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Biogenic CO_2 Emissions in the EU Biofuel and Bioenergy Sector: Mapping Sources, Regional Trends, and Pathways for Capture and Utilisation

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Abstract: The European biofuel and bioenergy industry faces increasing challenges in achieving sustainable energy production while meeting carbon neutrality targets. This study provides a detailed analysis of biogenic emissions from biofuel and bioenergy production, with a focus on key sectors such as biogas, biomethane, bioethanol, syngas, biomass combustion, and biomass pyrolysis. Over 18,000 facilities were examined, including their feedstocks, production processes, and associated greenhouse gas emissions. The results highlight forestry residues as the predominant feedstock and expose significant disparities in infrastructure and technology adoption across EU Member States. While countries like Sweden and Germany lead in emissions management and carbon capture through bioenergy production with carbon capture and storage systems (BECCS), other regions face deficiencies in bioenergy infrastructure. The findings underscore the potential of BECCS and similar carbon management technologies to achieve negative emissions and support the European Green Deal's climate neutrality goals. This work serves as a resource for policymakers, industry leaders, and researchers, fostering informed strategies for the sustainable advancement of the biofuels sector.

Keywords: biogenic gases database; biofuels; bioenergy; carbon capture; utilisation and storage; syngas; biomass combustion; bioethanol; biogas; biochar

1. Introduction

The global transition to renewable energy sources is critical for addressing climate change and achieving carbon neutrality. Within this context, the European Union (EU) has positioned biofuels and bioenergy as integral components of its renewable energy strategy, contributing significantly to the reduction of fossil fuel reliance and greenhouse gas emissions [1]. However, while bioenergy is often lauded for its sustainability, it is also a source of biogenic carbon dioxide (CO_2) emissions, which arise from the combustion, fermentation, and processing of biomass. Unlike fossil-derived CO_2, biogenic CO_2 is part of the short-term carbon cycle, yet its management remains essential to maximising the environmental benefits of bioenergy.

In 2023, global biofuel production levels reached 960,000 barrels of oil equivalent per day, in comparison to the 12,000 barrels of oil equivalent per day that were produced in 2000 [2]. Growth has largely been driven by policies that encourage the use and production of biofuels due to the perception that it could provide energy security and reduce greenhouse gas emissions in relevant sectors. Blending mandates, sustainability criteria, fuel quality standards, and import tariffs have impacted the biofuel market. The global biofuels market is expected to reach a market size of USD 143.8 billion by 2028 [3]. Bioethanol is the largest liquid biofuel globally with a share of 62%, followed by FAME biodiesel at 26%. The rest of the biofuels, including HVO (hydrogenated vegetable oil) and renewable diesel, have a share of 12%. North and South America together produce 75% of all biofuels globally, with Europe accounting for a smaller share of 14%.

Biogas production also plays a significant role in the bioenergy sector. In 2020, 38.1 billion m^3 of biogas was produced globally, equivalent to an energy content of 1.46 EJ [4]. Europe was the world leader in biogas production in 2019, accounting for more than half of global output with 30.6 billion m^3 of biogas (0.70 EJ). Typical feedstocks for biogas production include manure, sewage, crop residues (e.g., straw), the organic fraction of municipal waste, and energy crops such as maize and grass silage. Biogas is used across various sectors, including electricity, heat, and transportation.

Currently, most bioethanol is produced using starch- or sugar-based feedstocks such as wheat, corn, or sugarcane (first-generation bioethanol). To meet rising demand, expansion must focus on lignocellulosic materials, such as forest and agricultural residues or waste (second- or third-generation bioethanol). Biodiesel is primarily produced from fats and oils, with vegetable oil being the most common feedstock. However, non-agricultural feedstocks like waste oils are gaining prominence in regions such as the United States and Europe. As biofuel production rises steadily, biogenic emissions also increase annually.

Conventional carbon capture and storage (CCS) is based on the long-term storage of CO_2 in geological or ocean reservoirs. However, this approach faces high costs and significant limitations, such as the potential risk of leaks from storage sites and the need for proximity between CO_2 sources and reservoirs. Consequently, CCS is more feasible for large, centralised sources that benefit from economies of scale in pipeline transport. Alternative biogenic carbon sequestration methods tailored to biofuel production plants of varying scales are urgently needed.

This study seeks to expedite progress toward sustainable bioenergy, playing a crucial and constructive role in the attainment of the UN Sustainable Development Goals (SDGs). It aims to contribute to the European Green Deal objectives by integrating carbon capture, utilisation, and storage (CCUS) techniques into the biofuels value chain. This integration is designed to facilitate the decarbonisation of the European Union's economy. To realise this objective, this study aims to address these gaps by providing a comprehensive assessment of biogenic CO_2 emissions in the EU biofuel and bioenergy sector. The objectives are to map the sources, quantities, and geographic distribution of biogenic CO_2 emissions across EU member states, identifying key biofuel and bioenergy plants contributing to these emissions and to evaluate the current state of CO_2 capture and valorisation technologies in the sector, including their potential for scalability and integration.

The findings will contribute to advancing CO_2 management practices, fostering innovation in bioenergy technologies, and supporting the EU's broader climate and energy objectives.

2. Methodology

The investigation encompasses five distinct biofuel and bioenergy sectors:

(i) Biomass gasification for syngas production.
(ii) Biomass combustion for renewable electricity and heat generation.
(iii) Biomass fermentation for bioethanol production.
(iv) Anaerobic digestion for biogas and/or biomethane production.
(v) Biomass pyrolysis for biochar production.

For each of these sectors, individual plants within the 27 member states of the European Union (EU-27) have been identified. General data, including location, name, and end-products, have been documented. Moreover, pertinent information such as production capacity, feedstock type and consumption, fossil and biogenic CO_2 emissions, CO_2 capture technologies employed, and the amount of fossil and biogenic CO_2 captured have been collected.

To gather these data, a comprehensive internet search was carried out, including inter alia individual plant websites, government websites, environmental agency platforms, and the websites of national and international associations relevant to each sector. Additionally, a systematic review of scientific literature and research articles was carried out using specialised databases.

Nevertheless, for the case of biogas and biomethane production, the EBA 2023 report [5] is considered an accurate and valid source for assessing the current state of this sector in Europe, as a one-to-one survey is not feasible due to the large number of biogas and biomethane installations in the EU.

For all sectors, in cases of missing data, an approach was adopted for the CO_2 emissions estimation based on the plant type, capacity, and feedstock. The methods for estimating CO_2 emissions produced from biomass gasification, combustion, fermentation, digestion, and pyrolysis are described below.

2.1. Biomass Gasification (Syngas)

To estimate the biogenic CO_2 released from gasification plants, the following methodology was applied. It was assumed that on average, syngas contains 25–30% CO, 25–30% H_2, 40–60% N_2, 10–15% CO_2, and 1–5% CH_4 [1]. To estimate the CO_2 equivalent emissions, only the carbon-containing components were taken into account: CO, CO_2, and CH_4. The parameter that is usually reported for gasification plants is the heat generation capacity.

To estimate the syngas annual production (V_{syngas}) of a gasification unit (Equation (1)), the calorific value of syngas was assumed to range between 4 and 6 MJ/Nm^3, based on [2].

$$V_{syngas}\left(Nm^3\right) = \frac{\text{Power(MW)} \times \text{Time(s)}}{\text{Calorific value}\left(\frac{MJ}{Nm^3}\right)} \quad (1)$$

Thus, the corresponding CO_2 mass was calculated considering the ideal gas law equation (Equation (2)).

$$M_{CO_2}(\text{tons}) = \frac{P}{R \times T} \times V_{syngas} \times (\%CO2) \times MW_{CO_2} \times 10^{-6} \quad (2)$$

where M_{CO_2} is the mass of carbon dioxide (tons), P is the atmospheric pressure (101,325 Pa), R is the universal gas constant (8.31 m^3 Pa K^{-1} mol^{-1}), T is the room temperature (273.15 K), $\%CO_2$ is the mole fraction of carbon dioxide in syngas (mol%), and MW_{CO_2} is the molecular weight of CO_2 (44 g/mol).

The estimated CO_2 equivalent emissions from biomass gasification processes were then presented as a range reflecting minimum and maximum impact.

2.2. Biomass Combustion (Combined Heat and Power)

The solid fuel or biomass combustion process can be defined as the complete oxidation of the fuel and the generation of heat stream. The first step of thermal degradation of biomass produces a pyrolysis gas of moisture and volatiles, and the leftover solid is made of char and ash. The gaseous pollutants include CO_2, CO, NO_x, SO_2, HCl, KCl, NaCl, and other trace elements [3]. Then, homogeneous oxidation of the emitted volatiles and heterogenous oxidation of the char take place for the complete combustion. Hence, the potential CO_2 equivalent emissions are estimated based on basic thermodynamic and engineering calculations [4]. Therefore, to simplify the calculations, the following assumptions were made: (a) complete combustion conditions; (b) only the carbon-containing components have been taken into account, CO and CO_2; (c) the flue gas behaves as an ideal gas; (d) the carbon content of biomass feedstock was set as equal to a 50% dry and ash-free basis [5]; (e) in case of co-firing, the carbon content of coal (lignite) was set as equal to a 70% dry basis [6,7]; (f) the moisture content of the fuel was set at 20% [8]; (g) the net calorific value (NCV) of woody biomass was assumed to be 15 MJ/kg biomass and of lignite was 18 MJ/kg lignite [7,9,10]; (h) plant operation per year was 8000 h.

For combustion or co-firing plants where reports on CO_2 released per year were unavailable, an estimation approach based on the assumptions above was adopted to calculate the potential biogenic emissions. A combustion plant generates power in form of heat and electricity. Therefore, using the power capacity of a plant, the annual biomass consumption is defined by Equation (3).

$$M_{biomass}(kg) = \frac{Energy_{biomass}(MJ)}{NCV_{biomass}\left(\frac{MJ}{kg_{biomass}}\right)} = \frac{Power(MW) \times Time(s)}{NCV_{biomass}\left(\frac{MJ}{kg_{biomass}}\right)} \quad (3)$$

In the case of a co-firing plant, Equation (3) is modified to Equation (4).

$$M_{biomass}(kg) = \frac{Energy_{total}(MJ) - Energy_{\ coal}(MJ)}{NCV_{biomass}\left(\frac{MJ}{kg_{biomass}}\right)} \quad (4)$$

where $M_{biomass}$ is the biomass consumption (kg), $Energy_{biomass}$ is the energy produced in the form of heat and/or electricity using biomass as fuel (MJ), power is the plant's capacity (MW), $Energy_{coal}$ is the energy produced in the form of heat and/or electricity using coal as fuel (MJ), Time is the annual operational period of the plant (seconds), $NCV_{biomass}$ is the net calorific value of woody biomass (MJ/kg biomass), and NCV_{coal} is the net calorific value of coal (MJ/kg coal).

Thus, the amount of CO_2 emitted from biomass combustion was estimated using Equation (5).

$$\begin{aligned} M_{CO_2}(tons) &= M_{biomass}(kg) \times 10^3 \times (1 - y\%) \times C_{biomass}\% \times \frac{MW_{CO_2}}{MW_C} \\ &= 1470 \times M_{biomass}(kg) \end{aligned} \quad (5)$$

where y% is the moisture content of the biomass (%), and $C_{biomass}$ is the carbon content of biomass.

2.3. Biomass Fermentation (Bioethanol)

Biomass fermentation is applied to produce bioethanol while emitting biogenic gases [11,12]. The latter are estimated based on the basic fundamentals of anaerobic respiration, where energy is derived from the breakdown of carbohydrates to monomers such as glucose.

By applying basic stoichiometric calculations, biogenic CO_2 emissions can be estimated, given a plant's annual bioethanol production, using Equation (6).

$$\begin{aligned} M_{CO_2}(\text{tons}) &= \frac{MW_{CO_2}\left(\frac{kg}{kmol}\right)}{MW_{CH_3CH_2OH}\left(\frac{kg}{kmol}\right)} \times \rho_{CH_3CH_2OH}\left(\frac{\text{tons}}{m^3}\right) \times M_{CH_3CH_2OH}\left(Nm^3\right) \\ &= 0.754 \times M_{CH_3CH_2OH}\left(Nm^3\right) \end{aligned} \tag{6}$$

where $MW_{CH3CH2OH}$ is the molecular weight of ethanol (46.07 g/mol), $\rho_{CH3CH2OH}$ is the density of ethanol at room temperature (0.789 tons/m^3), and $M_{CH3CH2OH}$ is the bioethanol production per year of the plant (tons).

This derived conversion factor was employed throughout this approach, in instances where the emissions reports were missing. In all cases, it was considered that bioethanol is produced via fermentation. While CO_2 is also emitted during other production stages such as growth, transportation, and pretreatment, only CO_2 generated during the fermentation process is regarded as "biogenic" and is estimated via this method.

2.4. Biomass Pyrolysis (Biochar)

The estimation of biogenic CO_2 emissions from pyrolysis processes involves a systematic approach grounded in carbon balance principles. Slow pyrolysis was chosen for the analysis since it is primarily utilised for biochar production due to its longer residence times and lower temperatures in contrast to fast pyrolysis techniques. Thus, slow pyrolysis can enhance the net reduction in CO_2 emission when biochar is applied to soils [13]. Biochar production data, including annual quantities and types of biomass used, were collected. This information serves as crucial input for estimating CO_2 emissions. The estimation of biogenic CO_2 emissions proceeds by calculating the carbon input from the biomass and the carbon output from the produced biochar. The disparity between these values represents the carbon content transformed into gases during pyrolysis. For this approach, the following assumptions were made: (a) complete combustion of the co-products of the gas phase (gas and tars); (b) if the biomass type is unknown, the carbon content was set at 50% d.b. [14]; (c) for the production of charcoal, slow pyrolysis is favoured; (d) the carbon content of the end-product/biochar ranges from 80 to 85% of the feedstock's carbon content since bio-oil (liquid) and gaseous products are also formed but in small quantities, thus [14,15].

To estimate the biogenic CO_2 emissions from biomass pyrolysis, Equation (7) is applied:

$$M_{CO_2}(\text{tons}) = M_{biomass}(\text{tons}) \times C_{biomass}\% \times Y_C\% \times \frac{MW_{CO_2}}{MW_C} \tag{7}$$

where $M_{biomass}$ is the biomass feedstock in the pyrolysis unit (tons), $C_{biomass}$ is the carbon content of the biomass used (%), and Y_C is the carbon yield of pyrolysis unit and ranges from 15 to 20%. Thus, the biogenic CO_2 emissions from a pyrolysis unit are estimated to range between 0.28 and 0.37 g per g of biomass with 50% d.b. carbon content.

2.5. Anaerobic Digestion (Biogas, Biomethane)

In the EBA 2023 report [16], the energy production via anaerobic digestion was the parameter reported for each country. Thus, the estimation of biogenic CO_2 emissions was necessary. In a typical AD plant, parameters such as biogas/biomethane production, electricity and heat generated, biofertiliser (digestate) production, and dry ice production (CO_2 solidify) are reported.

While emissions are observed in several production stages, in this study, the following assumptions were taken into account to estimate the biogenic emissions: (a) the digestate treatment was not taken into consideration; (b) heat generation and dry ice (solidification of CO_2) were taken as by-products of the process; (c) biogas composition was 50–75%*v/v* CH_4 and 25–50%*v/v* CO_2 [17,18]; (d) the flue gas behaved as an ideal gas; (e) in the case of biomethane production or biogas upgrading, the CO_2 was captured and not emitted in the atmosphere, and the methane content was above 96%*v/v*; (f) there was no moisture in biogas; (g) the high heating value (HHV) and the low heating value (LHV) of methane were 39.8 and 35.8 MJ/m^3, respectively [19]; (h) only methane (CH_4) is combustible; (i) if not given, the efficiency to convert biogas to electricity was set to 0.38 [20].

In most cases, the plant's annual report details the volume of biogas/biomethane produced (Nm^3). For these cases, the CO_2 is estimated using Equation (8).

$$\mathrm{M_{CO_2}(tons)} = \frac{P}{R \times \mathrm{T}} \times \mathrm{V_{CO_2}}(\%v/v) * \mathrm{Q_{biogas}}\left(\mathrm{Nm^3}\right) \times \mathrm{MW_{CO_2}}\left(\mathrm{g} * \mathrm{mol^{-1}}\right) \times 10^{-6} \quad (8)$$

where V_{CO2} is the % CO_2 in the biogas stream (%*v/v*), and Q_{biogas} is the annual biogas production.

Thus, the biogenic CO_2 emissions range between 0.49 and 0.98 g CO_2 per 1 Nm^3 of biogas produced.

In cases where the energy content of biogas is reported, where reports provide the capacity of the plant or the energy content of the annual biogas that was combusted, a different approach is used to define the emissions. For example, as with natural gas, fuel suppliers for CHP plants use the high heating value (HHV) of the fuel to measure its capacity [21]. When the energy input is reported, the biogas production can be calculated using Equation (9), and the biogenic emissions are then estimated with Equation (10).

$$\mathrm{Q_{biogas}(Nm^3)} = \frac{\mathrm{E_{input}\ (kWh)}}{\mathrm{HHV_{biogas}\ (kWh/m^3)}} \quad (9)$$

where E_{input} is the energy content of biogas that is introduced in the CHP plant per year (kWh), and HHV_{biogas} is the high heating value of biogas (kWh/m^3).

Thus, the biogenic CO_2 emissions range between 0.06 and 0.18 g CO_2 per 1 kWh of energy input in a CHP plant.

In cases where the electrical output of the AD plant is reported, the biogas production can be estimated by the LHV and the CHP efficiency of converting biogas to electricity (Equation (10)).

$$\mathrm{Q_{biogas}(Nm^3)} = \frac{\mathrm{E_{output}\ (kWh)}}{\mathrm{LHV_{biogas}\ (kWh/m^3)} \times \eta\ (\%)} \quad (10)$$

where E_{output} is the electricity produced by the CHP unit (kWh), LHV_{biogas} is the low heating value of biogas (kWh/m^3), and η is the engine efficiency (%).

Thus, the biogenic CO_2 emissions range between 0.19 and 0.56 g CO_2 per 1 kWh of electricity produced by the CHP plant.

3. Results and Discussion

Since February 2024, extensive research has been carried out diligently, and so far up to 200 plants have been documented with a variety of end-products such as bioethanol, biochar, syngas and bioenergy. The main challenge of this documentation was the incomplete emission reports from the plants. The data correctness depends on each country's registration accuracy. Nevertheless, this fact was anticipated since the reporting of biogenic emissions is not mandatory.

The minimum data necessary to include a plant in our analysis were the feedstock type; the annual feedstock consumption; and the annual production, or in the case of combustion, the heat capacity. Optional details, such as feedstock moisture content and process efficiency when available, were used to provide more accurate results.

The following graphs provide a visual representation of biogenic emissions and the distribution of the documented facilities across Europe. These visual aids are integral to understanding the spatial patterns of emissions and the geographic spread of facilities involved in bioenergy, biofuel, and biochar production. More specifically, Figure 1 provides a comprehensive overview of the geographical distribution of bioenergy, biofuel, and biochar production facilities across the EU-27, aiming to identify distinct regional patterns while the biogas/biomethane sector is studied separately. Central and Western Europe, particularly Austria and Germany, boast a substantial number and diverse range of plant types. The well-established circular economy practices in these countries support their success within the framework of the European Green Deal (EGD) strategy. In Northern Europe, the Scandinavian countries (Sweden, Finland, Denmark) have a significant number of heat and power plants utilising wood chips and pellets. This is closely linked to their high proportion of forested land, their early adoption of bioenergy production in the late 1990s, and the European Commission's promotion of waste-to-energy initiatives in the 2000s [22]. Conversely, Southern Europe shows moderate distributions, while Eastern Europe has limited facilities, with only a few noted in Hungary and Romania. The distribution by plant type reveals that biochar plants are predominantly concentrated in Central and Western Europe, where agricultural and green biomass residues are readily available [23]. In contrast, bioethanol plants are more evenly distributed but are primarily located in Central Europe. Combined heat and power (CHP) plants and gasifiers, on the other hand, are notably concentrated in regions with extensive forestry land and significant industrial activity, where they serve to meet local energy needs while contributing to carbon footprint reduction through carbon-neutral energy sources.

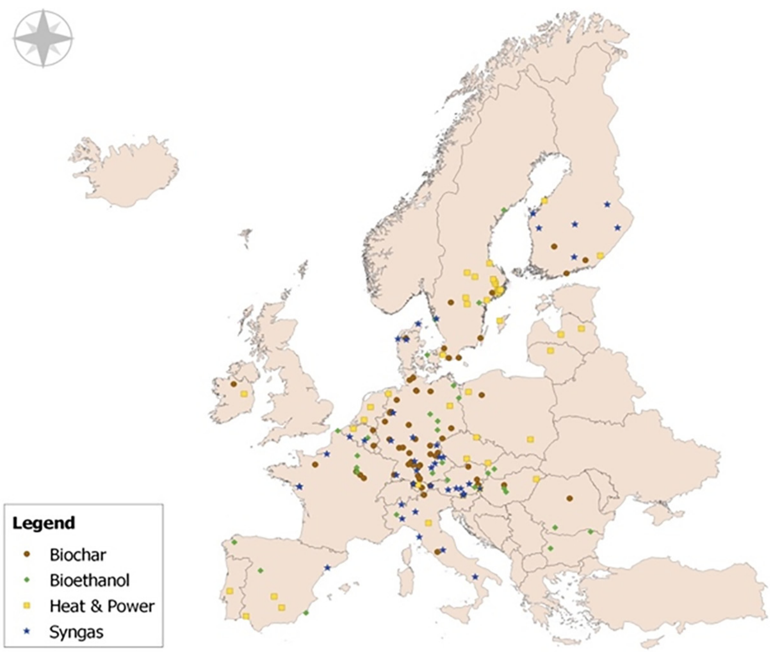

Figure 1. Geographic distribution of biofuel and biochar production plants in the EU-27 (190 plants).

For the case of biomethane production, the Gas Infrastructure Europe and European Biogas Association have created the European Biomethane Map 2024, which includes all infrastructure for biomethane production and is accessible through the following link: European Biomethane Map [24]. The geographical distribution of biomethane plants within the EU-27 reflects the varying levels of adoption and development of biomethane production across member states. Countries in Western and Central Europe, such as Germany, France, and the Netherlands, exhibit the highest concentration of biomethane plants. This is largely due to well-established policies supporting renewable energy, robust infrastructure for biogas upgrading, and a strong emphasis on achieving carbon neutrality. In contrast, Eastern European countries show a lower density of biomethane facilities. This disparity may be attributed to factors such as limited infrastructure, lower levels of investment, and varying degrees of regulatory support for biomethane production. However, some countries in this region, like Hungary, are gradually expanding their capacity as part of efforts to diversify energy sources and meet EU climate targets. Northern Europe, including countries like Sweden and Denmark, also demonstrates a significant presence of biomethane plants, leveraging their strong forestry sectors and early adoption of renewable energy strategies. Meanwhile, Southern Europe displays a moderate but growing number of plants, with countries like Italy making strides in utilising agricultural residues and organic waste for biomethane production. Overall, the distribution underscores the influence of regional policies, resource availability, and technological readiness in shaping the biomethane landscape across the EU-27.

The ranking of the total biogenic emissions (excluding biogas/biomethane plants) by country is presented in Figure 2, while the biogas/biomethane sector is studied separately. From Figure 2, it is evident that Sweden is the largest emitter across the rest EU Member States with a significant contribution comparing to the total documented emissions, summing up to 11 million tonnes of biogenic CO_2 per year. This is justified by the significant presence of biomass combustion plants in Sweden. Following this, Finland and Poland emit 4.46 and 2.9 million tonnes of biogenic CO_2, respectively. A significant disparity is observed between the top three emitters. Observing the list further, a moderate difference is noticed among countries like Germany, Belgium, Ireland, Czech Republic, France, and Italy, which are contributing minor amounts to the overall emissions. Countries with minor contribution or with no record of emissions, like Greece, Estonia, Malta, Luxemburg, Portugal, Romania, and Bulgaria, are likely correlated with underdeveloped bioenergy infrastructure and energy policies within the nations.

Figure 3, as reported by EBA 2023 [25], presents the ranking of total biogenic emissions from biogas and biomethane plants by country. The data indicate that Germany is the largest emitter among EU Member States, accounting for nearly 22.5 million tonnes of biogenic CO_2 annually—a substantial share of the total documented emissions. Italy follows with 6.3 million tonnes per year, while Spain and the Czech Republic each emit 2.1 million tonnes annually, highlighting a significant disparity among the top four emitters. France and Poland contribute between 1.5 and 2 million tonnes of biogenic CO_2 per year. Meanwhile, countries with minimal contributions or no recorded emissions, such as Romania, Malta, Luxembourg, the Czech Republic, and Bulgaria, likely indicate limited development of bioenergy infrastructure and less advanced energy policies in these regions.

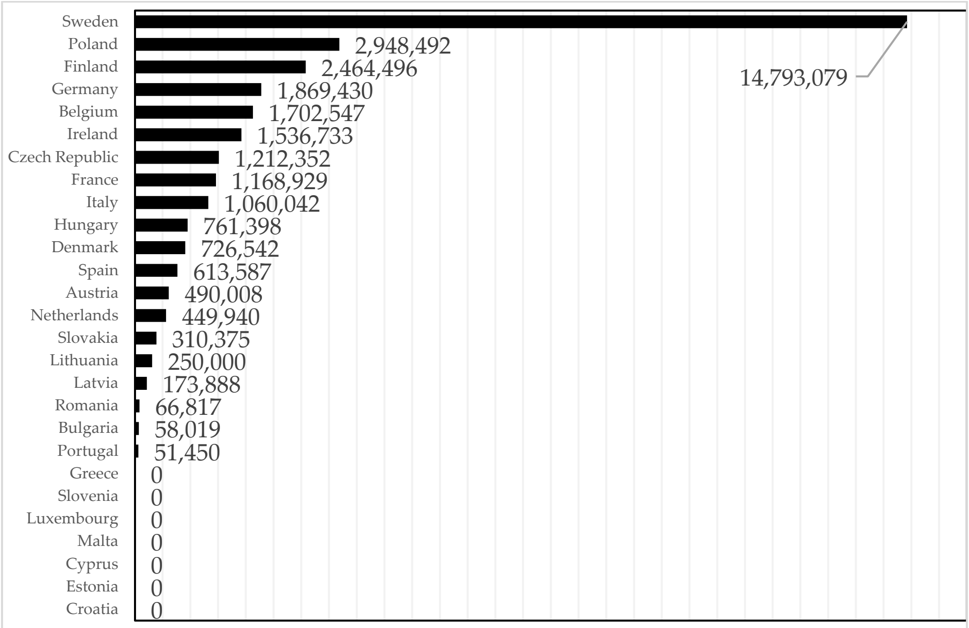

Figure 2. Summary of biogenic CO_2 emissions (tn/y) recorded in the data inventory from syngas, bioethanol, biomass combustion, and biochar production per country in the EU-27.

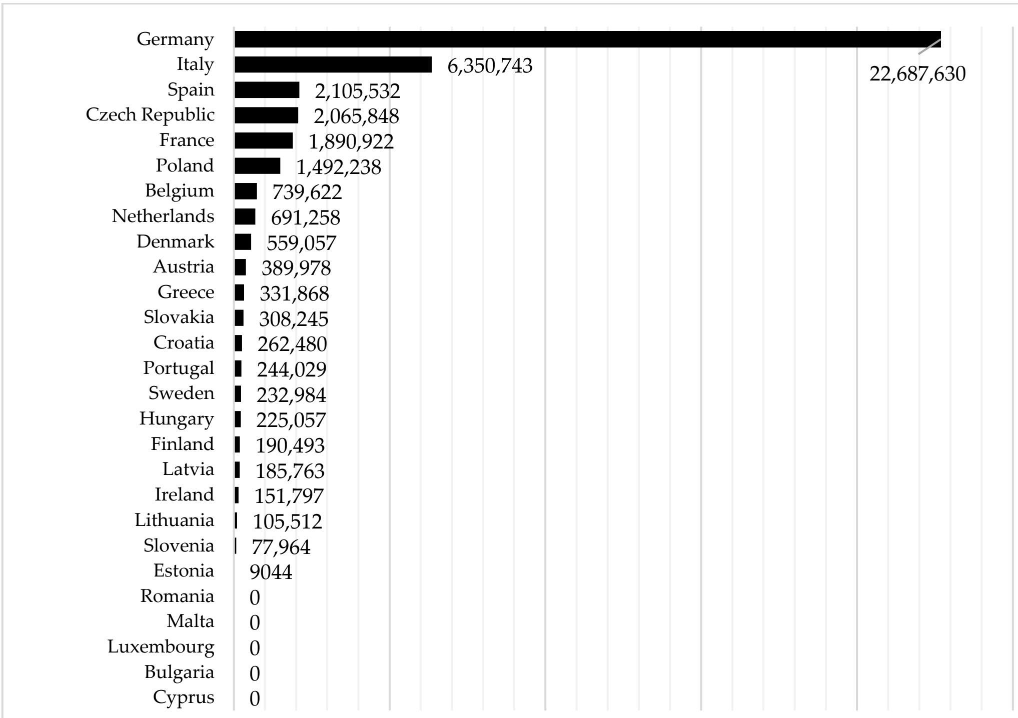

Figure 3. Summary of biogenic CO_2 emissions (tn/y) from anaerobic digestion recorded by the EBA report 2023 per country in the EU-27.

In Figure 4, the heat maps illustrate the spatial distribution of biogenic emissions in relation to the biomass processing over Europe for all sectors. The heat maps highlight the bioenergy infrastructure and provide a clear visualisation of regional disparities. Countries with higher emissions, like Sweden, Germany, and Finland, may need to focus on carbon capture technologies to reduce their carbon intensity. On the other hand, countries with lower emissions, such as those in Southern Europe, need to draw attention towards the development and growth of their bioenergy infrastructure while also keeping under control the emissions [26].

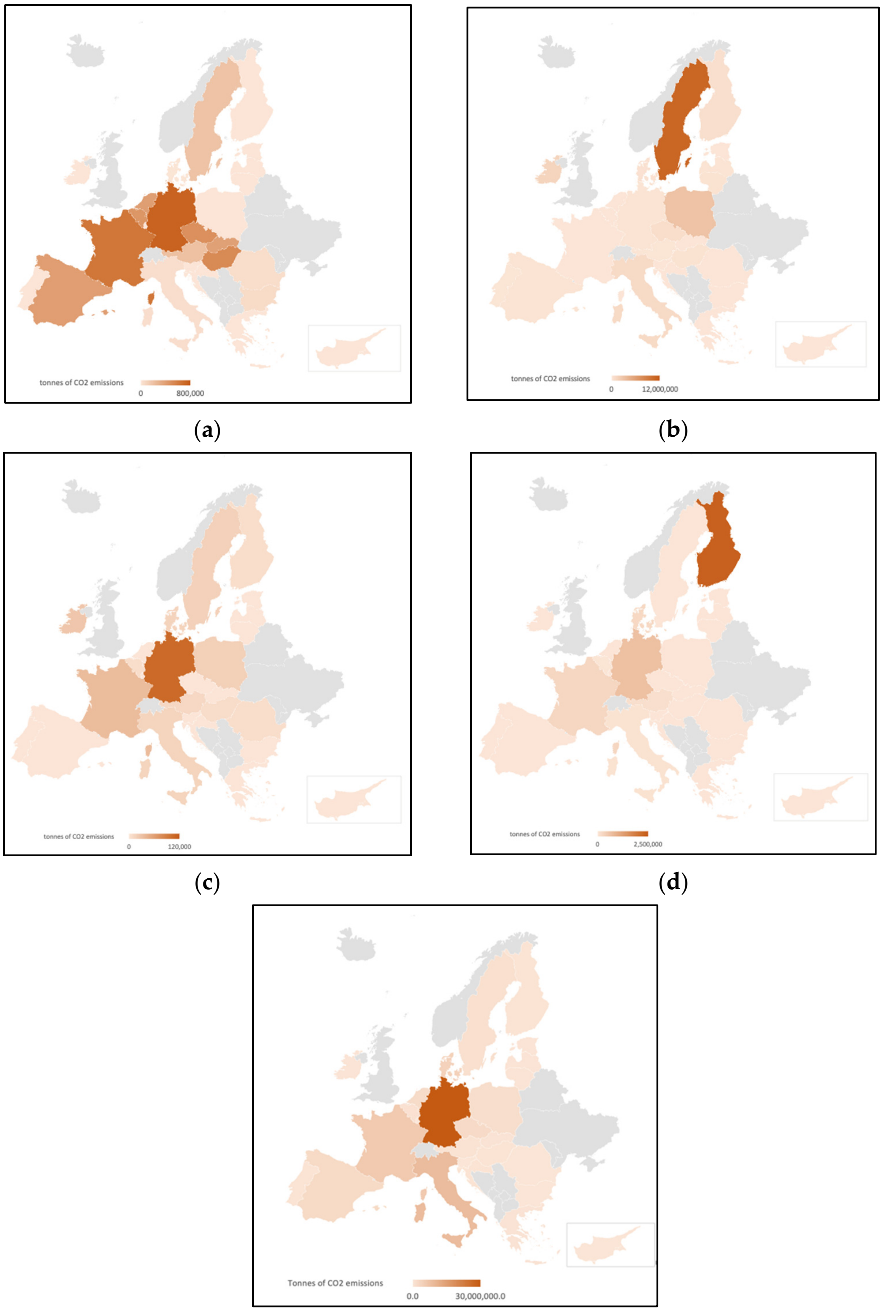

Figure 4. Heat maps of biogenic emissions across Europe, occurring from biomass processes: (**a**) alcoholic fermentation, (**b**) direct combustion, (**c**) pyrolysis, (**d**) gasification, and (**e**) anaerobic digestion.

While this study focuses on quantifying biogenic CO_2 emissions from biofuel and bioenergy production, it is useful to contextualise these figures within the broader landscape of fossil-fuel-derived emissions. In 2023, the European Union's total greenhouse gas emissions were estimated at 3.4 billion tonnes of CO_2 equivalents, reflecting a 7% decline from 2022 due to reductions in fossil fuel use. Notably, emissions from coal, oil, and natural gas combustion still accounted for the vast majority of the EU's CO_2 footprint, despite ongoing decarbonisation efforts.

By contrast, the biogenic CO_2 emissions recorded in this study, while significant, are fundamentally different as they are part of the short-term carbon cycle. Unlike fossil CO_2, which adds to atmospheric carbon levels over geological timescales, biogenic emissions are reabsorbed by biomass growth under sustainable management. However, this does not eliminate the need for carbon capture and utilisation (CCU) technologies in the bioenergy sector, particularly for large-scale combustion and anaerobic digestion plants, which contribute substantial emissions despite their renewable nature.

Countries such as Sweden and Germany demonstrate the potential for bioenergy-based carbon neutrality, with Sweden capturing up to 60% of its biogenic CO_2 through BECCS and flue gas treatment. However, the overall adoption of BECCS and similar technologies across the EU remains below 13%, highlighting the need for further investment in carbon-negative bioenergy systems. Expanding the deployment of these technologies could bridge the gap between bioenergy sustainability and long-term climate targets, enabling the sector to contribute more effectively to the European Green Deal's goal of climate neutrality by 2050.

3.1. Feestock Type Analysis

Figure 5 presents an analysis of biomass feedstocks and their categorisation by type. According to the collected data, up to 70% of the plants utilise forestry residues, with 65% of these being secondary forestry residues (SFR), such as wood chips and pellets, contributing to 12.3 million tonnes of CO_{2eq} biogenic emissions. The remaining 35% process primary forestry residues (PFR), including green waste and branches, accounting for 11.9 million tonnes of CO_{2eq} biogenic emissions.

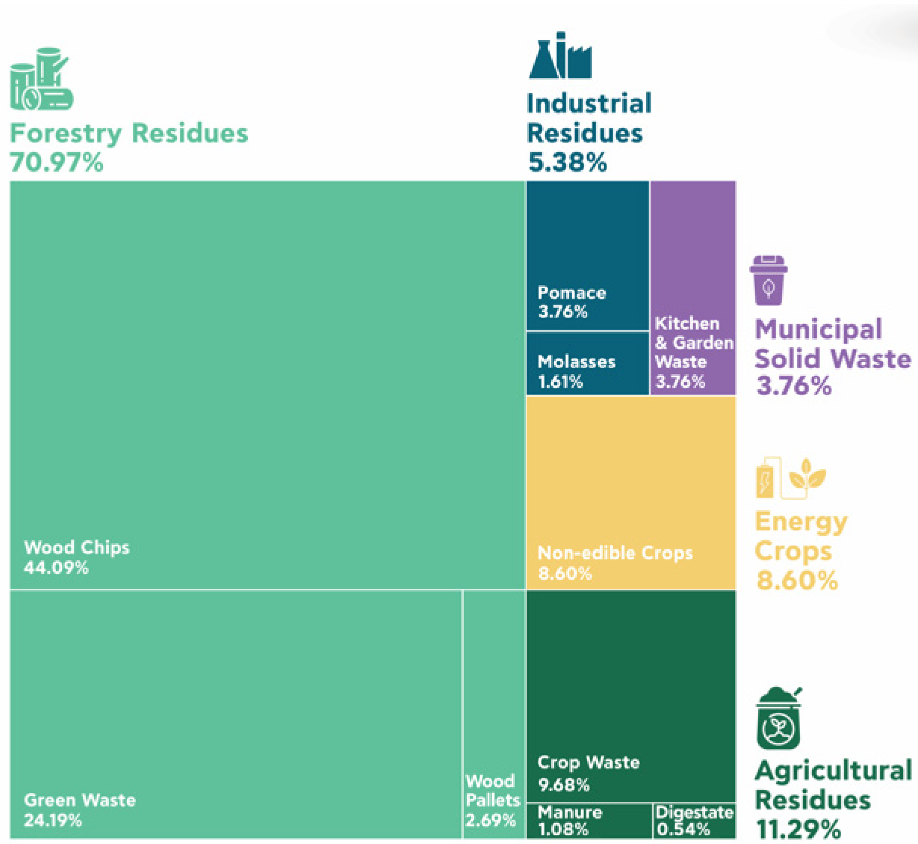

Figure 5. Feedstocks used in bioethanol, syngas, biomass combustion, and biochar production plants in the EU-27 (190 plants).

Agricultural residues rank second, primarily consisting of cereal crop waste (up to 85%), with a smaller proportion of plants using animal manure or digestate to meet their energy needs. Due to their composition, agricultural residues are more suitable for producing biofuels like bioethanol or biochar, which serves as a carbon sink. Most plants producing bioethanol rely on agricultural biomass residues, emitting a total of 2.5 million tonnes of CO_{2eq} biogenic emissions.

Energy crops, such as miscanthus, giant reedgrass, reed canary grass, and switchgrass, represent another significant feedstock. These low-cost biomass sources are used exclusively for renewable energy production, particularly bioethanol, due to their high sugar content. Processing energy crops generates 2.8 million tonnes of CO_{2eq} biogenic emissions across 16 documented plants.

Industrial residues, including pomace from olive and wine production and molasses from sugar refining, along with municipal solid waste (MSW) such as kitchen and garden waste, form another promising biomass stream. Approximately 10% of the plants are supplied by these two waste streams, collectively contributing 1.55 million tonnes of CO_{2eq} biogenic emissions. Figure 5 provides a detailed breakdown of the categorisation and distribution of raw materials among the various feedstock categories.

The EBA Report [16] provides comprehensive tracking and updates on biogas and biomethane production facilities, offering valuable data and insights to enhance bioenergy infrastructure and inform the development of policy frameworks. Biogas is generated through the decomposition of organic materials, with the feedstocks categorised by their source, as shown in Figure 6. Approximately 79% of anaerobic digestion plants in Europe utilise agricultural residues, including straw, husks, corn kernels, sequential crops, and manure. The second most common feedstock for biogas production is sewage sludge from municipal wastewater treatment plants (bioethanol, syngas, biomass combustion, and biochar production), accounting for around 10% of the total. Organic waste from landfill sites also serves as a notable feedstock, contributing to 5% of the plants. The remaining facilities process organic solid waste from municipalities and industries, as well as the organic fraction of wastewater from industrial residues, further diversifying the feedstock sources used for anaerobic digestion.

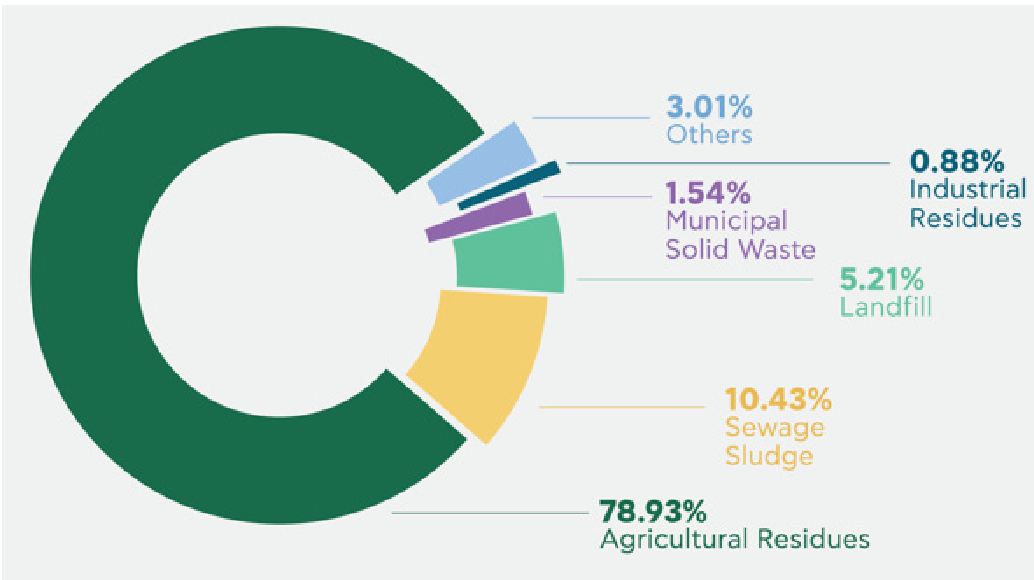

Figure 6. Feedstocks used in biogas and biomethane production plants in the EU-27 (18,140 plants).

Tables 1–5 present the corresponding biogenic CO_2 emissions per country for each feedstock type (excluding biogas/biomethane plants) and for all technological readiness levels (TRL). The background colour presents the sum of the lines below (up to the next background colour), The bold signifies the sum of what follows (up to the next bold) for all tables.

Table 1. Detailed overview of valorisation of forestry residues for bioenergy, syngas, and biochar production, categorising it by various types of plants and TRL with their biogenic CO_2 emissions during processing.

Forestry Residues	Plants	CO_2 (Tonnes per Year)
	133	**28,425,989**
Biomass Combustion Plant	**38**	**21,933,008**
TRL 9 Commercial	**38**	**21,933,008**
Sweden	15	14,240,541
Poland	2	2,900,000
Belgium	1	1,200,000
Italy	1	915,200
Czech Republic	3	722,580
Finland	2	500,020
Denmark	1	300,000
Lithuania	1	250,000
Hungary	1	220,500
Spain	1	200,000
Latvia	2	173,888
Germany	2	156,900
Austria	3	51,989
Portugal	1	51,450
Netherlands	2	49,940
Gasification Plant	**43**	**5,926,051**
TRL 6–7 Demonstration	**3**	**420,714**
Germany	1	373,575
Italy	2	47,139
TRL 9 Commercial	**40**	**5,505,338**
Finland	7	3,952,586
Germany	10	538,375
France	2	377,110
Denmark	4	370,039
Austria	9	187,478
Italy	5	43,570
Belgium	2	24,394
Sweden	1	11,785
Pyrolysis Plant	**52**	**566,930**
TRL 4–5 Pilot	**2**	**1151**
Sweden	2	1151
TRL 6–7 Demonstration	**12**	**77,220**
Sweden	5	39,404
Germany	5	25,104
Austria	1	9533
Finland	1	3178

Table 1. *Cont.*

Forestry Residues	Plants	CO_2 (Tonnes per Year)
	133	**28,425,989**
TRL 9 Commercial	**38**	**488,559**
Germany	22	314,600
Poland	1	45,613
Austria	5	26,534
France	4	25,422
Finland	2	22,244
Belgium	2	22,244
Romania	1	19,067
Sweden	1	12,833

Table 2. Detailed overview of valorisation of agricultural residues for bioenergy, bioethanol, syngas, and biochar production, categorising it by various types of plants and TRL with their biogenic CO_2 emissions during processing.

Agricultural Residues	Plants	CO_2 (Tonnes per Year)
	21	**2,481,258**
Biomass Combustion Plant	**1**	**1,470,000**
TRL 9 Commercial	**1**	**1,470,000**
Ireland	1	1,470,000
Bioethanol Plant	**9**	**726,142**
TRL 4–5 Pilot	**1**	**2**
Germany	1	2
TRL 6–7 Demonstration	**1**	**4069**
Denmark	1	4069
TRL 9 Commercial	**7**	**722,071**
Germany	1	300,000
France	2	185,360
Slovakia	1	131,862
Romania	1	47,750
Italy	1	38,000
Sweden	1	19,100
Pyrolysis Plant	**10**	**280,402**
TRL 6–7 Demonstration	**2**	**20,900**
Italy	1	16,133
Denmark	1	4767
TRL 9 Commercial	**8**	**259,502**
France	1	95,333
Denmark	1	47,667
Ireland	1	61,600
Germany	3	31,778
Hungary	1	20,900
Austria	1	2224
Gasification Plant	**1**	**4714**
TRL 9 Commercial	**1**	**4714**
Germany	1	4714

Table 3. Detailed overview of valorisation of energy crops for bioenergy, biofuel, and biochar production, categorising it by various types of plants and technological readiness levels (TRL) with their biogenic CO_2 emissions during processing.

Energy Crops	Plants	CO_2 (Tonnes per Year)
	16	**2,686,519**
Bioethanol Plant	**16**	**2,686,519**
TRL 6–7 Demonstration	**1**	**4783**
Sweden	1	4783
TRL 9 Commercial	**15**	**2,681,736**
Hungary	2	519,998
Belgium	2	455,909
Spain	3	406,887
Netherlands	1	400,000
Germany	3	394,700
Slovakia	1	257,850
Austria	1	188,374
Bulgaria	2	58,019

Table 4. Detailed overview of the valorisation of industrial residues for bioenergy, bioethanol, and syngas production, categorising it by various types of plants and TRL with their biogenic CO_2 emissions during processing.

Industrial Residues	Plants	CO_2 (Tonnes per Year)
	11	**1,561,697**
Bioethanol Plant	**6**	**1,057,909**
TRL 9 Commercial	**6**	**1,057,908**
Austria	1	23,857
Czech Republic	1	489,772
France	2	448,330
Germany	2	95,950
CHP Plant	**4**	**466,414**
TRL 9 Commercial	**4**	**466,414**
Sweden	2	459,714
Spain	2	6700
Gasification Plant	**1**	**37,374**
TRL 6-7 Demonstration	**1**	**37,374**
France	1	37,374

Table 5. Detailed overview of valorisation of municipal solid waste for bioethanol production, categorising it by types of plants and TRL with their biogenic CO_2 emissions during processing.

Municipal Solid Waste	Plants	CO_2 (Tonnes per Year)
	1	**3767.5**
Bioethanol Plant	**1**	**3767.5**
TRL 9 Commercial	**1**	**3767.5**
Sweden	1	3767.5

A total of 132 plants utilising forestry residues are listed in Table 1. These plants are categorised based on plant type, TRL, and country of operation. When evaluating the processing technologies and technology readiness for valorising forestry residues, several plants use the biomass directly or with minimal processing. For example, bioenergy production (thirty-eight at TRL 9) and syngas production through biomass gasification (three at TRL 6–7, forty at TRL 9) are both mature, commercially established technologies.

An alternative approach for utilising this feedstock involves pyrolysis to produce biochar or fermentation to produce bioethanol, a renewable energy biofuel. As shown in Table 1, there are several commercial and pre-commercial plants (two at TRL 4–5, twelve at TRL 6–7, thirty-eight at TRL 9) producing biochar, although these still require process validation, either as a replacement for fossil fuels or as a means of carbon storage.

Additionally, no plants were found to produce bioethanol from forestry residues, mainly due to the high production costs, which can vary significantly depending on location, season, and the complex composition of the residues. More critically, the cost of the necessary pretreatment (such as delignification) and enzymatic hydrolysis to efficiently convert cellulose and hemicellulose into monomeric sugars results in high ethanol production costs. This process is economically unfeasible unless other by-products can be extracted during production [27,28].

The majority of plants primarily produce biochar through biomass pyrolysis, with most of them located in Germany. This highlights the emerging waste management practices for woody biomass aimed at effectively addressing the negative impacts of GHG emissions [13,29]. Many pyrolysis plants, currently at the pre-commercial stage, are still in the process of optimising various parameters to maximise biochar yield and stability, so they can fully demonstrate their environmental benefits [30]. While Germany has the highest number of documented units, Sweden leads in terms of the volume of forestry residues used, with a carbon footprint approximately ten times greater. Sweden has been utilising forestry residues as a carbon-neutral fuel since the late 1990s to provide heat and electricity to its population, benefiting from its extensive forested areas, which cover up to 70% of the land, and its relatively low population density.

Since the European Commission introduced its first directive on biofuels and renewable fuels for transport [31], followed by the Renewable Energy Directive (RED) [32], the production and consumption of first-generation biofuels began to rise across the EU [33]. Due to their high sugar content, agricultural residues have been identified as a promising raw material for sustainable energy production, contributing to the EU's renewable energy targets and the transition away from fossil fuels. However, despite their availability in large quantities, agricultural crop residues present challenges, such as potential conflicts with the food supply chain and the risk of crop land erosion [34,35].

As shown in Table 2, EU Member States are encouraged to produce sustainable fuels while improving soil fertility and minimising negative impacts. Most plants are focused on advancing process maturity and capacity for bioethanol and biochar production. While the Renewable Energy Directive continues to evolve to meet its targets, pre-commercial plants across Europe are working to provide integrated solutions that enhance both environmental and economic efficiency before the commercialisation of these processes.

Currently, 21 plants have been documented using 4.00 million tonnes of agricultural crop residues, contributing to a total carbon footprint of 2.48 million tonnes of biogenic CO_{2eq} per year, with 20% carbon capture. As numerous studies explore methods for valorising this raw material [36–38], attention has turned to bioethanol and pyrolysis plants.

In addition to concerns about promoting first-generation biofuels, there has been growing interest in second-generation biofuels, which can be considered truly carbon-neutral as they derived from non-food biomass, such as energy crops. The cultivation and use of energy crops offer a reliable pathway to producing renewable energy without impacting the food supply chain or the environment [39–41]. The use of energy crops across the EU-27, along with their corresponding biogenic emissions, is presented in Table 3, totalling 2.69 million tonnes of biogenic CO_2 per year.

Biofuels generated from energy crops are crucial to assess sustainable management strategies and develop efficient bioenergy production systems with improved environmental and agro-economic conditions. Moreover, energy crops are mainly used to produce transport biofuels on account of the easy extraction of sugars from this raw material, thus making the process more viable and affordable for commercial scale applications with minimum impact of land-use change [42–44]. Nevertheless, it is questionable whether the use of land, even for non-food energy crops, is sustainable [45,46]. Europe is updating its policies in line with the Renewable Energy Directive [32] and is focused on promoting the production of advanced biofuels from energy crops cultivated on marginal lands. As part of this, the implementation of carbon capture technologies has been proposed, with significant research directed towards achieving "negative emissions" processes. By combining bioenergy production with carbon capture and storage systems (BECCS), it is possible to generate carbon-neutral biofuels while simultaneously capturing CO_2 from the atmosphere to support biomass growth. However, the large-scale deployment of BECCS with energy crops is not yet feasible due to concerns about land-use changes, which could negatively impact food crop cultivation and the food supply chain. To implement BECCS systems with energy crops successfully, EU Member States must carefully regulate and manage investments in this technology to meet the European Commission's target goals for 2050 [39,47–49].

Following the European Commission's set targets and the increasing cost of residues disposal, industries have begun implementing waste management strategies to support renewable energy production. These strategies, particularly in the food and beverage sector, are documented in Table 4. These industries, including breweries and olive mills, generate various organic residues. Alongside these waste streams, municipal kitchen organic waste, with similar characteristics and potential energy value, is another resource. Plants utilising this waste are listed in Table 5. To date, 11 plants have been documented using these residues, resulting in up to 1.56 million tonnes of biogenic CO_2 emissions, either by producing bioethanol to increase revenue or by generating bioenergy to meet their own heat and power needs.

While the technology for valorising these organic residues has advanced, techno-economic factors still need to be considered before industries take the next step in contributing to biofuel production and renewable energy generation, while also offsetting their emissions [50]. In contrast, while industrial and municipal organic residues can facilitate the transition away from fossil fuels, a well-established and sustainable supply chain system is crucial for creating new, flexible pathways to achieve carbon neutrality [51].

Table 6 provides an overview of the distribution and CO_2 emissions from biogas and biomethane plants across the EU-27 Member States. A total of 18,140 biogas plants are in operation, producing over 60 million tonnes of CO_2 annually. Germany is the leading producer, with 11,000 plants generating more than 22 million tonnes of CO_2 per year. Other significant contributors include Italy, the Czech Republic, and France. While there are fewer biomethane plants (1104), they still contribute notably to CO_2 emissions, with Germany again at the forefront, emitting over 300,000 tonnes annually. The widespread use of TRL 9 commercial technologies in both biogas and biomethane plants highlights their maturity in the market, although there are notable differences in their distribution and impact across Europe.

Table 6. Detailed overview of valorisation of biomass for biogas and biomethane production, categorising it by TRL with their biogenic CO_2 emissions during processing [5].

Country	Plants	CO_2 (Tonnes per Year)
	18,140	**41,298,061**
Biogas Plant	**17,036**	**40,366,829**
TRL 9 Commercial	**17,036**	**40,366,829**
Austria	423	386,443
Belgium	192	735,464
Bulgaria	-	-
Croatia	42	262,480
Czech Republic	603	2,065,536
Cyprus	-	-
Denmark	123	390,082
Estonia	13	4678
Finland	87	185,295
France	1191	1,709,759
Germany	11,000	22,349,784
Greece	75	331,868
Hungary	82	223,498
Ireland	43	150,731
Italy	1800	6,237,149
Latvia	49	185,555
Lithuania	41	105,512
Luxembourg	-	-
Malta	-	-
Netherlands	260	628,393
Poland	383	1,492,238
Portugal	62	244,029
Romania	-	-
Slovakia	80	307,699
Slovenia	24	77,964
Spain	250	2,099,580
Sweden	213	193,092
Biomethane Plant	**1104**	**931,232**
TRL 9 Commercial	**1104**	**931,232**
Austria	15	3534
Belgium	8	4158
Czech Republic	6	312
Denmark	59	168,975
Estonia	7	4366
Finland	27	5198
France	514	181,163
Germany	254	337,846
Hungary	1	1559
Ireland	2	1066
Italy	51	113,594
Latvia	1	208
Netherlands	82	62,865
Slovakia	1	546
Spain	5	5951
Sweden	71	39,892

3.2. Biogenic CO_2 Management and Valorisation

The integration of bioenergy with carbon capture and storage (BECCS) is a pivotal strategy in achieving climate targets by enabling negative emissions, particularly within sectors where emissions are challenging to mitigate [52]. BECCS, as a technology, holds promise in transitioning towards carbon neutrality by linking large-scale biomass energy production to CO_2 capture and permanent storage [44,53]. The main challenge for BECCS lies in developing scalable, commercial processes for capturing and storing CO_2.

Out of the 188 plants for biomass combustion, gasification, pyrolysis, and fermentation documented, 130 facilities have been identified as actively applying carbon capture, utilisation, and storage (CCUS) technologies across the EU-27. These facilities are presented in the inventory database as previously mentioned along with the methods used for emissions management. A variety of technologies to reduce, capture, or valorise biogenic CO_2 emissions are reported. Examples include the following:

- Sorption-enhanced water gas shift (SEWGS) for syngas production, integrating CO_2 capture into the process to enhance hydrogen generation.
- Cryogenic capture and liquefaction, primarily used in bioethanol plants where the CO_2 stream is relatively pure, allowing for efficient storage or utilisation.
- Biochar-based carbon sequestration, which stabilises carbon in solid form through pyrolysis and uses the biochar as a soil amendment.
- Amine scrubbing and selective non-catalytic reduction (SNCR) in biomass combustion plants to capture and purify CO_2 from flue gases.

Based on the data collected, the following comparative figures are presented (Figures 7–12). From these figures, it is obvious that most plants that apply CCUS technologies are in Germany, followed by Sweden and Austria. However, while Germany hosts almost half of these plants, it captures only 10% of the biogenic gases captured by Sweden. Most plants applying CCUS in the EU-27 are pyrolysis plants, while just a few (less than 10) are bioethanol plants. Nevertheless, the biogenic CO_2 captured from the pyrolysis plants amounts to just 11% of the biogenic emissions captured from biomass combustion plants. It is also noteworthy that in the Netherlands, almost all biogenic emissions are captured, but this is largely because only one CCUS plant was identified. For the countries that have several CCUS plants, the highest share (almost 60%) is held by Sweden. As for the plant types, in the pyrolysis plants, most of the biogenic CO_2 produced is captured.

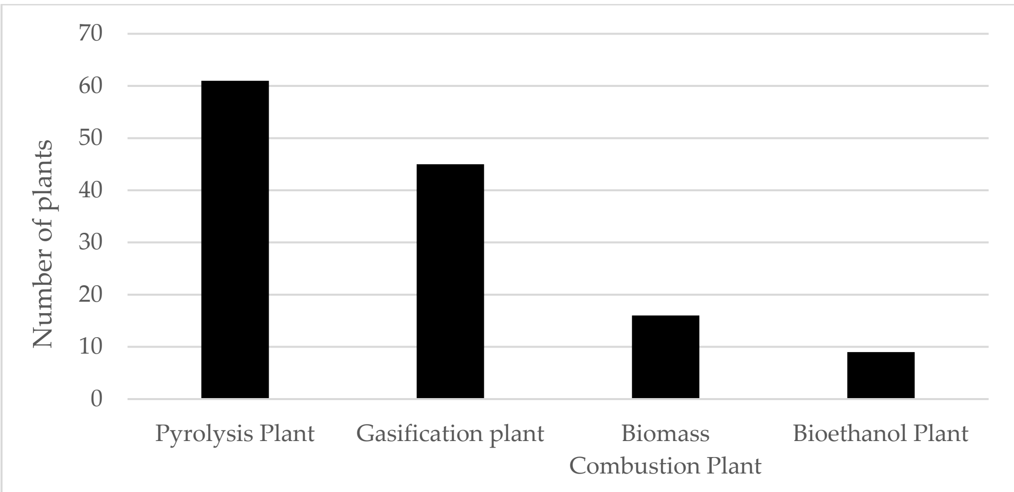

Figure 7. Distribution of units included in the inventory database applying CCUS technologies per sector.

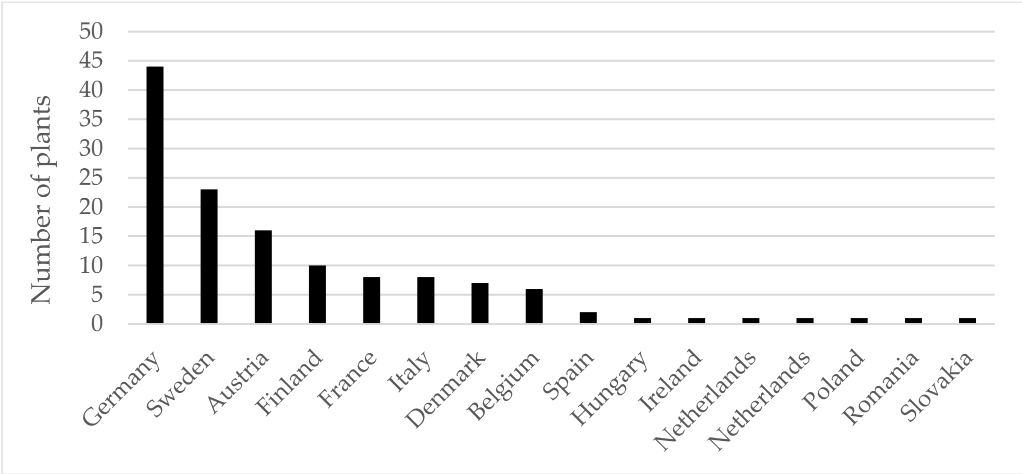

Figure 8. Distribution of units included in the inventory database applying CCUS technologies per country.

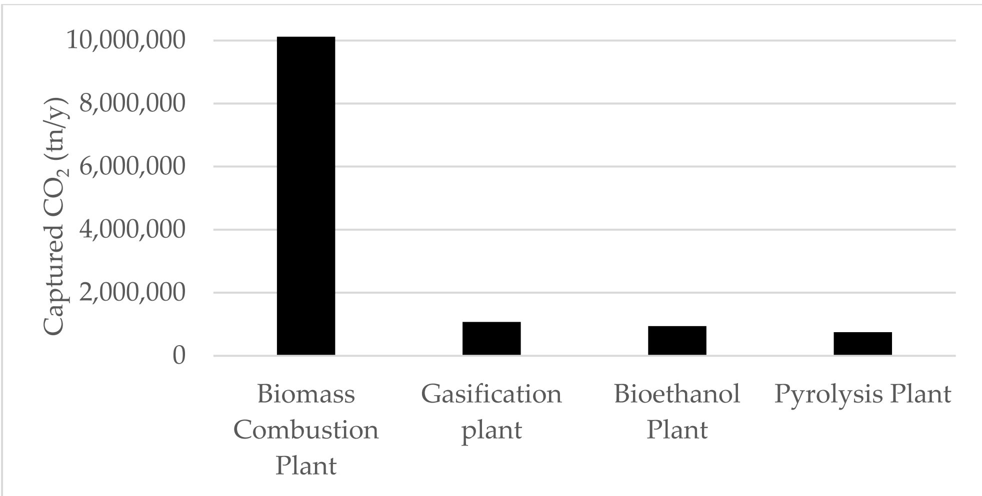

Figure 9. Distribution of CO_2 captured from units included in the inventory database applying CCUS technologies per sector.

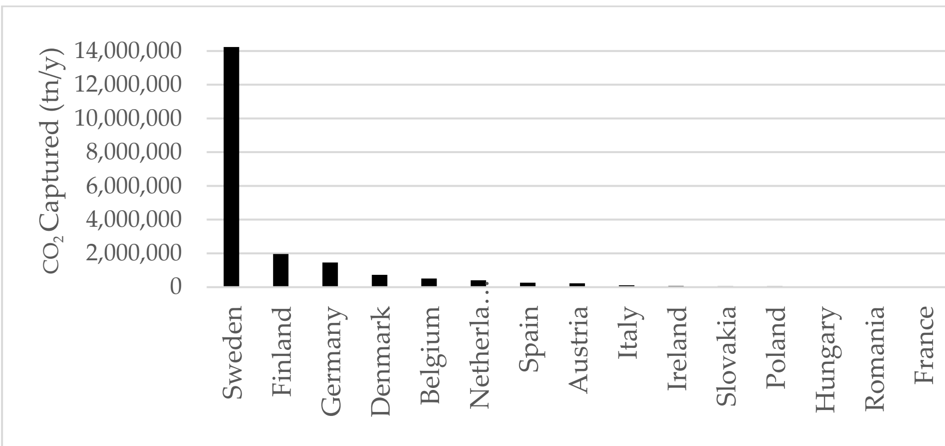

Figure 10. Distribution of CO_2 captured from units included in the inventory database applying CCUS technologies per country.

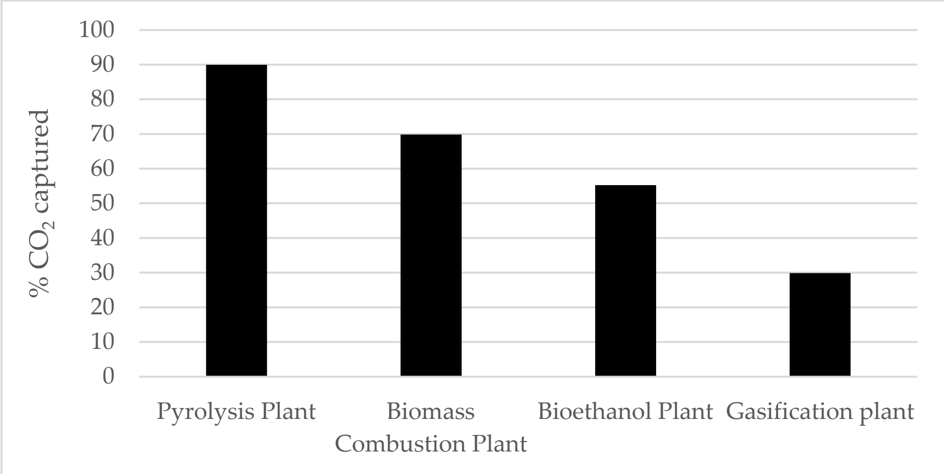

Figure 11. % CO_2 captured in respect to total biogenic CO_2 emissions from units included in the inventory database applying CCUS technologies per sector.

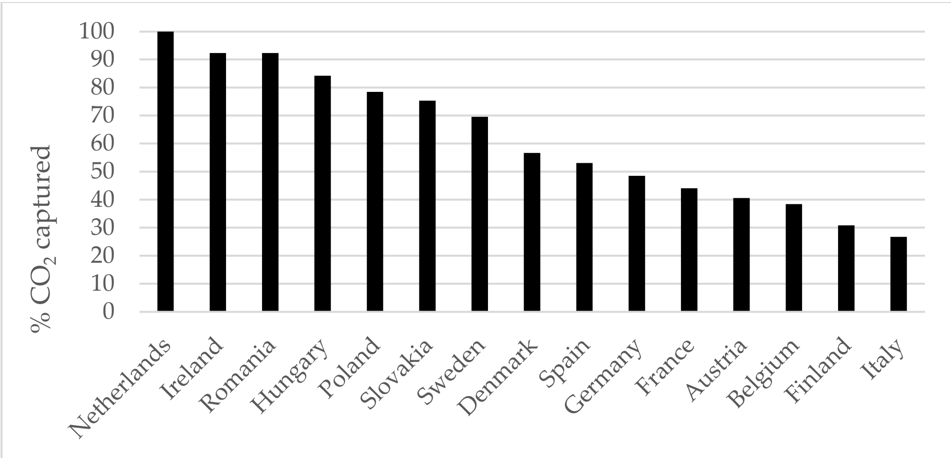

Figure 12. % CO_2 captured in respect to total biogenic CO_2 emissions from units included in the inventory database applying CCUS technologies per country.

Although Sweden has a much larger carbon footprint than the rest of the EU-27, as shown in Table 1, it is also the country with the highest percentage of carbon capture, around 60% of emissions from biomass combustion plants for energy recovery with selective non-catalytic reduction (SNCR) combined with flue gas condensation. Regarding the agricultural residues described in Table 2, in total, these plants documented valorising 3.05 million tonnes of agricultural crop residues with a carbon footprint of 991,000 tonnes of biogenic CO_2 eq. and up to 50% carbon capture, while recovering soil fertility in lands with carbon sequestration and supplying the food and beverage industry with pure CO_2 from alcoholic fermentation. However, from the emissions produced from processing energy crops (Table 3), just 30% are documented to be captured.

Table 7 outlines a range of bioenergy or biochar plants and their corresponding CO_2 emissions, providing a detailed breakdown of the emission outputs from different biomass conversion processes such as biomass combustion plants, gasification plants, bioethanol production, and pyrolysis. Biomass combustion plants represent the largest share of biomass plants, with substantial CO_2 emissions reported. Gasification and bioethanol plants follow, each demonstrating the potential for CO_2 reduction through innovative capture technologies. Pyrolysis plants, particularly those producing biochar briquettes, show significant potential for negative emissions, contributing to long-term carbon storage with soil amendment practices.

Table 7. Carbon capture and storage (CCS) technologies and emissions management techniques applied in biochar, gasification, bioethanol, and biomass combustion plants identified in CRONUS database.

	Plants	CO_2 Emissions (Tonnes)	CO_2 Emissions Captured (Tonnes)
	131	**20,622,603**	**12,885,105**
Biomass Combustion Plants	**16**	**14,489,415**	**10,117,500**
Selective non-catalytic reduction	14	13,728,295	9,587,500
Flue gas condenser	1	461,120	280,000
Amine scrubbing and dust filter	1	300,000	250,000
Gasification Plants	**45**	**3,588,340**	**1,071,929**
Sorption-enhanced water gas shift	45	3,588,340	1,071,929
Bioethanol Plants	**8**	**1,708,857**	**943,973**
Liquefaction	7	1,512,948	843,973
Stack gas recovery	1	195,909	100,000
Pyrolysis plant	**62**	**858,235**	**772,236**
Biochar briquette	62	858,235	772,236

In addition to the emission data presented in Table 7, different biogenic gas management (stack gas recovery, flue gas condenser, SNCR) and capture technologies, including liquefaction/cryogenic capture, amine scrubbing, and SEWGS, are employed for CO_2 utilisation in industries like horticulture, food and beverage, and soil amendment. These examples underscore the technical feasibility of integrating CCS with bioenergy systems, though challenges related to economic viability and scalability persist.

Biochar is used as a carbon sink because when biochar is applied to soil (direct application to soil is the standard procedure), it locks away carbon, reducing the amount of carbon released into the atmosphere. This process is often referred to as a form of biogenic carbon capture [54].

Moreover, the overall CCUS management for the biochar, bioethanol, and biomass combustion plants are presented in Table 8 linked with the sum of the captured emissions.

Table 8. Valorisation sector targeted by carbon capture, utilisation, and storage (CCUS) technologies applied in biochar, bioethanol, and biomass combustion plants identified in the CRONUS database.

	CO_2 Emissions (Tonnes)
	20,622,603
Biomass Combustion Plants	**14,489,415**
Selective non-catalytic reduction	13,728,295
Flue gas condenser	461,120
Amine scrubbing and dust filter	300,000
Gasification Plants	**3,588,340**
Sorption-enhanced water gas shift	3,588,340
Bioethanol Plants	**1,708,857**
Liquefaction	1,512,948
Stack gas recovery	195,909
Pyrolysis Plant	**858,235**
Biochar briquette	858,235

Despite technical feasibility, economic uncertainties and high investment costs continue to pose challenges to BECCS implementation. BECCS remain essential for providing negative emissions, thus compensating for the unavoidable GHG emissions in other sectors [55,56]. Furthermore, the source and lifecycle of biomass is increasingly critical, as outlined by the RED III directive [57], in determining the overall success of BECCS in the coming years. In summary, BECCS technology presents a promising route to reducing greenhouse gas emissions and aiding the transition to a carbon-neutral society, though significant economic and technical barriers remain to be addressed for its widespread adoption. The background colour presents the sum of the lines below (up to the next background colour), The bold signifies the sum of what follows (up to the next bold).

4. Conclusions

This study provides a detailed overview of emissions, plant distribution, and the implementation of technologies such as BECCS, offering critical insights into the European bioenergy landscape. The findings revealed that forestry residues constitute the majority of feedstocks utilised across bioenergy and biochar production plants, with secondary forestry residues contributing significantly to total emissions. Agricultural residues, mainly cereal crop waste, rank second, playing a crucial role in bioethanol and biochar production. Energy crops like miscanthus and switchgrass are also notable due to their high sugar content for bioethanol. Industrial residues and municipal solid waste (MSW) form an emerging biomass stream. High-emission countries such as Sweden, Germany, and Finland dominate the bioenergy sector, yet Sweden notably captures a substantial proportion of its biogenic CO_2 emissions through advanced BECCS technologies.

While this study highlights progress in carbon management, it also underscores significant disparities in infrastructure and technology adoption across EU Member States. Over 70% of the plants documented utilise their effluent streams for energy recovery or carbon capture, yet less than 13% of plants employ BECCS or equivalent technologies. This limited adoption is particularly evident in regions with underdeveloped bioenergy infrastructure, such as Southern and Eastern Europe, where the potential for expansion remains vast.

BECCS have emerged as a cornerstone of sustainable bioenergy strategies, providing a means to achieve negative emissions through carbon sequestration and valorisation. The results show promising trends in pyrolysis and biochar production, where carbon is stored in solid form, and in bioethanol plants utilising cryogenic capture technologies to supply carbon dioxide for industrial applications. However, gaps in data reporting and technological readiness, particularly in smaller plants and less industrialised regions, highlight the need for targeted policy support and further investment.

In conclusion, this study not only maps the current state of biogenic gas management but also serves as a tool to guide the implementation of BECCS and other CCUS technologies. By addressing regional disparities and scaling up carbon capture, the EU bioenergy sector can play a transformative role in meeting the European Green Deal's climate neutrality objectives by 2050.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	anaerobic digestion
BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CCUS	carbon capture, utilisation, and storage
CHP	combined heat and power
EBA	European Biogas Association
EGD	European green deal
FAME	fatty acid methyl ester
GHG	greenhouse gas
HHV	higher heating value
HVO	hydrogenated vegetable oil
LHV	lower heating value
MSW	municipal solid waste
NCV	net calorific value
PFR	primary forestry residues
RED	Renewable Energy Directive
SDGs	Sustainable Development Goals
SEWGS	sorption-enhanced water gas shift
SFR	secondary forestry residues
SNCR	selective non-catalytic reduction
TRL	technological readiness level
UN	United Nations

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