Background paper

Last updated: September 2022

Industrial Biorefineries

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Note
This background paper summarises the key statements and discussion points from various workshops held on this topic between March and September 2022, under the leadership of the aforementioned authors and with the participation of external stakeholders. This is not a Bioeconomy Council position paper. Its contents, views and conclusions do not represent recommendations for action or the results of studies carried out by the German Bioeconomy Council, rather they exclusively reflect the contents of the discussions conducted by and with experts.

General statements and a description of how industrial biorefinery technologies specifically contribute to accelerating the raw materials transition and a circular economy
Biorefineries utilise primarily biogenic raw materials alongside both gaseous substances (e.g. biomethane or CO_2) and material flows such as waste and wastewater to produce a range of reusable materials. This is achieved by exploiting biological resources (e.g. enzymes or microorganisms) from all available by-product streams. The origins of biorefineries are in biotechnology and biotechnological process engineering and how they interface with conventional manufacturing environments.

Designed as an integrative utilisation plan, a biorefinery's purpose in an industrial context is to enable renewable and other raw materials (e.g. from secondary sources) to be processed into chemicals, biomaterials and other material products, as well as combustibles and fuels. The raw material source is fully exploited (comparable to an oil refinery that produces a variety of different substances from crude oil). Ideally, this process links the use of materials and energy, prioritising the use of materials. Sustainability plays a decisive role in the – ideally – circular manufacturing processes, as do economic factors such as profitability. This allows them to compete effectively with many existing manufacturing processes that have been developed and perfected over time. Consequently, industrially viable biorefinery concepts require an efficient interplay between technology, raw materials (water, low CO_2 energy, biomass, residual waste and waste materials as well as wastewater), updates to the legal framework where necessary and economic considerations. The social context must also be taken into account, as the technology in industry should really only be implemented if it has obtained broad public acceptance.

Biorefineries are far from a new concept. Many of the traditional processes for converting biomass have long been used, e.g. in the sugar, starch and pulp industries. Nevertheless, biorefineries and their products are still in the early stages of development compared to traditional petroleum refineries, which have been used and perfected for around 150 years. As a rule, biorefineries aim to make carbon compounds, the main component of biomass, usable for platform chemicals or products. Other biomass components are also becoming increasingly important, as is recycling raw materials from residues and wastewater, such as compounds that contain nitrogen and phosphorus, i.e. plant nutrients and other non-organic substances (e.g. metals from biomining) in particular. However, the raw materials transition requires advanced, more complex refineries that integrate the manufacture of organic or biocatalytic products and energy sources. This means that a reduction in, or a move away from, crude oil as the central raw material used in the manufacturing and processing industry is needed and that other raw materials should be handled in a more resource-efficient manner.

VDI Guideline 6310, "Classification and quality criteria of biorefineries", distinguishes biorefinery concepts as: sugar biorefinery, starch biorefinery, vegetable oil and algal lipid biorefinery, lignocellulose (green) biorefinery, synthesis gas (syngas) biorefinery, electrobiorefinery. Recently, a waste, flue gas and wastewater refinery have also been considered.

The development of a biorefinery can be broken down into three phases. Phase I biorefineries manufacture one main product from one raw material. A classic example is the production of biodiesel from oil-bearing plants such as rapeseed (vegetable oil biorefinery). Phase II biorefineries employ a range of different processes to produce a variety of products. A biorefinery enters phase II as soon as side streams are integrated into the process, making it possible to manufacture even more products, e.g. a biorefinery based on the milling of wet grain. Here, hydrolysis converts residual and waste materials from grain production, i.e. foliage, ears or chaff and straw, into chemical raw materials such as sugar and levulinic acid. A phase III biorefinery, e.g. lignocellulose biorefinery, is capable of converting a variety of different raw materials (straw, chaff, forest biomass such as undergrowth and wood, municipal waste, etc.) into a wide range of products such as plasticisers, solvents and lubricants. Moreover, biorefineries are becoming increasingly important in how other gaseous and liquid material flows are used (i.e. in a wastewater or waste biorefinery).

Industrial significance

Currently, existing biorefineries are mainly based on substrates such as maize, wheat, sugar cane and sugar beet, meaning they fall into the categories of either a sugar or starch biorefinery. This type of biorefinery has the advantage that substrates containing sugar or starch can be converted into bioethanol, for example, relatively easily and efficiently. Indeed, these production processes have been used and perfected over decades. The conditions for cultivating the biomass used have long been analysed and designed with the most successful land use strategy in mind. One disadvantage of a starch or sugar-based biorefinery is the so-called "plate vs. tank" discussion, as the use of land and fertile soil required for producing these substrates is in direct competition with growing food crops or fodder. This has increasingly led to the development of biorefineries that are based on secondary sources.

According to the "EU Biorefinery Outlook to 2030" study, around 300 biorefineries in the European Union already generate a turnover of several billion euros with bio-based products and currently produce around 4.6 million tonnes of Europe's chemicals and materials. These refineries are mainly located in northern and central Europe, particularly in Germany, France, the Benelux countries and northern Italy. There are now 59 chemical and material biorefineries in Germany, plus a few more pilot and research facilities that practically cover all common platforms. Examples include Biowert Industrie GmbH's grass factory in Brensbach, Hesse, which processes meadow grass into green electricity, fertiliser, plastics and insulating materials; Cargill Deutschland GmbH's German site in Krefeld, where various starches and sweeteners for the food and technical industries are produced from maize; the biorefinery belonging to Swiss speciality chemicals group Clariant in Straubing, which makes sugar and ethanol from straw and maiden grass, and the waste and wastewater demo projects in Baden-Württemberg known as the "Bio-Ab-Cycling" programme.

One biorefinery currently in the spotlight is UPM, Europe's largest paper manufacturer. At its Leuna site, around EUR 750 million is being invested in the world's first fully integrated wood-based biorefinery. From the end of 2023, chemical substances such as bio-monoethylene glycol (MEG), bio-monopropylene glycol (MPG) and lignin-based functional fillers will be produced here from wood. Regional and certified industrial hardwood and wood residuals from sawmills will serve as the base for the raw material for an annual production capacity of 220,000 tonnes of chemicals.

The following diagram provides an overview of existing biorefinery concepts and their products.

Biorefinery concept	Feedstock	Products	Markets
Sugar and starch biorefinery	Sugar beet, sugar cane, cereals, maize, potatoes	Molasses, pulp, glucose, fructose, other sugars, lactic acid, starch, bioethanol, fertiliser	Fine and food chemicals, fodder industry, paper, cardboard & cardboard packaging, biofuels
Vegetable oil and algal lipid biorefinery	Rapeseed oil and palm oil, algae	Proteins, lubricants, biodiesel, tenside, algae biomass (biogas, electricity and heat)	Fodder industry, lubricants market, detergents and body care products, biofuels, chemicals
Lignocellulosic biorefinery; green biorefinery	Wood, straw, grasses	Glucose, xylose, cellulose, hemicellulose, lignin, biogas, ethanol	Electricity and heating market, fine and special chemicals
Syngas biorefinery	Wood, straw	Biofuel, chemicals	Biofuels, fine and special chemicals
Biogas biorefinery	Slurry, maize silage	Fertilisers, chemicals, biofuels	Biofuels, electricity and heating market, chemicals

Source: FNR, Marktanalyse Nachwachsende Rohstoffe, Vol. 34

Contributions to the circular economy

The raw materials transition requires new ways of handling natural resources. The amount of waste materials generated must be reduced as far as possible or eliminated altogether. Closed substance cycles and material cycles can conserve environmental, climate and ecosystems. Indeed, when taking the Sustainable Development Goals (SDGs) into account such as affordable and clean energy, fair work, economic growth and climate protection, in particular, the use of waste biomass, other waste and wastewater can be considered as an opportunity for the innovative use of secondary raw material sources. This, in turn, enables progress to be made via circular bioeconomy towards a closed-loop economy.

Biorefineries that process secondary raw material sources (solid, liquid and gas) have the potential to drive forward a circular bioeconomy and expand the spectrum of existing chemical conversion procedures by means of biotechnological processes and new substrates. This makes them an irreplaceable component of a circular economy that can utilise material flows in cascades and recycle raw materials.

A number of pilot and demonstration facilities, such as those at the Fraunhofer Centre for Chemical-Biotechnological Processes (CBP) in Leuna or at various companies and sewage treatment plants in Baden-Württemberg, show that it is feasible to combine and cascade the use of both biological resources and residual and waste materials. The task is then to adapt these facilities so they can be applied broadly in industry and implement the biorefinery approach as the basis for industrial manufacturing of the future. However, these approaches have very much been company-specific so far and have not yet become an integral part of overarching value-added networks.

Current status, conflicting goals and obstacles to the sustainable implementation of biorefinery technologies

Raw materials (biomass, water, energy, wastewater)

Existing biorefineries – both nationally and internationally – are predominantly operated with primary biomass (sugar, starch, oil plants, forest wood, grass). Consequently, there is a classic conflict of objectives in the competition for land regarding food production and environmental protection (e.g. water pollution control, soil and biodiversity protection). This limits the availability of biomass for running biorefineries. Climate policy decisions, such as the increased use of forests as CO_2 reservoirs or the increasing demand for renewable raw materials in other sectors (e.g. the construction industry), are leading to an additional shortage of raw materials in biorefineries. Policymakers must therefore establish a holistic approach to prioritising the use of biomass as part of bioeconomy strategies. This does not apply equally to the use of secondary raw material sources in biorefineries, although the waste hierarchy must be taken into account here.

Approaches such as using wastewater as a nutrient medium for growing algae, recovering valuable raw materials from it, or producing hydrogen offer opportunities to expand the raw material base without using agricultural land. There are numerous research and regulatory questions in the complex and multi-layered process chain for which practical test and pilot facilities seem particularly useful.

Industry is increasingly endeavouring to replace traditional chemical and physical processes with biotechnological ones, wherever this is possible and economically viable. Most of these processes take place in an aqueous medium, e.g. in fermentation processes. On the one hand, industry is trying to manufacture products more efficiently using biotechnological methods. On the other, the question still remains as to how this water can be used in a way that saves energy and costs – e.g. how recyclable substances can be separated efficiently from the fermentation broths or how to treat these fermentation broths so that they can be reused.

Water and energy are other key aspects of production for biorefineries. They are required, in particular, for the production of primary biomass (fertiliser production, machinery, field irrigation) and must therefore be included in the life cycle assessments of biorefineries. Rising and, in some cases, strongly fluctuating energy prices, which are mainly purchased on the electricity market at present, constitute an economic challenge for companies.

At the same time, climate protection policies require that the energy supply be converted to renewable sources that have the lowest possible impact on the environment. Industry must consider this as part of a (business) location policy to realise the full economic potential of biorefineries and their contribution to CO_2 efficiency. For example, supplying biorefineries with renewable electricity is essential for a holistic approach. However, total supply is hardly feasible for the biorefineries currently in operation due to the volatility of existing renewable energy sources, as well as the use of fossil fuels in generating biomass along with insufficient storage capacities.

Furthermore, greater importance in the political context must be given to implementing biorefineries through logistics, adapting existing or developing new infrastructures, supply chains for raw materials, involving new industrial partners, exploring market acceptance and the closely related socio-economic issues.

The supply of substrates/educts from upstream value chains such as agriculture and forestry or other material flows must be taken into account from the outset where a holistic sustainability assessment of products made in biorefineries is concerned. This is because there are fewer sustainability risks and a wider range of raw material qualities and raw material compositions if residual and waste materials are also used. Determining the sustainability of products in their entirety is a challenge because there has been no international agreement on the assessment standards for raw and waste materials used.

Manufacturing

Products from biorefineries (such as succinic acid) are usually still more expensive than their petrochemical counterparts, and a real shortage of fossil raw materials is not in sight. However, manufacturers are capitalising on the popularity of the sustainable image of bio-based chemicals in products, using this to justify charging private consumers higher prices. As a result, chemical Verbund sites no longer consider handling "perishable" biomass to be impossible, rather they recognise its availability locally as an advantage.

Depending on distances involved, transporting biomass and other raw material sources to the biorefinery and then returning the residual products to farms or other industrial facilities can account for a large amount of a biorefinery's operating costs. This means that the majority of today's facilities are operated predominantly on a decentralised basis. The aim is to add these to existing plants (e.g. an industrial plant with waste or sewage treatment facilities).

While fossil raw materials are generally obtained from point sources, and petrochemical refineries are supplied with raw materials via a single connection point using pipeline systems, the large-scale provision of the raw material for the biorefinery, in terms of biomass, requires correspondingly large areas of cultivation or catchment areas from which to obtain residual materials. Moreover, there is an additional need for logistics here, as solid biogenic raw materials cannot generally be pumped. The situation may be different with secondary raw material sources. An infrastructure already exists with municipal or industrial wastewater, meaning that the operation of the facility simply has to be expanded. Regional collection systems have often already been set up for biowaste.

The further development of biorefineries can boost the demand for bio-based products. This must focus primarily on secondary substrates, scaling of processes and, in turn, an increase in production volumes. However, scaling processes is cost-intensive and constitutes a challenge, especially for smaller companies.
Setting up and expanding facility systems should be supported, especially to attract plant manufacturers to this concept. The scaling and, hence, competitiveness of new bio-based processes can continue to be driven forward by national and regional public funding schemes.

Technology
The biotechnology field (e.g. further development of numerous microorganisms, higher product concentrations to make processes more economical, continuous vs. batch production) still has much potential. Indeed, Germany has a solid technological basis to exploit this potential. However, many of the processes and technologies available for converting biogenic raw materials and secondary substrates into economically competitive products are not currently in a position to consider themselves competitive. Adapting technologies to each base material and their volatile raw material qualities and compositions is another key challenge.

The weak point of many bio-based processes is often the complex downstream processing of aqueous multi-component solutions. In biorefineries, valuable bulk chemicals are rarely produced in easily separable mixtures with a suitable composition. Recyclable materials are often present in aqueous solutions, which are regarded as wastewater, and are thus ultimately not recycled both due to their low concentration and the fact that extracting them is considered too complex. Purifying (e.g. filtering and extracting) intermediates with a high degree of purity from complex mixtures is yet to be achieved. Consequently, particularly attention must be given to both the separation procedure and conversion of the substrates. Further dovetailing and networking of biotechnology with other key technologies, such as materials research for membrane development or microelectronics, could make valuable contributions here. The processing of large amounts of data collected from a multitude of sensors is becoming increasingly important for optimised operation of the biorefinery.

Furthermore, technologies and processes in traditional industries must be adapted specifically to integrate new raw materials or side streams, especially when it comes to residual and waste materials with a wider range of content. Biorefineries that achieve extensive further utilisation/recycling of biogenic raw materials, e.g. from algae, both to manufacture a broad spectrum of bio-based products and for integration into the process and value chains that exist within established user industries, are currently in their infancy. Consequently, extensive work in research and development is required in order to establish and market integrated biorefineries. Standardised product descriptions and, possibly, the introduction of new product classes are also required. Here more investigation is required as to whether the standardisation activities using biogenic solid fuels or secondary fuels can be further extended.

Regulatory framework

Much like any other manufacturing facility, biorefineries have requirements to fulfil in terms of safety, the environment and health and safety, alongside other legal framework and approval criteria. Although the regulatory framework is not linked to technology, various regulations such as the German Federal Emission Control Act (BImSchG) do, indeed, impose restrictions on it. In addition, long-term investments in biorefineries require a reliable legal framework that extends beyond individual legislative periods. Current EU regulations, such as the Industrial Emissions Directive (IED), concerning the authorisation and operation of industrial plants in Europe, should not have an impact on existing or already approved construction projects. Additional bureaucracy, which leads to procedural delays and cost increases for project sponsors, must be avoided.

Current regulations prohibit the direct use of waste as nutrients for food production, for example. Moreover, the term “residual materials” also needs to be redefined and a standardised, uniform definition agreed upon. The classification of biomass as waste or residual material has varying legal consequences and can result in different requirements for demonstrating sustainability and for determining greenhouse gas reductions. The regulations adopted at EU level are also decisive for industrial biorefineries based on residual and waste materials. It is recommended that German government ministries responsible take this into account in their legislation (e.g. Amendment to the German Ordinance on Biowastes) or agree on a common line and take this to Brussels.

Cooperation

To date, there has been a lack of networking between different sectors of industry and their respective material flows, including those independent of biomass use, and their competencies, e.g. CO_2 emitters, plant construction or in digitalisation, meaning a sustainable value-added network needs to be established. Many companies do not consider that the use of their side streams falls under the term “bioeconomy”. There is also a lack of information on how secondary raw materials and side streams can be sustainably reused. Consequently, stronger cooperation is required between research, industry and politics, e.g. in national or cross-state initiatives. It is crucial that individual companies, in particular, e.g. from the chemical industry, which do not currently see biorefineries as their core business, engage with the topic. Many industries and companies also lack knowledge about the possibilities and opportunities for contributing to bioeconomic value chain. In this respect, there is greater need for communication.

Possible recommendations for overcoming these obstacles and for supporting the sustainable use of biorefinery technology

Strengthen joint action with communication measures

The path to a circular economy with lower CO_2 emissions, independence from fossil raw materials and petrochemicals, as well as newly emerging conflicts of objectives, are calling for policymakers to improve interaction between all those involved – this will prevent frictional losses, duplication of work, and will promote joint and collective action in the innovation process. This also requires a clear positioning in how biomass use is prioritised and how other solid, liquid and gaseous residual and waste materials are used (e.g. as part of the biomass strategy).

Set up joint research platforms

Greater importance should be attached to setting up demonstration facilities in terms of funding. There is no research platform that takes greater account of the interests of industry and that has the human resources and infrastructure for safety and plant engineering assessment. It would be important to plan this such that it could be used as widely and universally as possible by many industrial companies.

Selective supplementing of the funding policy

Project funding for research and development, such as the "Biorefineries Technology Initiative", published in 2017 by the German Federal Ministry of Education and Research (BMBF), or the German Federal Ministry of Food and Agriculture's (BMEL) "Renewable Resources" funding programme, should continue to drive the scaling of laboratory processes forward and provide investment incentives for industry. In future, funding calls should be extended to include the individual steps of ongoing projects that are not always part of an entire product development. The idea of such "process intensification" could be well promoted in small research projects. The state should support modular biorefinery construction as a concept, on the one hand in order to enable biorefinery flexibility and, on the other, to make the capital commitment manageable for small companies. It is particularly important to encourage plant manufacturers to favour this type of production.

Adapting the legal framework

The government should intensify efforts to harmonise international sustainability assessments for raw materials as a whole. The authorisation processes for operating these facilities should be shortened, particularly for demonstration plants that can use raw materials variably. The setup of regulatory innovation centres (real laboratories) that perform research and evaluation alongside the authorities would be a suitable measure for speeding this process up and for bringing authorities, researchers and industry together as early as possible.

In general, environmental legislation should be more strongly integrated as a legal framework for plant construction. Existing areas such as waste and wastewater regulation or resource efficiency should also be considered in the context of the bioeconomy.