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Review

Economic Trends in the Transition into a Circular Bioeconomy

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Abstract: The shift away from fossil fuels needed to reduce CO_2 emissions requires the use of renewable carbon and energy sources, including biomass in the bioeconomy. Already today, the bioeconomy has a significant share in the EU economy with traditionally bio-based sectors. For the future, the energy, mobility and chemical sectors have additional high expectations of the bioeconomy, especially for agriculture and forestry to produce biomass as an industrial feedstock. Numerous studies have been published on the availability of feedstocks, but these often only look at individual applications. Looking at the total demand and considering the sustainability limits of biomass production leads to the conclusion that the expected demand for all industries that could process biomass exceeds the sustainably available capacity. To mitigate this conflict between feedstock demand and availability, it is proposed that the organic chemical sector be fully integrated into the bioeconomy and the energy sector be only partially integrated. In addition, recycling of wastes and residues including CO_2 should lead to a circular bioeconomy. The purpose of this manuscript is to help fill the research gap of quantitatively assessing the demand and supply of biomass, to derive economic trends for the current transition phase, and to further develop the theoretical concept of the bioeconomy towards circularity.

Keywords: bioeconomy; biomass; residuals; waste; agriculture; forestry; chemical industry; energy sector; bio-energies; bio-fuel

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1. Introduction

All international framework policy agreements on climate protection, such as the Paris Climate Agreement (UN 2015) and most recently the Glasgow Agreement in November 2021 (UN 2021), call for the reduction of greenhouse gas (GHG) emissions and thus inevitably the reduction of fossil fuel consumption. The same applies to the European Green Deal (EC 2019) and the declaration "Stepping up Europe's 2030 Climate Ambition" (EC 2020c). Today, this is the most important driver for the concept of the bioeconomy, which is based on renewable raw materials and energies (Knudsen et al. 2015). Building on this, strategies for transformation to a bioeconomy were published early in the century in Europe (EC 2006), the United States (White House 2012), and other countries (Birner 2018). These early strategies were primarily technology-driven. Keywords were "biotechnology applications in primary production, health, and industry" (OECD 2009) and "transforming life sciences knowledge into new, sustainable, eco-efficient and competitive products" (Aguilar et al. 2010). Initially, edible raw materials such as starch and sugar available on the market found industrial applications, but with the increasing discussion about competition with food (food/fuel conflict) non-edible raw materials and bio-resources as a whole came increasingly into focus. Today, the idea of closing material cycles, including that of carbon, is coming to the fore, and processing byproducts such as CO_2 and waste are increasingly being identified as promising carbon sources (Kircher 2018).

In principle, all industries that use carbon today can process renewable carbon sources instead of fossil ones. Such raw materials are provided by agriculture and forestry as well as fisheries and aquaculture, and are processed by the traditionally bio-based sectors food and feed, the wood processing industry including biogenic construction materials, cellulose and paper, and biogenic fibers (cotton, wool). In addition, there are the hitherto almost exclusively fossil-based industries of energies (fuels, heat, electricity) and organic chemistry. A detailed overview of the industries assigned to the bioeconomy according to the Statistical Classification of Economic Activities in the European Community (NACE) is given by Kardung et al. (2021) The feedstock demand of these industries for carbon and energy sources is a real challenge as the global economy consumes twice as much fossil carbon as is fixed in agricultural and forestry biomass. This article explores the extent to which future demand for biogenic carbon and energy sources can be met in a sustainable manner, whether prioritizing certain applications is necessary and possible, and how recycling can reduce the need for primary raw materials.

The article first presents the status of the European bioeconomy, the current production volume of biogenic carbon and energy sources and their consumption in the various industries. It then analyzes future demand and options for expanding supply or increasing feedstock efficiency. Finally, the paper examines how the current economic policy framework in Europe supports the development of the circular bioeconomy, or how it should be further developed.

2. Methods

For the evaluation of quantitative data on the status of the European bioeconomy and the supply of biomass, official data collections available online, scientific publications and studies by independent institutions were used. Biomass data were evaluated in terms of volume (tons), energy content (EJ; exajoule), and carbon content (tons C). Depending on the database, the data differ, sometimes significantly (Camia et al. 2018; Camia et al. 2019; EC JRC 2019; FAOSTAT 2021). Therefore, the latest consolidated statistics published by Camia et al. 2019 and approved by European Commission (EC) Services are used. This data basis reports average production over several years (2006–2015), groups individual crops into product groups (sugar, starch, oil crops, and wood), and reports usable biomass and residues separately.

The qualitative trend analysis included academic studies and qualitative studies published by industry associations, which were evaluated using qualitative research and evaluation methods (Yin 2016; Friedrichs 2018). For the evaluation of industrial trends and framework conditions, company news, regulatory guidelines and directives, and scientific publications were considered. For the trend analysis in the chemical industry, senior executives and scientists from the German companies BRAIN, Clariant, Covestro, Henkel, Südzucker, Werner & Mertz, the Italian company Novamont, the industry associations Association of the German Chemical Industry (VCI), European Chemical Industry Council (CEFIC), and the research institutions Dechema Forschungsgesellschaft, Provadis School of International Management and Technology (Germany), and VITO (Belgium) were interviewed according to political, economic, social, technological, legal, and environmental aspects (PESTLE) (Rastogi and Trivedi 2016) on the state of the art and future technical and economic trends, taking into account societal expectations and acceptance as well as the economic policy framework in the EU.

The following keywords were used as search criteria for the online research: bioeconomy, biomass, residuals, waste, agriculture, forestry, chemical industry, energy sector, bio-energies, bio-fuel, waste management, municipal solid waste, greenhouse gas, CO_2, recycling, emission, turnover, added value, employment, food, feed, bioenergy, bio-based chemicals, bio-based materials, regulations, European Commission, emissions trading system, Europe and World.

3. Results

3.1. Status of the Bioeconomy

According to the definition of the EU, the bioeconomy includes agriculture, forestry, fisheries and agriculture as primary production sectors that supply carbon and energy sources. They are positioned at the beginning of value chains. Important sectors of higher value added are the food, feed and beverage industries, and sectors providing bio-based products like textiles, wood processing, paper, fuel and energies (EC 2018a). For these industries, the EU records the number of employees and the value added (Table 1) (Ronzon et al. 2020).

Table 1. Employment and value added of the European bioeconomy (EU27, 2017).

Sector	Employment	Value Added		
	(Million)	(Billion EUR)	Share of Total (%)	(Million EUR Per Workplace)
Agriculture	9.3	189	31	20
Forestry	0.5	25	4	50
Fishing, agriculture	0.2	7	1	35
Food, beverages and other agro-manufacturing	4.4	215	35	49
Bio-based textiles	0.7	21	3	30
Wood products and furniture	1.4	47	8	34
Paper	0.6	42	7	70
Bio-based chemicals and pharmaceuticals, plastics and rubber	0.4	60	10	150
Liquid biofuels	0.02	3	1	150
Bioelectricity	0.02	4	1	200
Total	17.5	614	100	

For the year 2017, about EUR 600 billion of value added has been reported, which represents 4.7% of GDP and the turnover has been reported at EUR 2.2 trillion. In 2018, the European bioeconomy (EU27, UK) continued to grow with 18.4 million workers and a turnover of EUR 2.43 trillion (Renewable Carbon 2020). An overview of the size of the bioeconomy in the EU, the US and individual European countries is provided by Kutay et al. (2021). As Table 1 shows, the Agriculture and Food, beverages and other agro-manufacturing sectors have by far the largest share of employment and value added. These sectors, which predominantly serve food markets, employ 78% of the workforce in the bioeconomy and generate 66% of the value added. The bio-based chemicals, fuels, and electricity sectors accounted for 2.4% of bioeconomy jobs in 2017. However, they generated 12% of the value added of the bioeconomy, i.e., a high value compared to the share of jobs. Biobased chemicals and pharmaceuticals, plastics and rubber accounted for 80% of this high value added (Ronzon et al. 2020).

Table 2 shows today's share of bio-based production in sectors of the bioeconomy (Kircher 2021a). The traditional sectors of agriculture and forestry, food and animal feed, and paper are basically bio-based, with the exception of fossil fuels and energies for the operation of transport logistics and processing. The bio-based share is also high in fibers and pharmaceuticals, although there is considerable potential for development. The situation is different for energies (fuel, heat, electricity) and especially for chemical products. They are still dominated by fossil raw materials and the share of bio-based products is still below 10%, except for heat.

Table 2. Share of biobased production in sectors of the bioeconomy (EU, 2016).

Traditional Bioeconomy	Industrial Bioeconomy					
Agro-Industry, Forestry, Fishery, Food, Beverages, Feed, Paper, Wood Processing	Textiles	Pharma-Ceuticals	Energy: Heat	Energy: Fuel	Energy: Power	Chemicals, Plastics
100%	50%	30%	16%	6%	6%	4%

How much biogenic raw material is available for this product portfolio is the topic of the next section.

3.2. Feedstock Supply Today

On average over many years, around 1300 Mt/a (million ton per year) of biomass (dry mass) is provided in Europe by agriculture including pasture management, forestry and fisheries, and imports (EU28) (Table 3) (Camia et al. 2018).

Table 3. Origin of biomass in the EU according to different sources (EU28; average 2006–2015, Mt/a dry mass).

Agriculture	Forestry	Fishery	Import	Total
956	280	<10	67	1313

The most important biomass sources in terms of volume are agriculture and forestry. However, not every plant biomass is equally suitable as an industrial raw material. The protein, sugar, and starch content determines the value as food and feed. Vegetable oils, sugars, and hydrolyzed starch, for example, can be processed into fuels, plastics, and lubricants and more chemicals, and pharmaceuticals (Yu et al. 2014; Tomaszewska et al. 2018). Lignocellulose also has potential as a chemical feedstock (Isikgor and Becer 2015), is an energy-rich fraction of biomass with a high calorific value that provides 6% of global primary energy (FAO 2021d), and is suitable as a construction material because of its mechanical stability (Yousuf et al. 2020; EC JRC 2019). While the wood produced by different tree species is largely similar in composition (Table 4) (Kizha 2008), the composition of crops can vary significantly. As examples, Table 5 shows the specific composition of a sugar, a starch, and an oil crop. Sugar beet and maize are characterized by one main ingredient each (sugar, starch), while soy bean is rich in both protein and lipids (OECD 2002; pig333 2021; FAO 2021e).

Table 4. Composition of different wood (dry matter, %).

Wood Type	Volatile	Ash	Lignocellulose		
			Lignin	Cellulose	Hemicellulose
Softwood	0–5	5	25–35	40–45	25–28
Hardwood	0–5	1	15–25	40–50	25–40
Pine	0.7	0.5	34.5	40.4	24.9
Poplar	1	2.1	25.6	41.3	32.9

Table 5. Composition of different crop (sugar beet, soy bean; maize; dry matter, %).

Crop Group	Crop	Protein	Sugar	Starch	Lipids	Other
Oil crop	Soy bean	37%	6%	0%	20%	37%
Sugar crop	Sugar beet	6%	67%	0%	<1%	27%
Starch crop	Maize	11%	<1%	75%	10%	4%

The cultivation volume of the various crops therefore reflects their current use. Tables 6 and 7 show the harvested biomass for crops that (i) are produced for food and (ii) are today already either partially used for industrial material and energy (sugar, starch and oil crops) or (iii) are grown exclusively for industrial purposes. The harvested biomass consists of a usable portion (economic biomass) and of non-usable or low-value components (residues). Agricultural economic biomass accounts for 473 Mt, with sugar and starch crops dominating by far. In addition, there is wood production, which provides an annual 10-year average of 194 Mt of stem wood (Camia et al. 2018). Thus, agriculture produces 71% and forestry 29% of the economic biomass of 668 Mt (Table 6) (Camia et al. 2018; EC JRC 2019).

Table 6. Production of economic agricultural biomass by crop group (EU28; average 2006–2015; EU28; excluding plants harvested green, permanent crops and pulses) and wood.

	Sugar and Starch Crop	Oil Crop	Crops for Material Utilization	Crops for Energetic Utilization	Wood	Total
			Million Tones (Mt)			
Total	435.49	37.03	1.02	0.19	194	668.14
Share of total	65.2%	5.5%	0.15%	0.03%	29.0%	100%

Table 7. Production of agricultural residues by crop group (average 2006–2015; EU28; without plants harvested green, permanent crops and pulses) and wood residues.

	Sugar and Starch Crop	Oil Crop	Crops for Material Utilization	Crops for Energetic Utilization	Wood	Total
			Million Tones (Mt)			
Total	341.93	90.21	0.16	0	29.6	461.9
Share of total	74.0%	19.5%	0.03%	0%	6.4%	100%

Table 7 shows the volume of these residues for the economic crop volumes listed in Table 6 (Camia et al. 2018; EC JRC 2019).

Agricultural residues, estimated at 432 Mt of total harvest of 904 Mt (48%) for the crops mentioned in Tables 6 and 7, remain partly on the cultivated land or are used in a low-value way, e.g., as raw material for biogas fermentation, as stable fodder (straw) or as animal feed (oil press cake). Residuals from sugar and starch crops account for 76%, those from oil crops for 23%, and those from industrial crops for less than 1%. Energy crops are fully utilized, resulting in no or small residuals. In principle, quantitative analysis of residues is difficult because the residues remaining on the cultivated land are generally recorded only imprecisely or not at all. Therefore, the published data are based on empirical models (EC 2018b). According to Piotrowski et al. (2015), about 25% of all residues are recycled, with the remainder rotting on the cropland. Bell et al. (2018) report that 100 Mt of this could be processed industrially.

As mentioned earlier, biomass can serve as both a carbon and energy source. The chemical industry is particularly interested in its function as a carbon source. The carbon content of crop biomass averages 47.5% of dry matter (Kähler et al. 2021), while that of wood is 51.9% (Diestel and Weimar 2014). Table 8 shows the carbon volume that agriculture and forestry supply. Almost 80% comes from agriculture and there over 80% from sugar and starch crop. Forestry contributes 20% of the supply of renewable carbon sources. The estimation of the carbon volume in the produced biomass is important to discuss below its feedstock potential compared to the future demand.

Table 8. Carbon content of agricultural biomass by crop group (average 2006–2015; EU28) and wood (calculation by author).

Biomass Type	Sugar and Starch Crop	Oil Crop	Crops for Material Utilization	Crops for Energetic Utilization	Wood	Total
			Million Tones (Mt)			
Economic biomass	206.85	17.59	1.13	0.09	114.5	340.16
Residual biomass	162.42	42.86	0.077	0	15.2	220.55
Sum	369.27	60.45	2.21	0.09	129.7	561.71
Share	65.7%	10.8%	0.4%	0.02%	23.1%	100%

The same applies to the energy content. The potential of biomass as an energy source has been studied by Material Economics in 2021. According to this study, 55 Mt of wood or the harvest on 5–7 million hectares provide an energy content of 1 EJ. The results of the study on the supply of biomass in the unit of bioenergy are shown in Table 9 (Material Economics 2021).

Table 9. Current supply of biomass (EJ).

	Current Biomass (EJ)					
	Agricultural Biomass (Crops, Residues, Grazed Biomass; Without Residues Left on Field)	**Forest Wood Incl. Residues**	**Industrial Byproducts**	**Paper, Wood, Other Waste**	**Net Biomass Trade**	**Agricultural Residues Left on Field**
	14.5	5.4	1.8	1.4	0.4	5.4
Total	23.5					5.4
Share	61.7%	23,0%	7.7%	5.9%	1.7%	

Today, the energy content of EU-biomass is 23.5 EJ; additional 5.4 EJ. Residues left on the field could provide an additional 5.5 EJ.

Besides biomass, the EU today uses fossil carbon sources with an accumulated carbon content of 959 Mt carbon (Table 10; EU28; 2017) (EEA 2018) (carbon content in coal 75% (EIA 2021), in oil 84% (Speight 1999), in natural gas 75% (UBA 2016)). The energy content of these commodities together with renewable power, biofuels and nuclear energy is 52.3 EJ (Table 10) (47: EEA 2018). A comparison with Table 9 shows that the EU consumes practically twice as much non-biogenic carbon and non-biogenic energy as the total biomass of Europe could offer annually.

To place the European biomass supply in the global situation, the worldwide supply should also be addressed. In 2011, biomass from agriculture and forestry was produced worldwide in the order of 11.4 billion tons of plant dry matter, with agriculture contributing 82% and forestry 18% (Table 11) (Raschka and Carus 2017). A comparison with Table 3 shows that the EU contributes about 10% to global crop biomass production.

Table 10. Primary energy consumption by fuel type (EU28; 2017).

<table>
<tr><th>Source</th><th colspan="3">Fossil</th><th colspan="3">Renewable Energies</th><th rowspan="2">Total</th></tr>
<tr><th>Energy and Carbon Content</th><th>Mineral Oil, Petroleum Products</th><th>Natural Gas</th><th>Solid Fossil Fuels</th><th>Biofuel *</th><th>Other</th><th>Nuclear Energy</th></tr>
<tr><td>Oil equivalent (Mt)</td><td>582.0</td><td>398.4</td><td>228.4</td><td>233.5</td><td>155.7</td><td>210.7</td><td>1808.7</td></tr>
<tr><td>Carbon (Mt)</td><td>488.9</td><td>298.8</td><td>171.3</td><td>84.1</td><td></td><td></td><td>1043.1</td></tr>
<tr><td>Share of carbon</td><td colspan="3">91.9%</td><td>8.1%</td><td></td><td></td><td></td></tr>
<tr><td>(EJ)</td><td>18.5</td><td>12.6</td><td>7.2</td><td>7.4</td><td>4.9</td><td>6.6</td><td>57.2</td></tr>
<tr><td>Share of EJ</td><td colspan="3">67.0%</td><td colspan="2">21.5%</td><td>11.5</td><td>100%</td></tr>
</table>

* Bioenergy contributes 60% to renewable energy (Scarlat et al. 2019b).

Table 11. Global biomass supply (2011, dry mass).

<table>
<tr><th>Type of Biomass</th><th colspan="2">World</th><th colspan="3">EU</th></tr>
<tr><th></th><th>[Mt]</th><th>Share</th><th></th><th>(Mt)</th><th>Share</th></tr>
<tr><td>Agrobiomass</td><td>4190</td><td>40%</td><td rowspan="3">82%</td><td rowspan="3">700–1000</td><td rowspan="3">77%</td></tr>
<tr><td>Pasture biomass</td><td>3700</td><td>31%</td></tr>
<tr><td>Crop byproducts</td><td>1380</td><td>12%</td></tr>
<tr><td>Wood</td><td>2120</td><td>18%</td><td>18%</td><td>200–300</td><td>23%</td></tr>
<tr><td>Total (Mt)</td><td>11,390</td><td></td><td></td><td>900–1300</td><td></td></tr>
<tr><td>Total (EJ) *</td><td>207</td><td></td><td></td><td>16–23</td><td></td></tr>
</table>

* estimation by author (55 Mt = 1 EJ).

3.3. Feedstock Consumption Today

The analysis of biomass supply is followed by the statistics of current consumption types. In the period 2006–2015, an average of 53% of the biomass used in the EU was used for food and feed, with consumption for livestock clearly dominating at 81%. A share of 47% served industrial purposes, with consumption almost equally distributed between the production of materials and energy. In total, biomass with a volume of 1210 Mt was consumed in 2015 (Table 12) (Camia et al. 2019). This consumption is covered by the biomass supply of 1313 Mt documented in Table 3. A slightly different usage distribution was reported by Gurría Albusac et al. (2017). According to this, significantly more biomass in Europe goes to food and feed (46%) than to industrial applications (34%; 17% each to bioenergies and bio-based materials). Bio-based materials include chemicals derived from cellulose and rubber from plantations as well as equal amounts of vegetable fats and oils and sugar and starch from agriculture (Piotrowski et al. 2015). Overall, the raw material share of biomass in the European chemical industry is 10% (CEFIC 2021a).

Table 12. Consumption of plant biomass in the EU by type of use (2006–2015 (Mt) dry mass).

<table>
<tr><th></th><th colspan="2">Food and Feed</th><th colspan="2">Industrial Use</th><th rowspan="2">Total</th></tr>
<tr><th></th><th>Animal Feed and Bedding</th><th>Plant-Based Food</th><th>Material Use</th><th>Bioenergy</th></tr>
<tr><td>Biomass (Mt)</td><td>520</td><td>110</td><td>290</td><td>280</td><td>1210.0</td></tr>
<tr><td rowspan="2">Share</td><td>43%</td><td>9%</td><td>24%</td><td>23%</td><td></td></tr>
<tr><td colspan="2">53%</td><td colspan="2">47%</td><td>100%</td></tr>
</table>

The aforementioned study by Material Economics (2021), starting from the energy content of biomass, looked at its use for the production of food, bioenergy and biomaterials. According to this study, today 55% of the energy content of biomass is used for food and feed, and 45% for industrial purposes. However, deviating from Camia et al. (2018), the study concludes that the share of consumption for the production of energies is much larger (27%) than that for materials (18%). The study also shows that today, in terms of energy content, about 10% of agricultural production serves industrial purposes. The lion's share of 90% goes into nutrition (of which 93% feed, 7% food). Raw materials for materials and energies, on the other hand, are 70% woody, i.e., non-edible biomass, with energy use exceeding consumption for materials by a factor of 1.5. In total, biomass is consumed with an energy content of 23.3 EJ (Table 13), which is covered by the energy supply of 23.5 EJ contained in the available biomass (Table 9).

Table 13. Consumption of plant biomass in the EU by type of use [EJ].

Application	Food and Feed	Industrial Utilization		Sum
		Energy Use	Material Use	
		Today's Consumption		
Animal Feed	10.6	/	/	12.9
Plant-based food	2.3	/	/	
Heating	/	2.8	/	6.3
Power	/	1.6	/	
Industry	/	1.0	/	
Road transport	/	0.7	/	
Other energy	/	0.2	/	
Wood products	/	/	2.8	4.1
Pulp production	/	/	1.3	
Share	55.4%	27.0%	17.6%	23.3

3.4. Future Feedstock Demand

In the EU, the industrial utilization of biomass is developing dynamically. Since 2000, the consumption for transport, electricity and heat generation, and industrial processes has risen in energy units from 2.6 EJ in 2000 to over 6 EJ in 2019 (Table 14) (Material Economics 2021). It should be noted that this already corresponds to 60% of total gross electricity consumption (EU27) (Eurostat 2020).

Table 14. Growth in consumption of biomass for industrial purposes by sector in the period 2000–2019 (EU27, UK).

Bioenergies			Biomaterials	
Road Transport	Power	Heating	Industrial Processing	Materials
2500%	470%	190%	150%	10–20%

Biomaterials, on the other hand, have only grown comparatively slightly by 10–20% (FAO 2021a; Ericsson and Nilsson 2018).

This development of bioenergies is part of an overall growing European and global energy market. For Europe, the European Commission projects a total demand for primary energies of 1100–1250 Mtoe (ton oil equivalent) (EC Staff Working Paper 2011), equivalent to 45–51 EJ for the year 2050. This corresponds to an increase of 80–100% compared to 2019 (616 Mtoe (Eurostat 2021d), equivalent to 25 EJ). Concerning bio-energies, the International

Energy Agency (IEA 2017) and the Renewable Energy Agency with the EU (IRENA and EC 2018) expect a demand for bioenergy in the range of 11.7–12.8 EJ. Scenarios developed for more industrial sectors claim even higher values of up to 18 EJ (European Climate Foundation 2010; Camia et al. 2018; EU Publications Office 2021; Powell et al. 2018; Terlouw et al. 2019; CCC 2018). All of these scenarios assume large volumes of biomass available for their respective purposes. The energy sector alone could claim biomass with an energy content of 12 to 18 EJ. Added to this would be the biomass demand for material use, which is assumed to grow from 4.1 today to 7 EJ. This results in a total demand of 19–25 EJ in the form of biomass for industrial use alone. However, the demand for food in the range of 14.5 EJ must also be covered in the future. This results in a total demand of biomass for food, materials and energy of 33.5 to 39.5 EJ (Material Economics 2021) (Table 15).

Table 15. Current supply and use of biomass (EU27, UK) (EJ).

Feedstock Sources	Current Supply	Demand in 2050		
		Feed and Food	Materials	Energy
Forest wood incl. residues	<5.8	/		
Agricultural biomass (crops, residues, grazed biomass; without residues left on field)	14.5	14.5	<7	12–18
Industrial byproducts	<1.7	/		
Paper, wood, other waste	<2.3	/		
Total	<24.3	/	33.5–39.5	
Not considered: Agricultural residues left on field	<3.9	/	/	/

However, this potential demand is only matched by a biomass supply with an energy content of up to 24.3 EJ in the EU in 2050 (Table 15) (Material Economics 2021), i.e., biomass produced in the EU would only cover 60–70% of the demand. Other authors have also pointed out this potential mismatch between feedstock supply and demand (Schipfer et al. 2017; Mandley et al. 2020).

For the sake of completeness, it should be noted that predictions of global bioenergy demand are also extremely challenging. Bioenergy capacities are projected to increase from 60 EJ (2020) to 77 EJ (2030) to 108–152 EJ by 2050 (IRENA 2014; Rogelj et al. 2018). Here, a comparison with today's global biomass production of 207 EJ (Table 11) demonstrates the challenge. In addition, global food demand including meat is expected to grow by 35% to 56% between 2010 and 2050 (van Dijk et al. 2021).

3.5. Increasing Biogenic Raw Materials

In principle, the increasing demand for biomass in Europe could be satisfied by expanding the farmland area, by improving the productivity, by importing biomass, by changing the usage and recycling, or by a combination of all measures. All measures must be evaluated in a global context, because demand is also increasing outside Europe.

Given the growing demand for raw materials, one option is to expand agricultural land. However, in Europe, for ecological reasons, it has been proposed not only not to expand agricultural land, but even to take it out of use, and respectively cultivate it less intensively. For example, land for nature conservation should be expanded to 30% of land area and 25% of agricultural land should be used organically (EC 2020b). This demand is made because only 16% of land and 53% of forests are classified as ecologically healthy (EC JRC 2020). Therefore, Piotrowski at al. (2015) assume no expansion of agricultural land by 2050, but anticipate an increase in cropland due to changes in land use. Thus, it is plausibly proposed that agricultural land will expand by 2% at the expense of pastureland (Piotrowski et al. 2015). In contrast, the European Commission assumes a 0.3% reduction in agricultural land to 161.2 million hectares. On this land, a shift in land use is assumed by expanding the cultivation of oil crops by 2030 at the expense of cereals (EC 2020a). Such a shift in land use could benefit raw material needs for fuel and chemicals. Worldwide, on the other hand, potential is seen for the development of additional agricultural land. The FAO assumes a 13% increase in harvested area from 1.49 billion hectares in 2020 to 1.68 billion hectares (FAO 2021b). The varying statements on land availability and land use suggest that the expansion of land in Europe will not make a decisive contribution to the production of biomass for industrial purposes.

Another option for the production of more biomass is through the improvement of agricultural productivity. For many decades, crop yields have been increased through more efficient plant varieties and optimized cultivation methods. For 2050, the FAO expects an average yield of important crops of 7.66 t/ha in a scenario of sustainably managed agriculture, which would correspond to a yield increase of 12.3% compared to 2020 (FAO 2021c). Combined with land expansion, the global harvest of commodity crops could grow by 24.6% from 23.6 billion t/y in 2020 to 29.4 bn t/y (FAO 2021b). The greatest potential for improvement is in developing countries. There, 80% of the production increases are expected from improved crops and cultivation methods and 20% from expansion of arable land (FAO 2009). In Europe, McKinsey and Company (2020) foresees an intensification of productivity which could be equivalent to the harvest from 60 million hectares under state-of-the-art cultivation methods.

Land-use changes and intensification of use must also take into account the ecological effects they cause. Indeed, biomass production is associated with significant greenhouse gas (GHG) emissions. In Europe, agriculture alone accounts for 9.6% of total emissions (EU28, 2015). Globally, agriculture is reported to be responsible for 24% of total GHG emissions (EPA 2021). Major sources are metabolic activities of soil microflora and enteric fermentation (Eurostat 2018). In addition, there are GHG emissions from agricultural machinery and energy-intensive fertilizer production. International Fertilizer Association estimates that the fertilizer industry is the source of 2.5% of the global GHG emissions, including 1.5% related to fertilizer use (Fertilizers Europe 2019; Hoxha and Christensen 2018). Since 2018, European countries have been required to remove these emissions from land use, land use change, or forestry from the atmosphere by reducing them elsewhere (EC 2018c).

Today, Europe imports 2% of its biomass needs for industrial purposes (Energy Transitions Commission 2021). However, increasing imports in a sustainable manner faces limits to global land expansion and environmental limits because cropland expansion can exacerbate global deforestation and biodiversity loss (FAO and UNEP 2020; Díaz et al. 2019; Curtis et al. 2018). In addition, global ecosystem services and boundaries, which are already stressed and in some cases damaged today, require conservation of land (Vialatte et al. 2019; Rockström et al. 2009; Strayer et al. 2009). All these parameters are reflected in the environmental footprint of biomass production that the EU would import and have to offset elsewhere. Therefore, importing biomass or bio-based intermediary products definitely is an option, but is only a limited one.

Another option for growing more biomass for industrial purposes is by changing the current land use. Potential is seen above all in the areas on which animal feed is grown, which in Europe and globally takes up about five times as much land as vegetable foods (Table 12) (Ritchie and Roser 2019). This land requirement is determined in part by feed conversion efficiency (Reuter et al. 2013), which is highly developed in the EU at 8.6% (raising 43.1 MT of cattle for slaughter (Eurostat 2015) consumes 500 Mt of animal feed (Hou et al. 2016)). In contrast, the global average feed conversion efficiency is only 5.4% (breeding 340 Mt of slaughter cattle (Ritchie and Roser 2019) consumes 5.3 bn t of feed (Herrero et al. 2013)). Between 2011 and 2030, feed efficiency specific to different livestock species is expected to increase by an average of 0.73% per year (Wirsenius et al. 2010), which could at least mitigate the increase in land use for feed. One important means is supplementation with limiting essential amino acids, which reduces protein requirements in feed (Polaris Market Research 2018). Another option to provide feed protein without using land is the cultivation of insects, preferably on vegetable residues (Madau et al. 2020). Further potential for saving animal feed or the land needed to produce it comes from the production of in vitro meat (Hocquette 2016; Kumar et al. 2021) or plant-based imitation meat (Bonny et al. 2017; Kumar et al. 2017). Studies by various consulting firms predict that up to 60% of the meat consumed in 2040 will be either cultivated in vitro or produced based on vegetable raw materials (Kearney 2019; Deloitte 2019; Innova Market Insight 2021).

It is not only the way meat is produced that can reduce land requirements. Although food demand in Europe is expected to remain unchanged or even show a slight downward trend by 2050 compared to today (Eurostat 2021b), shifts within the food sector from animal- to plant-based products are possible. In Europe, with the aging of society (Eurostat 2021a), the proportion of older people tending to consume less meat (Grasso et al. 2021) is increasing, and a trend toward vegan diets is currently observed among younger people. In 2021, the proportion of younger adults in the EU eating a vegan or vegetarian diet varies from 6% (Italy) to 16% (Germany) (Statista 2021c). Although the reduction of meat consumption is propagated by numerous NGOs (Greenpeace 2021; Slowfood 2020), the share price loss of the US-flagship company in this field Beyond Meat (Armental 2021) can be read as an indicator that the consolidation of a trend toward meat alternatives is not yet stable. On the other hand, established companies in the meat industry such as Tönnies (Germany), one of the largest European meat producers (Sharma 2021), are launching more and more meat-free protein sources in their product portfolio (Fleischindustrie 2021). In the United Kingdom, more than 20% of new food products were vegan (2020) (Dean 2021). Overall, Europe's vegan market is expected to grow to EUR 7.5 billion by the year 2025 (Pratchett 2021).

However, the European meat market is very different from the global situation, because meat consumption will probably increase there with the growing prosperity in emerging and developing countries (Ritchie and Roser 2019; EEA 2011).

Another way to save land for feedstock production is to intensify the utilization of residuals and by-products and recycling of waste materials (Trinks et al. 2020). For example, lignocellulose is a key component of cereal straw, which is increasingly being processed into fuels (Azimov et al. 2021; Hoefnagels 2018; E4Tech 2018). Basic chemical products could also be produced on the basis of lignocellulose (Dahmen et al. 2018; Yu et al. 2021; Demesa et al. 2020). This is significant because basic chemicals comprise chemicals produced on a million ton scale and therefore represent the lion's share of the chemical industry's feedstock needs.

Another neglected byproduct of biomass processing is CO2. For example, biogas contains 25–50% CO_2 (Li et al. 2019) and ethanol fermentation emits an almost pure CO_2 stream (Xu et al. 2010). Today, these emissions are released into the atmosphere in Europe, but in principle their technical use is also an option (Carbon Capture and Utilization; CCU) (Bushuyev Oleksandr et al. 2018; ZEP 2021). It would sequester carbon in carbon-containing products at least for their useful life (Kätelhön et al. 2019). Today, urea (Pérez-Fortes et al. 2014) and polycarbonate polyols (Langanke et al. 2014) are already produced based on CO_2, but the potential range of products is much broader (Hepburn et al. 2019). In fact, a study by the German chemical industry (E4Tech and Institute 2019) predicts that bio-based or renewable feedstock until 2030 will reach a share of 25% of total volume of organic chemicals feedstock and that from about 2040 CO_2 will become the preferred carbon source in chemistry alongside biomass and plastics recycling. By 2050, CO_2 is expected to reach a share of 54% as a carbon source for the German chemical industry, the most important in Europe, thus contributing alongside biomass and recycling to reduce the share of fossil carbon sources from today's 93% to 6% (Table 16) (Statista 2021b).

Table 16. Forecast of future carbon sources for the chemical industry in 2050 compared with today (Germany).

Year	Fossil Sources	Biomass	Recycling	CO_2
2020	93.0%	6.0%	/	/
2050	6.3%	27.8%	11.1%	54.7%

Suitable processes are under development (Hepburn et al. 2019), scaled up (Electrochaea 2021), are not far from competitiveness, such as methanol (Hepburn et al. 2019), or have reached industrial scale under particularly favorable site conditions (Lanzatech 2021; Carbon Recycling International 2021).

Today, a broad application of the use of CO_2 is still hindered by the high demand for hydrogen, the production of which is very energy-intensive. Currently, the potential of hydrogen is being discussed not only for chemistry, but also for applications in mobility and steel production, and preparations are underway to build the corresponding capacities (IRENA 2020). In particular, hydrogen can play a significant role as an energy carrier in the future, especially in Europe and Southeast Asia (Pflugmann and Blasio 2020). However, emission-free green hydrogen is comparatively expensive today compared to fossil-based hydrogen (EUR 0.59–2.11/kg H2 fossil versus EUR 2.7–6.5 kg H2 green) (IEA 2020). By 2050, hydrogen could meet up to 24% of energy demand in the EU (FCH 2019). With the increasing availability of hydrogen, the capacity of the global chemical industry to use CO_2 as a carbon source is assumed to be 0.3–0.6 Gt/a in 2050 with breakeven costs of \$80–320 per ton of CO_2 (Hepburn et al. 2019). Another crucial prerequisite, however, is that sufficient emission-free energies are available. In 2050, the German chemical industry alone would require as much electricity as is consumed in total in Germany today (E4Tech and Institute 2019) and consequently BASF, for example, is building a Europe-wide supply network for green energies (BASF 2021). Globally, the energy demand of the chemical industry could even grow by a factor of 2.8 by 2050 (IEA et al. 2013). Without hydrogen, biotechnological processes using photosynthetically active microalgae that harness solar energy can fix CO_2 (Williams and Laurens 2010). Their biomass can also serve as feedstock for fuel, carbohydrates, proteins and polymers (Laurens 2017), but is comparatively costly with breakeven costs of \$230–\$920 per tonne of CO_2 (Hepburn et al. 2019).

Recycling of products after use is another feedstock option. A common practice of waste recovery is to use the energy content by burning it in waste-to-energy plants. Between 1995 and 2019, the capacities of waste incineration were increased to 60 million tons annually in Europe. The emission volume of this waste incineration was estimated at 95 Mt CO2-eq in 2019 (Gardiner B 2021); representing 2.7% of the total emission of 3500 Mt CO_2 (EU27, 2019) (EEA 2021). An alternative method, especially for biogenic waste is biogas fermentation, which not only standardizes complex waste materials to methane, but significantly reduces CO_2 emissions compared to incineration (Demichelis et al. 2019). However, it should be noted that while recycling reduces the consumption of primary raw materials, the need for other resources and energy for production remains (Korhonen et al. 2018). That the chemical industry will need to switch to biogenic and recycled carbon sources for its organic products as fossil carbon sources are phased out is a trend (Paulus and Giegold 2020) that the European chemical industry has stated it will drive (CEFIC 2021b). Globally, carbon demand just for carbon sequestered in chemical products is expected to increase from 450 Mt today to 1000 Mt by 2050 (Kähler et al. 2021). With a share of 15% in the global chemical industry (CEFIC 2021b), a carbon demand of about 67 Mt can be estimated for the EU chemical industry today.

3.6. General Framework Conditions

The European economic policy framework is designed to reduce emissions caused by fossil fuels. Eighteen countries levy taxes on the emission of CO_2, which have helped to reduce the environmental footprint of the companies concerned (Ionescu 2020). In the area of energy production, the Renewable Energy Directive (RED II) (EC 2018d) was adopted in 2018 for this purpose, which prescribes an increasing share of renewable energies, including bio-energies. Large manufacturing industries (power generators, steel, cement, glass, chemical, domestic European aviation) are subject to the EU ETS (emissions trading scheme) (EC 2021h; EC 2021b). With its increasing cost of emissions allowances, it is a proven effective economic control instrument (Bayer and Aklin 2020; Trading Economics 2021). Emissions that are primarily energy-related (SCOPE 1 and 2) are charged, while emissions that result from use and disposal (SCOPE 3), among other things, are only recorded statistically (Carbon Trust 2021). In this way, the EU ETS forces the raw material change, especially in energy production (Kircher 2021b). Beyond Europe, different emission pricing schemes have been implemented in Canada, China and USA (OECD 2021; Borghese and Montini 2016). In principle, the EU ETS could also support the recycling of CO_2 as a carbon source through carbon capture and utilization technologies (CCU). However, inhibiting regulations currently stand in the way of this (Frieden 2021). Emissions from product disposal are to be reduced in the EU by reducing landfilling of MSW (municipal solid waste) from 24% in 2018 to 10% by 2035 (EC 2021e) and by increasing recycling. The European Commission has set quotas to recycle and prepare for reuse 55% of MSW by 2025, 60% by 2030 and 65% by 2035 (EU 2018; EEA 2021). Especially for cities, where waste is generated in large volumes on a limited area, waste recycling has potential (EC 2021g). This is also supported by the EU "Fit for 55" strategy, which calls for a 40% reduction in emissions by 2030, including from the waste industry (EC 2021c). Energy generation through incineration of biogenic waste is also classified as a sustainable method of waste disposal (Scarlat et al. 2019a). However, because bio-based and fossil-based municipal solid waste are co-incinerated, the resulting fossil-based emissions, which are not charged by the EU ETS, are critically viewed (Hockenos 2021).

The financial community increasingly rates fossil commodities as a risk factor (E3G 2019), fears investments in fossil-based projects as "stranded assets" (Carbon Tracker 2018; Bos and Gupta 2019), and more and more frequently rejects such investments (Bloomberg Green 2021; Allianz 2021). Accordingly, Willis and Spence (2021) report that investments in non-fossil based opportunities provide better returns compared to the S&P 500 Index and another study concludes that the improvement of the environmental performance and the ability to innovate of companies correlate with investment behavior according to sustainability criteria (Ionescu 2021a). In line with the trend away from fossil fuels, the consumption of biomass for industrial purposes is increasing. Accordingly, agricultural products have significantly increased in price in the EU since September 2020; one of the top performers is rapeseed, whose market price has increased by 53% (EC 2021a). Rapeseed oil is the basis for biodiesel and chemical products. As prices for agricultural products rise, so do the costs of farmland. With only a few regional exceptions, prices for agricultural land in the EU have increased since 2011 and in some cases even multiplied (Observator Finansowy 2018) and European as well as non-European investors are buying European farmland (Tian et al. 2020). One of the top cost drivers is the growing market for bioenergies (Demartini et al. 2016; Kirschke et al. 2021). Applications such as heavy-duty transport fuel (aviation, shipping) will depend on carbon-based fuels of high energy density for the foreseeable future. Suitable feedstocks include biomass (Cheng and Brewer 2017; EASA 2021), wastes such as used cooking oil (Chen and Wang 2019), and CO_2 (Ineratec 2021). Indeed, numerous airlines have confirmed the suitability of bio-based and other alternative fuels (BP 2021; Lufthansa 2021). While heavy-duty fuel depends on carbon, bio-based heat and electricity can find carbon-free alternatives in solar and wind energy, hydropower, geothermal energy, and nuclear power. Therefore, it was already called for in 2013 to rely on bioenergies with some reservation in order to protect planetary boundaries and ecosystem services (EEA 2013). Nevertheless, major economic sectors today face demand from the EU Commission not to change the current plans for bioenergies (EC 2021f). Current plans call for bioenergies to supply up to 28% of the EU's gross inland energy consumption by 2050 (Mandley et al. 2020). In the long term, cost competition may tip the balance if rising costs for bioenergies lead to competitive disadvantages with carbon-free energies that are being expanded globally (Frankfurt School-UNEP Centre and BNEF 2019; IAEA 2021).

In order for the economic policy framework to lead to the desired results, investments must increasingly take sustainability criteria into account. This applies both to low-carbon energies (Ionescu 2021b) and to the chemical sector, to which this article devotes attention. By 2050, the financial requirement is estimated at 2.5% of global gross national product (Kircher 2019). The European Commission has therefore announced in its current Green Deal to mobilize EUR 1000 billion for the EU over the next 10 years (EC 2021d). This corresponds to 0.75% of EU GDP annually (EUR 13,300 billion; 2020) (Eurostat 2021c). However, the climate protection and transformation of the economy discussed here are only part of the tasks ahead. The United Nations estimates that the implementation of the 2030 Agenda for Sustainable Development will require investments of $5–7 trillion per year at the global level (ECB 2021). This would be equivalent to about 6–8% of today's global GDP of $87 trillion (Statista 2021a).

4. Discussion

The presentation of the current state of the European bioeconomy has shown that it already makes a significant contribution to the overall economy in terms of production volume, employment and value added. The supply of raw materials from agriculture and forestry largely covers the need of the food and feed, textiles, wood products and paper sectors, although it should be noted that the production of biomass strains natural resources to the limits of planetary boundaries and ecosystem services, and in some cases beyond. It is therefore suggested that in the future, the analysis of EU agricultural and forestry production data should be complemented by an analysis of ecological capacity limits. This is all the more necessary because, as the bioeconomy continues to develop, more sectors will have to be integrated, namely energy production and organic chemistry, and the question arises as to how their very high raw material requirements can be provided. It has been shown that numerous studies, especially on bioenergies, underestimate the limitations of the raw material supply. There is still a considerable need for research on whether and to what extent the production of biomass in Europe can be expanded in a sustainable manner, namely within planetary boundaries, ecosystem service capacities and taking into account the consequences of climate change. This must also take into account changing biomass production in terms of quality; for example, whether heavy-duty fuels and organic chemistry increase the demand for vegetable oils of certain qualities. In any case, it can be considered certain that today's consumption of fossil carbon and energy sources cannot be completely replaced by biomass.

Therefore, two options are proposed, namely prioritizing biomass use and increasing feedstock efficiency. Unlike the energy sector, which can offer carbon-free energy for most applications, the organic chemistry sector relies on carbon. Therefore, the obvious choice is to integrate only those parts of the energy sector into the bioeconomy that cannot do without carbon-based energies. These are essentially heavy-duty fuels; expectations for bio-heat and bio-power, on the other hand, should be scaled back. Organic chemistry, on the other hand, must be completely supplied with renewable carbon sources. The long value chains of chemistry, which contribute much more to value creation and employment than energies, also argue for making the limited resources of the bioeconomy available to traditional sectors and preferably to the chemical industry. This applies to the economic structure specific to Europe with its strong chemical industry (CEFIC 2021b); other economic regions may require different solutions.

Such a prioritization would reduce the future demand for biomass, but would still result in an increase in demand of 12% of today's Europe's biomass for the chemical industry alone. This exceeds the share of biomass currently used for material utilization by a factor of 30. To consider only the demand for carbon is admittedly a simplification. Biogenic raw materials have a different composition than fossil carbon sources, consist of chemically diverse components and are therefore also differently suited for the diversity of chemical products. Here, too, there is still a need for research into which fractions of the biomass are economically and ecologically most suitable for which chemical products and can be made available in large volumes without endangering the nutrition of the growing world population.

In order to meet the increasing demand for biogenic raw materials, the options of expanding agricultural land, land efficiency, plant breeding and reducing the cultivation of feed for meat production have been investigated. All options have potential, but given the sensitive planetary boundaries, the cultivation of further land in Europe and worldwide must only be considered restrictively, and land efficiency must only be increased sustainably.

One way out is to systematically close carbon cycles. The established bioeconomy uses the natural carbon cycle for this, which binds CO_2 from the atmosphere into biomass by means of photosynthesis using solar energy. Technical carbon cycles, on the other hand, avoid the emission of CO_2 into the atmosphere by recycling residual materials from processing, including CO_2, and products back into the production cycle after use. Only a broad application of such technologies, some of which are already available, will make the bioeconomy a circular bioeconomy. Because these processes are energy-intensive, they are linked to an increasing energy demand.

Admittedly, residual materials and wastes that are suitable for use as industrial raw materials in the future are currently being used in part for energy production, classified as renewable energies and included in the long-term planning as a sustainable energy source. What their reallocation for material recovery means for energy capacities, emission reduction and for value creation and business models of waste management is a topic for further research.

With regard to the economic policy framework, it was shown that the EU ETS in particular drives the raw material change in energy production by charging SCOPE 1 and 2 emissions. Emission allowance prices broke through the €65 per ton CO_2 threshold in November 2021, having been below €30 earlier in the year. As the number of allowances is reduced annually, further increases in the price of tradable allowances can be expected, bringing them closer to the breakeven costs of CO_2 use.

The use of biogenic instead of fossil raw materials for the carbon bound in chemical products, on the other hand, is not supported because the resulting SCOPE 3 emissions are not priced. How the inclusion of these emissions in the EU ETS would affect its steering effect is worth investigating scientifically. Another issue is the adaptation of the framework conditions of CO_2 recycling to the requirements of the transition phase into the circular bioeconomy. In this phase, which will still take decades, CO_2 will be increasingly emitted from biogenic sources and decreasingly from fossil sources. Would it not make sense to design the framework conditions in such a way that the recycling of CO_2 of any origin is supported by the economic policy framework? This consideration also leads to the question of whether the theoretical concept of the circular bioeconomy should be further developed to the effect that the differentiation between biogenic and fossil CO_2 should be dispensed with. The advantage of such a step could be the faster introduction of large CO_2 recycling capacities in emission-intensive industries. The disadvantage could be the accompanying sharp increase in energy demand and the possible decrease in pressure to reduce emissions. Both aspects would have to be compensated by a targeted adjustment of the framework conditions. Finally, it should be mentioned that the regionally very different economic policy framework conditions lead to distortions of competition, the braking effect of which on the circular bioeconomy has not yet been investigated. However, their scientific analysis is necessary in order to harmonize the conditions globally in such a way that not only a level playing field is created, but also that incentives are created to provide the necessary investment resources for waste management (recycling), the chemical industry (raw material conversion) and the energy industry (emission-free energies).

5. Conclusions

The bioeconomy already contributes significantly to the economic power of the EU today. By 2050, the energy and organic chemistry sectors, both of which still have the raw material transformation to non-fossil raw materials largely ahead of them, will have to be integrated. This means that the biomass-producing sectors of agriculture and forestry will also face considerable additional demand that cannot be met in a sustainable way. Therefore, the energy sector must fundamentally focus on carbon-free energies and limit bioenergies to heavy-duty fuels. Organic chemistry, on the other hand, must be fully integrated into the bioeconomy. For a sustainable supply of raw materials, it is necessary to focus more on the recycling of waste and CO_2 and thus to further develop the theory and practice of the bioeconomy into a circular bioeconomy. This requires an adjustment of the EU ETS to create an incentive for the use of biogenic or recycled raw materials for product-bound carbon. In parallel, incentives must be created to recycle waste as a source of carbon rather than energy. To ensure that these European measures do not have a distorting effect on international competition, the economic policy framework must be harmonized worldwide.

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