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Bioeconomy: Biomass and biomass-based energy supply and demand

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ABSTRACT

This paper addresses the challenges of the transition from a fossil fuel-dependent to a bio-based economy and implications related to the production of food, feed, bioenergy and other bio-based materials. The objective is to provide a comprehensive review of global biomass and biomass-based energy supplies and demand, with particular attention to the EU. Furthermore, factors related to setting priorities in the use of non-food biomass are discussed, as food security will remain the top priority. Finally, the changes in the bioenergy balance indicators in the Member States of the EU and new plant breeding technologies are analyzed. Overall, this study describes the complexity of the bio-based value chains in making decisions on how best to use biomass. The article presents a comprehensive review on global biomass and biomass based energy supplies and demand, discusses the European chemical industry perspective, analyzes the changes in the biomass based energy balance indicators in the Member States of the EU, and considers the challenges of the new plant breeding technologies.

Introduction

To date, over 50 countries have developed bioeconomy strategies [1]. The global economy is mainly based on fossil fuels to produce electricity, heat, chemicals, fuels and energy. In the total primary energy supply, fossil fuels account for 81 %, nuclear energy represents 5 % and renewable energy sources 14 % (of which the contribution of biomass is about 70 %). The chemical sector accounts for 11 % and 8 % respectively of the global primary demand for oil and natural gas; however, roughly half of the energy inputs to the sector are consumed as feedstock for chemical products [2]. An alternative to fossil resources is biomass and its conversion into food, feed, and bio-based products such as bioplastics, biofuels and bioenergy [3]. The growing use of biomass for industrial raw materials will impact the food and other bio-based material production leading to an increasing share of agriculture in gross domestic product (GDP).

Global food supply combined with replacing fossil fuels is an extraordinary challenge since the supply of global land and biomass is limited. Only 22 % of the Earth’s surface area (18 % of the land and 4 % of the ocean) is fertile. In addition, global population will grow by 25 % – from 7.8 to about 10 billion – and demand for food will increase by 60 % by 2050 [4]. Furthermore, 33 % of the global population are overweight, and of this percentage, 30 % are obese [4]. In contrast, 800 M people are undernourished due to caloric deficit, and 2 billion due to micronutrient deficit [4]. Changing diets will have a larger impact on land use than population growth. Current diets are not compatible with sustainable resource use. For example, meat production takes 6 times more land to produce the same amounts of calories as cereal production due to the inefficient conversion of the calories in feeds. The increasing use of land for the supply of food and other bio-based materials will reduce land use for meat production. Meat production requires about 70 % of global land [5].

Fossil resources produce around 10B tons of fossil carbon, and global agriculture produces 7B tons of bio-carbon annually [6,7]. Global agricultural production must increase by a factor of 2.5 to cover 10B tons of fossil and bio-carbon consumption (the lower energy content of biomass is not taken into consideration) in order to replace fossil fuels [8]. Fossil resources are biomass that has undergone transformations over periods of millions of years. Their use as fuels is limited, therefore, a transition to a sustainable energy system is needed. The total value of ecosystem services is estimated to be 49.4 T International $/year, i.e. translated into US$ values based on Purchasing Power Parity [9].

Abbreviations: CEFIC, European Chemical Industry Council; ETS, Emissions Trading System; GDP, gross domestic product; GHG, greenhouse gas; GM, genetically modified; IEA, International Energy Agency; REN21, Renewable Energy Policy Network for the 21st Century; WBA, World Bioenergy Association.

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Biomass is today used primarily for feed, then for food and finally for energy, fuels and chemical feedstock production. It accounts for 13 % of global final energy consumption (other renewables add an additional 5 % to total final energy consumption). In the energy industry, renewable sources play a very important role in the “decarbonization” process of the economy, referring to the process of reducing the amount of greenhouse gas (GHG) emissions produced by the burning of fossil fuels. The industrial organic chemical sector produces 550 M tons of chemicals and 275 M tons of nitrogen-fertilizer; however, the chemicals produced contain only 500 M tons of carbon. In addition, organic compounds used in organic chemistry contain about 100 M tons of carbon [10]. At present, mainly sugar, starch and vegetable oil are used for the supply of biofuels and biochemicals [11]. The increasing demand for bioproducts has been driven by consumers and the replacement of fossil fuels with renewable energy sources. The factors influencing the competitiveness of biochemical products also includes the price level of feedstocks, for example lignocellulose, sugars, starch and oils [11]. Price comparisons of bio-based carbon to fossil-based carbon, as well as cost comparisons of processing bio-based materials with the corresponding fossil-based materials cannot be easily specified, but depend on the raw materials and the molecular economy of the processes into the final products. Fossil fuels and basic chemicals are produced by refining mineral oil with a very high carbon efficiency and low labor intensity. In contrast, biomass requires more processing steps with a higher cost and labor requirements (see bioethanol production).

In the energy industry renewable sources such as solar, wind, hydro- and geothermal energy are carbon free, as is nuclear energy. The transport sector uses one third of total final energy demand and is responsible for 23 % of global energy-related CO_2 emissions. About 96 % of global transport energy needs are met by oil products, the rest by electricity and biogas; therefore, increased use of renewables in the transport sector has a high priority in the decarbonization of this sector. The transport sector can be partly decarbonized by the use of biofuels and other renewable energy sources, e.g. solar and wind [12]. The EU and the USA have introduced caps on food-based biofuels. Although just 2 % of global land is used for the feedstock production of the biofuels industry, the “fuel versus food” debate indicates that biomass used for industrial purposes is a sensitive issue in society. Demand for some feedstocks (e.g. maize, oilseeds, sugar cane, vegetable oil) is relatively high: 20 % of global sugarcane, 12 % of global vegetable oil and 10 % of global coarse grain production is used to produce biofuels. Since biofuel represents a very small percentage of overall changes in land use, reduced competition for crops can be experienced.

About 50 countries have introduced carbon pricing systems, representing over 20 % of annual GHG emissions. The price of CO_2 European Emission Allowances increased from €4 to €25/t between 2017 and 2019 [13]. According to estimates, EU carbon markets saved cumulative emissions of about 1.2B tons of CO_2 from 2008 to 2016, or 3.8 % relative to total emissions over this period. Carbon markets can work even when prices are low; however, current debates in the EU focus on the inclusion of the transport and housing sectors in European emissions trading [14]. German carbon-pricing reform will allocate a price of €25/t to CO_2 emissions in the heat and transport sectors not included in the EU Emissions Trading System (ETS) from January 2021. The EC is planning a revision of the current ETS rules, which should come into force from 2023 [15]. In the energy and chemical sectors, biotechnological innovation has reduced dependence on petroleum and fossil fuels with a positive impact on the environment. The bioeconomy and circular economy are converging through the integration of the economic aspects of the circular economy and the sustainability of the bioeconomy. The internationalization of the different bioeconomies is a top priority in the formation of the circular bioeconomy [16].

This rest of this paper first presents biomass supplies and its uses, followed by a discussion of the role of biomass in energy production and the implications related to the production of food and feed, bioenergy and biochemicals including also microbial biomass feedstock. The outlook for the EU chemical industry makes it clear that a radical transformation towards the production of bio-based chemicals is needed [16]. Finally, the changes in the bioenergy balance indicators in EU Member States and new plant breeding technologies are analyzed. Overall, this study attempts to explain the complexity of the value chains in the bioeconomy in order to make decisions on how best to use biomass.

Material and methods

The role of biomass supply in the production of bio-based products is presented, based on a review of relevant literature, in combination with results from relevant studies and global models. Various combinations of the following terms were used to search the literature: bioeconomy, biomass supply, bioenergy, biofuels, biochemicals, biotechnology and climate change. The literature on bioeconomy strategies is already substantial; however, the effects of increasing biomass supply on the output of bio-based products have not been addressed in detail. Furthermore, there is a lack of available publications relating to the prioritization of different uses of biomass. The EUROSTAT database [17]. is the most comprehensive source of comparable statistics on biomass flows – agriculture, forestry, food and feed, wood pulp, biomaterials, energy – and biomass-based energy supply balance indicators in the EU. The World Bioenergy Association (WBA), the Renewable Energy Policy Network for the 21 st Century REN21 and the International Energy Agency (IEA) give an insight into global energy, bioenergy and renewables statistics. The European Chemical Industry Council (CEFIC) provides reliable figures on the European chemical industry.

The Yield Stability Index (YSI) was developed [18] to capture the level of stability for a yield series (i.e. a simple time series of yields from biomass, crop or other agricultural product). First, a simple linear trend should be fitted to the previously normalized data (the time series is divided by its average) of a country. Then the difference (called the residual) can be evaluated between the actual yield and the trend line (expected yield). The normally distributed histogram is used to model these residual series of all countries studied. This means that the most frequent differences are around zero and higher than zero differences occur with less frequency. The YSI of a given country for a given yield series is calculated as FD – UD where FD is the sum of favorable and UD is the sum of unfavorable (residual) differences of a country’s yield series compared to the normal distribution. For the calculation of FD, the authors take into consideration only the middle 4 segments of the residual and normal distribution (meaning that the difference between a given trend and the actual data is closer to 0). Positive values indicate more stable trend lines around the average while negative values indicate higher fluctuations around the trend line. The Eurostat database and YSI index were used to analyze the performance of the 28 EU Member States for the main indices (gross inland consumption, transformation input, final energy consumption) between 2002 and 2016. The authors have used this methodology since it can capture the extent of fluctuation around the trend. Calculation of the YSI and the regression slopes were performed with R-project (R version 4.0.0 (Arbor Day) [19].

Results

Biomass supply and use

The total global biomass supply from agriculture and forestry is estimated at about 11.9B tons of dry matter annually, of which 61 % is produced by agriculture and 39 % by forestry (Fig. 1). Agricultural crops account for 47 % and residues harvested above ground for 14 %. Collected crop residues are categorized as grazed and burned biomass, feed and bedding. Approximately 50 % of the total above ground biomass residues (1.7B tons) remains on the soil for soil carbon management [20]. Of the total global woody biomass production, fuelwood (including power generation) accounts for 23 %, followed by primary

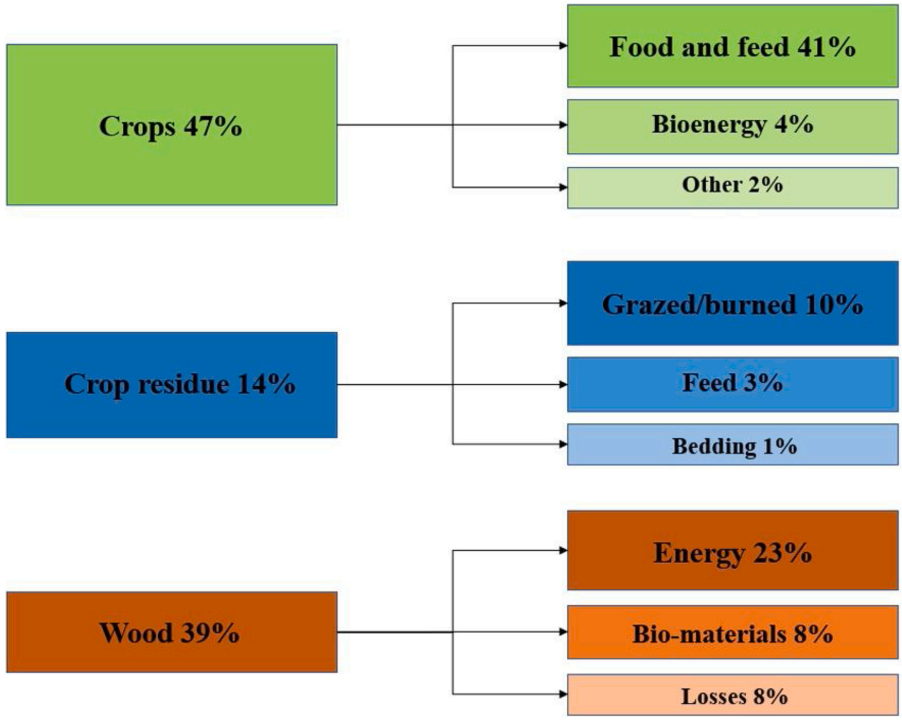

Fig. 1. Global biomass supply and use by sectors in 2015 (%). Source: Authors' own construction, based on van den Born, van Minnen [20].

woody biomass (industrial roundwood) at 8 %, and losses at 8 %. Agricultural crops are used for food and feed (41 %), energy (3.5 %) and other uses, such as waste and seed (2 %). Grazed biomass and harvested residues are used as feed and bedding. Of the harvested residues accounting for 14 %, 10 % is grazed by livestock or burned, 3 % is used for feed, and 1 % for bedding. Wood biomass is primarily used as fuelwood for heating and cooking and power generation (23 %), and as industrial roundwood for construction and paper and cardboard production (8 %). Industrial roundwood is converted to saw logs for wood products, construction and paper and pulp production. Finally, waste production (primary residues) makes up 8 %.

In 2015, the total biomass supply in the EU accounted for 1.1B tons of dry matter, accounting for roughly 9 % of global biomass production. The biomass balances show that 67 % is supplied by the agricultural sector and 33 % by the forestry sector (Fig. 2). Of the biomass production derived from agriculture, crops represented 47 %, followed by grazed biomass (11 %) and crop residues (9 %). In the forest-based biomass supply, primary woody biomass constituted 22 %, followed by co-products and by-products, including wood pellets (9 %) and post-consumer wood (2 %). The biomass supply from the aquatic sectors is less than 2 M tons of dry matter annually, i.e. a negligible amount of total biomass supply (0.2 %); however, the relative importance of the marine based sectors in the bioeconomy is higher compared to their extremely low share of total biomass [22]. In 2015, the total biomass use

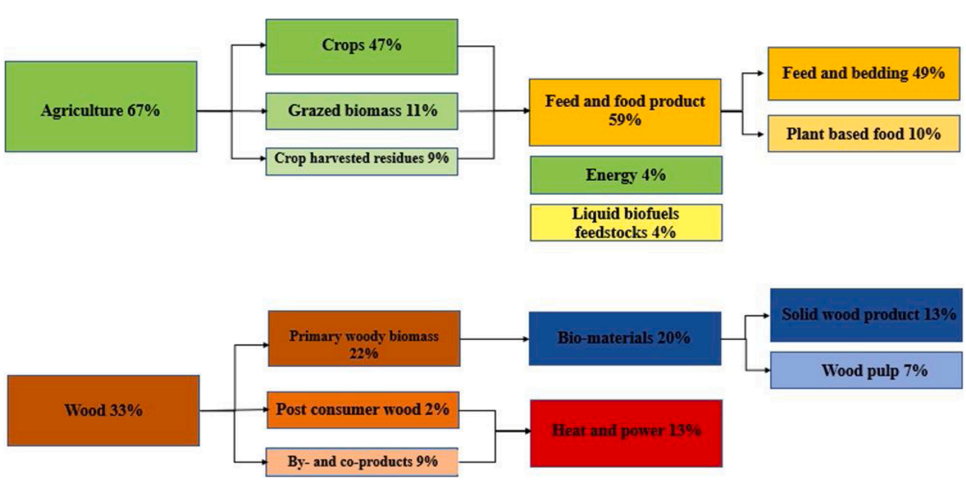

Fig. 2. Biomass supply and use by sectors in the EU in 2015 (%). Source: Authors' own construction based on European Commission [21].

was 1.06B tons of dry matter (Fig. 2). In 2015 the EU was a net importer of total bio-based products in weight of dry matter (28 M tons). The trade balances of animal products (feed equivalent), solid wood products and bioenergy were positive; however, the EU was a net importer of processed products (biomass equivalent) plant-based food, fish and seafood, fishmeal and oil, wood pulp, wood pellets and roundwood [21,23,24]. Agricultural biomass is used as feed and bedding including animal-based food (49 %), plant-based food (10 %), liquid biofuels feedstocks (4 %) and energy (4 %). Grazed biomass and harvested residues are used as feed and bedding. Wood biomass is used as solid wood product and wood pulp for biomaterials (20 %) and as heat and power for bioenergy production (13 %). Regarding the share of biomaterial and bioenergy uses, roughly two thirds of wood primary and secondary sources were used for materials while a third was used for energy. Energy and pellet use of wood biomass has been increasing in the last two decades. The biomass flows show that 67 % is used in the feed and food sector, followed by biomaterials (20 %) and bioenergy (13 %) [21]. Bioenergy includes biofuels produced from energy crops of about 30 M tons of dry matter (4 % of biomass from agriculture).

Bioenergy in the energy supply

At present, biomass accounts for 10 % of the global energy supply and 13 % of energy consumption. In 2016, the global primary energy supply was 13.8B tons of oil equivalent or 576 exajoules (EJ). Fossil fuels (coal, mineral oil and natural gas) constituted 81 %, nuclear power 5 % and renewable energy sources 14 % of the total primary energy supply. Biomass was the largest renewable energy source globally at 10 % (70 % of all renewable energy sources) followed by hydropower at 2.5 % and other renewables (solar, wind, geothermal and tidal etc.) at 1.5 % (Fig. 3). The share of renewable energy sources increased by just 1 % since 2000 even though the supply of renewables increased by over 30 % over this period, showing that the global primary energy supply is increasing at almost the same pace.

Roughly 36 % of primary energy consumption goes in losses through the demands of the energy industry and different transformation transmission and distribution processes. In 2016, the gross final energy consumption amounted to 8.8B tons of oil equivalent (bn toe) or 367 EJ. Fossil fuels represented 80 %, nuclear 2 % and renewables 18 % of the gross final energy consumption worldwide. Since 2000, the renewable energy share of 18 % has remained practically unchanged (increasing by only 0.3 %) even though renewable energy consumption has risen by 30 %, since final energy consumption is rising at the same rate. Biomass represented the largest share of renewable energy source with of 13 % in the world's energy supply followed by hydropower with 3 % and other renewables (solar, wind, geothermal and tidal etc.) with 2 % (Fig. 4).

In 2016, the primary supply of energy in the EU was 0.75 bn toe (5 % of global primary energy production). Nuclear energy accounted for 29 % in primary energy production, followed by renewable energy sources (28 %), coal (17 %), natural gas (14 %), oil (10 %) and non-renewable wastes (2 %). Biomass accounted for 18 % and other renewable resources for 10 % (hydropower 4 %; wind 3.5 %; solar 1.5 % and geothermal 1 %). Renewable energy sources overtook coal in primary energy production for the first time and will probably overtake nuclear energy in the short term (Fig. 5). Despite the rapid growth of other renewable resources, bioenergy is projected to remain the main renewable energy source in the long term. If the EU wishes to reach a net-zero emissions economy in 2050, fossil fuels will need to be phased out and the energy supply provided by renewable energy sources, primarily biomass [28].

The ratio between net imports and gross available energy indicates the import dependency for energy. Between 2005 and 2016 the import dependency for all fossil fuels ranged from 52 % to 54 % in the EU [21]. Final energy demand in the EU in 2016 was 1.1 bn toe (13 % of global gross final energy consumption). The share provided by oil was 39 %, followed by natural gas (22 %), renewable energies (17 %), nuclear 18 % and coal (4 %). Since 1990 the share of coal has fallen but the share of renewable energy sources has increased significantly (Fig. 6). The EU has set a target of a 20 % renewable energy share (RES) to be reached by 2020. In 2016 the RES in gross final consumption of energy was 17 % (in heating and cooling 19.1 %, in electricity 29.6 %, and in transport 7.1 %). The share of biomass in renewable sources accounted for 10.5 %, of which 75 % was used for heating/cooling, 13 % for bioelectricity and 12 % for transport Eurostat [17]. For 2030, a RES of 32 % is binding at the EU level.

The role of the bioeconomy in the EU with special attention to the chemical industry

In 2015, the bioeconomy in the EU achieved a turnover of €2.3 T, of which the bio-based industries accounted for 26 %. According to estimates, the food sector represented the highest share (50 %), followed by

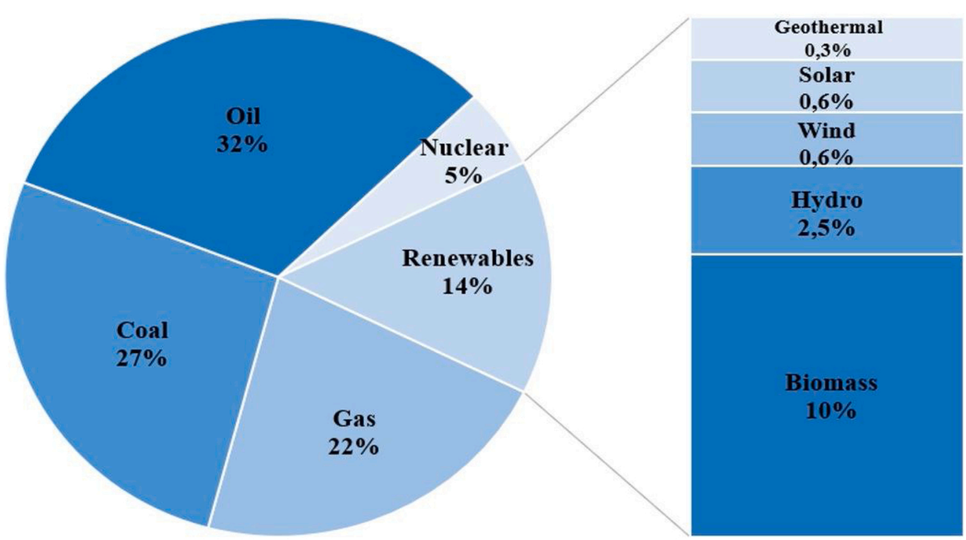

Fig. 3. Global energy supply by fuel in 2016 (%). Sources: REN21 [25]; WBA [26]; IEA [27].

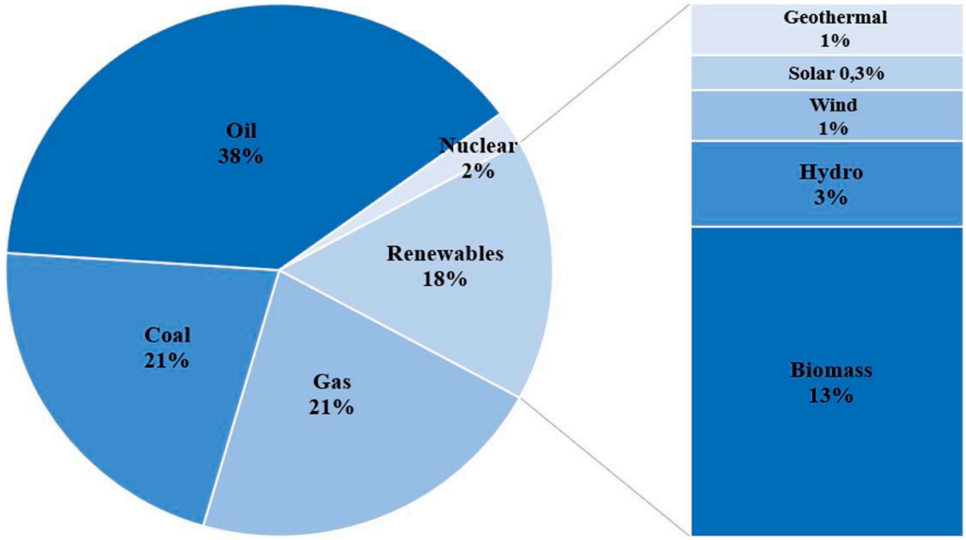

Fig. 4. Global gross final energy consumption by fuel in 2016 (%). Sources: REN21 [2]; WBA [26], IEA [27].

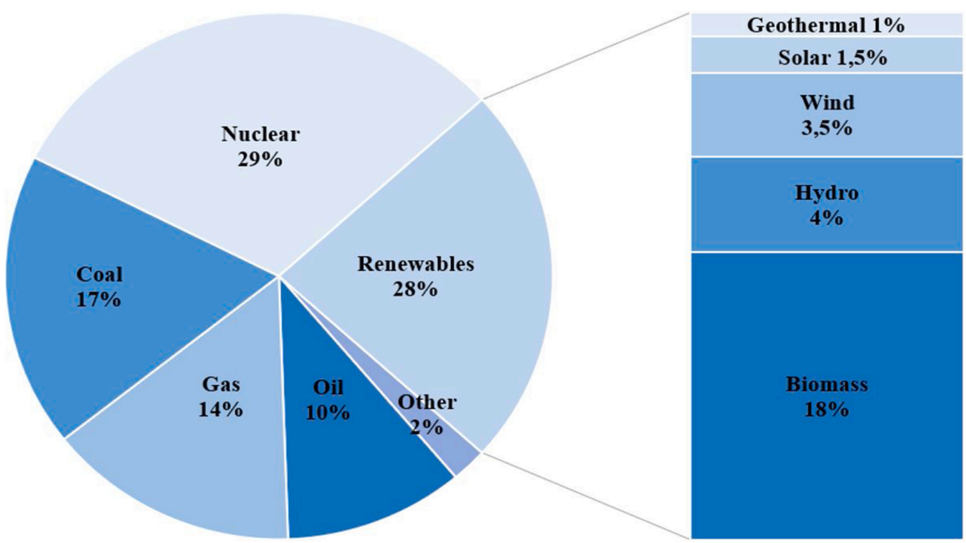

Fig. 5. Primary energy production by fuel in the EU-28 in 2016 (%). Sources: Bioenergy Europe [29]; European Commission [21].

agriculture (17 %), production of paper (8 %), and other sectors. The overall share of the food, agriculture, fishery and forestry sectors amounted to 75 % of total turnover. In 2015 an annual growth rate of 13–26 % was generated in the production of biochemicals, bio-electricity, and rubber and bioplastics [3,23,30]. Furthermore, the bio-economy contributed 4.2 % to the GDP in 2015. Two thirds of value added was generated by the agriculture and food sectors, followed by the production of biochemicals, pharmaceuticals, plastics and rubber (9 %), wood products (8 %), paper (7 %) and textiles (5 %). The EU bio-economy employs around 18 M people, of whom 80 % work in the agriculture, forestry, fishery and food sectors. EU Member States have a high share of jobs in the bioeconomy with a comparatively low added value due to a high rate of employment in the less productive sectors. Due to the ongoing restructuring of agriculture the number employed in this sector has declined. This is the main driver of decreasing employment in the bioeconomy. Nevertheless, in the bio-based industries one million new jobs could be created by 2030 [30].

World chemicals turnover accounted for €3.347B in 2018. The EU chemical industry ranked second after China, with a share of 17 % and sales of €565B. Chemicals represent the fourth ranked sector with 7.6 % of EU manufacturing turnover accounting for 3.3 M employees. Global chemical sales expanded three times in value between 1998 and 2018, while the relative share of the EU chemicals market halved due to increased competition from other regions. The EU is the largest chemical exporting and the third largest chemical importing region in the world, with a positive trade balance [31]. Investment in biochemicals production capacity is starting to increase from a very low base. Bio-based surfactants and solvents are the most important bio-based products utilized in chemistry; however, production of biopolymers and bio-based plastics is expected to grow at a higher pace. On the other

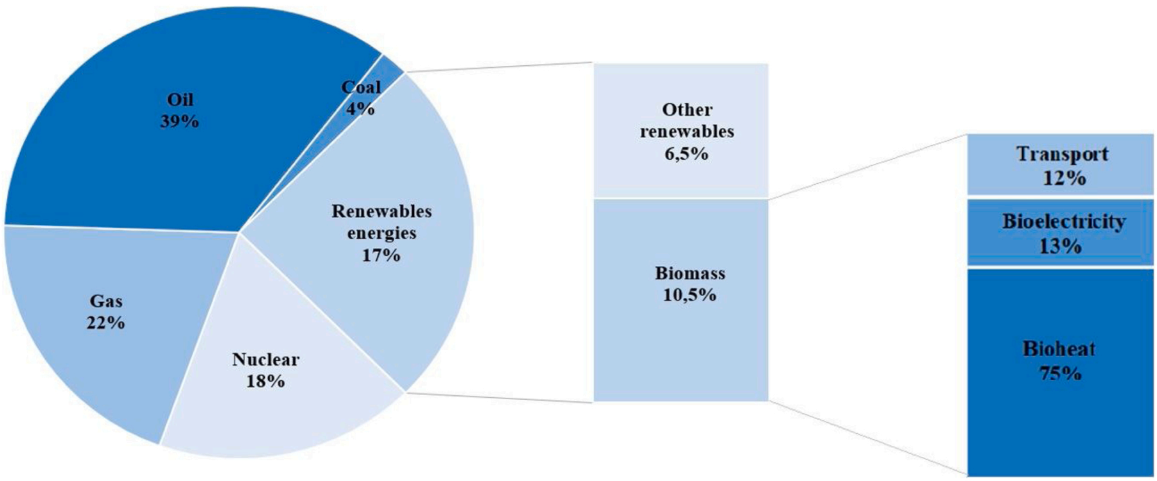

Fig. 6. Gross final energy consumption by fuel in the EU in 2016 (%). Sources: Bioenergy Europe [29]; Eurostat [30].

hand, rapid technical progress can also be seen in the USA, Brazil and Asia with abundant sugar and starch feedstocks.

In the EU, 10 % of the total volume of organic chemicals raw materials/feedstock used for chemicals production is bio-based. Bio-based feedstock use is expected to increase to 25 % by 2030. According to estimates, 1.6 M tons (mt) of starch and sugar, 1.6 mt of vegetable oil, and 0.6 mt of bioethanol and natural rubber, chemical pulp and glycerol are used for chemical production. As agricultural raw materials, 13.6 mt of wheat, 22.5 mt of coarse grains, 3.9 mt of molasses and 4.4 mt of oilseeds are used for industrial applications. This amount is quite low compared to the total biomass supply of over 1B tons of dry matter and agricultural crops of over 500 mt. The biomass demand for biochemicals in 2030 is still projected to be much lower than the demand for bioenergy or biofuels [32,33]. According to Eurostat, by 2015 out of 534 products the number of fully or partly bio-based products had increased to 110 (NACE Division 20: Manufacture of chemicals and chemical products). About 80 % of the products in the NACE Division 20 were non bio-based, 20 % were fully or partly bio-based and the share of fully bio-based products was just 8 % [32,34].

The chemical sector in the EU has a positive trade balance, even with increasing global competition. For bio-based chemicals, abundant feedstocks of sugar, starch, vegetable oil and ethanol are needed. EU trade in total agricultural products shows a slight deficit; however, the trade balance for sugar is positive, but negative for coarse grains (starch), oilseeds (vegetable oil) and ethanol etc. North- and South-America, and Asia with sufficient feedstocks will progress even faster in the production of biochemicals.

In the EU, GHG emissions must be reduced to 50 % of 1990 levels by 2030. Furthermore, the EU set a net-zero GHG emissions target and will become climate neutral by 2050, therefore fossil fuels will be phased out and substituted by renewable energy sources. Between 2002 and 2016 final bioenergy consumption grew by roughly 50 % and reached 86.336 M toe (Fig. 7). Data was downloaded with respect to biomass supply, transformation and consumption from EUSTAT, based on the World Economic database DBnomics [35] and the value is given in energy units of toe. The transformation input includes mainly input to conventional thermal power stations, electricity, CHP (combined heat and power) and heating plants [36].

The major suppliers, producers, and consumers, and the best and worst performing EU Member States in the bioenergy sector were

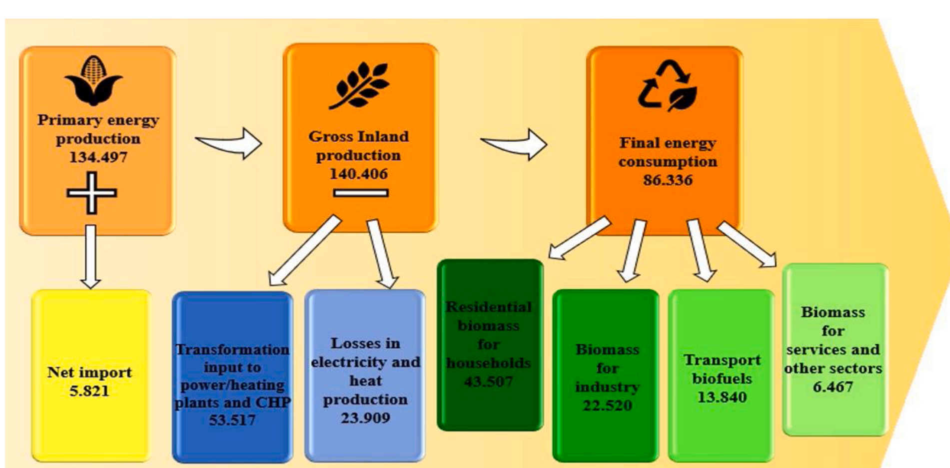

Fig. 7. Use of biomass for energy production in 2016 in the EU (Mtoe). Source: Eurostat [30].

identified. Based on the average data for the period 2002–2016 in the EU, Germany was the leading Member State – followed by France, Sweden, Finland, Italy – in the production of biomass-based energy in the EU. In contrast, Malta, Cyprus and Luxembourg played a negligible role in this area. Among the 'new' EU Member States, Poland, Romania and the Czech Republic deserved mention in primary production as well as final consumption of bioenergy. Germany, the Netherlands and Latvia were the largest exporters of bioenergy, while Italy and the UK were the leading importers. Sweden and Finland had the highest levels of bioenergy in primary production and final energy consumption.

Trends and fluctuations in the three major balance indicators for energy by biomass, namely the gross inland consumption (GIC), transformation input (TI) and final energy consumption (FEC) were examined for all the EU-28 Member States between 2002 and 2016 by using the Yield Stability Index (YSI) and the Ordinary Least Squares (OLS) regression slopes (B) (Table 1). A positive YSI indicates that a given country has an appropriate system and technology related to energy production and consumption and it is well adapted to the environmental and other changing conditions. On the other hand, a negative YSI index illustrates high risks of fluctuations in production and consumption. In the best-case scenario, a country should have lower fluctuations (indicated by the high and positive YSI) and an increasing trend (indicated by the higher regression slopes). GIC increased in several Member States, especially in Malta, United Kingdom, Luxembourg and Cyprus. Growth rates were sustainable and stable primarily in the largest exporters of bioenergy (Netherlands and Latvia). In contrast, Portugal showed a downward trend in FEC. Slovenia, Lithuania, Cyprus and Belgium need to improve their technology in order to reduce risks of a lower adaptability to changing conditions. Stronger trends and higher regression slopes can be observed in TI particularly in Croatia, Malta and Bulgaria. Growth rates were rather sustainable in TI compared to GIC and FEC, first of all, in Romania and Spain. Based on the YSI, growth rates in GIC and FIC as well as TI proved to be sustainable, with production technology well suited to the changing conditions of the country, and the existing technology can maintain the yield trends with lower fluctuations in most of the Member States. The strongest increase and the lowest technological risk can be observed in TI.

Table 1
Yield Stability Indices and regression slopes of GIC, TI, FEC for the EU-28 between 2002 and 2016.

	GIC		TI		FEC	
Country	YSI	B	YSI	B	YSI	B
Belgium	0.40	1.60***	0.27	1.62***	−0.24	1.91***
Bulgaria	0.27	0.91***	0.53	3.80***	0.47	1.02***
Czechia	0.40	1.12***	0.13	2.07***	0.59	1.06***
Denmark	0.40	0.84***	0.53	0.87***	0.59	1.03***
Germany	0.40	1.24***	0.53	1.76***	0.35	1.14***
Estonia	0.27	0.64***	0.40	1.97***	0.35	0.10
Ireland	0.27	1.35***	0.27	2.33***	0.12	1.33***
Greece	0.00	0.37**	0.53	1.38***	0.35	0.35**
Spain	0.13	0.64***	0.67	0.94***	0.47	0.63***
France	0.40	0.61***	−0.13	1.33***	0.59	0.45***
Croatia	0.53	0.15*	0.53	4.28***	0.71	0.12
Italy	0.40	1.35***	0.00	2.07***	0.00	1.54***
Cyprus	−0.13	1.65***	0.00	1.09***	−0.12	2.09***
Latvia	0.53	0.30***	0.40	1.37***	0.47	0.12
Lithuania	0.40	0.67***	0.53	2.05***	−0.35	0.15*
Luxembourg	0.27	1.81***	−0.40	1.67***	0.47	2.35***
Hungary	0.40	1.35***	0.40	1.36***	0.35	1.63***
Malta	0.40	4.28***	0.27	4.16***	0.47	4.91***
Netherlands	0.53	0.77***	0.53	0.69**	0.00	1.17***
Austria	0.40	0.87***	0.53	1.34***	0.82	0.72***
Poland	0.00	0.97***	0.40	2.48***	0.59	0.64***
Portugal	0.40	0.03	0.53	1.46***	0.47	−0.22*
Romania	0.00	0.43***	0.67	2.04**	0.00	0.55***
Slovenia	−0.40	0.60***	0.53	1.13***	−0.12	0.57***
Slovakia	0.27	1.58***	−0.13	2.69***	0.35	0.22***
Finland	0.40	0.35***	0.53	0.49***	0.35	0.27***
Sweden	0.27	0.51***	0.40	0.53***	0.71	0.50***
United Kingdom	−0.27	1.85***	0.40	1.56***	0.12	2.74***
EU28	0.13	0.89***	0.40	1.37***	0.00	0.80***

GIC: Gross Inland Consumption, TI: Transformation Input, FEC: Final Energy Consumption.
*** $p<0.001$.
** $p<0.01$.
* $p<0.05$.
Source: Authors' own calculation based on Eurostat [30].

From genetically modified to genome edited organisms

Applications of new plant breeding technologies in the EU are lagging way behind other regions in the world in the fields of agriculture and industry alike, with negative implications for the competitiveness of these sectors. Without a change in regulatory approaches, the EU will fall further behind in the use of these technologies [37]. In the past decades extensive and continuous legislative activities gradually laid a solid foundation for the commercial launch of genetically modified organisms (GMOs) to boost the bioeconomy [38]. While some regions abstained from the cultivation of GM crops on political grounds, several others embraced this innovative technology with great economic benefits. Since 1996, the International Service for the Acquisition of Agri-biotech Applications (ISAAA) has continuously monitored a comprehensive set of parameters associated with GM crop cultivation, such as the total production area, the proportion of GM varieties in the total production of a crop, country-level data (where available), yield, traits, trends, and socio-economic and ecological effects. The annually published ISAAA briefs, the latest being issue number ISAAA [39], are of great help in finding and understanding trends in the green biotech sector.

The total cultivated area of 1.7 M ha in 1996 had increased ~113-fold by 2018, to 191.7 M ha. Traditionally, the Americas have embraced biotech crops since their commercial availability, where the proportion of GM crops in total production is over 90 %. On the other hand, Europe and Russia have taken a more reluctant position. In fact, in Europe only two countries cultivate the only authorized GM maize (event MON810), namely Portugal and Spain, and on a relatively small scale.

Four species continue to dominate worldwide GM production: soybean (95.9 M ha), maize (58.9 M ha), cotton (24.8 M ha) and canola (10.1 M ha). In addition, several other GM plants are in production, such as alfalfa, sugar beet, papaya, squash, eggplant, potatoes, and apples. From the trait perspective, the two traditional 'input traits', – insect resistance and herbicide tolerance – are always popular. Recently, radically different input traits have been introduced, mostly aimed at increasing product biomass either directly [40] or by increased tolerance to abiotic stressors (e.g. drought and saline) [41]. In addition to the development of new transformation events, combining or 'stacking' already existing ones in a single plant is another, cost effective way to achieve value added products. Globally, 42 % of the production area is used for growing crops with stacked events. An interesting and relatively new direction in innovation is the development of so called 'output traits' [42]. In contrast to 'input traits' where the benefits are mainly apparent to farmers (i.e. reduced pesticide use, no till practices), 'output traits' usually change the composition of the crop, thus providing direct health benefits to the consumer. Some characteristic output traits are, for example, high oleic acid soybean [43,44], low acrylamide potato [45] or non-browning apples [46].

According to the latest ISAAA estimate, global economic gains contributed by biotech crops between 1996–2018 have amounted to $186.1B. How can this technology be integrated into the bioeconomy, and what can it contribute to sustainable development? Apart from economic benefits, there are many other consequences of GM crop cultivation. 1) Better resistance to pathogens and improved agricultural practices result in increased crop productivity, with 657.6 M tons of extra productivity between 1996 and 2018; 2) GM crops help to conserve biodiversity by saving land from conversion to agricultural fields (183 Mha saved between 1996 and 2018); 3) contributing to the minimalization of pollution by the reduced use of pesticides (671 M kg active ingredients saved between 1996 and 2018); 4) GM crop cultivation reduces CO_2 emissions (by 27.1B kg in 2016); 5) from a socio-economical perspective GM crops help reduce poverty by improving the economic situation of 16−17 M small farmers and their families, characteristically from the poorest regions of the world [47]. All these facets fit perfectly in a sustainable bioeconomy strategy.

The newly adopted genome editing techniques [48] are of great promise and are expected to find their way to crop breeding as well. At this point it is very difficult to estimate the economic impact of these new generation plants on the market. Notwithstanding the great economic potential of genome edited crops, their global adoption pattern seems to follow that of GMOs. While the Americas embraced the new technology, the European Union applies the same regulatory requirements on them as on transgenic plants.

Conclusions

Biomass is at the core of the bioeconomy and the demand for it is increasing worldwide with the transition to a low-carbon economy. The word' biomass' covers a heterogeneous set of categories representing different values and qualities, ranging from waste streams in the paper and pulp industry to high quality food products. Worldwide, 55 % of biomass is used for feed and food products, followed by bioenergy (27 %), and biomaterials (8 %), with other use and losses accounting for 10 %. Due to the limited availability of biomass, food security has first priority over all other uses, but other sectors such as chemical and energy production are also prioritized. The market for bio-based chemicals is still small but growing fast. The use of biomass for energy production reduces dependency on fossil fuels and GHG emissions. Unused and burned crop residues may contribute to sustainable potential use for energy and materials. Increasing use of primary forest residues and dead wood is another biomass resource for energy production, but waste (paper and timber, construction and saw logs) for energy production could also increase in the future.

In the EU, 59 % of biomass is used for feed and food products, followed by bioenergy (21 %) and biomaterials such as wood products and wood pulp (20 %). The total biomass supply in the EU accounts for 9 % of global biomass production. The EU is almost self-sufficient in biomass supply and use but heavily dependent on all fossil fuels, therefore the production of renewable energy and bio-based chemicals (materials) is promoted. In addition, the EU has set a net-zero GHG emissions target for 2050. In the EU, bioenergy consumption was initially higher in the energy and industrial sectors, other sectors became more prominent in later periods. Bioenergy production and consumption are increasing, but both production and use have experienced significant fluctuations since 2002. The chemical sector has a positive trade balance, even with increasing global competition. Bio-based chemicals offer an alternative to chemicals based on fossil materials, for which abundant feedstocks of sugar, starch, vegetable oil and ethanol are needed. In addition, the bio-based raw material demand for bio-based chemicals in 2030 is estimated to be much lower than bioenergy or biofuels, thus the material uses of biomass should be prioritized over energy (and fuels) uses. In addititon to biomass, non-bio-based renewable energy sources (solar, wind, water and other renewables energies) will play an increasing role in reducing dependence on fossil fuels.

Where ultimate limits on availability of biomass are envisaged, questions arise in relation to the principles used in determining the factors for the relative priorities in the use – energetic, material or chemical – of non-food biomass. The economic question is how to balance biomass valorization for energy against conversion into high-value bio-based materials. Nowadays microbial biomass shows a promising future for the development of sustainable materials for different applications. There is also the question of how much biomass is wasted or lost along the various supply chains. From a sustainability perspective, both the direct effects and the indirect effects of any land-use change induced by the rising demand for biomass must be considered, however, sustainability criteria may limit the growth of biomass use for energy.

Declaration of Competing Interest

The authors report no declarations of interest.

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