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Review article

Bioeconomy – present status and future needs of industrial value chains

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ABSTRACT

The necessary reduction of greenhouse gas emissions requires a comprehensive shift from fossil to renewable raw materials. This is accompanied by a fundamental reorganization of the value chains of the energy sectors and large parts of the manufacturing industry. In the long term, bio-based industrial raw materials will be processed preferentially by the chemical industry. In order to use the raw materials as fully as possible, sectors that support cascade use and the recycling of by-products and products after use will gain in importance. These are in particular the waste management and energy sectors, which will be integrated into the circular value chains of the bioeconomy. The industrial realization of these value chains depends essentially on the legal framework conditions, which must be developed further accordingly.

Introduction

The bioeconomy has the task of forming the necessary new value chains for the product groups that are still based on oil, natural gas and coal today, as part of the shift in raw materials from fossil to renewable energy and carbon sources [1]. This is not only about technical aspects, but also about designing each processing stage in such a way that added value is generated and the process chain becomes an economical self-sustaining value chain. Taking into account the planetary limits [2–5], however, it seems unrealistic to replace all fossil-based value chains completely by bio-based alternatives as today the global economy consumes twice as much fossil as biogenic carbon [6,7]. It is therefore important to identify those sectors that are dependent on the bioeconomy's renewable carbon sources. In principle, the energy sector can be largely supplied by carbon-free energy sources [8]. Many materials and chemical products, on the other hand, depend on carbon and priority must therefore be given to the value chains leading to them. Along these value chains, economic and environmental sustainability require the comprehensive use of all components of biomass [9], and processing residuals including CO_2. Due to these processes often being very energy-intensive, the value chains of the bioeconomy and those of energy production must be integrated [10]. The transformation to such a new economic structure is complex and requires investments in infrastructure and production capacities, training in specialist personnel, and the involvement of the population and achieving social acceptance. This process will take decades as the Paris Climate Convention has set the target of achieving climate neutrality before the end of the century [11]. The transition phase in particular is critical and difficult, as on the one hand bio-economic value chains are to be built up, while at the same time they have to assert themselves economically against a still dominant economy based on fossil raw materials. How this process is structured therefore depends to a large extent on the general conditions and how the necessary restructuring of the infrastructure progresses.

Raw material shift until 2050

The Paris Climate Convention has defined the target of limiting global warming to a maximum of 2 °C above the pre-industrial level by 2050 on the basis of a sober assessment of economical costs in terms of ecological impact and restructuring [12,13]. Translated into greenhouse gas emissions, such a temperature increase corresponds to a volume of only 1100 gigatons of CO_2 equivalents, for which emission is still acceptable [14]. Consequently, to keep global warming below 2 °C in the long term, the Paris Climate Agreement calls for a 95 % reduction in greenhouse gas emissions by 2050 compared to 1990 levels. Among the greenhouse gases, CO_2 is by far the largest contributor and therefore reducing this emission is a priority. It is essentially derived from the combustion of fossil carbon and energy sources, which is why the change from fossil to renewable energy and carbon sources is necessary. 189 of the 197 parties to the Convention have ratified the Paris Agreement to achieve this change in raw materials by 2050 [15].

Fossil and bio-based value chains

Fossil raw materials are produced by sectors of the coal, oil and gas industry. Today, 96 % of coal, oil and natural gas are used in the energy

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sector, which in turn supplies the mobility, producing industries, commerce, trade, services, and households. In the EU, electricity, heat and fuels are still predominantly fossil-based (71.5 % of electricity, 80.1 % of heat production and 94.4 % of fuels; 2017 [16]). The chemical industry is even 90 % dependent on fossil raw materials [17,18]. These feedstocks are used both as a source of energy for chemical production processes and as a source of carbon for the diverse products of organic chemistry such as plastics, adhesives, lubricants, surface coatings, household chemicals and more. About 4% of the total fossil carbon consumption is bound in chemical products and another 4% is consumed as energy source in chemical synthesis [19,20] (this is a consumption share of 8% of mineral oil, 1.7 % of natural gas, and 0.02 % of coal [21]). With its products, the chemical industry supplies the value chains of practically all sectors of the manufacturing industry. With bitumen, the building sector also consumes a part of the oil. Taking this materially used oil fraction into account as well, the chemical sector has a share of about 9% in the consumption of fossil carbon sources [22], about half of which is bound in products. Fig. 1 shows the basic value chains of the fossil-based economy, from the sectors producing oil, gas and coal to the diverse industries of the end consumers.

Possible alternatives to fossil raw materials are the various forms of biomass, delivering biogenic energy and carbon sources. Biomass is mainly produced by agriculture and forestry. Fisheries and marine sources also have potential as alternative industrial raw materials, but from today's point of view they play a rather subordinate role. Today, the food industry is the largest consumer of biomass from agriculture, accounting for more than 80 %. Other buyers are the energy sector (14 %) and the manufacturing industry (2%) (Germany, 2017) [23]. More than 52 % of the bio-energy sector is supplied by forestry. The wood-processing industries (furniture, construction timber for the building industry) and the pulp and paper industry account for 48 % (Germany, 2016) [24].

Fig. 2 shows these bio-based value chains. Comparison with Fig. 1 illustrates the overlaps already established between fossil and bio-based value chains in the energy and material use of fossil and bio-based raw materials. In principle, the energies and materials generated today from fossil raw materials can also be produced from biomass. In fact, the production of biogas as a heat source and for electricity generation is an established technology. Combined heat and power plants use wood and straw as energy sources and bioethanol and biodiesel are produced in large volumes for the fuel sector worldwide. In the construction sector, wood is established as a building material and the chemical sector already supplies plastics, lubricants and adhesives, skin care products and pharmaceuticals on a biological basis. A list of seventeen building-block chemicals produced from crop biomass with a global production capacity between 10,000 (adipic acid) and 490,000 (epichlorohydrin) t/year has recently been published [25] (Table 1). Together, the bio-based industries form the value chains of the bioeconomy, which today generates a turnover of €2,300B in the EU and creates 18.1 million jobs. These account for 8.2 % of jobs (EU28) and 4.2 % of the gross national product [26]. In the EU, 4.6 % of fuels, 4.7 % of electricity and 17 % of heat production are bio-based; other renewable energies account for 1% of fuels, 2% of heat and 23.8 % of electricity production (EU, 2017) [27]. In the chemical industry, biogenic raw materials account for 10 % (Fig. 3). When assessing these average figures, however, it should be borne in mind that the bioeconomy in northwestern Europe is generally more developed than in the southern and eastern countries [26].

These examples demonstrate, on the one hand, that bio-based value chains for energy, fuels and chemical products are established, and the fact that production of biobased chemicals has doubled between 2001 and 2018 is a positive indicator [28]. However, the share of total production is still only small; in the EU it is about 4% (Table 1) [10]. The reason lies basically in the fundamentally different structures of fossil-and bio-based value chains. Fossil raw materials are extracted in high volumes globally from only a few highly productive deposits of limited area, and are almost ready to be transformed into large-scale products predominantly for the energy sector but also for the multi-stage chemical sector, and for the construction sector as has been shown in Fig. 1. In contrast, the production of bio-based raw materials requires the decentralised management of very large agricultural and forestry areas, which is of particular importance to the infrastructure and logistics sector because of the associated transport costs. Therefore biorefineries, the integrated biomass processing facilities, are organised in a decentralised way as well. The bio-based value chain is also extended and made more complex by seed and agrochemical sectors involved in early biomass production. Here the energy sector plays an important role as a buyer; it consumes around half of forestry production and one tenth of agricultural harvest. In principle, among the bio-based value chains, the food sector is the most important, consuming over 80 % of agricultural production. The industrial use of agricultural biomass in sectors other than food and energy accounts for only 2%.

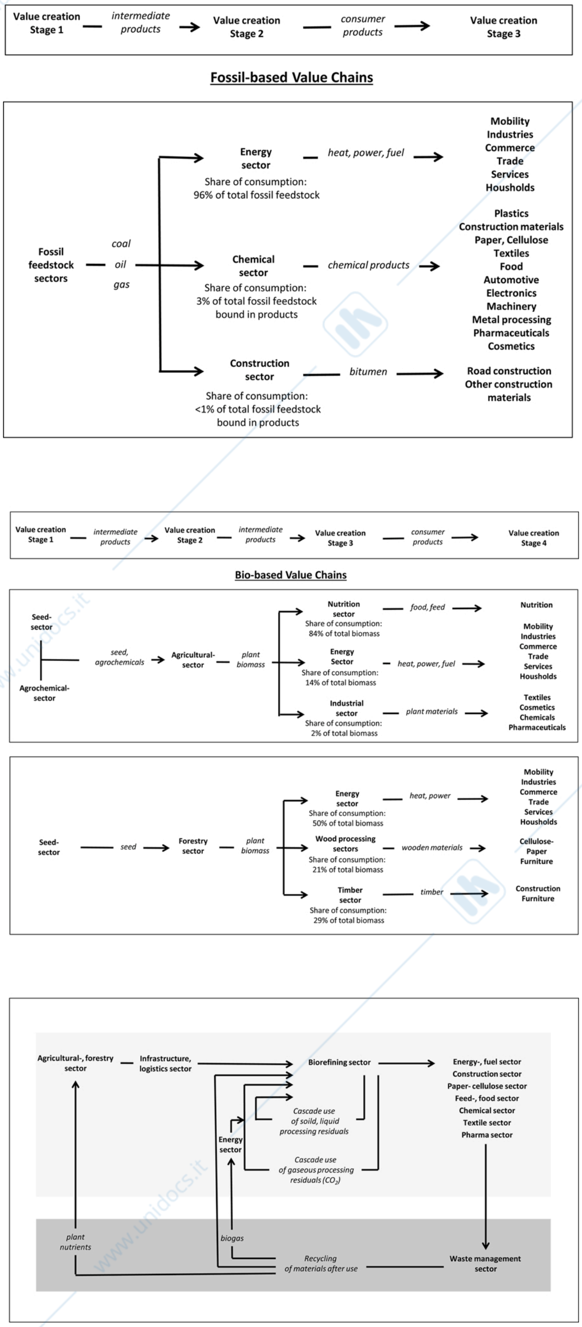

Fig. 1. Value chains based on fossil raw materials and their share in consumption [15–21].

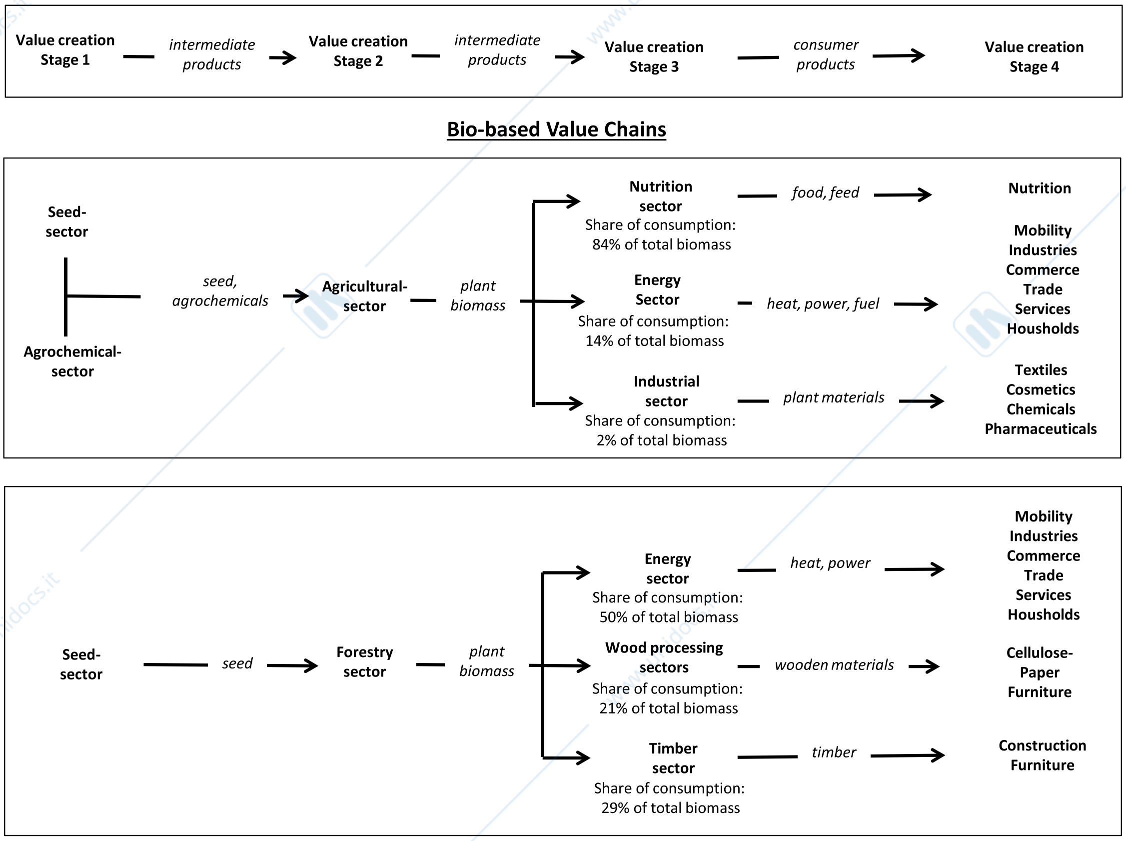

Fig. 2. Value chains from agricultural and forest biomass and their share in consumption [22,23].

Table 1
Share of biobased chemicals (EU, 2015) [28].

Sector	Products	Land area to produce raw materials (1.000 ha)	Percentage of land area whose harvest is processed using a specify method: incineration	chemo-catalytical	bio- technological
Energy	Biogas	1.350			552 %
	Biodiesel	560		229 %	
	Bioethanol	246			100 %
	Solid fuels	11	0,4 %		
Materials	Industrial starch	129		5,3 %	
	Industrial oils	120		5,3 %	
	Medicines, dyes	12		0,4 %	
	Industrial sugar	12			0,4 %
	Plant fibers	2		0,1 %	
		2.442	0,4 %	34 %	656 %

In the course of the raw materials turnaround, all the industries mentioned above are facing enormous change. The producers of fossil raw materials, production of which will gradually be cut back, will practically lose their business basis, thus must be prepared for substantial economic losses [29]. The EU, for example, is planning to reduce the share of fossil fuels to only 5% by 2050 [30]. On the other hand, agriculture and forestry will be confronted with a growing demand for biogenic raw materials. Sectors that have so far not, or only partially, processed biogenic raw materials such as chemistry, textiles, construction etc, must increasingly integrate themselves into the value chains of the bioeconomy, and new competitors for raw materials are emerging for those sectors that have already been bio-based [31].

These are the economic sectors of the value creation chains that will be affected by the shift towards the bioeconomy. Further indispensable components of value chains are industrial site operators, the connecting infrastructure, logistics and waste management. That all together build the general concept of integrated biorefineries.

Value chains develop dynamically

The interaction of the sectors can be understood as a network whose nodes and interconnecting meshes will change fundamentally as the bioeconomy evolves. Nodes can be understood as industrial locations where different industries form interfaces and are synergistically integrated into each other. To stay in the picture, the meshes are represented by the connecting infrastructure and logistics.

Today, this global production network shows a few very large nodes in the production of fossil raw materials, because the production sites for crude oil, natural gas and coal are concentrated in a manageable number of very rich deposits. Important regions for the production of oil and gas are Russia, the Middle East, West Africa and North America [32]. Coal is produced predominantly in China, India, USA, Indonesia and Australia [33], among others. In some cases, these nodes have integrated forward to very large refinery and chemical sites where fuels, basic chemical products (ethylene, propylene, butadiene, benzene, toluene and more)

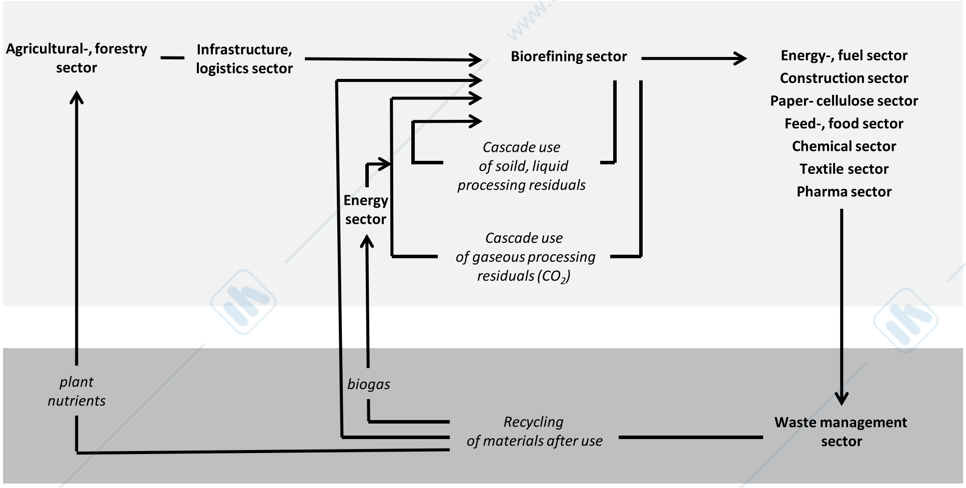

Fig. 3. Sectors involved in a circular bioeconomy.

and bitumen are produced. A significant example of a very large site where fossil fuels are extracted and processed is Jubail in Saudi Arabia. Other locations are connected to the raw material producing regions over very long distances by pipelines and tankers. Examples include Houston (USA), Shanghai (China), Jurong (Singapore), and ARRR (EU; Antwerp in Belgium, Rotterdam in The Netherlands and the Rhine-Ruhr region in Germany). These locations are characterized by very large processing capacities that can fully exploit the advantages of the "economy of scale". From the producers of basic chemicals, the value chains extend to the producers of plastics and special and fine chemicals, which finally supply the processors of the sectors mentioned in Fig. 1. One could describe this picture of raw material production and processing into fuels, chemical products and construction materials as a "black network" of global reach.

A comparable "green network“, which starts from biological carbon sources, also covers the world. The production of raw materials is in agriculture, forestry and the marine sector. The production areas here are extensive and distributed worldwide [34]. Due to the lower energy and carbon density of the harvested biomass compared to fossil raw materials, the volume of raw materials to be processed is correspondingly larger and thus the distances for the connecting logistics, whose capacities cannot be expanded endlessly, are limited to shorter distances [35–37]. Consequently, the nodes, i.e. the capacities of the processing biorefineries, are much smaller. The "green network" is therefore rather more closely meshed and regionally pronounced [38,39].

The meshes of both, the fossil- and the biobased networks, are still largely linear from the nodes of raw material production, through processing into consumer products and to disposal. Therefore the majority of the products are not recycled after use. Worldwide, a large proportion of the products are disposed of in landfills. In the EU(27) for example on average 60 % of waste is disposed of in landfills, although the data for the individual countries varies greatly. They range from no landfill in Western European countries to almost 100 % in Romania. Even in the case of recycling, energy recovery, not material use is the standard. In the EU(27) an average of 43 % of the waste volume is recovered energetically, with the share in Western Europe even reaching 70–80 % [40]. Recycling including composting of biogenic waste is even worse. At best 40–60 % are treated in this way even in Western Europe [40,41]. A similar situation applies to sewage sludge from wastewater treatment [42] and very likely for fermentation residues from fermentative production processes as well. Thus, only a very small part of the carbon contained in the products is returned to the production cycle by the waste management industry.

Nevertheless, the two networks, the black and the green, already partially overlap and complement each other. The degree of overlap is, however, for the time being only small, as Fig. 3 for energy, fuel and chemicals has shown, although climate protection requires the raw material shift from fossil to renewable resources to be largely completed by 2050. This poses an enormous challenge for all players in the fossil-based and bio-based value chains. The current producers of fossil raw materials must develop new business models and the processors of coal, natural gas and crude oil must switch to other, including bio-based, raw materials [43,44]. This is not without consequences for the producers and processors of bio-based raw materials, because they will face competition for the raw material base with the existing fossil-based value chains.

It cannot be stressed enough that the global economy consumes much more fossil than biogenic carbon. Coal (7.8B tonnes [45]), oil (4.0B tonnes [46]) and natural gas (4.0B cubic meters [47]) together supply 12B tonnes of fossil carbon annually worldwide. Another 6−7B tonnes of biogenic carbon are produced by agriculture and forestry [48]. In view of the increasing demand for food for the growing world population, the already partially damaged ecosystem services and the planetary limits to be observed, it would be extremely challenging to replace the volume of fossil carbon consumed annually today by raw materials based sustainably on primary biomass. Rather, (i) priorities should be set for the use of biogenic carbon, i.e. carbon from primary biomass, residues from its processing and the recycling of biobased products after use. Furthermore, (ii) biogenic carbon sources should be used as completely as possible through coupled and cascaded use [49], and (iii) carbon should be recycled not only through the natural carbon cycle but also in a technical cycle [50]. These conditions for the use of renewable carbon sources will develop future interfaces between different carbon processing industries and offer the potential for the development of new value chains.

Fossil and bio-based value chains are quite different

The optimization of biobased value chains is one option to relieve the burden on them; another is to consider whether there are other than bio-based alternatives for previously fossil-based value chains. In fact, it is not at all necessary to serve all product areas of the fossil-based economy through the bioeconomy; this applies above all to the energy sector. To a large part the energy sector can fall back on carbon-free energy sources (solar, wind, hydro, geothermal and nuclear energies) [30]. Only parts of the fuel sector, in particular aviation, will remain dependent on carbon-based fuels for the foreseeable future, because only they provide the necessary energy density [51]. Among the new industries to be developed for biogenic carbon sources, the chemical industry in particular is dependent on carbon sources [51], because by definition the products of organic chemistry contain carbon; there is no alternative to this element. The development of the new value chains for the bioeconomy should therefore give priority to chemistry. In a biorefinery cascade concept focused on value added products, energy, fuels and building materials are apparently only of secondary importance, since they are virtually supplied as part of the coupled and cascade use [52]. For example, CO_2 can be used as a carbon source for bioethanol [53], waste oil as a starting material for biodiesel [54], the organic fraction of municipal waste as feedstock for platform chemicals [52], and lignin as a raw material for bio-asphalt [55].

If one looks at the existing value chain for chemicals, the translation into a bio-based value chain initially appears to be less challenging. Up to now, (i) crude oil has been produced, (ii) fractionated into basic chemical products in the refinery, and (iii) further processed by chemical companies into the diverse products of this economic sector by means of chemical catalysts. In this admittedly simplified presentation, three main value-added stages lead to chemical products. In the bioeconomy, the raw material crude oil would be replaced by biomass produced by agriculture. Biomass is also fractionated by extracting sugar from sugar beet or sugar cane or by pressing vegetable oils from oil seeds. In the third step, the chemical industry uses biotechnological methods to transform sugar and vegetable oils into chemical products. At first sight, this value creation chain seems as simple as the fossil-based model. Only on closer inspection do fundamental differences become apparent.

First, the fossil-based value chain is to be examined more closely as a benchmark. Although the production of crude oil and natural gas is more complex and more expensive today than it was a few decades ago, it is still cost-effective in terms of market price [56]. Although the quality of the raw materials differs from region to region, the differences are in principle only slight. Transportation to the refineries for further processing by pipeline and tanker is technically simple, which is why a highly efficient global logistics infrastructure has developed. Processing into fuels and chemical products in the refineries is not technically complex and is also advantageous because the carbon content of these raw materials is very high at 70–85 % [57–59]. Furthermore, an oil refinery operates without residual materials, because all oil fractions have a commercial use in the energy (electricity, heat, fuels), chemicals and building materials sectors.

So what does the bio-based value chain look like on closer inspection? The production of raw materials already consists of a large number of value creation steps. In contrast to oil production, farmers cannot harvest the raw material biomass directly, but have to resort to upstream value creation stages at the manufacturers of seeds, fertilizers and pesticides. The areas to be cultivated are distributed worldwide, are subject to very different climatic conditions and result in biomass of a wide variety of plant varieties. Because of the large areas involved, the logistics of biomass harvesting are complex. This is not the only reason why it requires processing at a short distance from the production region. The limited shelf-life and consequently costly storability of biomass also requires short transport routes to the biorefinery. In the biorefinery, the biomass is fractionated into its many components. The protein fraction is predominantly used in the food and feed sectors, but the economically most important target products for other industrial purposes are sugar, starch and vegetable oils. The water content is often very high; freshly harvested sugar beets, for example, contain around 20 % sugar, 5% beet pulp and 75 % water [60]. All biomasses also contain lignocellulose to a greater or lesser extent. The protein content of biomass also varies; soybeans, for example, contain a lot of protein, so that these fruits are important sources of both oil and protein. Biomass therefore consists of very different components, which should not only be used as fully as possible, but also according to its highest potential to generate value. This is exactly the basis of the biorefinery concept, which aims to fully utilize biomass in terms of both material and energy [61].

The first step in biomass processing is fractionation into the various components, whereby the processes are geared to the respective target products protein, carbohydrates, starch or oils. All processes separate the water contained in the crop. This water is highly polluted organically and must be disposed of; at best it goes into biogas fermentation and is thus energetically used for the production of heat and electricity. What remains is the residue from biogas fermentation, which in turn must be disposed of. Uncontaminated sewage sludge is used as fertilizer in agriculture; otherwise it is used to generate energy in waste management [62].

Another by-product of fractionation is biomass. In the processing of sugar beet, this is the leached beet pulp that is commercialized as animal feed. Sugar cane provides leached cane (bagasse) that is used to generate energy. Starch is extracted from potatoes, corn, wheat and other cereals. The residual biomass of potatoes (pulp) and corn can be used as animal feed; that of cereals is largely used to generate energy. The press cakes of oilseeds, which remain after oil pressing, are rich in protein and also go into animal feed. The industries involved in the fractionation of biomass are therefore sugar refining, oil mills, animal feed production, energy management, waste disposal and fertilizer management. If starch is also included in the production of sugar, other industries come into play. On an industrial scale, starch is enzymatically split by amylases to form mono-sugar, which means that the enzyme production industry is also involved. Further enzymes are needed when lignocellulose is used as a source of sugar and is saccharified. In this case, another by-product is lignin, most of which is now used to produce energy and a small proportion as raw material in the chemical industry.

Cascade use and recycling

The extraordinary variety of by-products of processing of proteins, carbohydrates and oils has an important impact on other industries. In the fuel sector, for example, the chemical-catalytic production of biodiesel from vegetable oils leads to the by-product glycerine, which finds buyers in the chemical industry. The catalysts for the chemical-catalytic production of biodiesel are in turn provided by the chemical industry.

The fuel bioethanol and many chemicals are produced biotechnologically on the basis of sugar and vegetable oils. Fermentation processes lead to fermentation residues from the biomass of the microorganisms in the production process and to CO_2. Within the framework of cascade use, the fermentation residues are at best used as animal feed, otherwise they are used to produce energy or, in the case of genetically modified organisms (GMO), disposed of by waste management. The vast majority of CO_2 is released unused into the atmosphere; only a very small proportion is used in the beverage and chemical industries [63]. This carbon loss in the form of CO_2 is largely due to the cellular energy production of microorganisms for their metabolic performance in biotechnological processes. Although fossil-based processes also lead to energy-related CO_2 emissions and thus carbon losses, these can be avoided by using emission-free energies. This does not apply to the generation of the metabolic energy of microbial production systems.

The utilization rate of carbon from biomass in fermentation processes is therefore basically comparatively low. In relation to the carbon source sugar, fermentation processes usually find less than 50 % of the biomass carbon in the target product. This also explains why the European chemical industry uses 10 % bio-based raw materials [64], but only 4% of its products are bio-based [28]. This is because on average, only half of bio-based raw materials consist of carbon, which in turn is only partially transformed into products.

In summary, it can be said that, according to the state of the art, biomass is only partially utilized by means of coupled and cascade utilization. The rest is mainly CO_2 and is emitted into the atmosphere.

An optimized carbon yield, and thus also an extension of the value chain, can only be achieved by intensifying the use of materials and involving other sectors. In fact, numerous projects are on the way to utilizing biomass processing residues that have not been used or have only been used for energy purposes. In the Netherlands, for example, the suitability of lignin as a component of road surfaces for car traffic has been tested very successfully for several years [65]. Still in the research stage, but promising, is the conversion of lignin into important basic aromatic chemicals [66]. The lignin used here has the advantage of being a comparatively pure residual material from paper processing or wood saccharification. Other residues are of such a complex composition that they are only suitable for biogas fermentation. According to the state of the art, biogas is used to produce energy. However, the methane contained in biogas could also develop potential as a carbon source for the chemical industry, just like the fossil alternative of methane in natural gas. Biogas fermentation can therefore act as a standardization method for complex residues. In this way, residues from fermentation processes and sewage sludge from wastewater treatment can also be used. For sewage sludge, which in the EU is increasingly not permitted to be spread on agricultural land because of reduced limits for contamination, options for recycling into chemical products are being investigated. Since wastewater treatment and biogas fermentation are part of the waste management sector, the industrial sector that is essential for closing the technical carbon cycle of value creation chains in the bioeconomy is named here. Waste management is also responsible for the recycling of consumer products after use. In order to intensify recycling here, basically two strategies are possible. On the one hand, suitable product design can facilitate the separation of product materials and thus recycling [[67,68]; non-separable products can alternatively be degraded to synthesis gas by gasification. The CO contained therein can be used as an energy or carbon source. In Belgium, the first production-scale plant is currently being built that uses gas fermentation to convert CO into ethanol [69].

CO_2 is a carbon-containing gas that occurs in large volumes in value chains of the bioeconomy. Many fermentative production processes emit CO_2. In bioethanol fermentation, for example, the conversion rate of sugar is only 48 %, the rest is largely lost as CO_2 [70]. The same applies to the utilization of residues through biogas fermentation and wastewater treatment. Biogas contains 25–35 %, sewage gas 20–35 % CO_2 [71]. CO_2 is also produced at the municipal waste disposal stage when products are incinerated after use for energy recovery. There are several options for the use of CO_2. The most obvious is the natural carbon cycle, which uses atmospheric CO_2 to build up biomass through the photosynthetic biosynthesis of plants and algae. Reactors for the cultivation of algae can also be directly supplied with $CO_2$by an emission stream from a technical plant [72]. In this case the release of the greenhouse gas into the atmosphere is avoided; the carbon is kept in a technical cycle. The energy source for the reduction of CO_2 is in both cases sunlight. Alternatively, CO_2 can be reduced microbially to methane using H_2 as a reducing agent. The world's largest plant for converting CO_2 into methane is currently being built in Switzerland. The fact that the technology provider is the spin-off of a manufacturer of heat-generating equipment [73] shows the unusual interfaces that new value chains can create. CO_2 is also the carbon source for artificial photosynthesis. In Germany, a chemical company is currently building a pilot plant that will produce butanol and hexanol [74]. What both processes have in common is that they rely on the feeding of H_2, provided by means of water electrolysis, which requires a high energy consumption. It is thus foreseeable that another interface will gain in importance for the value-added chains of the bio-economy, namely that with the energy sector.

Integration with the energy sector

A study carried out for the German chemical industry even concluded that the widespread use of such technologies can develop CO_2 into one of the most important carbon sources for chemical products in the long term [28]. A prerequisite would be the expansion of renewable power generation by a capacity equivalent to today's complete power generation [28] and would mean at least a doubling of power generation. The future will show whether CO_2 will become so important as a carbon source for chemicals, but in any case it is foreseeable that the integration of the bioeconomy into the energy sector will become increasingly important. On the one hand bio-energy and bio-fuel will contribute to the energy sector and on the other this sector relieves biomass sectors by providing the energy necessary for the recycling of CO_2. In this context, it must be taken into account that with the increasing share of renewable energies, processes are required that tolerate a volatile energy supply, as is typical for solar and wind energy. Power peaks, which are also characteristic of volatile energies, that cannot be used immediately, can be used to produce H_2 by water electrolysis and with it CO_2 is to be reduced to methane. In fact, microbial methods transforming CO_2 to methane tolerate such a volatile H_2 supply [75]. In this way, electricity can literally be stored in the form of methane. In addition, the raw material efficiency of biomass valorized is improved because CO_2, the by-product of most biotechnological processes, is utilized. For the complex coordination of the volatile energy supply with the points of consumption, the cross-sectional technology of digitalization can develop into an important field of application, thus integrating another sector into the bioeconomy.

Necessary infrastructure

The future value-added chains of the bioeconomy will therefore involve a wide range of sectors, which can be assigned to biomass production, the diverse manufacturing industry, the construction industry, the energy sector and waste management. In order to raise this potential, it is necessary to link the sectors by means of a suitable private and public infrastructure. This applies in particular to the logistics of raw materials, intermediates, residual and waste materials and, last but not least, energy, which, as just mentioned, must be supplemented by an infrastructure of digitalization. Even today, biomass is already a bulk commodity which is produced, stored, transported and processed on a large scale. Wheat, maize, rice and oil seeds are traded worldwide with a total volume of 1B tons (2017) [76]. One could therefore get the impression that for the additional biomass needed for industrial use, the existing infrastructure would only have to be expanded to meet future demand. While it is true that the existing infrastructure can be built on, it is also true that the future bioeconomy will fundamentally change the infrastructure that still serves a fossil-based economy today.

This applies locally, regionally and nationally. Local industrial locations must prepare themselves to deal with raw materials of lower carbon and energy density compared to fossil feedstock. Loading and unloading facilities and storage facilities may therefore have to be adapted to a larger volume requirement. For example, converting a coal-fired power plant to wood as an energy source means handling a fuel volume that is about twice as great as that of coal, because wood has only 60 % of the energy density of coal [77].

Regionally, raw materials have to be transported to the processing site. The challenge that this poses for logistics can be demonstrated using the example of an oil refinery in Germany. This refinery uses crude oil to produce fuels and basic chemicals for BASF's chemical site in the vicinity. The refinery is supplied with crude oil via a pipeline that connects it to the seaport of Bremerhaven, almost 600 km distant. The refinery has a processing capacity of 17 M metric tons of crude oil containing approximately 14.5 M metric tons of carbon. If this volume of carbon were to be delivered in the form of sugar, 33 M tons of sugar would be required, a volume more than six times the amount of sugar produced in Germany in 2018/2019, not counting the carbon losses of biotechnological processes.

This consideration also illustrates the dimension of the raw material volumes to be handled in the future bioeconomy. They are very large and the demand will not only have to be met from regional sources, but will also develop links between international biomass regions in North and South America, Russia and Southeast Asia and the industrial centers in North America, Europe and China. After local and regional logistics, this is the third dimension of infrastructure to be developed.

The role of biotechnology

Biotechnology plays a central role in these value chains. Biotechnological methods of plant breeding enable the targeted development of plant varieties adapted for industrial use. Compost, sewage sludge and fermentation residues are biotechnological fertilizers. Acidification by microbial silage plays an important role in the storage of biomass [78]. When it comes to obtaining the raw material sugar from biomass, enzymatic processes are part of the saccharification of starch and lignocellulose [79]. Fermentation processes are the basis for the production of fuel (bioethanol), food additives such as vitamins, animal feed supplements such as amino acids, biopolymers (lactic acid for poly-lactide, PLA), skin care products (sphingolipids) and pharmaceutical agents (monoclonal antibodies) [80]. Composting and wastewater treatment by bacteria and fungi are central to the disposal of biomass [81]. Biogas fermentation is a bridge to energy production [82] and is also a method for standardizing complex carbon sources, which is the only way to recycle them as raw materials. There is also potential for biotechnological recycling of CO_2 if energy is available in the form of sunlight for photosynthesis or in the form of electricity for gas fermentation and technical photosynthesis [83] (Fig. 4).

The importance of biotechnology in the production of bioenergy and bio-based materials and chemical products is illustrated by the example of Germany where the harvest of two-thirds of the area under cultivation for energy and industrial plants is further processed using biotechnology (2018; Table 2; land area data [84]). Biotechnological processes such as enzymatic catalysis and fermentation are often combined with other technologies. Examples are the physical-thermal pretreatment of lignocellulose prior to enzymatic saccharification [85] or the chemo-catalytic polymerization of lactic acid produced by fermentation to the bioplastic PLA [86]. It is therefore foreseeable that the new value creation chains of the bioeconomy will increasingly use biotechnological processes, but will by no means displace physical-thermal and chemo-catalytic methods. Developers of new processing technologies for the bioeconomy should therefore be prepared to combine biotechnological with physical-thermal and chemical methods.

General conditions

So far, feedstock supply, biorefineries, raw materials and processing technologies have been discussed. These technical aspects and elements are certainly indispensable for the realization of the bioeconomy. However, political framework conditions are just as important for the development of bioeconomic value chains [87,88]. An important element of the framework conditions designed to reduce greenhouse gas emissions is the European Emissions Trading System (EU ETS) introduced in 2005 [89]. It obliges operators of more than 11,000 energy-intensive plants in the power generation and processing industry, as well as airlines, to buy rights to emit greenhouse gases from energy production (SCOPE 1 emissions [90]). These installations are responsible for around 45 % of the EU's greenhouse gas emissions, including from the chemical industry. The number of emission allowances is reduced by 2.2 % per year [91]. This also means that the total volume of permitted emissions will be reduced annually. Companies that continue to emit must buy corresponding rights on the market; those that have reduced their emissions can sell emission rights that are no longer needed. Since 2017, the price has risen from €5 per tonne of CO_2 equivalent to €29 today [92]. A gradual increase to up to €100 is expected by 2050. In this way, the total volume of emissions will be reduced annually on the one hand, and on the other hand emissions will be saved where it is technically possible and economically attractive.

Table 2
Share of farm land producing biomass to be processed by different methods (and area data [22]).

	Production		
Products	total	biobased	
	[1000 t]	[1000 t]	[%]
Plastics/Polymers	71.000	1.130	2%
Adhesives	8.580	86	1%
Man-made fibers	5.404	627	12%
Solvents	5.000	0,5	0%
Lubricants	3.900	627	16%
Surfactants	3.500	1.100	31%
Agrochemicals	1.800	0,5	0%
Cosmetics	1.263	556	44%
Paints, Coatings	882	164	19%
Total	101.329	4.291	4%

In fact, emissions from the chemical industry have fallen significantly and numerous companies have announced their intention to produce in a climate-neutral way. On closer inspection of the measures announced, the companies will in future concentrate on the use of renewable energies and thereby want to reduce SCOPE 1 emissions. A switch to renewable sources of carbon for the carbon contained in the products has not been announced, although this carbon will also be released into the atmosphere sooner or later as part of product disposal. However, those emissions are not attributed to the chemical industry, but to the waste management industry, which is not subject to the ETS. It must therefore be noted that the current framework conditions only partially encourage the chemical industry to change raw materials. The ETS also stands in the way of the recovery of emission gases because it covers SCOPE1 emission gases regardless of whether they are recovered or not. Companies that recycle the CO_2 of their emissions must therefore still buy emission rights.

There is an urgent need to adapt the framework conditions to the state of the art in such a way that they support the unfolding of the value chains from the production and recycling of sustainable carbon to the chemical product and its disposal. It is the task of politics to formulate the framework conditions in such a way that they can find the acceptance of economic actors from industry to consumers under different cultural conditions [89,93–95], do not overstrain natural resources, even in the long term [96], and include impact assessment [52] as well as monitoring systems [97]. Because many economic, ecological, social, political and cultural aspects overlap and must be taken into account in the development of bio-economic strategies with global reach, a comprehensive global diplomatic approach, a biodiplomacy, has recently been called for [98].

Conclusions

The integration of previously fossil-based industries has the potential to bring about considerable changes in the value chains of the bioeconomy. It will need interlocking innovations not only along the value chains, as mentioned in previous sections above, but also across boundaries as shown in Figure 5, requiring large-scale and long-term investments, for example in molecular and engineering aspects of improved and novel bioprocesses. The agriculture and forestry sectors are confronted with a considerably increased demand for bio-based raw materials for industrial applications. This requires the infrastructure for logistics and storage to expand its capacities. Biorefinery industries supply the food, paper and cellulose industries as usual, but must prepare for a rapidly growing importance of the chemical and pharmaceutical, fuel and building materials sectors and more industrial branches. An integral part of the biorefinery sector is to complement the processing of primary biomass by the use of solid, liquid and gaseous residues through cascade utilisation, whereby the use of CO_2, technically feasible but not yet state of the art, would require the involvement of the energy sector. The waste management sector plays a key role in the recycling of products after use. Some components can be fed directly into the biorefinery sector, others are used for biogas fermentation and are therefore mainly used in the energy sector, while others are composted and provide plant nutrients to the agricultural sector.

Biotechnology will develop into a basic technology for the production of raw materials as well as their processing and recycling in the above sectors. The speed of the transformation from fossil-based to biobased value-added chains depends to a large extent on political framework conditions [99,100]. They must be further developed in such a way to support the sector's adaptation to the value chains of the bioeconomy.

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Declaration of Competing Interest

None.

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