Chapter

Feedstocks for Advanced Biofuels

Enrique Espí, Íñigo Ribas, Carlos Díaz and Óscar Sastrón

Abstract

Advanced (also known as second-generation and third-generation) biofuels must comply with sustainability criteria related to the feedstock used (not competing directly or indirectly with food or feed crops) and to their greenhouse gases emission reduction. These fuels must reach at least 0.2% of transport energy used in Europe in 2022, 1% in 2025, and 3.5% by 2030. In this chapter, sustainable feedstocks that could be used for producing advanced biofuels are reviewed: energy crops grown on marginal land; wastes and residues—agricultural, forestry, food, municipal solid waste, and other organic wastes and residues; and novel feedstocks—such as aquatic biomass (macroalgae and microalgae).

Keywords: advanced biofuels, energy crops, municipal waste, agricultural waste, forestry waste, biomass, algae

1. Rationale and regulation in Europe

The European Commission has recently published a document defining the European strategy to fight against climate change—A Clean Planet for all [1]. Recognizing that climate change represents threat to the planet, the Commission has set the goal, in accordance with the 2015 Paris Agreement, of keeping global warming below 2° above pre-industrial levels and pursuing efforts to limit it to 1.5° by 2050. Bioenergy is a key factor to achieve this goal, but reducing greenhouse gas emissions is not its only advantage: bioenergy can also contribute to energy security, create thousands of new jobs in Europe, especially in rural areas, and impulse the growing European bioeconomy, with synergies with other sectors, such as food, feed, bio-based materials, and chemicals.

Sustainable biofuels for transport, subject to the updated sustainability criteria currently proposed by the European Commission [2], are one important part of the bioenergy sector as they are easily deployable using existing transport infrastructure being the only near-term alternative to fossil fuels for some applications, such as marine or aviation fueling.

The Renewable Energy Directive (RED) [3], revised in 2018 (RED II) [2], the Fuel Quality Directive (FQD) [4], the "ILUC Directive" [5], and "the ILUC Commission Delegated Regulation" [6] define biofuel's sustainability criteria in the EU to ensure that they are produced in a sustainable and environmentally friendly manner. Current legislation requires a 7% cap on the contribution of conventional biofuels, including biofuels produced from energy crops to count toward the targets in 2020 and 2030. The RED II directive also sets as a binding minimum of 0.2% target for advanced biofuels by 2022 and 3.5% by 2030 (**Figure 1**). Finally, the directives harmonized the list of feedstocks (Annex IX) for the production of advanced biofuels across the EU. Those can be considered to count double (i.e., to

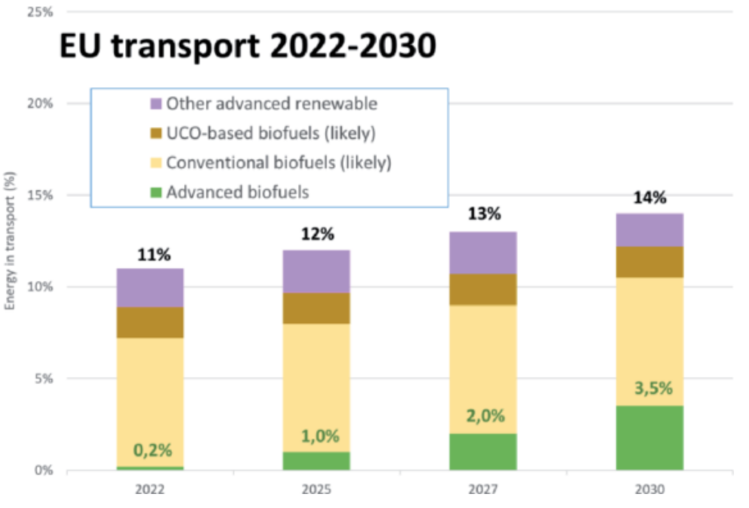

Figure 1.
RED II mandates about renewable energy in transport and contribution of advanced biofuels (Adapted from [7]).

be twice their energy content) in terms of their contribution toward the 2030 target of 14% for renewable energy in transport. If the advanced fuels are used for marine or aviation transport, their counting will be multiplied by 1.2. Some feedstocks such as Used Cooking Oil (UCO) and animal fats will be double counted but have specific cap of 1.7%. For liquid biofuels, the default GHG emission values and calculation rules are provided in Annex V. The greenhouse gas saving thresholds for biofuels in transport are 50% for plants with an operation start date before October 2015, 60% after October 2015, and will be 65% from January 2021.

EU points out that biofuel feedstock typically comes from cropland that was previously used for other agricultural uses such as growing food or feed. Since this agricultural production is still necessary, it may lead to the extension of agriculture land into noncropland, possibly including areas with high carbon stock such as forests, wetlands, and peatlands. This process is known as indirect land use change (ILUC). As this may cause the release of CO_2 stored in trees and soil, ILUC risks negating the greenhouse gas savings that result from the use of biofuels. To address this issue, RED II introduced a new approach, setting limits on high ILUC-risk biofuels, bioliquids, and biomass fuels with a significant expansion in land with high carbon stock. These limits will affect the amount of these fuels that member states can count toward their national targets when calculating the overall national share of renewables and the share of renewables in transport. Member states will still be able to use fuels covered by these limits, but they will not be able to include them when calculating the fulfillment level of their renewable targets. These limits consist of a freeze at 2019 levels for the period of 2021–2023, which will gradually decrease from the end of 2023 to zero by 2030. The directive also introduces an exemption from these limits for biofuels, bioliquids, and biomass fuels certified as low ILUC risk.

Just for comparing transport with other energy-consuming sectors, bioenergy accounts for approximately 12.3% of the gross energy consumed in Europe, almost double the weight of other renewable energies that represent 6.8% [8] (**Figure 2**), and is mainly used for the generation of heat, followed by the production of electricity and, in a minor extent, for transport fuels.

The weight of bioenergy in the European energy mix has been increasing in recent years (**Figure 3**) and must continue to grow in order to meet the objective set by the European Union, so the availability of raw materials that meet environmental, economic, and social sustainability criteria is a concern [10]. This chapter summarizes the situation of the feedstocks used, their future availability, and potential

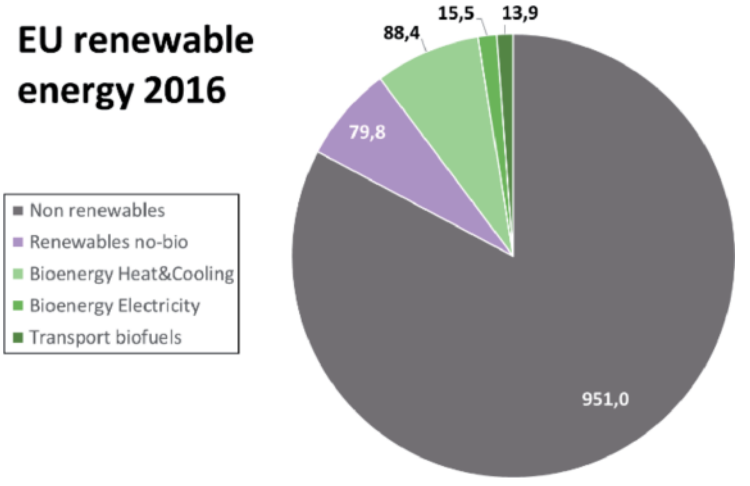

Figure 2.
Share of renewables in the EU's gross final energy consumption for 2016 (Mtoe/year) (Adapted from [8]).

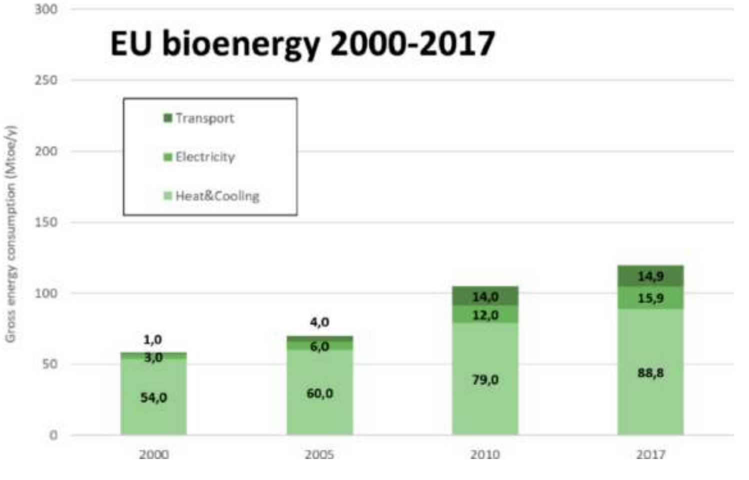

Figure 3.
Gross bioenergy consumption by markets 2000–2017 in EU28 (Mtoe/year) (Adapted from [9]).

supply according to the literature under different scenarios, with a special focus on aquatic biomass and some recommendations about the integration of the bioenergy sector with other bio-based industries to develop an integrated bioeconomy in Europe.

2. Advanced bioenergy and advanced biofuels

Biomass for electricity, heat, and cold (EHC) generation is used directly in solid form (wood, straw, etc.) or through intermediate energy carriers in solid form (pellets, chips, etc.), liquid form (bioliquids), or gas form (biogas). Although biogas can also be used as transport fuel, it undergoes a process of purification and reduction of impurities, then becoming biomethane. Solid fuels are sometimes treated to increase their energy density and storage stability through torrefaction or similar technologies, but minimizing changes needed in installed infrastructure.

In addition to applications for EHC, advanced bioenergy also includes advanced biofuels for transport. It is important to highlight that the objectives of advanced fuels for transport defined by RED II can not only be achieved through the use of advanced biofuels (produced from biomass) but also through other renewable fuels of nonbio origin, even from fossil carbon, if the energy needed to produce them is of renewable origin (**Figure 4**). All these options are clearly defined in the RED II [7] (**Table 1**).

2.1 Examples of advanced biofuels

Within the category of advanced biofuels for transport, a diverse range of products is included, depending on the feedstock used, the transformation process, and the application to which they are intended: road transport (diesel or gasoline engines), marine, or air transport (jet fuel). The most significant products are described below, some already available on a commercial scale and others with different degrees of development [11]:

- Hydrotreated vegetable oils (HVO)/hydroprocessed esters and fatty acids (HEFA) are chemically very similar to fossil diesel and kerosene. This fuel has

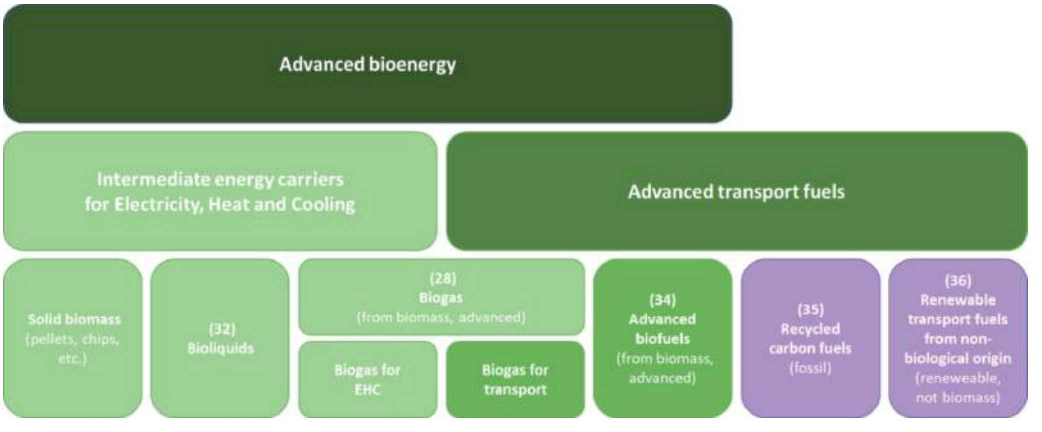

Figure 4.
Markets and products included in the advanced bioenergy definition (Adapted from [11]).

Some relevant definitions of RED II

(28) 'biogas' means gaseous fuels produced from biomass.
(32) 'bioliquids' means liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass.
(33) 'biofuels' means liquid fuel for transport produced from biomass.
(34) 'advanced biofuels' means biofuels that are produced from the feedstock listed in Part A of Annex IX.
(35) recycled carbon fuels means liquid and gaseous fuels that are produced from liquid or solid waste streams of nonrenewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations (GHG saving required for these fuels will be defined by the European Union before January 1, 2021.
(36) renewable liquid and gaseous transport fuels of non-biological origin means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass.

Table 1.
Some relevant definitions of RED II [7].

clear advantages over the ester-type biodiesel fuels, such as lower NO_x emission, deposit formation, storage stability, not degrading the engine oil and better cold properties. HVOs are paraffinic hydrocarbons that are free of aromatics and heteroatoms and have excellent combustion properties (high cetane number). They are also approved to use as aviation fuels. Currently, HVOs are widely produced from vegetable oils, and the technological challenge for the industry is to produce HVOs from sustainable feedstocks. A by-product of HVO production is bio-propane produced from glycerin hydrogenation and that can be used as BioLPG (liquid petroleum gases, such as butane and propane).

- Cellulosic ethanol is the most common advanced biofuels for Otto engines. It is produced by hydrolysis and fermentation of lignocellulose from agricultural wastes (straw, corn stover, bagasse, etc.), forestry waste (branches, etc.), organic fraction of municipal solid waste (OFMSW), or energy crops. The end product is identical to bioethanol produced from sugarcane or starch crops, and the technological challenge for the industry is to lower the production costs of lignocellulosic sugars. Ethanol can be blended with gasoline directly or used to produce ethyl-tertbutyl-ether (ETBE) that can also be used as gasoline component.

- FT liquids/biomass-to-liquid (BTL) fuels are produced also via gasification (syngas) but in this case followed by conditioning and fuel synthesis via Fischer-Tropsch or similar alternative processes. BTL fuels are used in diesel engines and aviation engines. An alternative to conventional gasification is the use of high temperature plasma gasification that can be applied to a wider range of feedstocks.

- Biomethanol can also be produced from syngas via a thermochemical route similar to the Fischer-Tropsch process for BTL. It can be directly blended with gasoline or used to produce methyl-tertbutyl ether (MTBE) or dimethylether (BioDME) via catalytic dehydration. BioDME can also be synthesized directly from syngas. In standard conditions, DME is a gas and can be used as transport fuel in a similar way to LPG.

- Biobutanol is an alcohol more compatible with existing fuel infrastructures and engines than ethanol. It can be produced also from lignocellulosic sugars with fermentation techniques. Currently, this route is under development, and the yield of sugars to butanol is not good enough to be economically competitive to ethanol. The technological challenge is to use advanced biotechnology to improve the bacterial butanol-producing strains.

- Other liquid advanced biofuels that are being developed are synthetic paraffinic fuel/hydrocarbons via chemical or biotechnological catalysis of plant sugars. **These routes** offer great potential for converting sustainable sugars into drop-in fuels, molecules that have similar properties to fossil gasoline or diesel.

- Biosynthetic natural gas (BioSNG) is produced by gasification of biomass, followed by a gas conditioning step, SNG synthesis, and gas upgrading. BioSNG can be used in a similar way to biomethane (biogas) produced biologically through anaerobic digestion and that also needs an upgrading step to reduce impurities to be used as transport fuel.

- Biohydrogen can potentially be produced from biomass via various routes and used as transport fuel, but the yield is low, and renewable hydrogen will more probably be produced through electrolysis of photoelectrolysis of water using renewable electricity. An indirect route to produce biohydrogen is steam reforming of biogas or BioSNG.

3. Feedstocks considered for advanced bioenergy

According to the European regulation, advanced bioenergy is produced from feedstocks not used as food or feed, that does not compete with food or feed crops for resources such as soil and water, and that has a minimum greenhouse gas emission saving when compared to fossil fuels.

Some examples of feedstocks used for the EHC market to produce solid fuels, bioliquids, or biogas for this sector are [12]: agricultural (straw, hay, etc.) and

Feedstocks listed in Anex IX of RED II

Part A. Feedstocks for the production of biogas for transport and advanced biofuels, the contribution of which towards the minimum shares referred to in the first and fourth subparagraphs of Article 25(1) may be considered to be twice their energy content:

(a) Algae if cultivated on land in ponds or photobioreactors;
(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC
(c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive
(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex
(e) Straw
(f) Animal manure and sewage sludge
(g) Palm oil mill effluent and empty palm fruit bunches
(h) Tall oil pitch
(i) Crude glycerine
(j) Bagasse
(k) Grape marcs and wine lees
(l) Nut shells
(m) Husks
(n) Cobs cleaned of kernels of corn
(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, precommercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil
(p) Other non-food cellulosic material
(q) Other ligno-cellulosic material except saw logs and veneer logs.

Part B. Feedstocks for the production of biofuels and biogas for transport, the contribution of which towards the minimum share established in the first subparagraph of Article 25(1) shall be limited and may be considered to be twice their energy content:

(a) Used cooking oil;
(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009.

Table 2.
Feedstocks listed in the Annex IX of RED II for the production of biogas for transport and advanced biofuels [7].

animal residues (manure), forestry residues, natural conservation matter (urban maintenance of green areas, hay, and shrubs), roadside vegetation, and waste (urban, industrial, biodegradable municipal waste, selected waste from the food and wood industry). None of them is biomass that can be used for food and feed, and their GHG savings are high enough to be considered as advanced.

The situation in the transport sector is different, since most feedstocks used today for conventional biofuels are mostly cereals, sugar, and oil crops used in the food and feed sectors. For this reason, EU legislation clearly defines advanced biofuels by the feedstock used, listed in the Annex IX of the RED-II (**Table 2**) and the GHG savings produced, directly and considering also indirect effects (ILUC).

4. Feedstocks used today in Europe

According to the EurObserv'ER, total primary bioenergy consumption of the EU28 was 99.8 Mtoe of solid biomass in 2017 [12] and 17.0 Mtoe of biofuels in 2018 [13] (last data published). According to the European Bioenergy Day website [9], biomass mobilized in Europe to produce energy accounted for **144.1 Mtoe** in 2017, an amount that is near to overpass the European production of coal. Approximately 70% comes from forestry resources, 18% from agriculture, and 12% from wastes (**Figure 5**). Aquatic biomass (algae) used for bioenergy is currently irrelevant.

Approximately **two thirds** of the biomass consumed in Europe is solid biomass for the EHC market, being mostly forestry residues and agricultural by-products: wood from silviculture, waste wood, short rotation coppice, agricultural waste, and so on. Biogas and biofuels represent **11.7** and **1.4%**, respectively, of gross inland energy consumption of biomass. Finally, renewable municipal waste used directly for energy production is the fourth type of biomass for energy reaching **7.3%** in 2017 [14].

4.1 Feedstocks for the EHC market

Wood has always been the most popular source of biomass of energy in Europe. The residential sector is the main user of wood (**27%**) but is closely followed by the industrial use of wood chips (installations above 1 MW (**22%**)) and small-scale use of wood chips (**14%**). Pellet consumption in modern appliances is also growing, representing **6%** of total EU wood energy consumption. Historically, the European bioenergy sector developed in close synergy with other wood user industries to use

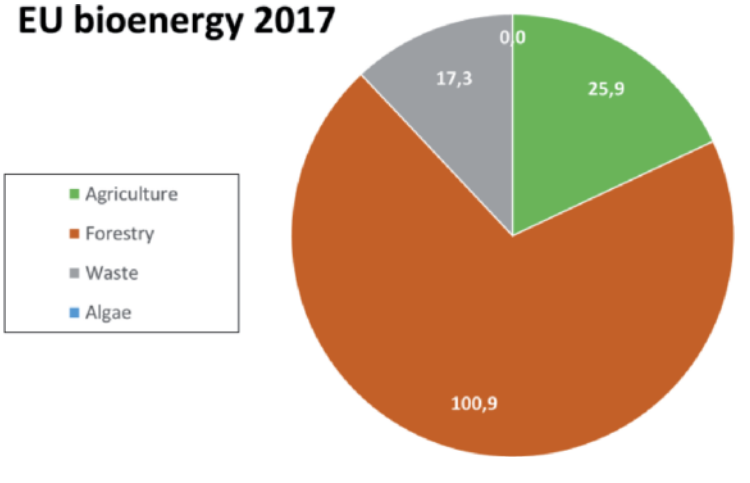

Figure 5.
Distribution of the biomass used for bioenergy in Europe in 2017 (Mtoe/year) (Adapted from [9]).

low value biomass such as thinnings, low-quality wood, tops and limbs, sawdust, or woodchips. In fact, bioenergy providers do not use any type of wood but mainly mobilize by-products of forest management operations and the wood industry.

In 2015, total amount of **245.2 million tons** of municipal waste was treated in Europe, of which **27%** (**67 million tons, mostly in Northern countries**) went to 492 waste-to-energy (incinerator) plants still remaining behind recycling (**30%**) and landfill (**24%**).

The European biogas sector is very diverse, depending on national priorities. In some countries, biogas production is seen as a waste management option, a renewable energy technology, or a combination of the two, countries have adapted their policies to favor certain feedstocks over others. Two countries represent the two ends of the scale: Germany and the UK. Germany produces **92%** of its biogas from agricultural crops and wastes, while in the UK, landfill and sewage sludge gas account for nearly 60% of the biogas production. Taking the EU28 big picture, field crops, manure, and agri-food industry waste represent around **75%** of the biomass used for biogas production, a share that **tripled** since 2010. Sewage sludge and landfills represent the **last 25%**. It is important to point out that although biogas is mainly used for the EHC market, its use as biomethane for the transport sector is increasing and should be taken into account in the future.

4.2 Feedstocks for the transport market

Today, the European biofuel sector is based on the use of bioethanol and biodiesel, which do not use the same feedstocks [15].

According to ePURE [16], the required feedstock for the 2018 production of ethanol (**5.81 Ml** of bioethanol) was mainly conventional not advanced (**11.11 Mt** of cereals, **2.07 Mt of sugar equivalent, mainly from sugar beets) and only 0.39 Mt of advanced (lignocellulosic and other listed in RED II Annex IX) (Figure 6).** This means that only about **2.9**% of the European cereal production and about **7.0**% of the sugar beet production are used to produce energy. Bioethanol production provides European farmers with **€6.6** billion income per year, and biofuels and food production can be mutually supportive, since **5.55** Mt. of co-products were produced in 2017 for nonenergy sectors, of which **4.20** Mt. was animal feed. Wheat is mainly used in northern Europe, while corn is used in Central Europe and Spain, and sugar beet users include France, Germany, and Belgium.

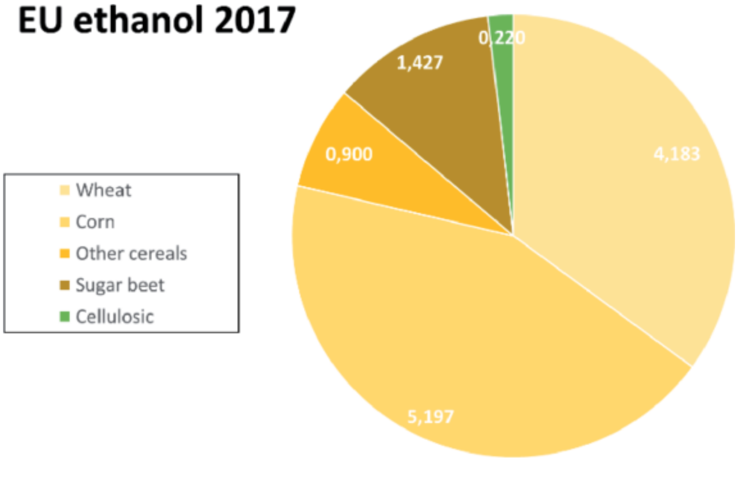

Figure 6.
Feedstock used for bioethanol production in Europe in 2017 (Mt/year, for sugar beet in Mt. sugar equivalent/ year) (Adapted from [16]).

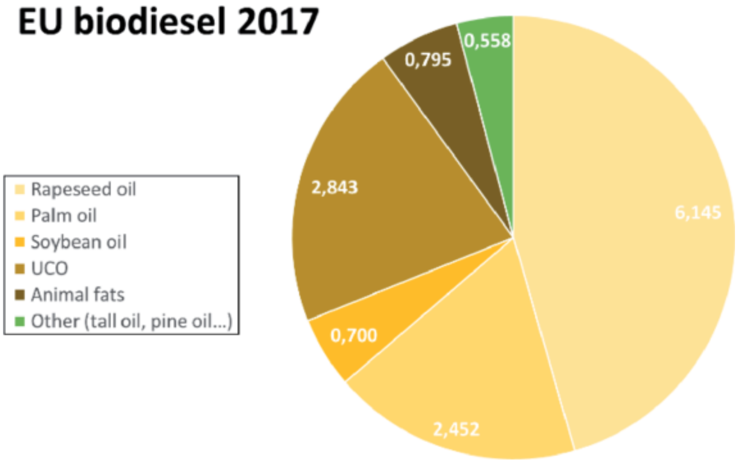

Figure 7.
Feedstock used for biodiesel production in Europe in 2017 (Mt/year) (Adapted from [15]).

Biodiesel's most used feedstock is rapeseed oil, accounting for **44%** of total production in 2017, according to Bioenergy Europe [15] (**Figure 7**). This is changing, mostly due to the higher use of palm oil and recycled vegetable oil/used cooking oil (UCO). In fact, UCO has become the second-most important feedstock in some countries such as the Netherlands, the UK, and Germany.

5. Future feedstock availability

The target of RED-II for advanced biofuels is to provide 3.5% of transport energy by 2030, multiple counting included. In the light of this ambitious target, and of the restrictions regarding raw materials that can be used, in recent years, different agencies and organizations have carried out studies to predict both the use and the expected and potential availability of raw materials in the short (2020), medium (2030), and long (2050) terms.

In a report for the European Commission, PriceWaterhouseCoopers and the EEV consortium [17] estimated the bioenergy demand per sector (**Figure 8**) and the feedstock supply to fulfill this demand (**Figure 9**) in 2030 in a scenario called Green-X EUCO27. The underlying policy concept of Green-X EUCO27 is to follow a least-cost approach for incentivizing the renewable requirements for 2030. The estimated demand of bioenergy in 2030 is 146.4 Mtoe/year (18.7 of them for transport), 36% more than in 2014. This demand will be fulfilled with 179.6 Mtoe/year of domestic biomass (plus 15.9 Mtoe/year of imported biomass and biofuels), 57% coming from forestry resources, 30% from agriculture, and 13% from waste and residues.

Regarding to the domestically available potential for biomass for energy, Bioenergy Europe based on literature review [14] calculated it to be between 169 and 737 Mtoe/year from 2050 onward (**Figure 10**). The middle range potential of 406 Mtoe, which is around 24% of the total energy consumption in EU28 in 2017, could be achieved by 2050—considering different constraints (e.g., costs). This means that, compared to the actual 144 Mtoe used in 2017, the potential gives enough room to almost triple the amount of bioenergy in the EU28 energy mix, with most resources coming from the agricultural sector.

Other review, coordinated by Ecorys for the European Commission [18], estimated the domestic biomass supply potential to be 562 Mt. dry mater/year in 2030 and 638 Mtdm/year in 2050 (under the reference scenario) and 700 Mtdm/year

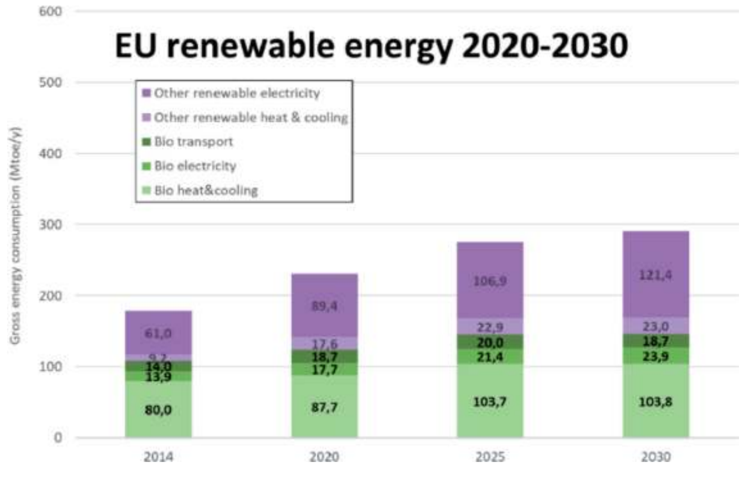

Figure 8.
Bioenergy and other renewable energy demand 2020–2030 in the Green-X EUCO27 scenario (Adapted from [17]).

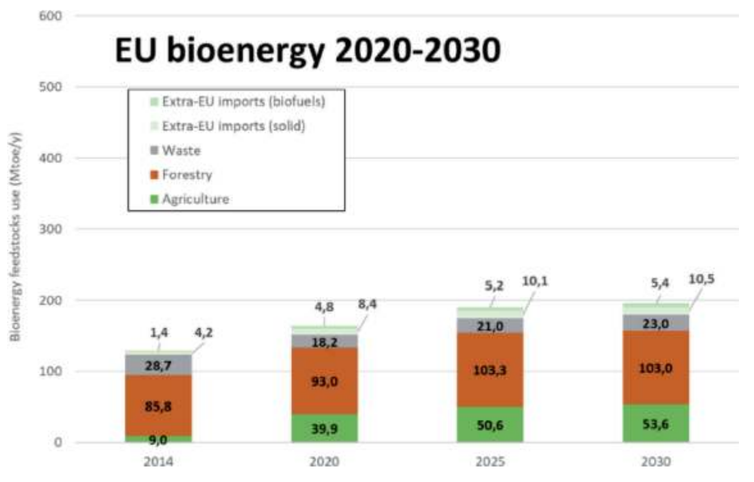

Figure 9.
Bioenergy feedstock supply 2020–2030 in the Green-X EUCO27 scenario (Adapted from [17]).

in 2030 and 1101 Mtdm/year in 2050 (under the high R&I scenario that boosts the potential of aquatic biomass) (**Figure 11**). These figures are slightly less optimistic than those of Bioenergy Europe, considering a conversion factor of 50% between tons of dry matter and tons of oil equivalent, but enough to triple the current bioenergy demand.

Some other references, such as ICCT, are not so optimistic about the biomass supply and express some doubts about the feasibility of decarbonizing all sectors together [19, 20].

In any case, the geographical distribution of the European potential biomass supply in 2030 is very different when it comes to agricultural, forestry, or waste origin, as described by the PWC study [17] and this something to consider when developing policies at a local level (**Figure 12**). Germany leads to the forestry potential, Spain to agricultural biomass, and the UK to biomass coming from wastes and residues.

Some other studies focus on the biomass availability predicted specifically for the advanced biofuel production, with the restricted criteria described in RED II. A study of the Arup URS consortium [21] provides a holistic analysis of the 28 feedstocks included in RED II Annex IX regarding the supply potentials, technology

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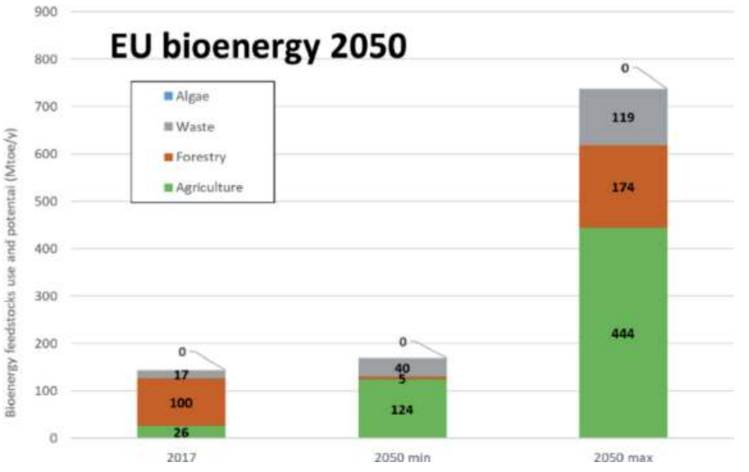

Figure 10.
Bioenergy feedstock potential 2050 in the EU28 MIN and MAX scenarios (Adapted from [14]).

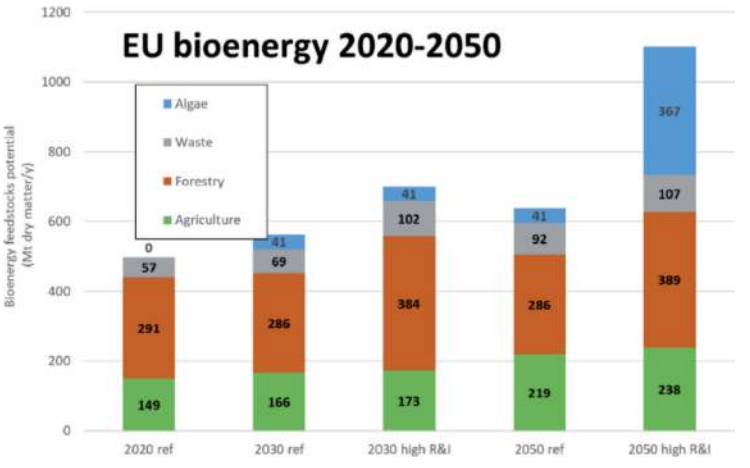

Figure 11.
Estimated potential biomass available 2020–2030–2050 in the EU in the reference and High R&I scenarios (Adapted from [18]).

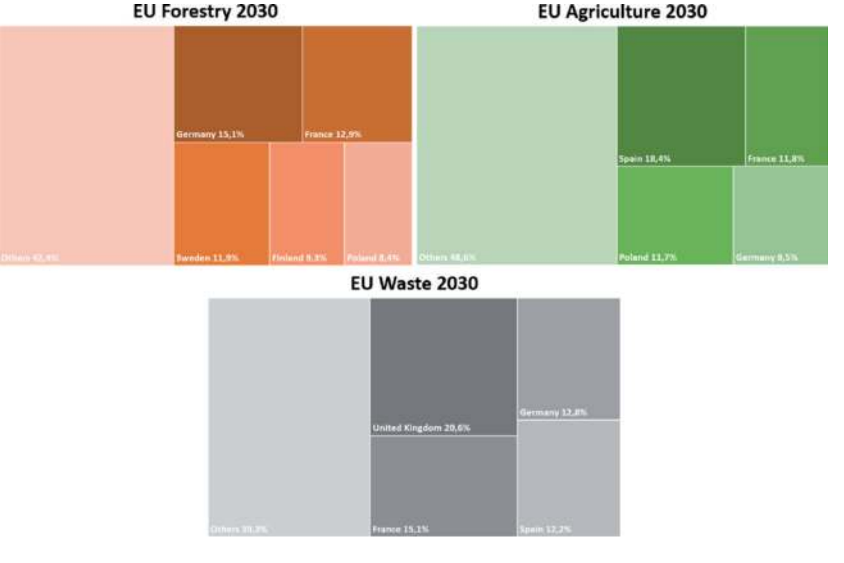

Figure 12.
Distribution of the European biomass potential per country in 2030 for different feedstock origins: forestry (above), agriculture (middle), and wastes (below) (Adapted from [14]).

compatibility, economics, and sustainability (**Figure 13**). According to this study, the potential feedstock supply for advanced biofuels in Europe is around 130 Mtoe/year in the short term (2020). The main conclusions of the study can be summarized as follows:

- **Availability**: municipal and industrial wastes, straw, manures, forestry, and renewable electricity have the largest supply potentials. Wine residues, tall oil pitch, and crude glycerin are most limited. Energy crops, short rotation forestry, and algae will also be in short supply by 2020 but have potential in the long term.

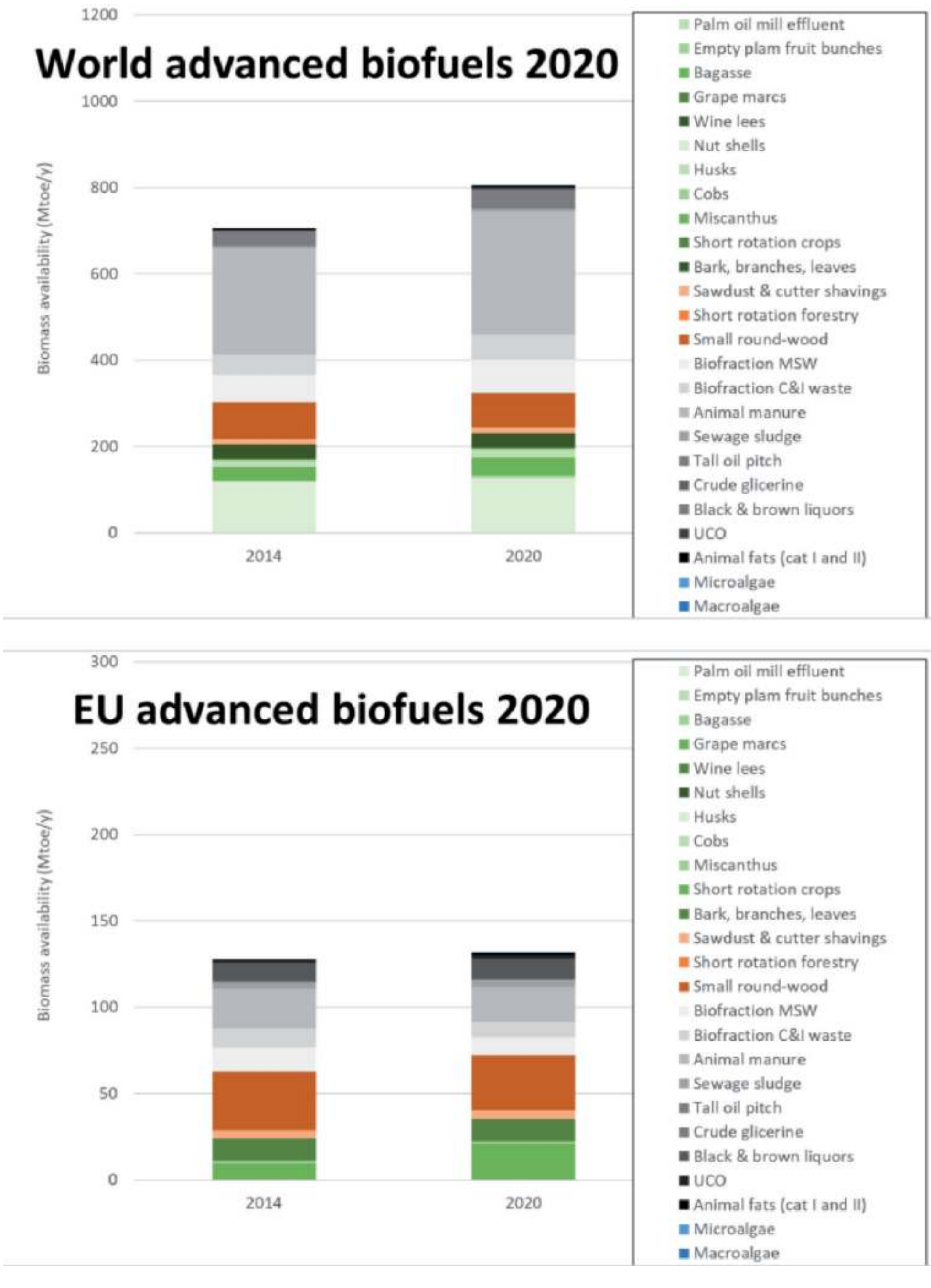

Figure 13.
Global 2020 feedstock supply potential for advanced biofuel production worldwide (above) and in the EU (below) (Adapted from [21]).

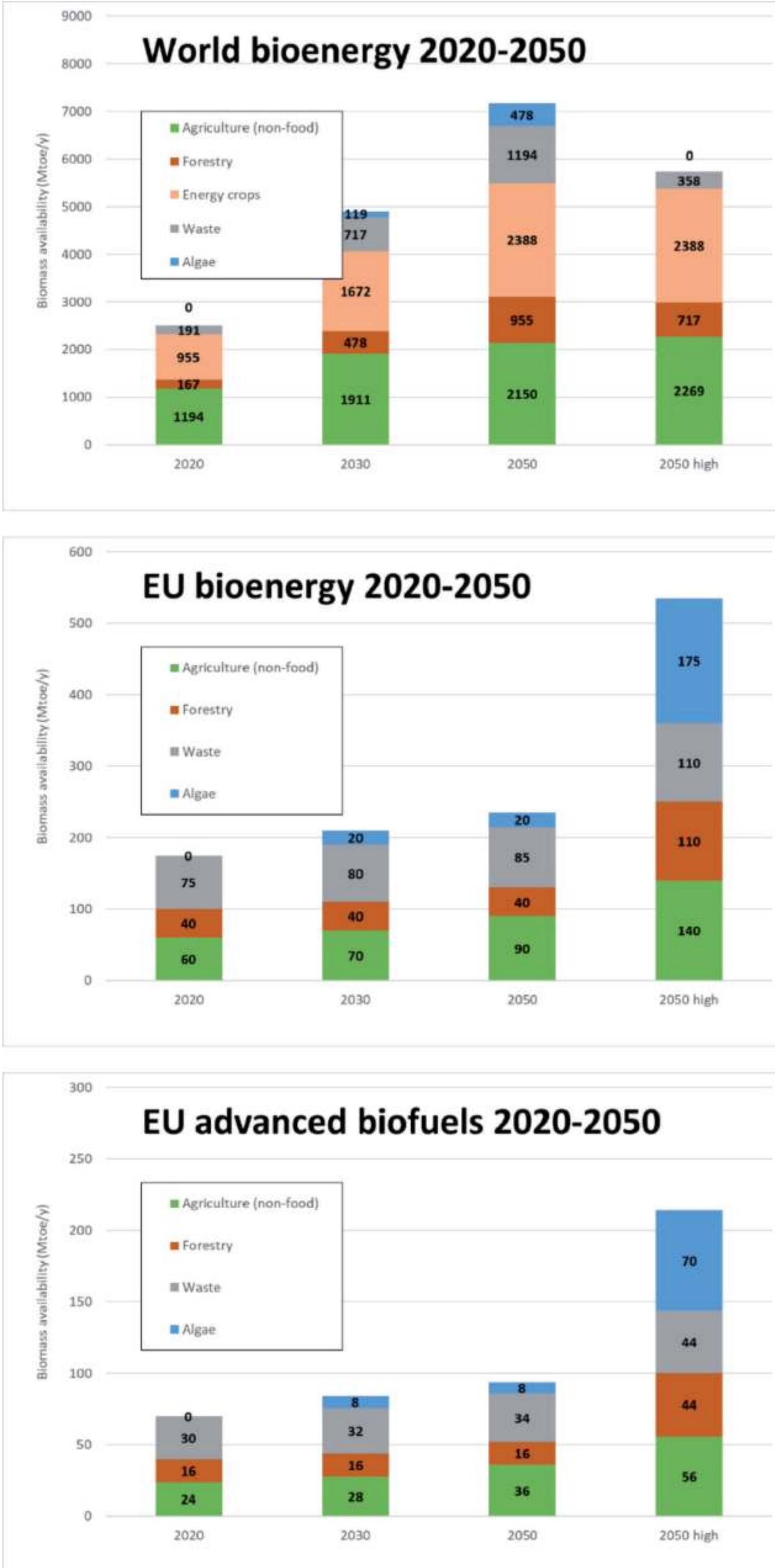

Figure 14.
Maximum biomass availability 2020–2030–2050 worldwide (above), in EU (middle), and in EU for transport (below) according to the IRENA (2020, 2030, and 2050) and IEA (2050 high) scenarios (Adapted from [22]).

- **Technology**: Many production technologies are still at pilot, demo or pre-commercial scale, including lignocellulosic ethanol and butanol, pyrolysis oil upgrading, gasification routes to alcohols, bio-Synthetic Natural Gas, Fischer-Tropsch diesel & jet, hydrothermal liquefaction (HTL), and renewable electrolysis. Some other technologies are commercially available but are only compatible with some of the Annex IX feedstocks.

- **GHG savings**: most feedstocks and routes are able to achieve GHG savings above 80%, but routes using MSW, C and I waste, bagasse, wine lees, algae, and waste carbon gases are more likely to fall into the 60–80% bracket, due to cultivation and transportation emissions and chemical and energy inputs.

Also with a focus on the transport sector, Concawe has also completed a literature review of the long-term availability of low-carbon feedstocks and fuels and the associated costs [22], describing scenarios for 2030 and 2050 in Europe and worldwide, based on IEA [23, 24], IRENA [25, 26], and other reports and reviews. When considering the availability of sustainable biomass in Europe, it should be noted that the whole of the bioenergy potential is estimated to grow from 175 Mtoe/year (2020) to approximately 350–535 Mtoe/year by 2050 (**Figure 14**).

According to the SGAB [27], the production of feedstock in Europe will be lower by 2050 and could range from 210 to 320 Mtoe/year (the majority coming from the waste sector). It is assumed that most of the biomass used in the EU economy will be produced within Europe (imports of sustainable solid biomass will be limited to 4–6% of the solid biomass used for bioenergy by 2050). For the transport sector, different sources estimate that the biomass contribution could range from 70 Mtoe/year (2020) to 140–210 Mtoe/year (2050). In terms of energy content, agricultural residues and wastes are expected to contribute the most, followed by forestry residues and algae.

World sustainable biomass availability is generally expected to increase continuously from a total of 2500 Mtoe/year by 2020 to 5700–7000 Mtoe/year by 2050 in the max scenario mainly based on agricultural residues and energy plants (>70%). The IEA 2050+ scenario forecasts a lower potential availability as defined by IRENA in their 2050 base scenario, with the main difference being the envisaged potential for algae. Indeed, the potential of algae is uncertain, and while several sources recognize its role in the 2050 scenario, other sources are more conservative and do not consider that there will be any relevant contribution before 2050. This point will be discussed later.

An interesting specific study highlights the potential of waste resources, "Waste—Europe's untapped resource" [28], and states that if all waste and residues were converted only to biofuels in the EU, 16% of road transport fuel could be provided in 2030 (technical potential of sustainably available feedstock from waste).

6. Algal biomass availability in Europe

Aquatic biomass, mainly macro and microalgae, is one of the most controversial feedstocks for advanced biofuels. It has attracted great interest in the recent years, as it does not compete with food crops for land use, does not need freshwater, and can absorb a great amount of carbon dioxide, and its productivity per hectare is much higher than any terrestrial crop [29, 30]. Some studies are optimistic about its weight in the future global biomass availability, but many others think that its techno-economic maturity is and will be far from being competitive for the bioenergy sector and that economics call for higher-value products, such as cosmetics, pigments, food supplements, proteins, and additives.

As with many technologies at currently low TRL, a lot of uncertainty surrounds the potential evolution of production costs for aquatic biomass. A qualitative analysis carried out [18] revealed that the technical potential of aquatic biomass produced domestically in the EU is significant but is quite limited due to the expected production costs. However, the level of uncertainty behind those figures is important; hence, a sensitivity analysis was conducted in order to assess the contribution of algae in the bioenergy mix depending on the production costs (**Figure 15**).

Another detailed study [31] based on a GIS model showed that algal biomass potential is limited by the limited availability of marginal land in densely populated Europe and by the slope of many of these areas or their status as protected areas. A general result was that about 50 Mt. dry matter microalgal biomass could be produced annually in Europe. This figure is in line with the 2030–2050 projections of IRENA (20 Mtoe/year) but far from the very optimistic IEA 2050+ scenario (175 Mtoe/year). The by far largest part would come from Spain (34 Mt/year), but countries such as Sweden, Italy, and Portugal also show considerable potential (**Figure 16**).

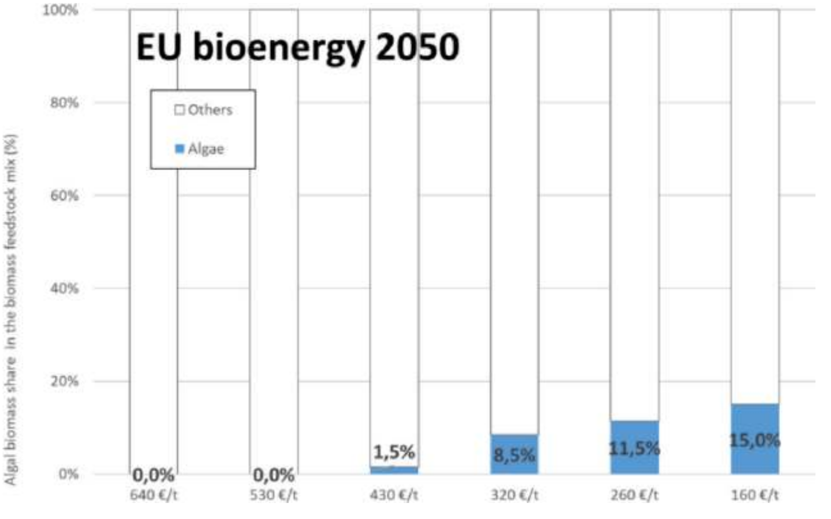

Figure 15.
Share of aquatic biomass penetration in the biomass feedstock mix 2050 under different productions costs for microalgae (Adapted from [18]).

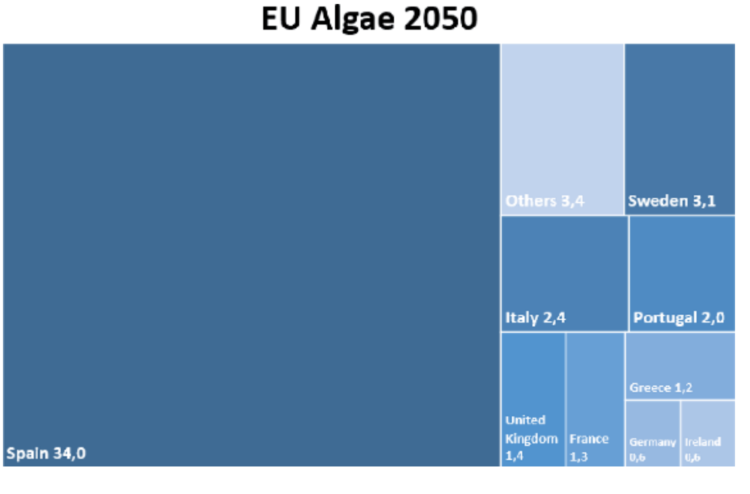

Figure 16.
Maximum microalgae biomass resource potential per country in EU (Mt dry biomass per year) (Adapted from [31]).

7. Developing an integrated bioeconomy in Europe

A recent study about the distribution of biorefineries in Europe [32] shows a total of 803 biorefineries identified. Only 177 of them (22%) are biorefineries in which integrated production of bio-based products (chemicals and/or composites) and bio-based energy (biofuels and/or other types of energy from biomass) is taking place, and that thus reflects the strictest definition of biorefinery. A certain degree of correspondence between the location of biorefineries and the locations of ports and of chemical clusters in the EU can be observed. The highest density of biorefineries is in Belgium, the Netherlands, and some highly industrialized regions of Germany, France, and Italy. The lower number of biorefineries in the Eastern part of the EU demonstrates an untapped potential. Worldwide mapping on the advanced biofuel production facilities is done by IEA Bioenergy Task 39 in its online database [33].

The sustainable supply of biomass for the energy sector passes in the medium term through the organization, coordination, and integration with the different sectors interested in available biomass resources. This includes both the productive sectors (agricultural, forestry, and waste management) and users (food, bio-based materials, and chemicals), so that supply chains and value chains are optimized, leading to an integrated economic sector based on the bioeconomy. The balanced distribution of available resources and the criteria or tools for decision making have been reviewed in different studies by FAO and others [34–36]. The EU is also responding to such an ambitious challenge by funding different projects aiming to develop, scale up, and deploy new technologies and value chains from an integrated approach [37]. Some of these projects are listed in **Table 3**, and the key R&D lines to boost bioeconomy are listed in **Table 4**.

Project acronym	Feedstock	Coordinating country	Years
PROMINENT	Cereal processing side streams	Finland	2015-18
VALCHEM	Woody feedstock	Finland	2015-19
US4GREENCHEM	Lignocellulosic feedstock	Germany	2015-19
FIRST2RUN	Cardoon from marginal lands	Italy	2015-19
PULP2VALUE	Sugarbeet pulp	Netherlands	2015-19
SMARTLI	Karft lignin lignosulphonates	Finland	2015-19
STAR4BBI	Lignocell. agri and forest residues	Netherlands	2016-19
BIORESCUE	Wheat straw and agricultural waste	Spain	2016-20
AGRIMAX	Agri and food waste	Spain	2016-20
GREENSOIREX	Lignocellulosic residues	Netherlands	2016-20
GRRENPROTEIN	Veg residues from salad processing	Netherlands	2016-20
ZELCOR	Lignocellulosic residues	France	2016-20
FUNGUSCHAIN	Mushrooms farming residues	Netherlands	2016-20
LIBBIO	Andes lupin from marginal lands	Iceland	2016-20
BIOSKOH	Lignocellulosic feedstock	Italy	2016-22
LIGNOFLAG	Straw	Germany	2017-20
BARBARA	Agri and food waste	Spain	2017-20
SYLEED	Wood residues	France	2017-20
POLYBIOSKIN	Food waste	Spain	2017-20
OPTISOCHEM	Residual wheat straw	France	2017-21
4REFINERY	Biomass, wastes	Norway	2017-21
DENDROMASS4EUROPE	Dendromass on marginal lands	Germany	2017-22
GRACE	Miscanthus, hemp on marginal lands	Germany	2017-22
AGRICHEMWEY	Byproducts from dairy processing	Ireland	2018-21

Table 3.
Some projects recently funded by EU to develop a bioeconomy based on advanced biomass feedstocks (Adapted from [37]).

Biomass from agriculture

Improving biomass cultivation (cropping)
- Food and energy crops breeding
- Agricultural practices improving
- Crop rotation and inter-cropping application
- Agroforestry and short-rotation crops development
- Marginal land for energy crops development

Improving biomass harvesting

Improving biomass pretreatment and densification

Improving biomass supply chain
- Biomass mobilisation optimisation
- Agricultural biomass logistics optimisation
- Agricultural biomass supply chain optimisation
- Technology transfer enhancement

Biomass from forestry

Improving forest biomass production
- Breeding of genetically improved plant material
- Fertilisation improvement
- Silviculture impriving

Improving forest biomass production
- Breeding of genetically improved plant material
- Fertilisation improvement
- Silviculture impriving

Improving biomass suply chain
- Biomass mobilisation optimisation
- Forestry biomass logistics optimisation
- Forestry biomass suplly chain optimisation

Biomass from waste

Optimising supply chain
- Source-separated biowaste collection and use
- Mechanically-separated biowaste collection and use
- Landfilled biowaste use
- Use of UCO, woodwaste, vegetal waste, paper and cardboard waste, textile waste, sewage sludge

Aquatic (algae) biomass

Improving microalgae cultivation systems and productivity
- Cultivation in open ponds
- Cultivation in photoreactors

Improving macroalgae cultivation systems and productivity
- Wild cultivation
- Aquafarms (mariculture)

Improving micro and macroalgae harvesting, and dewatering

Improving microalgae lipids extraction

Improving microalgae lipid-to-fuel conversion technologies

Improving micro and macroalgae GHG balance

Table 4.
Priority R&D lines to develop a sustainable biomass supply for and integrated bioeconomy in Europe (Adapted from [18, 24, 26]).

8. Conclusions

Advanced biofuels can be a key factor to a sustainable energy supply for transport, contributing to energy security, fight against climate change, and development of rural areas. However, Europe has to overcome some barriers in order to develop their full potential.

First, a stable demand is needed to establish a market and boost development, with production levels sufficient to achieve economies of scale. Current reasons that slow uptake are high barriers to entry, including long investment cycles, the capital-intensive nature, high fuel certification standards, and high production costs compared to fossil fuels and conventional biofuels. To overcome some of these barriers, the key points to consider can be summarized as follows:

- guarantying sustainable feedstock availability, minimizing supply chain risks, and mobilizing currently unexploited sustainable waste, biomass, and other resources;
- facilitating agricultural and forestry development of energy crops with higher productivity with low chemicals and energy input and using marginal land that does not compete directly with or displace land used for food crops;
- supporting the development of low-TRL technologies to produce advanced biofuels, increasing their efficiency, and of high-TRL technologies to deploy, reducing costs, and complying with GHG emissions goals;
- more specifically, supporting the development of technologies necessary to adapt advanced feedstocks into existing industrial processes (pretreatments);
- integrating the biofuels industry in a European bioeconomy system to take advantage of the opportunities both economies of scale and the use of existing infrastructure;
- recognizing of the role of advanced biofuels in transport, through a holistic approach across the whole well-to-wheels or even life-cycle value chain with a particular emphasis on the application of the principles of a circular economy.

Conflict of interest

The authors declare no conflict of interest.

Author details

Enrique Espí*, Íñigo Ribas, Carlos Díaz and Óscar Sastrón
Repsol SA, Madrid, Spain

*Address all correspondence to: eespig@repsol.com

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