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EU-Bioenergies: Status and Future Prospects

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Abstract: For climate protection and a sustainable economy, the European Union is pursuing a policy of switching from fossil to renewable energies, which should lead to a reduction in greenhouse gases (GHG) and a reduction in dependence on energy imports. This report uses publicly available databases and analyses to examine the extent to which these goals are achieved or are achievable by means of bioenergy (fuel, heat, electricity). In addition, EU regulations and databases relevant to bioenergy are critically scrutinised. Today, bioenergy accounts for around 10% of Europe's energy supply, making up more than half (59%) of renewable energies. There is potential to further increase bioenergy, but the future contribution to energy supply and independence from imports is rather to be estimated as moderate. The evaluation of GHG suffers from the fact that the official databases do not meet the requirements for a scientific evaluation. In order to make a sustainable contribution to the EU targets, besides energy, all other options for the use of biomass, the use of biogenic CO2 through carbon capture and utilisation (CCU) and the combination of bioenergy and carbon capture and sequestration (CCS) should be integrated. To promote the implementation of such an integrated approach, the pricing of GHG should be combined with incentives for the upscaling of sustainable bioenergy, CCU and CCS.

Keywords: bioenergy, biofuel, biomass, greenhouse gas, CO_2, carbon capture and utilisation (CCU), carbon capture and sequestration (CCS)

In order to achieve its climate protection targets, the EU is paying particular attention to the energy sector, which emits the largest share of greenhouse gases in the production of electricity, heat and fuels. Ambitious targets have therefore been set for the expansion of renewable energies. This also includes bioenergies (bioheat, biopower, biofuels), whose upscaling, however, has to deal with ecological and economic conflicts of objectives.

1. Introduction

The increasing concentration of greenhouse gases, the resulting climate change and, as a countermeasure, the reduction of greenhouse gas emissions are urgent fields of action of global importance. The EU has therefore set the goal of achieving climate neutrality by 2050 in accordance with the Paris Climate Agreement (European Parliament, 2023a). In particular, the reduction of energy-related emissions is urgent because the energy sector is the main emitter of CO_2 (Statista, 2023a). With regard to the climate effect of the greenhouse gas CO_2, the IPCC distinguishes between two carbon cycles of different duration, namely the cycle of fossil energy sources, which lasts for thousands of years, and the cycle of natural photosynthesis and natural geological and aquatic sinks, which lasts for a few to several hundred years (IEA Bioenergy, 2023a). In terms of climate protection, fossil energy sources, which originate from the slow carbon cycle, must be pushed back in favour of those from the carbon cycle of biological systems and carbon-free energies. The latter two are grouped under the umbrella term renewable energies. These include wind energy, solar energy, hydropower, ocean energy, geothermal energy, biomass and biofuels (European Parliament, 2023b) and accounted for 22.5 % of the EU's final energy consumption in 2022 (European Environment Agency, 2023a). For their further implementation, the EU has set ambitious goals (European Commission, 2023a). Part of the strategy is to intensify the use of biomass for energy. It is intended to contribute both to the reduction of greenhouse gases and to the reduction of dependence on energy imports (European Commission, 2023b). The purpose of this paper is to question the quality of the data on bioenergies, the extent to which bioenergies contribute to these goals today, what trends are emerging for the future, and how regulatory control instruments of the EU support the scale-up of bioenergy in a sustainable way.

2. Materials and Methods

For the research of quantitative data, regulations, general strategies and current developments on bio- and other renewable energies, including ecological, economical and social sustainability issues, the official database of the European Commission Eurostat, directives, regulations strategies, roadmaps, action plans and statements of the European Commission, and scientific literature were evaluated. Studies from 2010 to 2021 that examined the potential of bioenergy in the EU were included. Both, studies that looked exclusively at energy use and those that considered competing uses of biomass and sustainability issues were analysed. Furthermore, publications of companies, associations, and NGOs were included, which, although not meeting scientific standards, nevertheless contain information that, when critically evaluated, completes the picture of the official databases. Few references to the legal framework in Germany are given in German, because no English-language version is available.

In order to make the data from different references comparable, energies are indicated with the unit joule (J), oil equivalents (oe), watt-hour (Wh), and emissions with the unit CO_2-equivalents (CO_2eq). The following keywords were used for the research: EU, Europe, energy, bioenergy, MJ, PT, Mtoe, kWh, biofuel, bioenergy, e-fuel, heat, electricity, power, transport, agriculture, forestry, wood, woody biomass, primary biomass, biomass, waste, renewable, ethanol, biodiesel, natural gas, greenhouse gas, CO_2, emission, carbon footprint, RED, RED II, regulation, directive, clean, sustainable, sustainability, land, use, share of, energy return ratio.

3. Results

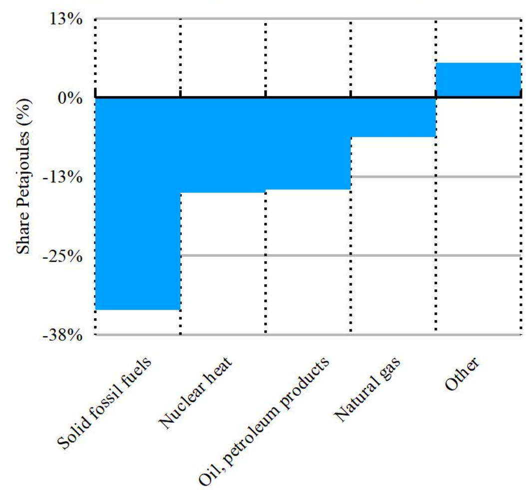
3.1. Europe's energy mix

In 2021, the EU has primary energy available in the amount of 61228 Petajoules per year (PJyr-1) (European Commission, 2023c). The final energy consumption was 39351 PJyr-1 (European Commission, 2023d). Compared to 2010, not only has the total gross available energy decreased by 9%, but the profile of energy sources has also changed. While the share of energy from fossil and nuclear sources has decreased, the share of renewable energy has increased by 45% as Figure 1 (Eurostat, 2023a; Eurostat, 2023b) shows. In 2021, 83% came from fossil and nuclear, and 17% from renewable primary energy sources (10408 PJ) (European Commission, 2023c). In terms of final energy consumption, the share of renewable energies is reported at 21.8 % (Eurostat, 2023b).

The EU defines renewable energy as wind, solar (solar thermal and photovoltaic), aerothermal, geothermal and hydrothermal, ambient, tidal, wave and other ocean energy, hydropower and energy from biomass, landfill gas, sewage treatment plant gas and biogas (EUR-Lex, 2018a).

Bioenergies (bioheat, bioelectricity, biofuel) had a 59.2% share among renewables (6141 PJ; 2017; more recent data not available). Three-quarters went to the Heating & Cooling application; 13% to electricity generation; and 12% to transportation fuels as Figure 2 (European Commission, 2019c; European Technology and Innovation Platform Bioenergy, 2020) shows.

Figure 1
Energy mix changes 2010-2021 (%PJ)



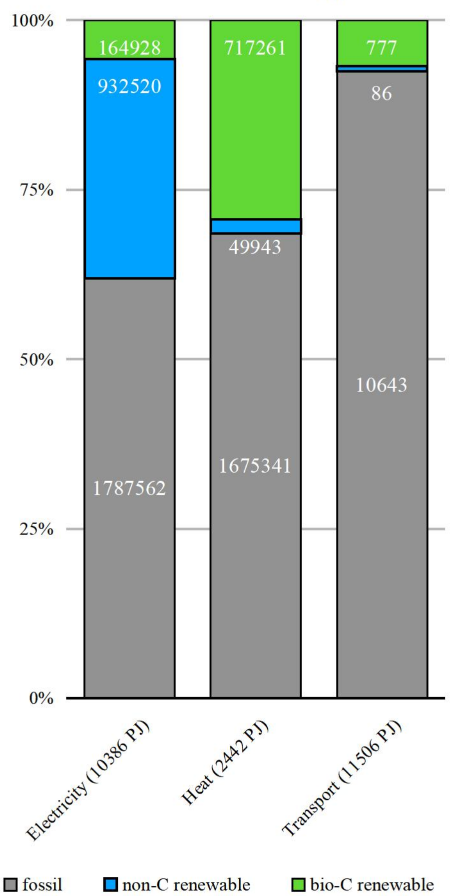
In the three applications mentioned above, the share of bioenergy is quite different. In 2021, bioenergy contributed to heat generation 29%, to electricity 6% and to transport fuels 7%, according to Wertz et al. (2022). The figure for transport fuels must be critically scrutinized because, in accordance with the RED adopted in 2009, it may contain virtual quantities that are calculated using multipliers in favour of advanced fuels based on non-food biomass.Thus, taking into account these multipliers, for the year 2019 the share of renewable fuels in transportation is reported at 8,9%; without multipliers the share is 6,3% (Farm Europe, 2021); for the year 2020 the share is reported at 10.2% with multipliers; without 7,5% (Biofuels International magazine, 2020). Euractiv (2023) explains that in 2018, RED II included not only changed multipliers in the Eurostat statistics for biofuels, but also the capping of certain types of fuel, so that the comparability of the statistics over a longer period of time suffers.

For the sake of completeness, it must be mentioned that raw materials that are statistically recorded as primary energy sources in Eurostat databases are not only used for energy, but also for materials. In 2021, 3951 PJ (6.5%) of primary energy sources in the EU were consumed for non-energy purposes such as chemical products or road construction. This consumption share is distributed among oil and petroleum products (81.9%), natural gas (16.4%), and solid fossil fuels (1.6%) (Eurostat, 2023c). Primary sources of bioenergy, which can also be utilized not only for energy but also for materials, are not differentiated in Eurostat statistics. Examples are construction materials (timber, insulation etc.), road construction (bio-asphalt) chemicals (adhesives, lubricants detergents, agro-chemicals, household chemicals etc.), plastics (biopolymers), food- and feed supplements. However, the fact that material use is increasing is demonstrated by an example from the USA, where the export of bioethanol for non-fuel industrial applications is continuously increasing and has reached about 1900 million liters (0.0644 PJ) in 2022 (United States Department of Agriculture, 2023).

3.2. Origin and use of the bioenergy sources

Overall, the EU imports an average of 55% of its energy. This import share has remained largely unchanged for 20 years (The World Bank, 2023; European Commission, 2023e). The share of fossil energies is 66%. In the second quarter of 2023, the most important suppliers for crude oil were Norway, the United Kingdom and Kazakhstan, for natural gas, Norway, the UK and the USA, and for coal Australia, the USA and Colombia. The share of Russia, the dominant supplier of all three fossil energy sources until 2022, has fallen sharply by 2023. (Eurostat, 2023d). Among the renewable energies, only raw materials for bioenergies are imported. However, their import share is only 4%; 96% comes from domestic European sources (2016; EU 28) (European Commission, 2019c).

Figure 2
Share of fossil and renewable energy sources

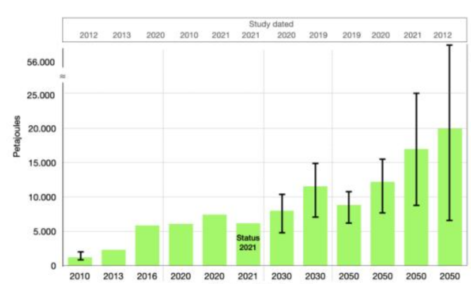


These almost exclusively domestic sources of bioenergy claimed 23% of European biomass in 2015. Another quarter of European biomass went into material use such as construction timber or furniture making, while around half of the biomass produced was claimed for nutrition (feed and food) (European Commission, 2019a). Among these consumption sectors, the bioenergy sector had the largest growth of +32% since 2010, followed by +5.6% for material uses and +2.9% for food, while the total volume of biomass recycled increased by only +8.5%. Jean-Luc Wertz et al. (2023) highlight that the still very small 0.1% share of biomass processed into bio-based chemicals in 2015 has increased by almost 48.4% since 2010 and is expected to further grow.

70% of the biomass required for energy recovery is provided by forestry as solid biomass, primarily for heat generation. 18% is provided by agriculture as primary biomass (sugar, starch for bioethanol; vegetable oils for biodiesel, energy corn for biogas) and by-products (straw for advanced fuel and heat). Biowaste as part of solid municipal waste or in the form of liquid waste (manure, wastewater) contributes another 12% (European Commission, 2019b; European Technology and Innovation Platform Bioenergy, 2023a). Agricultural and forestry products are thus by far the most important sources of bioenergy, accounting for 88%; bio-waste contributes 12%.

The actual resource for biomass is land. However, obtaining data on land use for bioenergy is complicated by the fact that biomass for bioenergy is only partially grown on land used exclusively for this purpose. When integrated multiple cropping schemes are used to grow biomass for both food and bioenergy, the allocation of land in published statistics is not clear. An example is when wheat is grown for food and the straw is used for energy. For 2017, Strapasson et al. (2020) indicate that 56.8% of the EU-28 land area is used for commercial biomass cultivation. On another 40.8% biomass grows wild and on 2.4% urban biomass is cultivated. It can be assumed that the biomass productivity on these areas is different, so that they are not directly comparable in terms of their bioenergy potential. Reliable data on land use for bioenergy in the EU could therefore not be researched.

Figure 3
EU-bioenergy potential estimated by various studies since 2010



3.3. Future potential of bioenergy

In an early study (2012), Bentsen and Felby (2012) published estimates that bioenergy should grow from 800-1600 PJyr-1 (2010), to 4300-6000 PJyr-1 in 2030, and to 3000-56000 PJ in 2050. In 2013, EEA published three scenarios that analysed the EU bioenergy potential from the perspective of the market, climate protection and resource efficiency. According to these, the potential from domestic sources was 2210 to 2357 PJye-1 (EU-28) (European Union, 2023). In contrast, a study published in 2016 had found a potential of 4011 PJyr-1 (European Commission, 2019c). Panoutsou and Maniatis (2021), on the other hand, estimate the future annual potential of bioenergy based on biomass for the year 2030 in three scenarios at 8708-14445 PJ and for the year 2050 at 9127-15323 PJ. About 46% should be generated from agriculture, 44% from forestry and 10% from waste. This estimate included the growing demand for biomass for other uses and the expansion of protected areas agreed for biodiversity protection. In contrast, Mandley et al. (2021) consider bioenergy of 18000 PJyr-1 to be feasible by 2050. In another study, Mandela et al. (2020) had assumed the potential of domestically available biomass for energy purposes in 2050 to be 9000 to 25000 PJ annually and the demand to be 5000 to 19000 PJ. This assumption is significantly higher than a study that had reported a potential of up to 6070 PJ for 2020, considering the same biomass sources (European Technology and Innovation Platform Bioenergy, 2023a). Wertz, Mental, and Perez (2022) cite as justification that the Panoutsou and Maniatis (2021) study included technological advances in future bioenergy development. Figure 3 (Panoutsou & Maniatis, 2012; Bentsen & Felby, 2012; European Commission, 2019c; Mandley et al., 2020; Eurostat, 2023a; Eurostat, 2023b; European Union, 2023) gives a graphical overview of the estimates published in the last two decades, which illustrates that more recent estimates see significantly less potential for bioenergy than the older ones. In the further, Mandley et al. (2020) indicate that up to1900 PJyr-1 could compete for non-energy applications; this would require around 10% of the raw materials estimated for bioenergy. However, most studies neglect the need for the material use of biogenic carbon sources.

The influence of sustainability issues on bioenergy potential is also only partially taken into account. For example, Moosmann et al. (2020) analysed that only 56% of policy documents concerning bioenergy and bio-based products address their sustainability. An important area of sustainability, biodiversity protection, is not taken into account by the studies on bioenergy potential mentioned above. However, biodiversity protection has a major impact because it restricts the amount of forest and agricultural land available for biomass cultivation. According to the new EU Biodiversity Strategy published in 2021 (European Commission, 2023f), 30% of land and marine areas are to be legally protected in the interests of biodiversity by 2030; two thirds of this is to be restricted and one third not used at all. The reduced land available for biomass production has a direct impact on the domestic bioenergy potential. It is therefore to be expected that the proportion of imported raw materials for bioenergy will increase. Consequently, Mandley et al. (2021) assume that the import share would have to grow from 4% today to 60% by 2050 to meet demand.

3.4. GHG intensity and mitigation

3.4.1 GHG intensity

Bioenergies cause GHG emissions in production, logistics and use. For example, detailed analyses have been published for bioethanol. The emissions balance includes upstream emissions from the production chain, including biomass cultivation, processing, transport and distribution as Table 1 (de Carvalho Macedo et al., 2015) shows. Downstream emission savings from CCS, from carbon capture and replacement, and from excess electricity from cogeneration are deducted (European Commission, 2018a; REDcert GmbH, 2023). In contrast to the actual emission intensity of biofuels, which is 64 gCO_2eq/MJ for bioethanol, upstream and downstream emissions are variable and depend on local conditions.

Table 1
Default upstream GHG emissions of bioethanol as a biofuel

Biofuel production pathway	Default greenhouse gas emissions (gCO_2eq/MJ)		
	Cultivation	Processing	Transport and Distribution
Sugar beet ethanol	12	26	2
Wheat ethanol	23	45	2
Corn ethanol	20	21	2
Sugar cane ethanol	14	1	9

For biofuels for transport, therefore, 12.1 gCO_2e/MJ is reported in Sweden, but 81 gCO_2e/MJ in Poland, only slightly lower than for fossil diesel (95.1 gCOe/MJ) (European Environment Agency, 2023a). Emissions data for other selected biofuels for transport were last examined by the EU Joint Research Center in 2018 (European Commission, 2018c). The GHG intensity of biobased heat and electricity includes upstream emissions from biomass cultivation, processing, and transport. In addition, standard emission factors for stationary combustion of biomass fuels are defined; according to the European Commission they shall be set at 0 g/MJ of fuel (European Commission, 2018b).

3.4.2 GHG mitigation

Official data on GHG mitigation through the use of bioenergy in the EU are not published but reports by associations are available. According to Sikkema et al. (2021), solid biomass for electricity and heating/cooling purposes contributed to 21% of overall GHG emission savings in the period 2010-2018. This statement can only be understood to mean that the emissions from the combustion of biomass have been assessed as "zero", in line with EU regulations (European Commission, 2018b), and are deducted from emissions from fossil fuels. The same assessment underlies the statement that according to the association ePURE in the year 2021 the use of bioethanol as biofuel reduced the emission intensity by 76.9% compared to fossil fuel (European renewable ethanol, 2022). In such publications, however, the methods of comparison are not disclosed, or if they are, they are not comparable, so that overall no reliable data or evaluations are available on GHG mitigation.

There are also only incomplete data on the absolute GHG emissions of bioenergy. In absolute terms, the GHG emissions of biomass power plants are said to be higher than those of fossil-fuelled power plants (Chatham House, 2021; Impactful Ninja, 2023). Thus, for the combustion of woody biomass emissions in the EU are reported amounting to 234 (2019) (BirdLife International, 2022), 330 to 380 MtCO_2 (2015) (Camia et al., 2021), and 580 Mt CO_2eq (2018) (European Environment Agency, 2023b). Since 2019, energy recovery, especially from primary wood, has increased sharply (Camia et al., 2021). Schwenk (2022), on the other hand, finds a total volume of only 154-250 Mt CO_2-eq/year for biogenic GHG emissions in the EU. The high uncertainty is explained by the fact that not all EU countries report biogenic GHG emissions (SCHWENK, 2022) and that the influences of land use, sequestration of CO_2 in natural sinks, etc. are complex and their assessment is not standardized (Minx et al., 2021).

3.5. Regulation on bioenergies

According to the European Commission bioenergy includes heat, electricity and fuels based on biomass (organic material such as trees, plants, and agricultural and urban waste) (European Commission, 2023g; Eurostat, 2023e). Through further development of the regulations, attempts are being made to steer the energy markets in such a way that the share of bioenergy increases, at the same time the sustainability of production improves and GHG emissions are reduced. For biofuels, the revised Renewable Energy Directive (RED II) defines sustainability criteria, quality standards and the reporting of emissions (EUR-Lex, 2018b). In addition, detailed quotas are specified: By the year 2030 „EU countries (are) obliged to ensure that the share of renewable energy in the final consumption of energy in transport is at least 14%“, and, at the same time, advanced biofuels are to achieve a share of at least 3.5% (European Commission, 2023h).

As raw materials, the EU Commission calls for the preferential production of bioenergy from non-recyclable wastes and residues and other alternative renewable fuels including e-fuels (Minx et al., 2021).

Concerning GHG-emissions for the sectors of heat and power generation, which are coupled in the power plant sector, it applies that new plants have at least 70% less GHG emissions than conventional power plants operated with fossil energy sources. From 2026 onwards, the requirement increases to an 80% reduction in emissions. This rule is intended to support the implementation of large scale plants (above 50 MW) that apply highly efficient cogeneration technology, or apply Best Available Techniques (BAT) or achieve 36% efficiency (for plants above 100 MW), or use carbon capture and storage technology (CCS) (Minx et al., 2021). Further detailed regulations must be observed with regard to the assessment of GHG associated with bioenergy. For example, the avoidance of GHG emissions through CCS is only taken into account if these GHGs are directly caused by the extraction, transport, processing and distribution of biofuel. The use of CO2 from biogenic emission streams is only assessed as a reduction in GHG emissions if this CO2 directly replaces CO2 from fossil sources (e.g. in CO2 enrichment in greenhouses) (carbon capturing and replacement; CCR). The processing of biogenic CO2, e.g. into e-fuels (CCU), on the other hand, is not accepted as reducing emissions. (European Commission, 2017)

In the individual member states, national biofuels policies are to be considered, which set national targets for the shares of biofuel and the reduction of the GHG intensity of fuels (European renewable ethanol, 2023).

Although European policy has steered the framework towards CO_2 reduction for decades, fossil fuels still dominate energy markets. According to its own assessment, the EU is therefore not on track to achieve the mandatory net-GHG reduction of 55% by 2030 compared to 1990 (European Commission, 2023i).

How regulation supports or does not support the achievement of the GHG target or the scaling of bioenergy through the setting of targets, quotas, emissions trading and other detailed requirements will be addressed in section 4 (discussion).

3.6. Monitoring and reporting

Monitoring the success of measures to expand bioenergy and reduce fossil GHG requires a standardized measurement and reporting system. According to the United Nations Framework Convention on Climate Change (UNFCCC), the EU Member States are obliged to provide national communications on the development of GHG emissions to the UN every 2 years. The EU Commission, for its part, must prepare annual reports on progress towards the Kyoto and EU emission targets. Since 2021, these reports are part of the integrated reporting system of the Governance on the Energy Union and Climate Action Regulation (European Commission, 2023j). For these reports, the emission data received by Eurostat from the Member States are aggregated at Eurostat (Umwelt

Bundesamt, 2023). In accordance with the regulation (EUR-Lex, 2018c), the member states define the monitoring methods for GHG monitoring themselves. Although comparability is required, a scientific analysis is not published and would therefore be useful.

In addition, the tracking of the GHG status is made more difficult by the fact that different methods are used for emissions reporting in the subordinate administrative units within the Member States. Here, too, a scientific evaluation is lacking. In Germany, for example, no standard has been adopted for recording emissions in communities, but a method called BISKO (Bilanzierungs-Systematik Kommunal) is widely used and is recommended by the responsible authority UBA (Umwelt Bundesamt) (Umwelt Bundesamt, 2020). It records energy-based GHG emissions for the stationary and mobile sectors, but no non-energy GHG emissions. To analyze the data, the territorial principle (the location of the emission) and the polluter pays principle (who causes the emission) are combined and a "final energy-based territorial balance" is reported.

In practice, this means, for example, that emissions from the non-renewable portion of waste from a waste-to-energy plant are allocated to the power generation sector rather than to the sector of waste management, respectively the waste incineration plant. Nevertheless, waste-to-energy plant emissions (except from the share of biowaste) will be burdened with costs through the German Fuel Emissions Trading Act (Bundesministerium der Justiz, 2023) from 2024 onwards. Also in other EU member states emissions from waste incineration plants are to be measured and reported from 2024. The proportion of fossil and biogenic waste is assumed to be fixed although it varies considerably depending on local conditions. Unlike in Germany, however, fossil fuel emissions will be charged only later (Waste Management World, 2023). This example shows that neither the methodology for recording energy-related emissions nor the cost burden is uniformly standardised across all administrative levels at EU and national level.

3.7. Technologies, infrastructure, economics

3.7.1 Technologies

Numerous technologies for bioenergy (fuel, heat, electricity) are already established. A fundamental hurdle for broader implementation is the cost of energy production, which was reported at 3-30 EUR/GJ in 2015 (European Commission, 2015). In contrast, the market price for natural gas is currently 2 EUR/GJ (2022) (Trading Economics, 2023). Promising new technologies include biomethane from biogas upgrading, methanation of bio-based syngas, fast pyrolysis and thermo-catalytic reforming of drop-in fuels, lignocellulosic fuels and aquatic biomass to fuels (European Commission, 2022a; European Commission, 2022b; European Technology and Innovation Platform Bioenergy, 2023b). Carbon capture and utilisation (CCU) processes, which use biogenic CO_2 emissions from biotechnological manufacturing processes (e.g. bioethanol) or combustion (e.g. wood-fired cogeneration plants), should also be added.

For technology development to bioenergy, an important criterion is the Energy Return Ratio (ERR), which must be above 1 to avoid spending more energy on bioenergy production than can be used in the final product. For the ERR of bioenergy, no publicly available data could be researched within the scope of this work. However, an ERR >1 should not be an absolute exclusion criterion, because such energy carriers can serve as energy storage of surplus energies, e.g. from solar or wind power peaks. An example is the methanation of CO_2 according to the Sabatier reaction (Meylan et al., 2017).

An important driver for bioenergy is the reduction of CO_2 emissions from fossil sources. The fact that bioenergy also contribute to CO_2 mitigation has already been explained. Mandley et al. (2020) conclude that in order to achieve the climate targets by 2050, 55% of total EU bioenergy use needs to be coupled with carbon capture and storage (CCS). A legal framework for the safe geological storage of carbon dioxide has been adopted by the European Commission (European Commission, 2023k), but in practice so far only fossil-derived CO_2 emissions have been treated with CCS methods. The Global CCS Institute (2023) lists in Europe 2 operational and more than 100 CCS facilities (capture, storage, transport, or integrated ones) under development. The most recent example is the planned capture and geological storage of CO_2 emissions from power plants in Copenhagen, Denmark (State of Green, 2023). In the USA, on the other hand, the storage of biogenic CO_2 from ethanol fermentation plants is also being discussed (Great Plains Institute, 2020; Capturemap, 2023). In contrast to fossil-fueled power plants, bioenergy plants are generally comparatively small-scale, and are distributed over the area. How CCS methods need to be adapted to such plants has not yet been investigated in Europe.

3.7.2 Infrastructure

Compared to fossil feedstocks, bio-feedstocks have a lower energy density, are often seasonal and perishable. The raw materials for bioenergy therefore require a public infrastructure for logistics and storage that is tailored to them. Apart from local examples, no planning or at least preparatory studies are known to have been carried out either at the national level of the Member States or at the EU level. One example is Kalundborg (Denmark), where since 1972 nine private and public companies have been exploiting the synergies of their material flows for the production of bioenergy, among other things, and have developed an appropriate infrastructure for this purpose (European Circular Economy Stakeholder Platform; 2023).

For e-fuels based on biogenic CO2, the supply of hydrogen, or electricity for its production, is essential. In 2022, hydrogen was mainly used in the production of chemical products and fertilizers and accounted for less than 2% of the EU's energy consumption. Today, natural gas is with a share of 96% the dominant feedstock for hydrogen. By 2020, production capacity is expected to increase from 11.3 Mt (2020; without coke oven gas hydrogen (Clean Hydrogen Partnership, 2022)) to 30 Mt (2030) and 100 Mt by 2050. In 2050, hydrogen could cover

25% of gross final energy consumption (Seck et al., 2022). In contrast, the European Commission assumes a demand of only 10 Mt hydrogen by 2030. According to the EU strategy on hydrogen (COM/2020/301) (EUR-Lex, 2020), adopted in 2020, hydrogen is to be produced on the basis of renewable energies (European Commission, 2023l). Among other things, for this purpose, EU electricity generation is expected to grow from annually 13478 PJ (2020) to 14860 PJ (2030) and 17377 PJ in 2050. ETIP (European Technology and Innovation Platform Bioenergy, 2021) even assumes a capacity of 24480 PJ in 2050 (The European Technology and Innovation Platform on Wind Energy, 2022). In order to achieve targets of this magnitude, the EU needs a long-term, reliable expansion strategy for electricity generation and distribution.

3.7.3. Economics

Concerning production costs of bioenergy only estimates have been published; specific data are not publicly available. In 2015, Ruiz et al. stated costs for energy crops in the range of EUR 3-30 per GJ and Klein et al. (2014) published production costs of USD 6/GJ bioenergy. In comparison, the current costs for the fossil energy source oil are around USD 13/GJ (USD 72/barrel). In addition to the cost of raw materials, further cost factors must be taken into account for the processing of fossil and bioenergy sources, all of which are to the detriment of bioenergy. The energy density of plant material is lower than that of fossil energy sources (mineral oil 42 GJ/t; miscanthus, wood 18 GJ/t; rape seed 26 GJ/t) (Hakala et al., 2009), which entails higher costs for logistics and storage. Processing is also more complex. Natural gas and coal are utilised more or less directly by incineration and crude oil after refining to produce heat and electricity or fuel. Wood and straw can also be used directly in biomass cogeneration plants to generate heat and electricity, but fuels require comparatively complex processes of anaerobic (biogas) or aerobic (bioethanol) fermentation or transesterification (biodiesel). The lower density of plant-based raw materials in combination with costly harvesting of large areas also limit the catchment area and, thus, the capacity of biorefineries, which has a negative impact on the economy of scale. All these factors result in considerable competitive disadvantages concerning CAPEX and OPEX compared to fossil fuels. However, with the increasing internalisation of the environmental damage costs caused by fossil fuels through emissions trading (EU-ETS), the competitiveness of bio-energy can be expected to increase. In 2022, Abrell et al. (2024) analysed that the CO_2 price of the EU-ETS, which only affects big companies in the sectors of energy generation and energy-intensive industries, would have to be between 130 and 210 EUR/t CO_2e, or in the range of 175-350 EUR/t CO_2e for the sectors of road transport, buildings, agriculture, waste and small industries defined in the effort sharing directive (ESR) (EUR-Lex, 2018c), in order to establish competitiveness with conventional fossil fuels. This assumes that the EU-ETS acts as the only steering instrument. Since starting the EU-ETS in 2005 the price of emissions allowances has grown up to 100 EUR/t CO_2e in February 2023 (Statista, 2023b). The competitive threshold also depends on the cost development of raw materials for bioenergy, which in turn depends on the one hand on the annual harvest quality, and on the other on the development of the competing markets for food and feed as well as raw materials for material utilisation (IEA Bioenergy, 2023b).

4. Discussion

4.1 Future potential of bioenergy

The studies on the potential for bioenergy examined have shown that expectations have been lowered over time and the most recent studies expect a capacity for bioenergy in 2030 that corresponds to a share of 13% to 20% of today's primary energy demand. Including an overall higher energy demand in 2050, the bioenergy share should reach 18% according to the IEA roadmap "Net Zero Emissions by 2050" (IEA Bioenergy, 2022) and 27% according to Mandley (Mandley et al., 2020). Compared to the current share of bioenergy of around 10%, a significant increase is therefore to be expected, although bioenergy will not play a dominant role. Its contribution to reducing the EU's dependence on energy imports will therefore remain moderate. For the strategic expansion of bioenergy, meaningful data on raw materials, production capacities and GHG are needed (4.1.1) in order to develop a strategy for scale-up, including the necessary infrastructure (4.1.2) and supporting regulation (4.1.3). There is a considerable need for research into these issues (4.1.4)

4.1.1 Data

Key factors for the sustainable further development of European bioenergy are the availability of i) primary biomass, ii) secondary biomass, iii) energy for the production of e-fuel (CCU) and iv) performance measurement through the monitoring of indicators.

i) In order to assess and plan the potential for bioenergy in the EU, data is needed on the availability of land for the production of primary biomass, on residues and waste as energy sources and on electricity for CO_2-based e-fuels. However, data collection on land for the production of biomass for energy purposes suffers from a lack of differentiation, as the combined cultivation of crops for energy and other purposes is not sufficiently recorded. In addition to domestic production, increasing imports of primary biomass are expected (Wieruszewski & Mydlarz, 2022); however, data on the import potential of raw materials or ready-to-use biofuels that meet the EU's sustainability criteria is lacking.

ii) Secondary raw materials are biogenic residues from agriculture, forestry and the marine sector, industrial residues and municipal biowaste. Data on their availability in the EU is insufficient because the type of disposal cannot be traced for 30% of the biowaste recorded in Eurostat (Kircher et al., 2023). It is therefore unclear whether these considerable quantities are available as energy sources.

iii) For the expansion of e-fuels, data on suitable CO_2 point sources and the need for renewable energies for their production must be integrated into European energy planning. Such data could not be researched in the context of this study; it remains to be researched.

iv) Bioenergy is reported by Eurostat as part of renewable energies, but not differentiated by type of bioenergy (Eurostat, 2023f). This data gap must be filled. The use of biofuels, which can be used for both energy and material purposes, must be differentiated. For example, bioethanol can be used both as a fuel for transportation and as a platform chemical for chemical production. Furthermore, the evaluation of official reports on bioenergy is difficult because certain bioenergy are weighted according to political guidelines without this being stated transparently. The same applies to the GHG associated with bioenergy, which are not recorded today (EUR-Lex, 2018d). In the interests of a scientific analysis of bioenergy, its raw materials and its greenhouse gases, Eurostat should collect data differentiated by raw materials, type of bioenergy, its production and the GHG associated with production and use. The publication of unweighted primary data is essential.

4.1.2 Strategy

The up-scaling of bioenergy requires an adaptation of the infrastructure for the production, logistics, storage and processing of raw materials and the corresponding energy use at EU, national and regional level. The associated long-term technical, ecological, social and economic issues require scientific work to develop a viable strategy, as also called for by the G7 (G7 Hiroshima Summit, 2023). With regard to the time horizon, a long-term bioenergy strategy must extend beyond the period up to the targeted replacement of fossil energy sources, i.e. up to the achievement of climate neutrality in 2050. After that, greenhouse gas concentrations are to be reduced to pre-industrial levels in accordance with the Paris Climate Agreement. In this context, CCU and CCS will gain importance as sink for CO_2 from bioenergy (Mandley et al., 2022). A study that examines biogenic GHG emissions in full, i.e. with regard to the production of biomass, the energetic and material use of primary biomass, biogenic residues and waste, including the CO_2 sinks CCU and CCS, could not be found within the scope of this study. Such a study, which is needed for a long-term bioenergy strategy, should consider all bioenergies, namely heat (for industry, buildings, services), mobility (on land, shipping, aviation) and electricity:

Bio-heat is associated with the combustion of biomass and thus significant GHG emissions. In order to avoid their emission into the atmosphere, CCU and CCS come into question; the technical, ecological and economic requirements and effects of which must be included in strategic planning.

The demand for electricity is expected to grow strongly because renewable electricity, together with nuclear energy, will increasingly contribute to heat generation and mobility and an additional strong growth in demand for electricity in applications such as data processing and CCU is foreseeable. At the same time, bio-power is in direct cost competition with carbon-free alternatives such as wind, solar and nuclear energy. There is a need for research to assess the long-term competitiveness of bio-power.

With the expansion of electro-mobility on land, the EU is steering the market for bio-fuels in such a way that it is likely to decline. Liquefied bio-methane from biogas and hydrogen (fuel cells) could become more important for heavy goods vehicles and shipping (Deniz & Zincir, 2016). However, the aviation sector will remain dependent on carbon-based fuels with high energy density for the foreseeable future (IEA Bioenergy, 2021). The market for bio-based aviation fuels and CO_2-based e-fuels is therefore particularly attractive due to its growth potential (Deutsche Energie-Agentur, 2022).

The expansion of bioenergy requires the mobilisation of all sustainably available raw materials, taking into account the various uses (food and feed, material use). In the interest of food security, non-food biomass, especially biowaste, should be prioritised for bioenergy. According to the EC (2023m), however, "the only sensible treatment for biowaste is composting or anaerobic digestion". This definition excludes, for example, pyrolysis to bio-oil and gasification to synthesis gas and should be revised in line with the state of the art.

4.1.3 Control instruments

To control the development of biofuels, the EU uses quotas for bioenergy, the different weighting of individual bioenergy in reporting, the pricing of fossil GHG, and in GHG reporting the consideration of defined reduction measures for biogenic CO2 emissions. Overall, these regulations are very complex and it can be assumed that companies need expert knowledge in order to bring bioenergy to the market in accordance with the regulations.

In principle, the EU Emissions Trading System (EU ETS) has proven itself as an effective market-based instrument for the reduction of GHG (Dechezleprêtre et al. 2023). However, the EU ETS only prices GHG from fossil sources. Biogenic CO_2 emissions are not subject to EU-ETS. Although it would contribute to climate protection, thus, there is no incentive to delay these significant emissions into the atmosphere through CCU or to avoid them through CCS. Another requirement with an inhibiting effect is that only hydrogen produced with renewable energies is permitted for the utilisation of CO_2 through CCU (European Parliament, 2023c). In view of the limited availability of renewable electricity (37%, 2021) (Eurostat, 2023f), this will slow down the upscaling of CCU. Another hurdle for CCU technologies is Article 49 of EU Regulation 2018/2066 (EUR-Lex, 2018d), according to which geological storage of CO_2 (CCS) is taken into account in GHG reporting, but not the use of CO_2 by CCU. This means that a promising tool of minimising GHGs in the atmosphere is being foregone. Overall, there is a considerable need for research into an integrated climate protection policy that links the pricing of GHG through the EU ETS with incentives for the upscaling of sustainable bioenergy, CCU and CCS, as Midtown et al. (2022) and Midttun et al. (2022) propose for the Green Deal.

4.1.4 Need for research

In order to put the development of bioenergy in the EU on a scientifically sound footing, a considerable need for research has been addressed several times in this article. Finally, the lack of primary data, especially on biogenic GHG, and the need to investigate the potential of bioenergy in competition with all other uses of biomass, including CCU and CCS, should be emphasised.

Finally, it should be noted that in the interest of a proper discussion in politics, business, science and the public, the frequently used buzzword of decarbonisation of energy should only be used if carbon-free energy is actually used. Only recently, the Hiroshima Communiqué of the G7 heads of state and government (20 May 2023) called for decarbonisation through biofuels ((G7 Hiroshima Summit, 2023). The authors were probably not aware that this is a contradiction in terms.

Conclusion

In the EU today, bioenergy is significant with a share of 29% in the heat generation sector, but contributes less than 10% each to electricity generation and transport fuels. A significant increase is possible by 2030 and 2050. For reasons of sustainable land use, however, the increased extraction of primary biomass for energy purposes is limited. Potential is mainly offered by the more intensive use of biogenic residues and wastes and the import of biomass. Little discussed in the literature is the material utilization of biomass for chemical products, building and road construction. It is expected that options for material use will increasingly compete with biomass for energy purposes.

The contribution of bioenergy to the reduction of greenhouse gas emissions in the EU is unclear because complete data or data comparable over time are not available for such an analysis.

It was also found that some of the regulatory instruments hinder the environmentally sustainable expansion of bioenergy.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

The data is available upon request from the author.

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