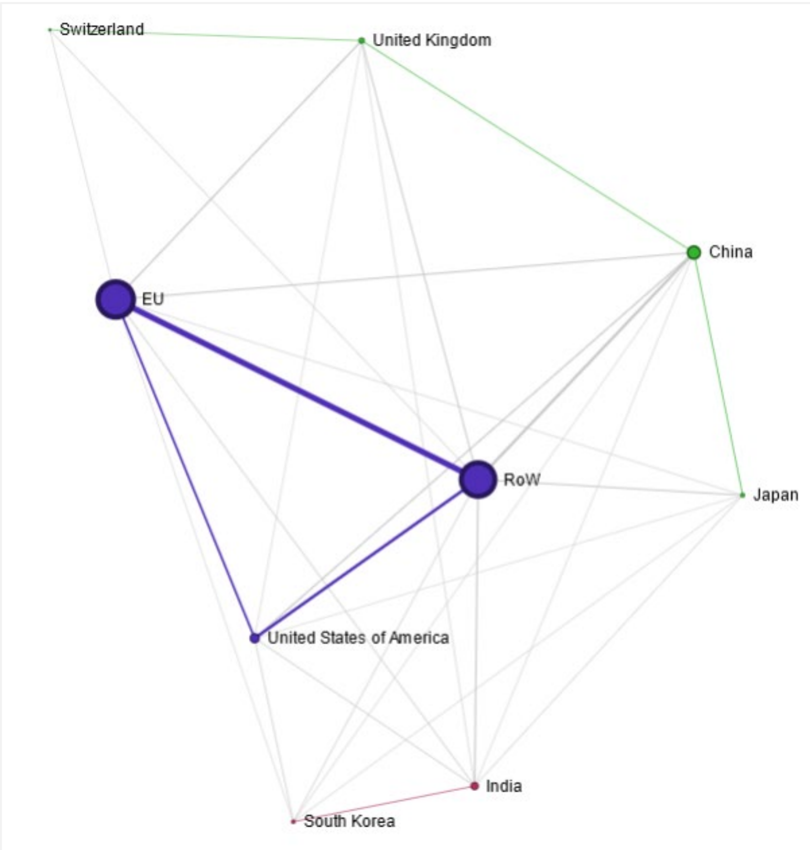
Figure 53. Global trend scientific publication on Biogas, 2010-2021



Source: JRC 2023

At global level, during the 2010-2022 period, strong scientific network on Biogas is observed between the EU, RoW and the USA, Figure 54

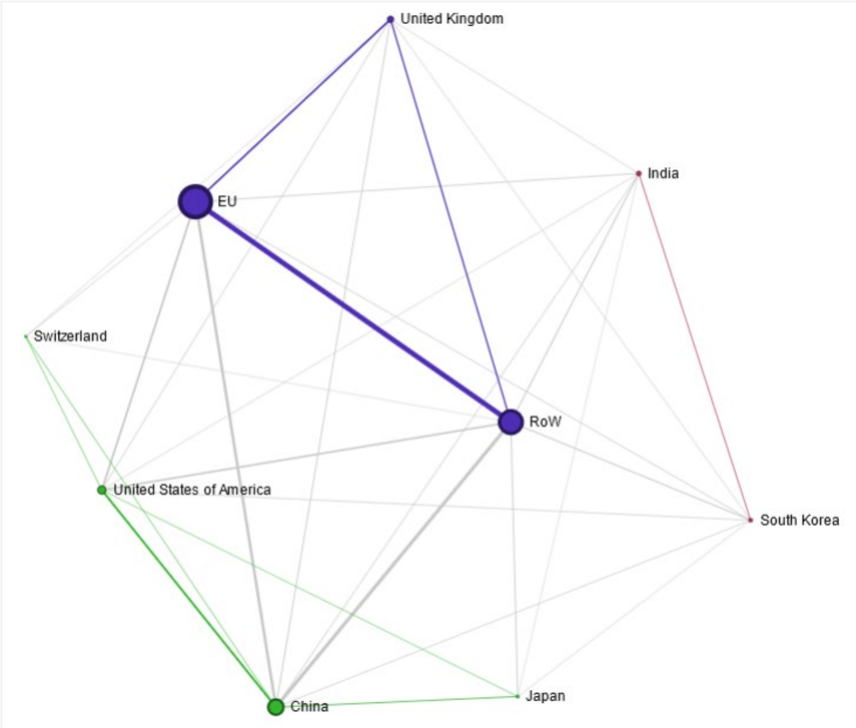
Figure 54. Biogas Scientific Network 2010-2022



Source: JRC 2023

At global level, during the 2010-2022 period, strong scientific network on Biomethane is observed between the EU, RoW and the UK, Figure 55

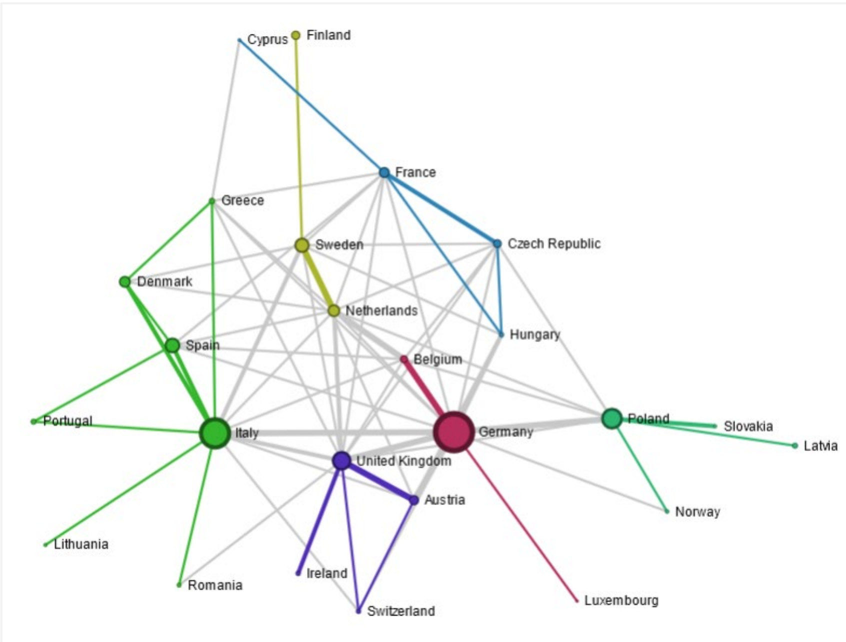
Figure 55. Biogas Scientific Network 2010-2022



Source: JRC 2023

At European level, during the 2010-2022 period, strong scientific network on biogas is observed between Germany Belgium and Italy Spain and Denmark, Figure 56

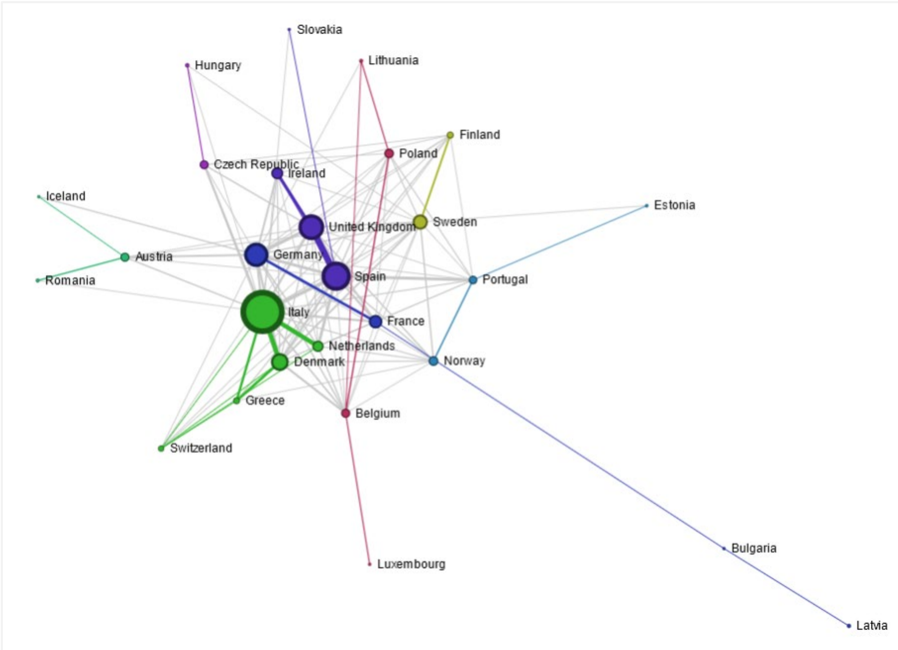
Figure 56. European Biogas Scientific Network 2010-2022



Source: JRC 2023

At European level, during the 2010-2022 period, strong scientific network on biomethane is observed between Germany France, Spain and UK, and Italy with Denmark and the Netherland, Figure 57

Figure 57. European Biomethane Scientific Network 2010-2022



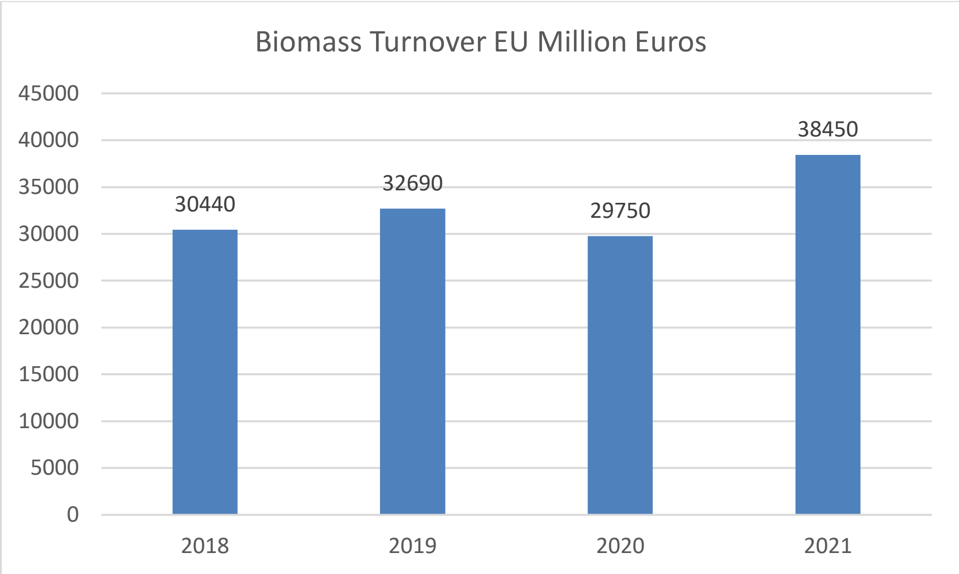
Source: JRC 2023

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. The turnover associated to Solid Biomass in EU after being steadily at around 30,000 million euros from 2018 to 2020, increased to 38,450 million euros in 2021, Figure 58.

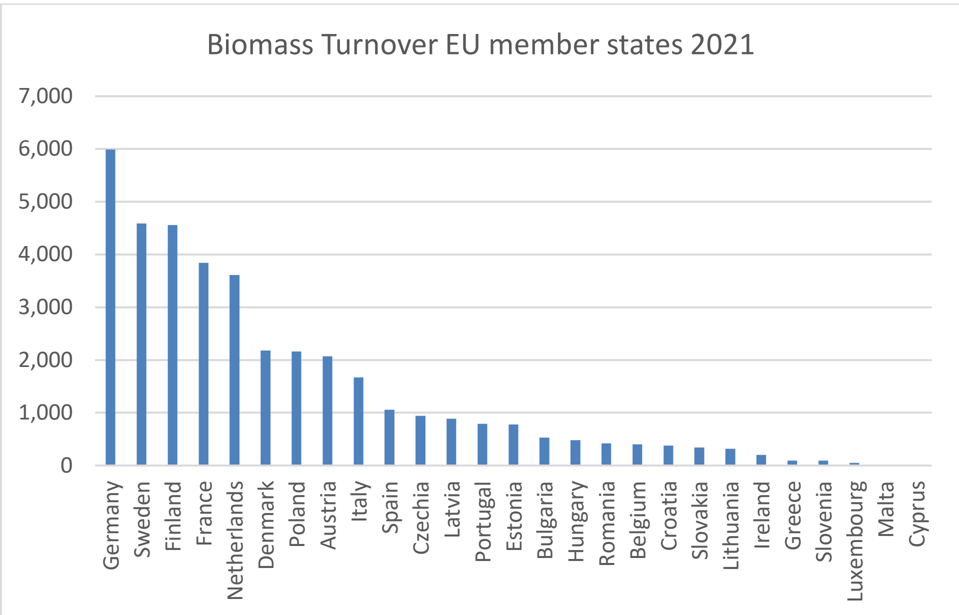
Figure 58. Turnover Solid Biomass to Energy, EU 2018-2021



Source: Eurobserver

At EU Member state level, concerning the year 2021, Germany had 6,000 million euros turnover, followed by Sweden and Finland with 4,500 million euros each, Figure 59.

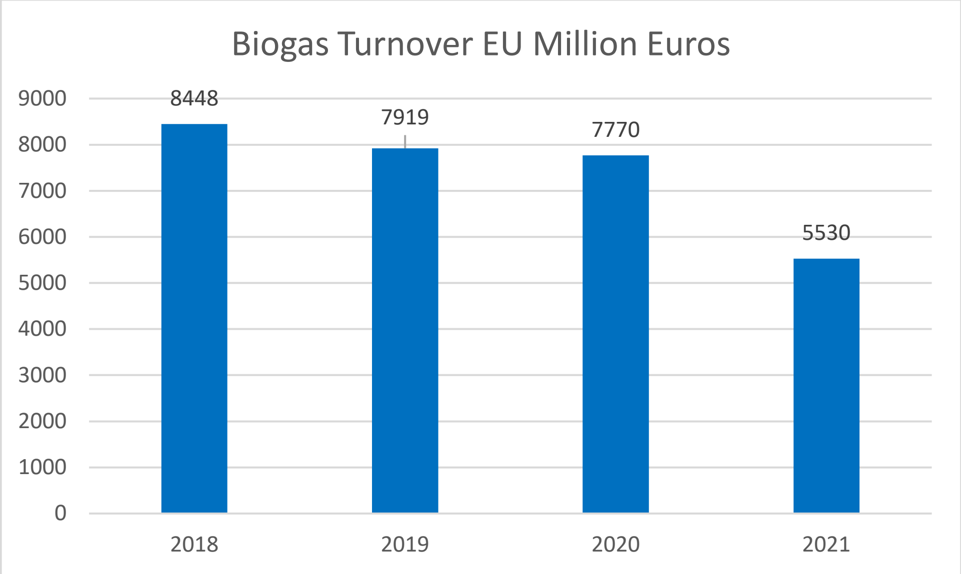
Figure 59. Turnover Solid Biomass to Energy, EU MS 2021



Source: Eurobserver

Eurobserver provides the turnover data for the biogas sector, the highest value was reached in 2018 with 8448 million euro, averaged above 7000 million euro from 2019 to 2020, and then dropped to 5530 Million euros in 2021, Figure 60.

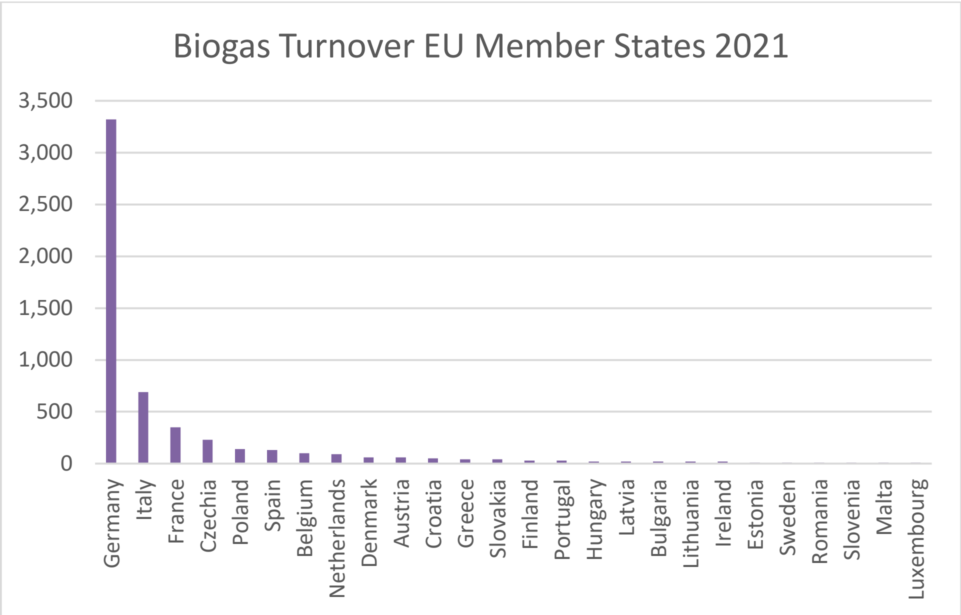
Figure 60. Turnover Biogas, EU 2021



Source: Eurobserver

By far Germany was the leading country in EU with almost 3300 EUR million euros turnover on Biogas, followed by Italy with 690 million euros, Figure 61.

Figure 61. Turnover Biogas, EU 2020

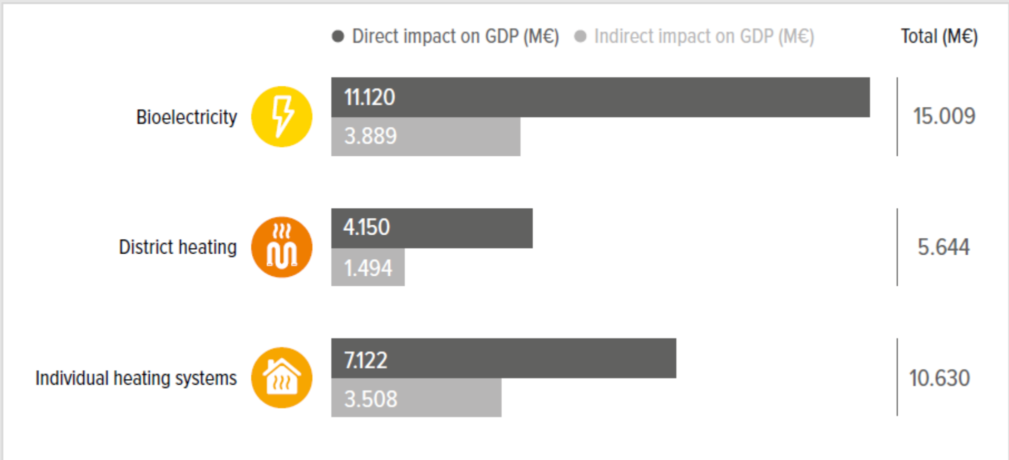


Source: Eurobserver

3.2 Gross value added

Deloitte (Deloitte, 2022) estimated the bioenergy sector's contribution to EU economy using three approaches recognised by the European System of National and Regional Accounts (ESNRA). Deloitte gathered data (added value, expenditure, jobs) from financial statements, publicly disclosed, regarding EU companies active in the bioenergy industry, with also searching additional info surveying bioenergy industry players. Furthermore, Deloitte computed the indirect effects of the bioenergy sector on other sectors of the economy using input-output methodology. The Deloitte report accounts the impact bioenergy H&P sector, in terms of GDP, at around 31282 million euros in 2019, representing 0.23% of the EU27's GDP, the direct impact reached 22392 million euros, while the indirect impact was 8890 million euros, Figure 62

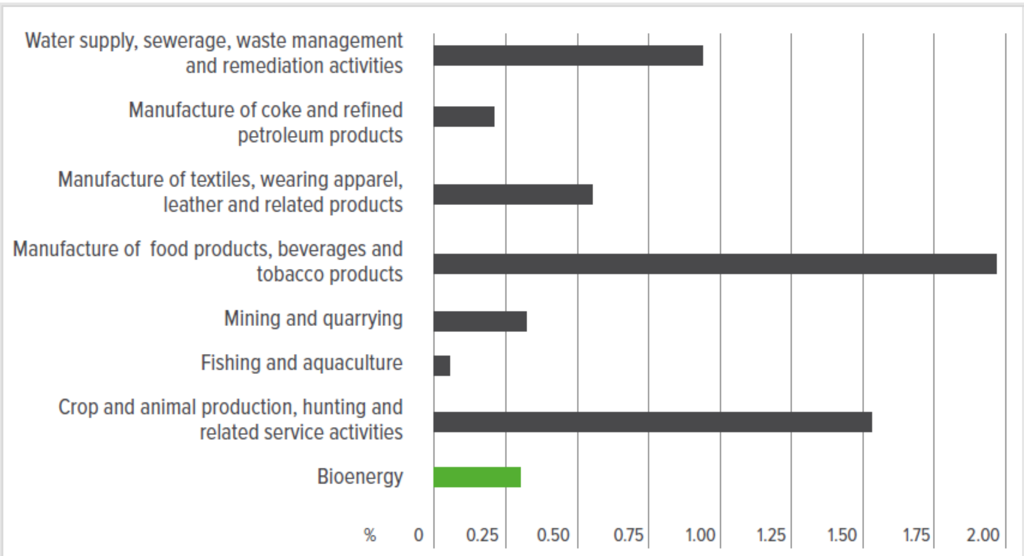
Figure 62. Bioenergy GDP Impact, EU 2019



Source: Deloitte

It is estimated each additional Mtoe of biomass for energy would have an impact of 359 million euros in terms of GDP. When we compare the GDP contribution of whole Bioenergy including biofuel for transport with other sectors, at EU level the GDP impact in 2019, it was comparable with mining and quarrying. Figure 63

Figure 63. Bioenergy GDP Impact share vs other sectors, EU 2019



Source: Deloitte

In 2019 according with Bioenergy Europe report, in EU the 70% of Bio-electricity came from combined H&P while 30% derived from Bioelectricity only plant, while solid Biomass and Biogas represented 80% of fuel input, Operational and maintenance had the major impact on GDP contribution with 6791 million euros on total 11120 million euros in 2019, Table 10.

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

Bioelectricity EU			
Impact on GDP (M€)	**Direct**	**Indirect**	**total**
Equipment Manufacturing	216	3889	**15009**
Construction	445		
Supply of feedstock	3668		
Operation and maintenance	6791		
Total	**11120**		

Source: *Deloitte*

According to Bioenergy report, in 2019, District Heating Solutions in EU operating both with CHP and heat only-plant, fossils as fuel were still the predominant source with a share of 72%, inside the 28% share of renewable, biomass was so far the mostly used source at 97% share, equipment with 1297 million euro and O&M with 1766 million euro had the major direct impact on GDP which totalled 4150 million euros Table 11.

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

Biomass District Heating EU			
Impact on GDP (M€)	**Direct**	**Indirect**	**total**
Equipment Manufacturing	1297	1494	**5644**
Construction	715		
Supply of feedstock	363		
Operation and maintenance	1766		
Total	**4150**		

Source: *Deloitte*

Bioenergy Europe report states for EU 27 a bio heat consumption of 41527 ktep for residential use (boiler and stoves) in 2019, the fuel used is mostly pellet and wood, it represents almost 50% of bio Heat consumption. Supply of feedstock with 4895 million euros, directly impacted more GDP which totalled 7122 million euros, **Table 12**.

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

Biomass Residential Heat EU			
Impact on GDP (M€)	**Direct**	**Indirect**	**total**
Equipment Manufacturing	1548	3508	**10630**
Construction	434		
Supply of feedstock	4895		
Operation and maintenance	244		
Total	**7122**		

Source: Deloitte

3.3 Environmental and socio-economic sustainability

3.4 Role of EU Companies

The European biomass industry is leader in the field of biomass power, in particular in solid biomass and biogas. European biomass heat industry deals with small scale (domestic scale stoves boilers using solid biomass such as wood pellets, fuelwood woodchips, etc.) to medium and large scale for heat generation. Even though support is declining, the EU remains the world's most important market for biomass power plants. This section provides a non-exhaustive overview of major players in the field of bioenergy, leading companies in manufacturing equipment and developing bioenergy technologies, not providing a ranking in terms of their market shares, capitalisation or R&D investments.

Alstom

Alstom Power Systems (Levallois-Perret, France) activities (Alstom Power Systems) include the design, manufacturing, services and supply of products and systems (gas, nuclear, hydro, wind and biomass) for power generation and industrial markets. Alstom Power Systems provides components including: boilers and emissions 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. (Framingham, the U.S) 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 operations and maintenance (O&M) costs of power plants. Ameresco provides solutions ranging from the upgrades of energy infrastructure such as distributed generation plants and onsite cogeneration to the development, construction and operation of renewable energy plants. Ameresco builds power and cogeneration facilities for renewable waste to generate power and heat from large, utility-scale biomass-to-energy 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 industries. ANDRITZ offers an extensive line of equipment and complete plant solutions for the production of high-quality feed and biomass products. ANDRITZ has a proven track record in designing and building feed and biomass plants, including engineering, installation, start-up, and commissioning, as well as aftermarket parts and service. ANDRITZ offer a range of pelletizing, grinding, mixing and screening equipment to handle the processing of dry materials and for production of biomass pellets, solid biofuel, and waste pellets.

Babcock & Wilcox

The Babcock & Wilcox Enterprises Inc. (Barberton, Ohio the U.S) is a global leader in advanced energy and environmental technologies and services for the power, renewable 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 fluidized-bed and stoker boilers, gasifiers, black liquor recovery boilers. Historically, the company is best known for steam boilers, biomass to energy, emissions control equipment, waste-to-energy facilities, boiler cleaning equipment, ash handling and conveying, etc.

BTG

BTG Biomass Technology Group BV (BTG) has specialised itself in the conversion of biomass into fuels, energy and biobased raw materials. BTS is the leading fast pyrolysis technology provider that deliver production plants that convert sustainable biomass residues into Fast Pyrolysis Bio-Oil (FPBO) that can replace fossil fuels. BTG-

Bioliquids delivers FPBO-plants that operate on biomass residues only, 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 having to invest in new engines or systems as advanced marine biofuel, for aviation and road transport.

Drax

Drax Group plc is an electrical power generation company (North Yorkshire, UK). The company operates three core business activities: wood pellet production processing biomass for electricity production; flexible, low carbon and renewable energy generation; and energy sales and services to business customers. The company also focusses on power generation, producing flexible, low carbon and renewable electricity as well as providing system support services to the grid from a portfolio of biomass, hydro, gas and coal technologies. The company is planning investments for improving the performance of its biomass business unit. Drax Group plc plans to conduct R&D activities for developing new types of biomass that can be burned efficiently.

ENGIE

Engie SA (Courbevoie, France) was formerly known as GDF SUEZ S.A.. ENGIE operates in the fields of electricity generation and distribution, natural gas, nuclear, renewable energy and energy services. It engages in the generation and sale of power through nuclear, thermal, and biomass resources; and seawater desalination activities, as well as offers engineering services in the areas of energy, hydraulics, and infrastructure. ENGIE decided to stop new investments in coal plants and invest into projects that promote low-carbon, renewable energies (solar, wind, geothermal, biomass, hydroelectric), nuclear, energy services such as heating and cooling networks and decentralized energy technology.

ENVIVA

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

NextFuel AB

NextFuel AB has developed a highly scalable new technology for converting fast growing grasses, and other types of crops, into a coal substitute (briquettes). NextFuel AB provides a torrefaction technology processing a variety of biomass raw material in addition to wood, including fast-growing, abundant, carbon rich plants like elephant grass and bagasse (waste from sugarcane). The patented NextFuel™ torrefaction reactor, based on the rotary drum principle, provides a high flexibility, processing both energy crops like different kinds of elephant grass, agricultural waste like bagasse and paddy straw, and forestry waste like wood residues and low quality wood.

Fortum

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

Green Fuel Nordic

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

Nature Energy

Nature Energy (Funen, Denmark), the largest producer of biogas in Denmark, and the leading producer of green gas to grid in Europe from farm and food waste. Nature Energy (former Naturgas Fyn) owns and operates seven large-scale biogas biogas plants and currently has a production capacity of more than 100 million m3 (approx. 5 % of the green gas in the European gas grid). Nature Energy has acquired in 2018 Xergi from Schouw & Co. and Hedeselskabet, one of Europe's leading suppliers of turnkey biogas plants. Xergi has more than 30 years of experience in designing and constructing biogas plants around the world.

Ørsted A/S

Ørsted A/S (DONG Energy) is a power company based in Fredericia, Denmark that develops, constructs and operates offshore and onshore wind farms, bioenergy plants and innovative waste-to-energy solutions. DONG Energy used to produce and supply heat and electricity from thermal and biomass power stations to business and residential customers. The 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 & district heating. Latest focus includes industrial biogas production from industrial waste streams (insulin and enzyme production at Novo Nordisk and Novozymes).

Sekab

Sekab (Domsjö, Sweden) is a green chemical company for the manufacture of chemicals and fuels. Sekab conducts research and development for new sustainable product opportunities. Sekab has developed processes and technologies that make it possible to manufacture bio-based products and advanced biofuels. CelluAPP® technology makes it possible to process various biomass feedstocks into environmentally friendly, high-quality and marketable chemical products and raw materials such as biogas, cellulosic sugars, ethanol and lignin. SEKAB technology technology consists primarily of four steps: pretreatment, enzymatic hydrolysis, fermentation and distillation.

UPM (Helsinki Finland) is a world leader in biomass use for pulp and paper, biochemical, biomaterials, biofuels and bioenergy and the second largest electricity producer in Finland. UPM invested in replacing a number of 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 petrochemicals use. UPM Lappeenranta Biorefinery started commercial production in 2015 of 120 million litres wood-based renewable diesel from crude tall oil (UPM BioVerno).

Valmet

Valmet (Finland) 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 on a mixture of different fuels (biomass to energy, waste to energy, multifuel solutions and solutions for combined heat and power production (CHP) based on various kinds of fuels. VALMET is a leading supplier of various boiler and gasification technologies, offering a selection of tailored solutions for flexible energy production. Valmet offers complete power plants for small and medium scale with comprehensive air emission control systems.

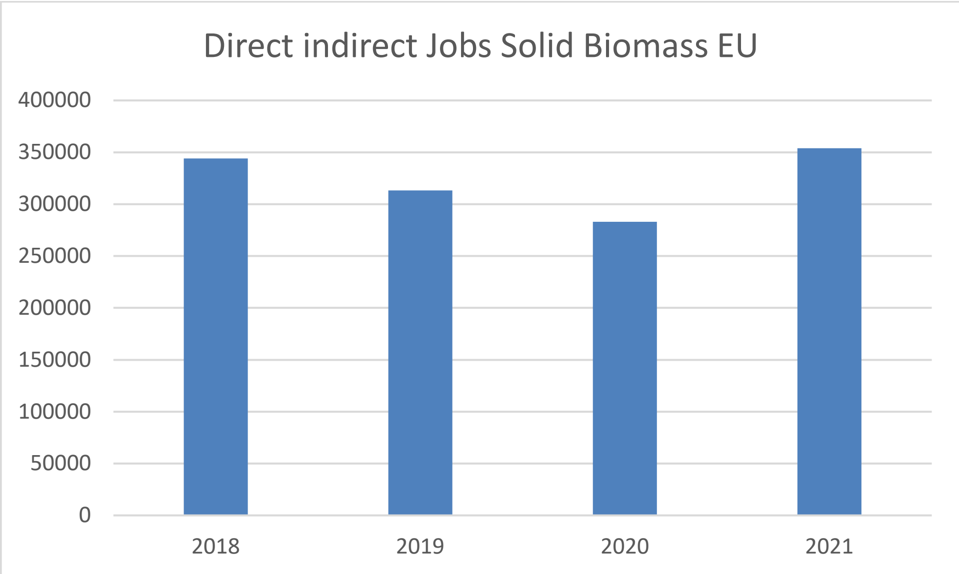
Vattenfall

Vattenfall AB (Solna, Sweden) is a state owned company for the production and distribution of electricity and heat from coal, natural gas, nuclear, wind, hydropower, solar power, biomass and waste. Vattenfall AB invests in renewable resources 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 conservation material and compost residues. The Vattenfall subsidiary Energy Crops GmbH operates over 2,000 hectares of energy wood plantations providing fuel supply of the heating installations in Berlin.

3.5 Employment

Data on Jobs in Eurobserver includes both direct and indirect employment. Direct employment includes RES equipment, manufacturing, RES plants construction, engineering and management, operation and maintenance, biomass supply and exploitation. Indirect employment refers to secondary activities, such as transport and other services manufacturing, RES plants construction, engineering and management, operation and maintenance, biomass supply and exploitation. Indirect employment refers to secondary activities, such as transport and other services. According to Eurobserver the number of employees for the solid Biomass sector (direct and indirect) in EU, was at 283,000 in 2020, regaining the 350,000 employees in 2021 (Figure 64).

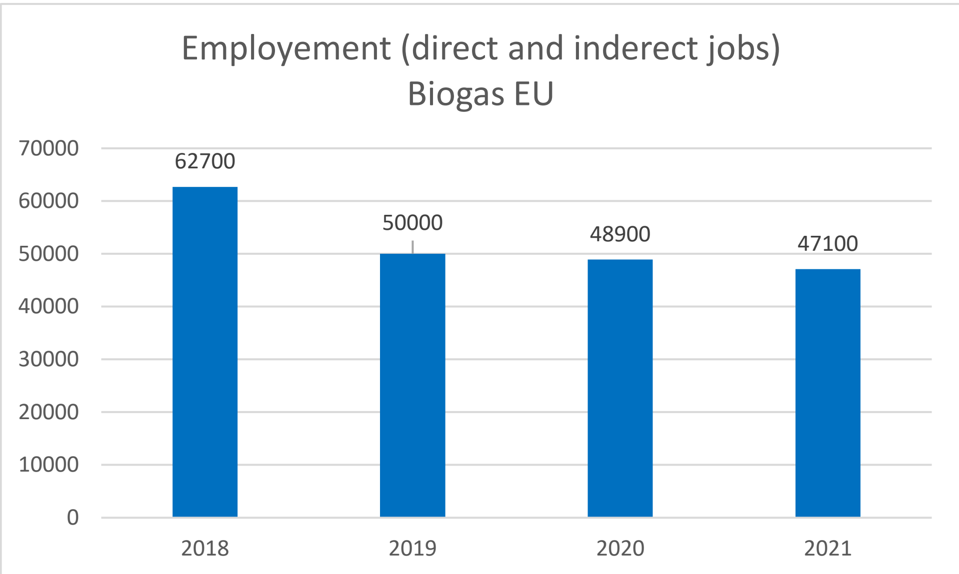
Figure 64. Number of jobs solid Biomass (direct and indirect) EU



Source: Eurobserver

Eurobserver also monitors the number of employees in the Biogas sector in EU (direct and indirect), jobs peaked at 62,700 employees in 2018, trending lower in the following years dropping to 47,100 employees in 2021, Figure 65.

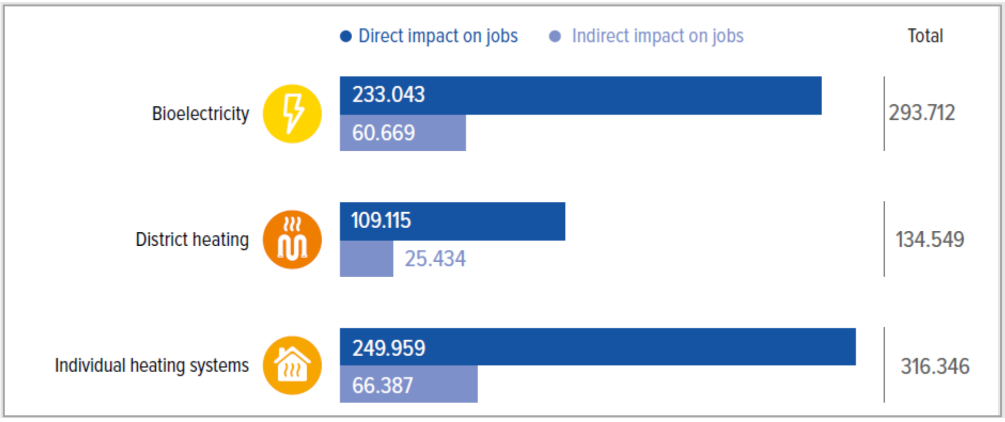
Figure 65. Number of jobs Biogas (direct and indirect) EU



Source: Eurobserver

Deloitte estimated the bioenergy sector's contribution to EU27 economy using three approaches recognised by the European System of National and Regional Accounts (ESNRA). Deloitte gathered data (added value, expenditure, jobs) from financial statements, publicly disclosed, regarding EU companies active in the bioenergy industry, with also searching additional info surveying bioenergy industry players. Furthermore, Deloitte computed the indirect effects of the bioenergy sector on other sectors of the economy using input-output methodology. According to the Deloitte report, EU 2019, the impact of bioenergy H&P on employment reached 744,608 FTE (Full Time Equivalent), with 592,118 direct jobs and 152,490 indirect jobs, Figure 66.

Figure 66. Bioenergy direct and indirect impact on jobs, EU 2019



Source: Deloitte

Overall the biomass to energy sector requires mostly construction and equipment manufacturing jobs during the installation of new plants, while plants operational and maintenance need permanent jobs, in particular collection, treatment and transport of biomass before its final utilization are typical activities for the bioenergy sources compare to other RES. The feedstock supply, with 153,000 direct jobs out of 233,043 total direct jobs is the sector in the chain with a major contribution. **Table 13.**

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

<table>
<tr><th colspan="4">Bioelectricity EU</th></tr>
<tr><th>Impact on Jobs</th><th>Direct</th><th>Indirect</th><th>total</th></tr>
<tr><td>Equipment Manufacturing</td><td>5818</td><td rowspan="5">60669</td><td rowspan="5">293172</td></tr>
<tr><td>Construction</td><td>4682</td></tr>
<tr><td>Supply of feedstock</td><td>153047</td></tr>
<tr><td>Operation and maintenance</td><td>69544</td></tr>
<tr><td>Total</td><td>233043</td></tr>
</table>

Source: Deloitte

According to Bioenergy Europe report, in 2019, District Heating Solutions in EU operating both with CHP and heat only-plant, fossils as fuel were still the predominant source with at 72%, in this sector the equipment manufacturing and operational and maintenance with respectively with 34,880 and 47,165 have the major impact on direct jobs, **Table 14.**

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

Biomass District Heating EU			
Impact on Jobs	**Direct**	**Indirect**	**total**
Equipment Manufacturing	34880	25434	**134549**
Construction	10088		
Supply of feedstock	16981		
Operation and maintenance	47165		
Total	**109115**		

Source: Deloitte

Bioenergy Europe report states for the EU a bio heat consumption of 41,527 ktep for residential use (boiler and stoves) in 2019, the fuel used is mostly pellet and wood, it represents almost 50% of Bio Heat consumption. Supply of feedstock, with 210,511 direct jobs, has by far the higher share of employees along 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	26390	66387	**316346**
Construction	8390		
Supply of feedstock	210511		
Operation and maintenance	4669		
Total	**249959**		

Source: Deloitte

3.6 Energy intensity and labour productivity

Concerning the Biogas and Biomethane the EBA report 2023 (European Biogas Association, 2023) considers different studies, due to inclusion of several sectors such as agriculture, waste management, water purification, logistics, etc the evaluation of job impact requires assumptions. Depending on methodology, which is not ever harmonized among the different references, the total employment rate ranges between 0.56 and 1.92 jobs/GWh. The number of direct jobs ranges 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 1.14 jobs created per GWh of biogas and biomethane produced. From those jobs, 0.32 are direct jobs and 0.77 indirect jobs. In Europe, in 2021, a total of 159 TWh of biogas and 37 TWh of biomethane was produced. Using the above-mentioned indicators, is estimated more than 220,000 jobs in the biogas and biomethane sector across Europe, of which approximately 65,000 jobs are direct jobs and 155,000 indirect jobs

3.7 EU Production Data

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

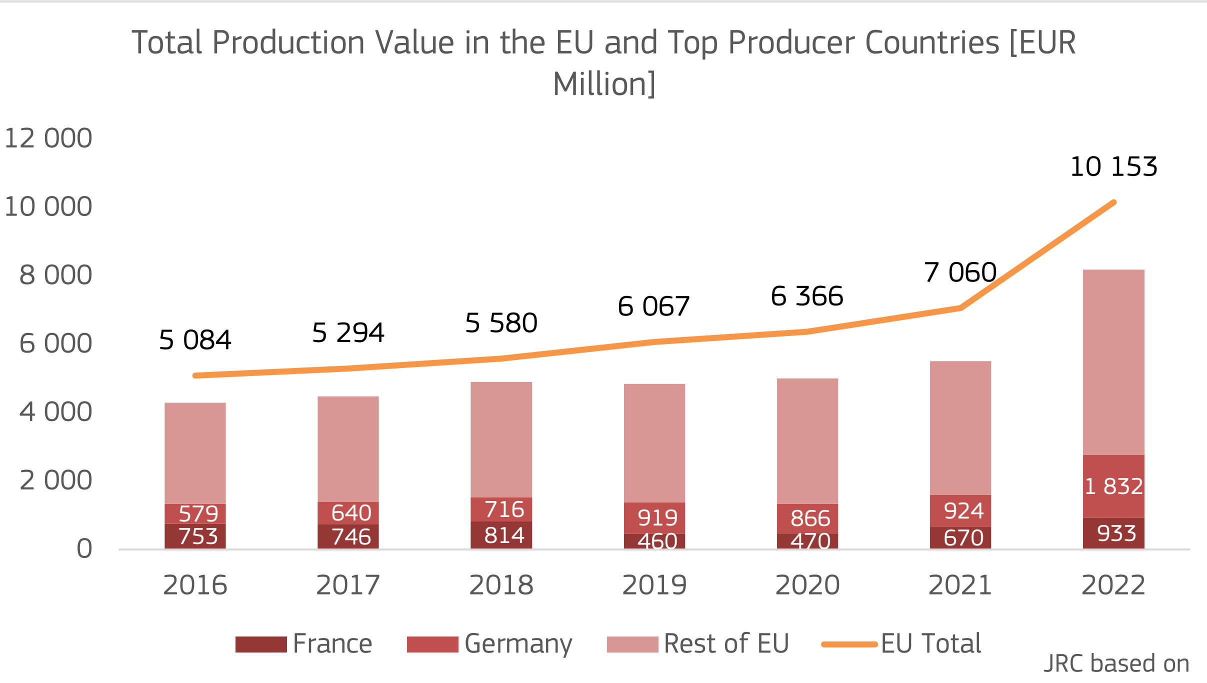
Prodcom provides statistics on the production of manufactured goods carried out by enterprises on the national territory of the reporting countries, Prodcom statistics aim at providing a full picture at EU level of developments in industrial production for a given product or for an industry in a comparable manner across countries.

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

230320	Beet-pulp, bagasse and other waste of sugar manufacture
440122	Wood in chips or particles
440131	Wood pellets
440210	Bamboo charcoal, incl. shell or nut charcoal, whether or not agglomerated
440220	Wood charcoal of shell or nut, whether or not agglomerated
440290	Wood charcoal, whether or not agglomerated

The value of energy carriers produced in EU countries steadily increase from EU 5084 EUR Million in 2016 to 10153 EUR million in 2022, the combined value produced in Germany and France represents 1/4 of EU production, Figure 67.

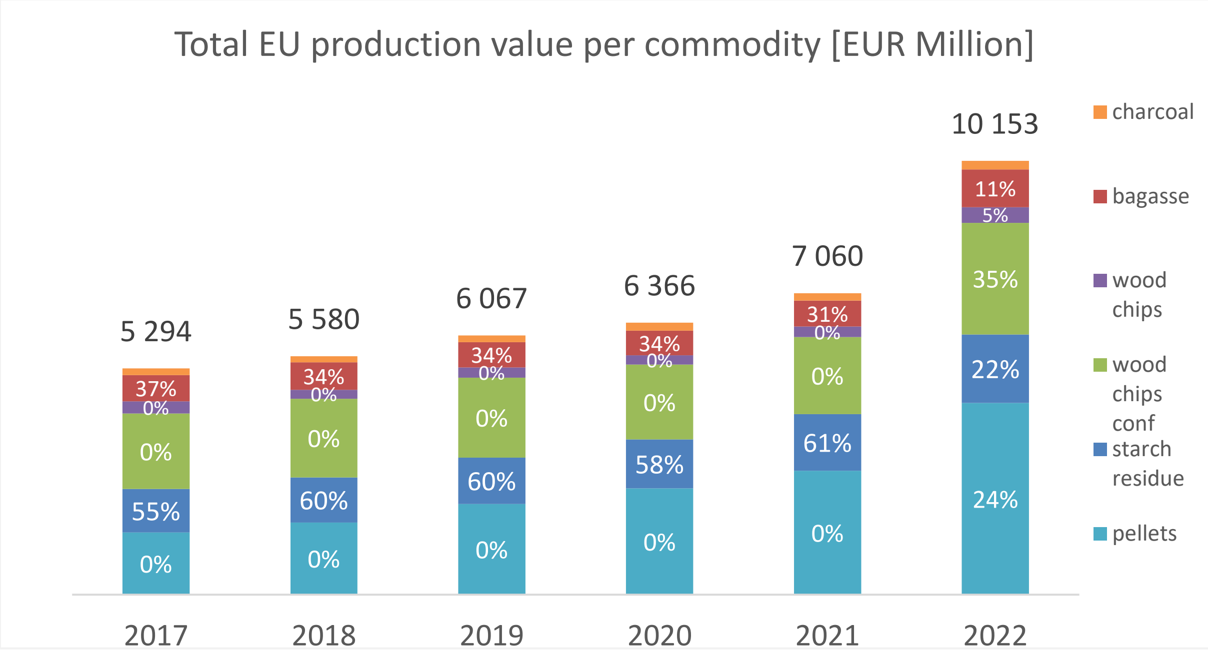
Figure 67. Biomass carriers production value EU



Source: JRC elaboration on Comext Eurostat's DB

Pellet and wood chips respectively with 44% and 26% share, represent more than 50% of value produced in EU, see Figure 68

Figure 68. EU production value per commodity



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 biomass electricity generation in 2020 were Germany, Italy, Finland, Sweden and Netherlands. Solid biomass was the main feedstock for bioelectricity production in 2020 in several Member States (such as Finland, Sweden and Poland), while in other Member States, such as Italy and France, different feedstock contribute to various extent to biomass electricity production. Important aspect to notice is the high contribution of biogas to electricity production in Germany with a share of 66 % of biomass electricity and an important biogas contribution to electricity production of more than more than 40 % in Belgium, Italy, Croatia and Latvia.

For Biomass Heating Germany having the leading position, followed by France, Sweden, Italy, Poland, Finland, etc. on renewable heating. On biomass heating Germany still holds the main position followed by France, Sweden, Poland Italy, etc. By far biomass is the dominant source for renewable heating in most MS, followed by heat pumps, that has a higher share in France, Italy and Sweden. Looking at feedstocks, solid biomass has the main role, with a good contribution of biogas in Germany, France and Italy

Looking at the deployment of biogas supply into different Member States the leading MS in 2020 was Germany that had a contribution of about 53 % into the biogas production at the European Union level with 9.4 billion Nm3. Other leading MSs include Italy, France, Czech Republic Denmark and The Netherlands. Biogas production from anaerobic digestion plants dominates in most countries in particular in Germany Italy, France, Czech Republic, Denmark etc. Biogas from landfill gas recovery, however, dominates in other Member States, including Spain, Greece, Portugal and Ireland. Biogas production from anaerobic digestion of sewage sludge from waste water treatment plants has also an important contribution in Germany, Poland, Spain and Sweden. When comparing to the natural gas use in various MS, biogas has a significant contribution in particular in Denmark (21.8 %), Sweden (16 %), and Germany (10 %) Latvia (9%) and Czechia and Finland (8 %).

Germany is the EU leader on the number of biomethane plants with 11,200 biogas plants, followed by Denmark (4,041 plants), France (2,207 plants), Netherlands (2,166) and Italy (2,114 plants).

The value of bioenergy energy carriers and feedstock produced in EU countries steadily increase from EU 5084 EUR Million in 2016 to 6276 EUR million in 2020, the combined value produced in Germany and France represents 1/3 of EU production.

For the triennium 2019-2021, concerning solid Bioenergy carriers and feedstock Latvia with around 1500 EUR Million and Germany with 1300 EUR Million lead the top 5 EU exports, prevalently delivered to other EU countries.

4.2 Trade (Import/export) and trade balance

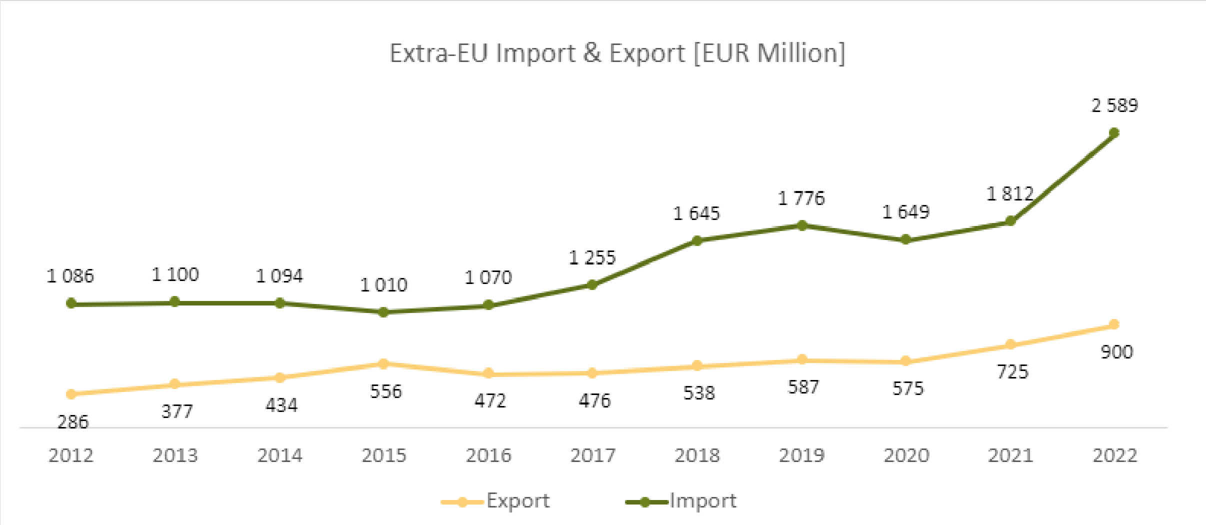
Statistics on trade have been performed by using the Comext Eurostat's reference database for detailed statistics on international trade in goods. It provides access to recent and historical data of the EU and its individual Member States, but also covers a significant number of non-EU countries.

Prodcom provides statistics on the production of manufactured goods carried out by enterprises on the national territory of the reporting countries, Prodcom statistics aim at providing a full picture at EU level of developments in industrial production for a given product or for an industry in a comparable manner across countries. The codes elaborated to provide the statistics in this chapter are listed in paragraph 3.7.

Considering the grouped EU member states, they more than double the value of import from Extra- EU countries from 1010 EUR Million in 2015 to 2589 EUR Million in 2022, while the export from EU to Extra- EU averaged 500 EUR Million from 2015 to 2020 than peak at 900 EUR Million in 2022,

Figure ***69***.

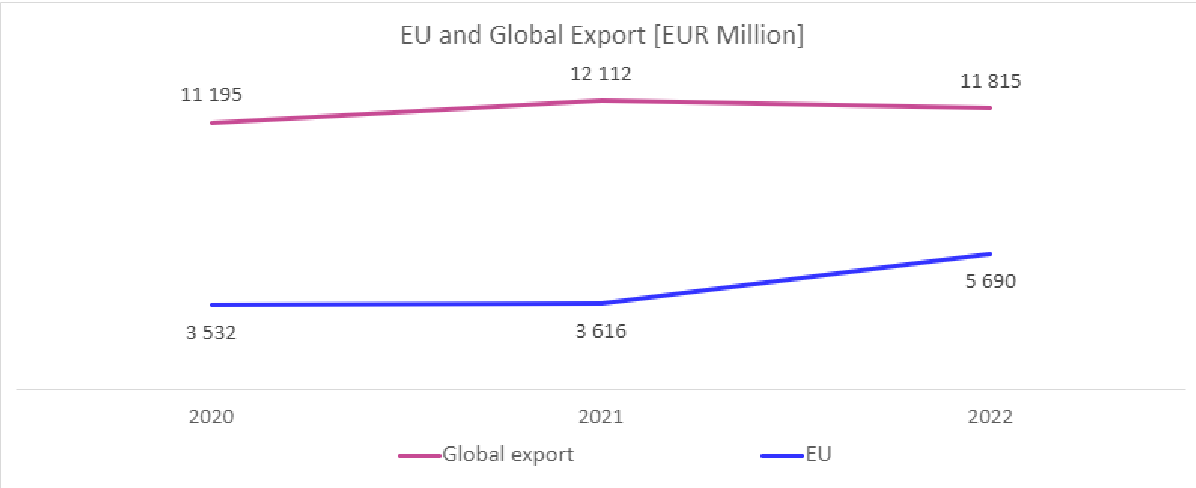
Figure 69. Biomass energy carrier and feedstock trade



Source: JRC elaboration from n Eurostat's DB

Considering also the EU internal market, for the triennium 2020 to 2022 the EU countries exported a value of bioenergy feedstock from 3532 to 5690 EUR Million annually, while the global export was almost stable at around annual 12000 EUR Million, Figure 70

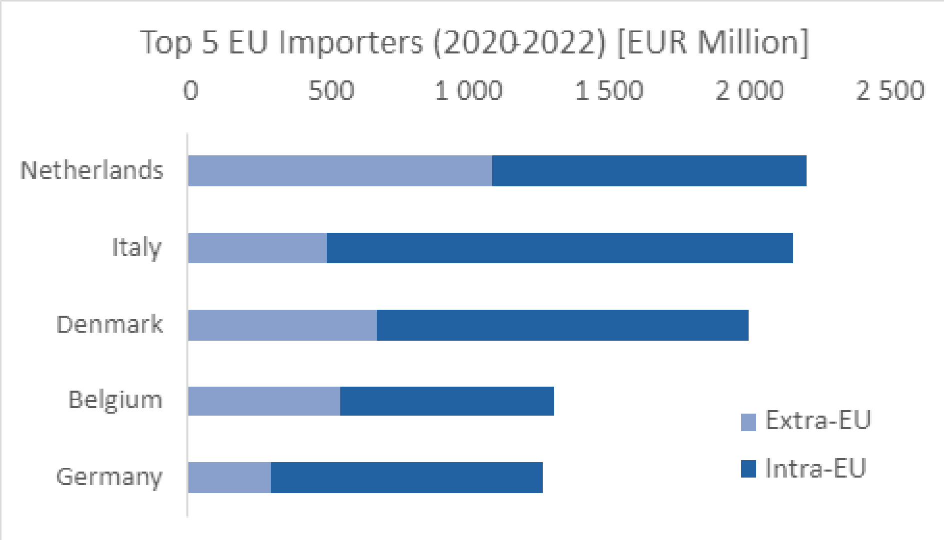
Figure 70. Biomass energy carrier and feedstocks trade EU and Global export, 2010-2022



Source: JRC elaboration on Comext Eurostat's DB

For the triennium 2020 to 2022, the top 3 EU importers are Netherland, Italy, which imported more than 2000 EU Million worth of biomass each annually followed by Denmark, Italy and Denmark imported mostly Intra-EU, Figure 71. Biomass energy carrier and feedstocks trade EU top 5 importers

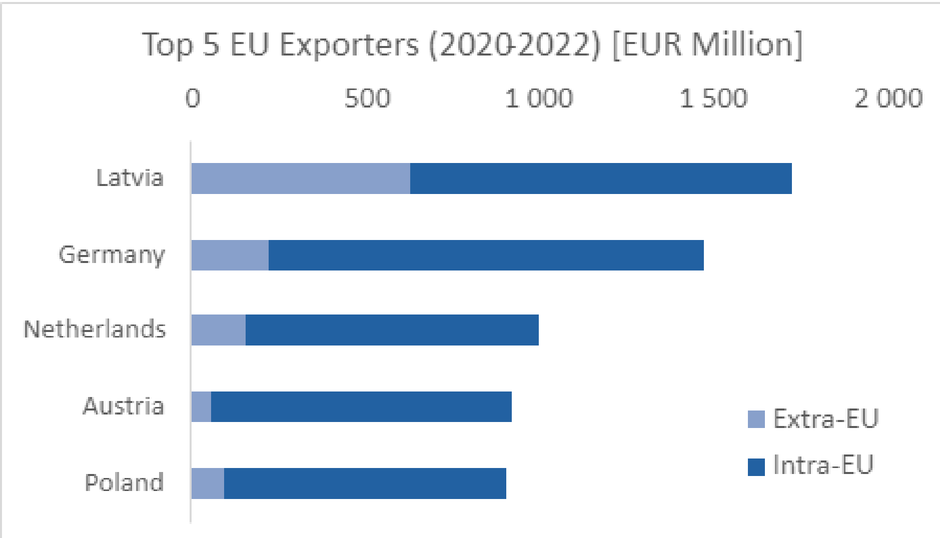
Figure 71. Biomass energy carrier and feedstocks trade EU top 5 importers



Source: JRC elaboration on Comext Eurostat's DB

For the triennium 2020 to 2022, Latvia with more than 1500 EUR Million and Germany with 1400 EUR Million lead the top 5 EU exports, prevalently Intra-EU Market, Figure 72.

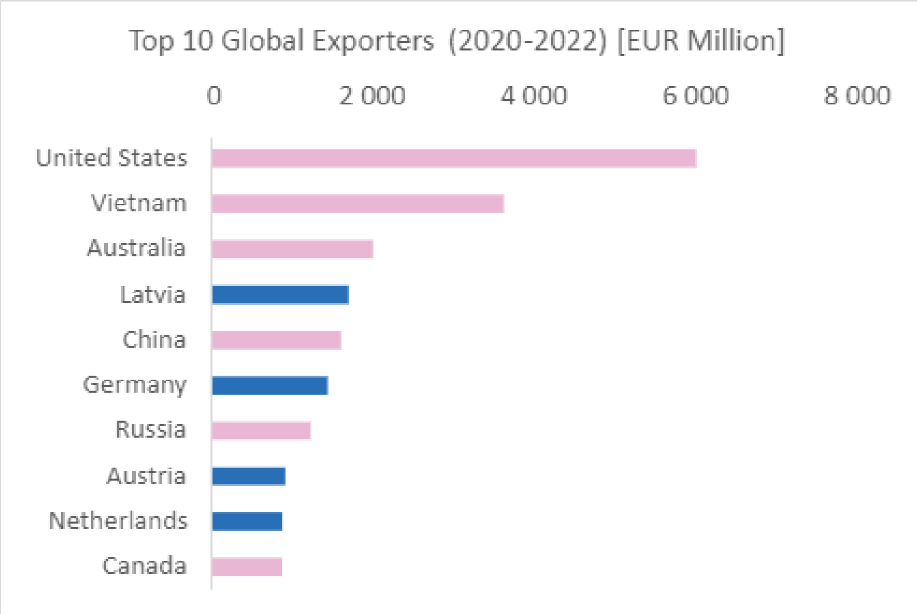
Figure 72. Biomass energy carrier and feedstocks trade EU top 5 exporters



Source: JRC elaboration on Comext Eurostat's DB

The US leads the top 10 Global exporters to EU with almost 6000 EUR Million exported during the triennium 2020-2022. Figure 73. *Biomass energy carrier and feedstocks top 10 exporters to EU, 2020-2022*

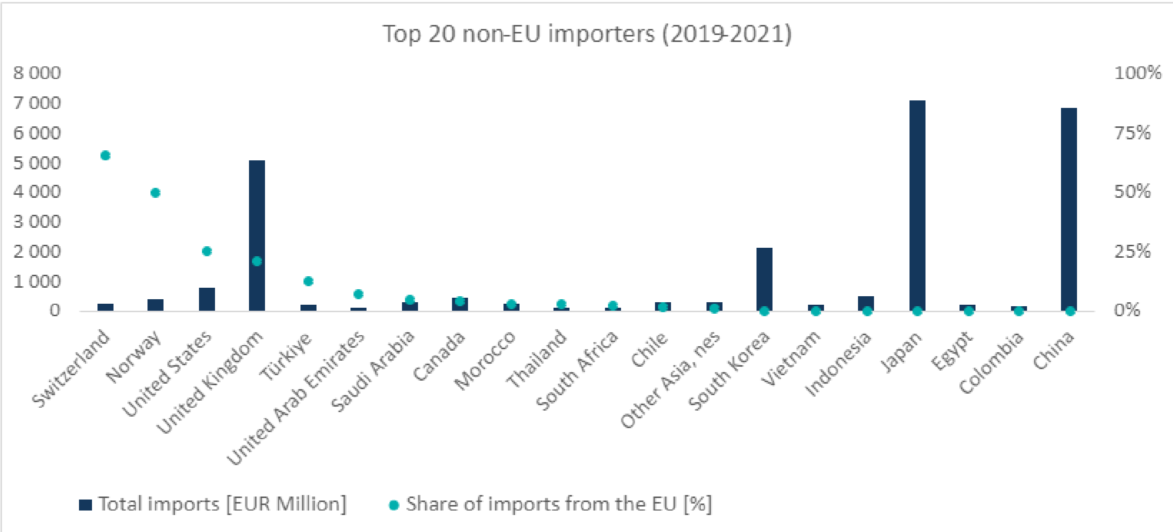
Figure 73. Biomass energy carrier and feedstocks top 10 exporters to EU, 2020-2022



Source: JRC elaboration on Comext Eurostat's DB

Japan, China and the UK are the top 3 non-EU importers, but only the UK relies 25% on the EU for its imports which amounted to 5000 EUR million during the triennium 2019 to 2021, Figure 74

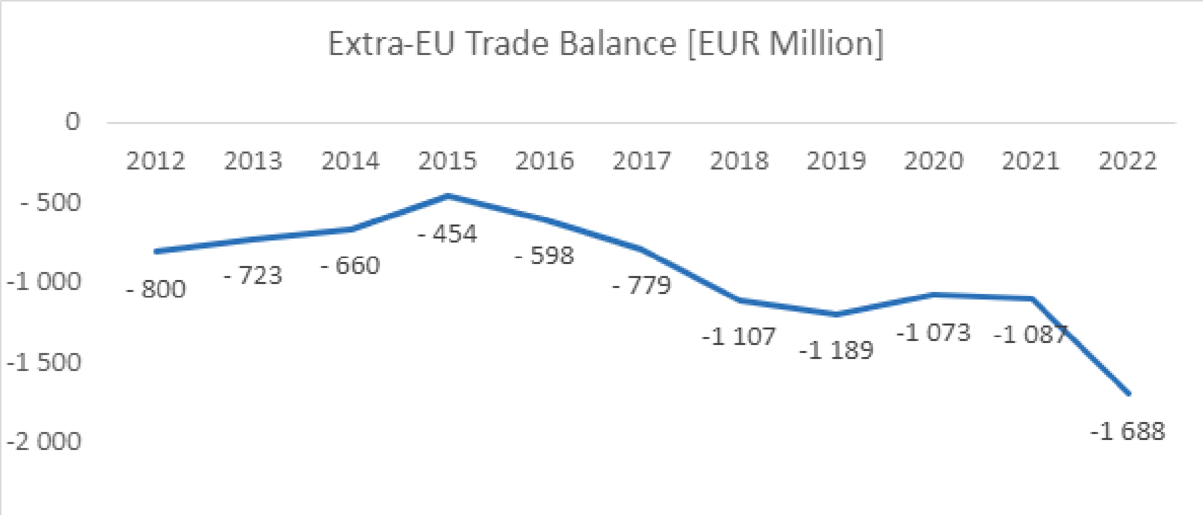
Figure 74. Biomass energy carrier and feedstocks top 20 non-EU importers



Source: JRC elaboration on Comext Eurostat's DB

The EU trade of Bioenergy feedstock is trending increasingly negative in the last years, passing from negative -454 EUR Million in 2015 to negative -1688 EUR Million in 2022, Figure 75.

Figure 75. Biomass energy carrier and feedstocks extra-EU Trade Balance



Source: JRC elaboration on Comext Eurostat's DB

4.3 Resource efficiency and dependence in relation to EU competitiveness

Most estimates show that biomass is likely to be sufficient to play a significant role in the global energy supply system until 2050. Biomass availability for energy use is a key issue for bioenergy deployment. Various feedstocks can contribute to meet 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 import of various materials, bioenergy deployment would also alleviate material dependencies of the EU. Several studies showed that the domestic available biomass in the EU could be sufficient to achieving the EU energy and climate targets for bioenergy for 2030 and 2050. The amount of available biomass potential will depend on the capacity to mobilise further unexploited potential and on additional more stringent sustainability criteria.

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. The increased competition between food, feed and fibre, wood products or new bio-based materials and bioenergy needs to be properly addressed allowing the prioritisation of biomass use according to the societal needs. The multiple uses 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. A number of factors could be considered in the prioritization of biomass use, such as the economic or social value of biomass products, the conversion efficiency of biomass, GHG emission reduction performances, etc.

According to the Renewable Energy Directive requirements, 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. Electricity production from biomass fuels higher capacity installations should be done with high-efficiency cogeneration. The 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.

Bioenergy can play a key role on short term to the decarbonisation of the economy toward a low carbon economy and in the same time to the increase of the energy security and energy diversification. 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. Biomethane can be used in connection with gas storage as energy storage solution enhancing energy security and balance the gas grid.

According to the REPowerEU, bioenergy from sustainable sourcing will ensure a sustainable energy production that can contribute to the REPowerEU objectives by prioritizing use of non-recyclable biomass waste and agricultural and forest residues. In particular biomethane can contribute on short term to the goals of the REPower initiative that aims at reducing the EU dependence on imported fossil fuels and to the diversification of energy supply. In conditions of high energy prices bioenergy, including biomethane production can become cost efficient. The EU has a leading role on bioenergy production today and further development can ensure EU technological leadership on new emerging technologies and key role in the transition toward a low carbon economy.

5 Conclusions

Bioenergy continues to be the main source of renewable energy worldwide and plays an important role as a modern and efficient source of energy. In the EU, bioenergy accounts for about 60% of the renewable energy used. IEA indicates that modern bioenergy is an essential component of the future low-carbon global energy system. IEA modelling shows that the deployment of Bioenergy with Carbon Capture and Storage (BECCS) is essential to reach net-zero emissions goals, as BECCS can compensate for the emissions in industry and transport sectors that are very difficult to abate. For the EU, PONTENCIA modelling projects a Bioelecricity increase in production from around 197 TWh in 2025 to 260 TWh in 2050, but its share dropping from 6.5% to 4.3%.

Various bioenergy technologies, although in different stages of development, have undergone significant improvements and technical advances in the last years. However, most of them face technical and non-technical challenges that impede on their large-scale commercial application. Some technologies still require effort to improve their technical, economic and environmental performances, to be demonstrated at scale and to ultimately achieve reliable long-term operation.

Bioenergy provides flexible low carbon power generation, increasing the diversity of energy supply for balancing the electricity grid and providing a key element enabling high shares of variable renewable energies, such as wind and solar. Bioenergy from sustainable sourcing will ensure a sustainable energy production that can contribute to the REPowerEU objectives by prioritizing use of non-recyclable biomass waste and agricultural and forest residues. The European bioenergy sector is a global leader in renewable technologies with more than 800.000 jobs and 50.000+ companies across the value chain

Biomethane injection can contribute on short term to the decarbonisation of the gas grids, and can be used to meet the electricity demand and balance the grid enhancing energy security. In particular, biomethane can contribute on short-term to the goals of the REPower of reducing the EU dependence on imported fossil fuels and to the diversification of energy supply.

Biomass availability, competition between the alternative use of biomass, as well as the environmental implications are major concerns for further bioenergy deployment. Bioenergy production, however, brings significant opportunities to deliver a number of social, environmental and economic benefits, in addition to the climate and energy goals, driving rural development.

A major issue related to the bioenergy is that biomass crops used for energy compete for land and resources with food crops and could cause land use changes, causing negative impacts on ecosystems, biodiversity and land use if not properly managed. The use of residues and wastes can be important sources for bioenergy with no land use impacts. Pollutant emissions from biomass combustion (nitrous oxides, carbon monoxide, particulate matter, volatile organic compounds, polyaromatic hydrocarbons) are of the greatest concern for local air quality, especially for small scale applications. However, as acknowledged by IEA, "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).

To limit certain negative impacts, RED II established the sustainability and GHG emissions saving criteria for biofuels, bioliquids and biomass fuels. RED II excludes several land categories, with high biodiversity value and high carbon stock, from being used for bioenergy. Defining sustainability criteria and setting standards helped to ensure that bioenergy is produced in a sustainable manner.

Sustainability and GHG criteria apply to all installations producing electricity, heating and cooling or fuels with a fuel capacity above 20 MW in the case of solid biomass, and with a fuel capacity above 2 MW in the case of gaseous fuels. Bioenergy from waste and processing residues needs to meet only the GHG saving criteria. A large number of bioenergy pathways can achieve large GHG emission reduction, above 80%, while some pathways do not comply with the GHG emission threshold, thus they are not eligible. Significant carbon emissions reductions can be achieved through the production and use of biochar for carbon storage on land and as a soil amendment.

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List of abbreviations and definitions

AD	Anaerobic digestion
BIGCC	Biomass Integrated Gasification Combined Cycle
BIG-GT	Biomass Integrated Gas Turbine
BtL	Biomass to liquid
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CFBC	Circulating Fluidised Bed Combustion
CHP	Combined Heat and Power
CPC	Coordinated Patent Classification
DH	District Heating
FBC	Fluidised Bed Combustion
FT	Fischer-Tropsch
GHG	GreenHouse Gas
HTC	HydroThermal Carbonization
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
LCA	Life Cycle Analysis
LCEO	Low Carbon Energy Observatory
LCOE	Levelised Cost Of Electricity
LFG	LandFill Gas
LHV	Lower Heating Value
MSW	Municipal Solid Waste
OPEX	Operational expenditure
PWS	Pressurised Water Scrubbing
PSA	Pressure Swing Adsorption
RED	Renewable Energy Directive
R&D	Research and Development
SCR	Selective Catalytic Reduction
SET Plan	Strategic Energy Technology Plan

SNG	Synthetic Natural Gas
TRL	Technology Readiness Level

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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 II extended the sustainability criteria to solid and liquid and gaseous biomass. According to the RED II, the biomass heating and cooling and electricity plants should achieve greenhouse gas emission savings of least 70 % in the case of installations starting operation from 2021 and 80 % for installations starting operation from 2026. Sustainability and GHG criteria apply to all installations producing electricity, heating and cooling or fuels with a fuel capacity equal or above 20 MW in the case of solid biomass fuels, and with a fuel capacity equal or above 2 MW in the case of gaseous biomass fuels. Bioenergy from waste and processing residues needs to meet only the GHG saving criteria. The fossil fuel comparator for the production of electricity was established at 183 g CO_{2eq}/MJ. 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[1] 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 health and biodiversity, and should therefore be avoided (Vera et al., 2022; Welfle et al., 2023).

[1] 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).

	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.
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 producing electricity, heating and cooling or fuels with a total rated thermal input equal to or exceeding 20 MW in the case of solid biomass fuels, and with a total rated thermal input equal to or exceeding 2 MW in the case of gaseous biomass fuels. Electricity from biomass fuels shall comply with energy efficiency criteria, depending on plant size for electricity-only and cogeneration installations.
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, 2019).
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

This annex provides an overview of the energy system models and scenarios used in CETO to support the technology development assessment and the strategic overview on clean energy technologies.

A3.1 POTEnCIA Model Overview

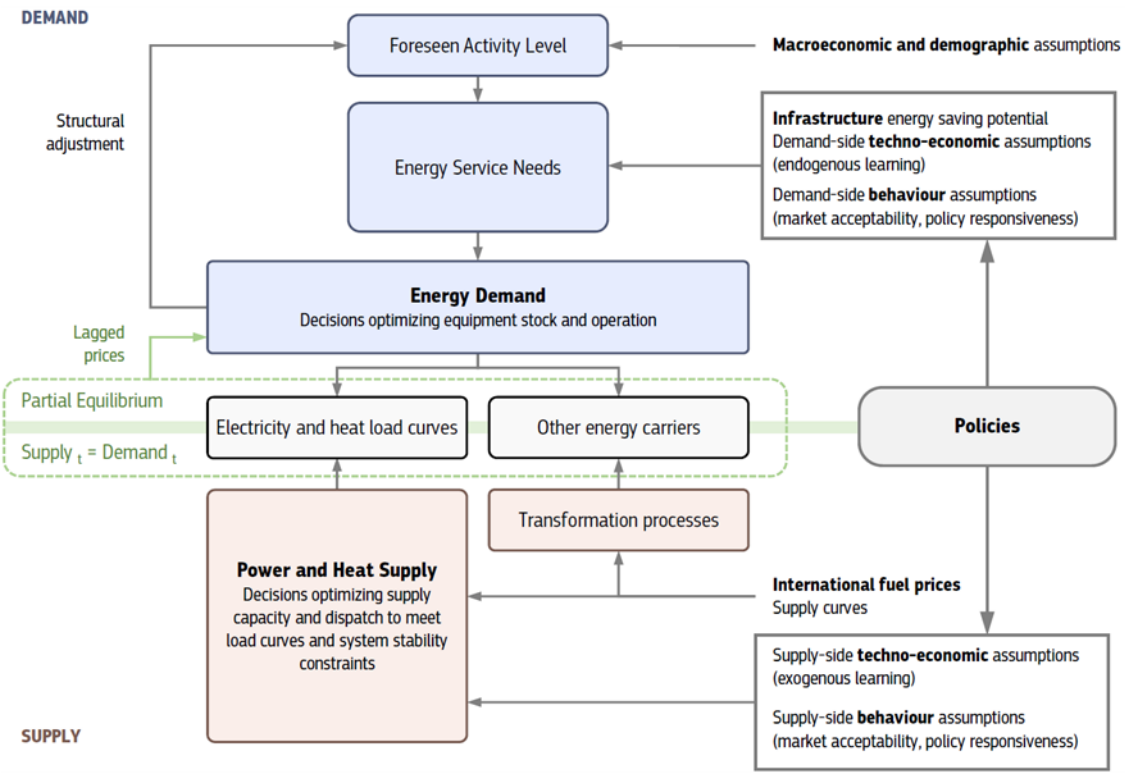
The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed 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 A3-1); detailed in the POTEnCIA model description and in the POTEnCIA Central Scenario report) 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. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

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 CO2 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). JRC-IDEES has been developed in parallel to POTEnCIA, and an updated release is planned in 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

Figure A3-1. The POTEnCIA model at a glance



Source: Adapted from the POTEnCIA Central scenario report

A3.2 POTEnCIA CETO Climate Neutrality Scenario overview

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 EU27 GHG emissions by 55% by 2030 versus 1990, and reaches the EU27´s climate neutrality by 2050 under general assumptions summarized in Table A3-1. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation 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 deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5% share of renewables in gross final energy consumption by 2030). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO2 emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Table A3-1. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario

General scenario assumptions	Modelled scenario and policy assumptions
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019

International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU

Source: JRC

A3.3 POLES-JRC Model

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. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.

POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand (Figure A3-2). International markets and prices of energy fuels are simulated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global framework: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2050 and is updated yearly with recent data and model updates.

The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES-JRC has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the "*Proposal for a revised energy efficiency Directive*" (COM(2016)0761 final) and "*The Paris Protocol – A blueprint for tackling global climate change beyond 2020*" (COM(2015) 81 final/2).

Moreover, POLES-JRC provided the global context to the *EU Long-Term Strategy* (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the *Integrated Assessment Modelling Consortium* (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

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://ec.europa.eu/jrc/en/geco

A3.3.1 Power system

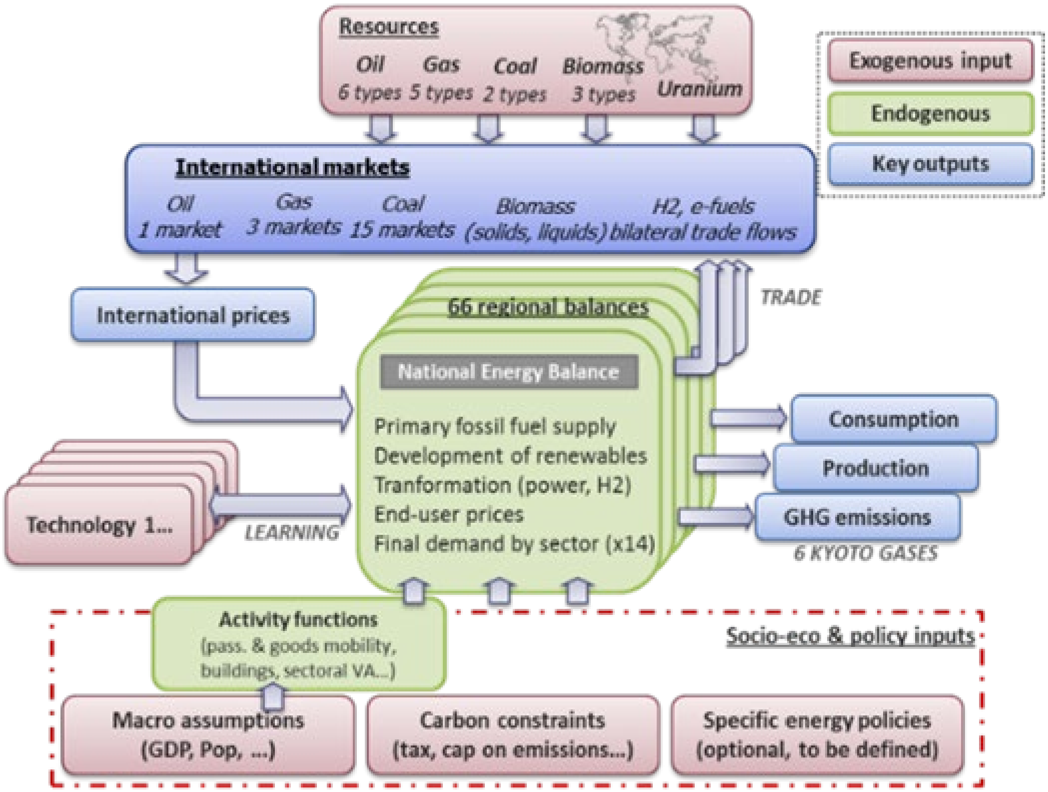
POLES-JRC considers 37 power generating technologies, covering existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operating and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of carbon capture and storage (CCS) technologies is linked to region-specific geological storage potential. In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investments and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), concentrated solar power (CSP), on-shore and off-shore wind, ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower.

CCS-equipped combustion power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included

Figure A3-2. Schematic representation of the POLES-JRC model architecture



Source: JRC

A3.3.2 Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i.e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and other fuels.

POLES-JRC uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to other CETO technologies influencing electricity consumption, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolysers.

A3.3.3 Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the demand, and the production cost of technologies.

A3.3.4 Hydrogen

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

Hydrogen can used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLESJRC models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

A3.3.5 Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM model[1]. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO_2) as well as agriculture (CH_4 and N_2O) are derived from GLOBIOM.

Power generating technologies using biomass are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of 1st and 2nd generation biofuels for gasoline and diesel is considered.

A3.3.6 Carbon Capture Utilization and Storage (CCUS)

POLES-JRC takes into account CCUS technologies for:

- 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 coal and biomass pyrolysis;
- Direct air capture (DAC) where the CO_2 is stored or used to produce synfuels (gaseous or liquid);
- CO_2 storage in geological sites.

A3.3.7 Model documentation and publications

A detailed documentation of the POLES-JRC model and publications can be found at:

- https://publications.jrc.ec.europa.eu/repository/handle/JRC113757
- https://ec.europa.eu/jrc/en/poles

A3.4 POLES-JRC CETO Global 2°C Scenario

The global scenario data presented in this CETO technology report refers to a 2°C scenario modelled with the POLES-JRC model. The 2°C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the long-term goal of limiting the temperature rise over pre-industrial period to 2°C in 2100.

The 2°C scenario was designed with a global carbon budget over 2023-2100 (cumulated net CO_2 emissions) of approximately 1150 $GtCO_2$, resulting in a 50% probability of not exceeding the 2.0°C temperature limit in 2100. A single global carbon price for all regions is used in this scenario, starting immediately (2023) and strongly increasing. The 2°C scenario is therefore a stylised representation of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures.

The POLES-JRC model has been updated with the latest technologies costs from recent literature. Most of the historic data used in the 2°C scenario refers to data used in the GECO 2022 scenarios (energy balances, energy prices, capacities).

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