Biorefineries Roadmap

as part of the German Federal Government action plans for the material and energetic utilisation of renewable raw materials
Foreword

In 2010, the German Federal Government formulated its objectives for a bio-based economy with the ‘National Research Strategy BioEconomy 2030’. Thereby, with research and innovation, we want to facilitate the structural change from an oil-based to a bio-based industry. To bring about this bio-based economy, with all its related opportunities for growth and employment, we need holistic and sustainable approaches.

This includes the greatly improved material- and energetic utilisation of renewable raw materials. Throughout, we must take the entire value chain into consideration – from biomass production up to the end product. Biorefineries, which in the future will produce an array of products, can take on an important task in this process. At this time, however, such concepts are predominantly at the research and development stages. As part of the ‘Action plan for the material use of renewable resources’, the German Federal Government, working in close cooperation with business and science, announced the drafting of a ‘Biorefineries Roadmap’ in order to determine the current status and future development of the various biorefinery concepts. This comprehensive overview of a range of technologies and of the paths to implementation has now been completed. Our special thanks go out to the more than 30 experts from a range of fields who, with great personal commitment, have contributed their expertise to the success of the roadmap. From the results it is evident that there is no small number of hurdles to be overcome before the full potential of biorefineries can be unlocked. But this will not deter us, and our top priority on the path towards this worthy goal is the harmonisation of economic, environmental and social concerns.

Also in the future, the Federal Government will support the necessary developments through targeted research funding. From the outset, the increased involvement of business will be of central importance. And it will be worth it, because we are stepping out onto a genuine field of the future.

Prof. Dr. Annette Schavan,
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Ilse Aigner,
Federal Ministry of Food, Agriculture and Consumer Protection
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Motivation and development of the Biorefineries Roadmap

Germany and all the countries in the international community face enormous challenges with regard to the issues of global population growth, dwindling fossil fuel resources, and the ever-advancing climate change. The central task will be to provide a growing world population with adequate food, energy and raw materials, while taking care not to impact the natural environment, and to actively reduce climate-damaging greenhouse gases. To these ends, it will be necessary to develop intelligent solutions that are in keeping with a resource-efficient and sustainable economy. Having set out these objectives, biorefinery concepts – as central elements of a bio-based economy, and promising largely waste-free use of biomass, efficient conversion routes, and pathways for the energetic and material use of biomass – could play an important role for a future bioeconomy in the utilisation and conversion of biogenic raw materials and residues.

For some years it has been possible to observe a growing trend towards the utilisation of renewable resources. The main determining factors here are price developments and regional availability in the markets for fossil fuels, in some cases the regulatory measures to promote the expansion of energy from renewable sources, and not least a greater awareness of issues such as sustainability and climate protection. In Germany alone, renewable resources are already cultivated on over 2 million hectares, or nearly a fifth of the arable land. Thereby, the contribution made by the energetic utilisation of renewable resources to the energy supply has steadily increased. The growth rates for material utilisation are somewhat lower, although Germany still occupies a leading position. Throughout, the material use of renewable resources, which can contribute to value creation and the preservation of jobs, also in rural areas, carries high innovation potential with regard to new technologies and products. Furthermore, by the fixation of carbon into long-life products, material utilisation makes a significant contribution to achieving national, European and international climate protection goals.

It is not least because of these advantages that in 2008 the German Bundestag requested the federal government to develop a strategy for the material utilisation of renewable raw materials, which could then be used to derive priorities for further research promotion. In September 2009, the Federal Cabinet subsequently adopted the ‘Action plan for the use of renewable resources as raw materials’. Among other objectives, the action plan will identify different fields of action for the advancement of material utilisation, i.e. application outside of the energy sector. One of these fields of action includes the topics of ‘Industrial Biotechnology’ and ‘Biorefineries’. Here, the ‘development of a roadmap for biorefineries by representatives from industry, research and the federal ministries’ is defined as a measure for implementation. The ‘Biorefineries Roadmap’ thus makes a contribution to the German federal government strategy for the development of a bioeconomy specified in the ‘National Research Strategy Bioeconomy 2030’, the federal government’s energy concept and ‘National Climate Initiative’, and in the action plans for the material and energetic utilisation of renewable resources.

Through joint leadership and as the most important sources of funding for research in this area, the Federal Ministry for Education and Research (BMBF) and the Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) and with the close involvement of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Federal Ministry of Economics and Technology (BMWi), a consensus was formed during the implementation of the plan on essential ‘research funding’. The government ministries selected 30 renowned experts from academia and industry to form a working group, the members of which are the authors of this ‘Biorefineries Roadmap’. Prof. Dr. Kurt Wagemann, Executive Director of DECHEMA, Society for Chemical Engineering and Biotechnology, took the role of Chair.

The working group held its first full meeting in September 2010. An important outcome was the establishment of a variety of technical and economic/ecological questions to be assigned to different sub-groups. At nearly 100 pages, the final version of the roadmap is a detailed and first-of-its-kind overview of the various platforms and technologies. The individual biorefinery types also underwent comprehensive analysis.

For a better understanding, it should be noted that the roadmap represents above all the positions of the participating experts, and not in all cases
Summary of the Roadmap

What is meant by a biorefinery?

A biorefinery is characterised by an explicitly integrative, multifunctional overall concept that uses biomass as a diverse source of raw materials for the sustainable generation of a spectrum of different intermediates and products (chemicals, materials, bioenergy/biofuels), allowing the fullest possible use of all raw material components. The co-products can also be food and/or feed. These objectives necessitate the integration of a range of different methods and technologies.

The biorefinery process chain consists essentially of system components for the pre-treatment and preparation of biomass, as well as for the separation of biomass components (primary refining) and the subsequent conversion/processing steps (secondary refining).

The primary refining in a biorefinery involves the separation of biomass components into intermediates (e.g. cellulose, starch, sugar, vegetable oil, lignin, plant fibres, biogas, synthesis gas), and usually also encompasses the pre-treatment and conditioning of the biomass. While component separation takes place at the biorefinery, one or more pre-treatment/conditioning processes can also be carried out decentralised where needed. In secondary refining, further conversion and processing steps generate a larger number of products from the intermediates. The by-products that occur as a result of primary- and/or secondary refining are used to supply process energy or, where applicable and in compliance with statutory requirements, they are further processed into food or feed.

There are two basic approaches to the implementation of a biorefinery concept: ‘Bottom-up’ and ‘top-down’. If the biorefinery concerns the expansion of an existing biomass processing facility (e.g. sugar, starch, pulp mill, oil mill, ethanol plant), it is referred to as a bottom-up approach. In contrast, the term top-down is used when the emphasis is on newly conceptualised, highly integrated systems designed for the use of various biomass fractions and the (zero-waste) generation of a variety of products for different markets. Thereby, there is no linking to existing biomass conversion processes; instead, systems for primary and secondary refining are specifically developed towards the biorefinery platform-based production of a range of products.

Both the bottom-up and top-down approach can be implemented centrally at a new site (‘greenfield’) or at an existing industrial site (‘brownfield’). In the latter case, this preferably takes place via integration into an existing industrial or chemistry park, or as an extension to existing biomass conversion facilities. It is also conceivable to decentralise the components of primary refining (e.g. biomass conditioning), giving rise to a hybrid structure.

Where are we today?

Biorefinery concepts have already been pursued for a number of years in Germany. For example, a range of activities aimed at investigating and developing diverse biorefinery paths are in various stages of realisation. Examples of these are:

- Sugar/starch biorefinery on the basis of cereal crops/sugar beet from the company Südzucker/CropEnergies in Zeitz (Saxony-Anhalt)
- Wood-based lignocellulosic biorefinery operated by a consortium coordinated by DECHEMA as part of the Fraunhofer Society’s Chemical Biotechnological Process Center at the chemical site in Leuna (Saxony-Anhalt)
- Lignocellulosic biorefinery based on straw from the Süd-Chemie company in Munich and Straubing (Bavaria)
- Grass silage-based green biorefinery from the company Biowert in Brensbach (Hesse)
- Grass-based green biorefinery from the company Biopos in Selbelang (Brandenburg)
- Straw-based synthesis gas-based biorefinery from KIT in Karlsruhe (Baden-Wuerttemberg)

A SWOT analysis (please refer to full version) has demonstrated that Germany is well positioned and occupies an excellent starting position for further developments in a European and international context with respect to the subject of biorefineries.
While activities to establish biorefineries have been underway in some EU Member States (e.g. Germany, France, the Netherlands) for around ten years, the topic only moved into focus at the EU level about three years ago. The financial resources envisaged for this area are comparatively low. For the first time, the current 7th EU Research Framework Programme (FP7) is explicitly promoting integrated biorefinery concepts with a total volume of over €70 million. The contents of the integrative biorefinery projects are extremely varied and for the most part encompass the development of new biorefinery processes and products, the optimisation and upgrading of existing conversion processes, and the industrial-scale demonstration of research results. An extensive project in the area of ‘Research Coordination’ was also provided with support through Star-COLIBRI (Strategic Targets for 2020 – Collaboration Initiative on Biorefineries). The goal of Star-COLIBRI was to stimulate cooperation between complementary research projects at the European level, which would promote progress in this area and counteract the fragmentation of research activities and results. The ‘Biorefinery Joint Strategic Research Roadmap for 2020’ and ‘Biorefinery Vision for 2030’, both aiming at providing a framework for the development of the biorefinery sector in Europe, have also been drawn up during the course of this project.

Table: SWOT analysis of sugar and starch biorefineries

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
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<tr>
<td>→ Can build on already existing structures in the sugar and starch industry</td>
<td>→ Product diversification not yet sufficient; refinement of intermediate products into new products requires improvement</td>
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<tr>
<td>→ The German sugar and starch industry is already established in Europe</td>
<td>→ Integrated production of bio-based products and bioenergy is capable of expansion</td>
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<tr>
<td>→ Strong, already globally well positioned German machinery- and systems engineering in the relevant areas</td>
<td>→ Connections between sugar/starch industry and chemical industry are underdeveloped</td>
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<tr>
<td>→ Strong research and development in Germany in the biotechnological conversion of carbohydrates</td>
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<tr>
<td>→ Raw materials are available in Germany, Europe and globally</td>
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<tr>
<td>→ Generation of surpluses in Germany is possible for the raw materials sugar beet and wheat</td>
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<tr>
<td>→ Technologically well advanced primary refining for the platforms sucrose and starch</td>
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<tr>
<td>→ Experiences are available in the chemical and biotechnological conversion of carbohydrates, whereby the range of intermediates from secondary refining must be expanded</td>
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<th>Opportunities</th>
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<td>→ Further development at existing sites in the sugar/starch industry into integrated biorefinery sites via a bottom-up development scenario</td>
<td>→ German sugar and starch industry poorly positioned in comparison to key global players (Brazil, US, Southeast Asia)</td>
</tr>
<tr>
<td>→ Additional value creation through the integration of other chemical and biotechnological processes and products</td>
<td>→ Shortage of raw materials due to increased demand for sugar and starch from the food industry</td>
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<td>→ Realisation of synergy effects through coupled processes</td>
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<tr>
<td>→ Export opportunities for German sugar- and starch-based technologies and systems in the establishment abroad of sugar- and starch biorefineries</td>
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What is a biorefinery platform, and which selected platforms are examined in more detail in the Roadmap?
The term biorefinery platform refers to the intermediate products that arise during primary refining and which serve as precursor for subsequent secondary refining. A few particularly promising biorefinery paths, which differ above all in platform type as well as secondary refining type, have emerged from among the biorefinery concepts:
1. Sugar biorefinery and starch biorefinery
2. Vegetable oil biorefinery and algal lipid biorefinery
3. Lignocellulosic (cellulose, hemicellulose and lignin) biorefinery and green biorefinery
4. Synthesis gas biorefinery
5. Biogas biorefinery

As part of the roadmap, these concepts have been more closely examined by means of schematic examples. In the course of preparations, it became evident that for the case of the biogas biorefinery, no detailed technological illustrations for specific biorefinery pathways can be provided. For a direct material utilisation of biomethane in the sense of an integrated, local biorefinery concept, there are currently no commercial utilisation options available that could be implemented by 2030 (the timeframe of the roadmap).

How are the selected biorefinery concepts assessed?
The following statements and analyses are limited to the above stated concepts 1–4. Here again, however, it should be noted that complete and valid data bases are not available for classification or for the comparison of analytical results. For this reason, for many biorefinery concepts, only limited assessment statements are possible at this time. Here, particular consideration should be given to the availability of sustainably produced biomass.

1. Sugar biorefinery and starch biorefinery
   a) Sugar biorefinery
   Sugar beet or sugar cane, among others, can serve as the raw material base for sugar production (primary refinery). Products include table sugar, fermentation raw materials, refined sugar as a precursor for chemical intermediate- or finished products (surfactants), organic acids, vitamins, and inorganic salts. In turn, the chemical intermediates and fermentation products (e.g., amino acids, lactate acid, citric acid, gluconic acid, and the esters and salts of these organic acids) are then either chemical intermediates or are further processed into finished products.

   b) Starch biorefinery
   A range of plants can serve as a raw material base for starch production; above all potatoes and cereal crops (wheat and corn) are used in Germany. In addition to native starch, products also include starch modifications and starch saccharification products. The resulting starch modifications (e.g., starch esters, starch ethers, dextrins) and starch mixtures are then further processed for use as thickening agents in the food industry, as an additive in paper production, or as an intermediate product in the cosmetics industry. A range of other fermentation products (see 1a) can also be produced and further processed.

   Capital expenditures of around €120 million can be expected for a facility in the order of magnitude of 200,000 tonnes of wheat/a. An accurate economic classification or ecological assessment of such a system would require further detailed studies.

2. Vegetable oil biorefinery and algal lipid biorefinery
   a) Vegetable oil biorefinery
   The precursors are oil seeds and -fruits. Following primary refining, crude vegetable oils (fats and oils) are available as raw materials for further processing. In addition to use as a fuel, vegetable oil is a valuable raw material for oleochemicals or for the production of biolubricants. Here, the vegetable oil can be used directly (e.g., as a solvent), or is cleaved to obtain fatty acids and glycerol. In turn, fatty acids are precursors for a whole raft of chemical products, and after processing can be found in cosmetics, surfactants, lacquers and dyes, among other products. Glycerol also has a range of applications; further processing produces pharmaceutical grade glycerol, and subsequent conversions and chemical reactions provide further chemical intermediates and products. Glycerol can also be used as a fermentation raw material. In turn, the fermentation products are either chemical intermediates or are further processed into finished products. Any incidental meal extract or press cake is generally used as an animal feedstuff.

   The considered model systems (400,000 t/a palm kernels and 530,000 t/a rapeseed) require a capital expenditure of approximately €100 million. Also here, it is not currently possible to provide reliable statements on the ecological and economic classification of such a system.

   b) Algal lipid biorefinery
   The precursor for the production of algal lipids (algae oil) is microalgae. Alongside triglycerides and polar membrane lipids, the algae crude oil contains
other lipophilic algae ingredients such as carotenoids, chlorophyll and phytosterols, which can be selectively extracted and modified in secondary refining. The triglycerides can be used either in the food industry or in the technical area. Triglycerides are also a potential raw material for the chemical industry. In the chemotechnical area, triglycerides can be used directly, or fatty acids and glycerol can be extracted via cleavage. In turn, fatty acids are precursors for a whole raft of chemical products, and after processing can be found in cosmetics, surfactants, lacquers and dyes, among other products. After drying, high-protein feedstuff is produced using the deoiled algae biomass, or the algal biomass can be converted as co-substrate into biogas through anaerobic decomposition.

Because it offers a much higher level of photosynthetic efficiency and because there is almost no use- or land competition, the use of microalgae as feedstock in biorefineries carries more promise than the use of traditional biomass crops. Only laboratory- and pilot plant data are available for many algal lipid biorefinery sub-processes, and the current level of data does not enable a viable and economically efficient technological conception. There thus remains a great need for research.

Table: SWOT analysis of vegetable oil biorefineries

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<th>Strengths</th>
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<tbody>
<tr>
<td>→ Can build on already existing structures for vegetable oil production and -processing</td>
<td>→ Raw materials for short-chain fatty acids are not available in Germany and Europe; only in tropical and subtropical countries</td>
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<tr>
<td>→ Already globally established German vegetable oil industry, as well as globally active companies working in Germany</td>
<td>→ Commercial production of secondary products from glycerol somewhat underdeveloped in contrast to products from fatty acids</td>
</tr>
<tr>
<td>→ Strong, already globally well positioned German machinery- and systems engineering in the relevant areas</td>
<td>→ Primary refining and secondary refining frequently not yet integrated in one site</td>
</tr>
<tr>
<td>→ Research-intensive SMEs available for material conditioning of vegetable oils</td>
<td>→ Integrated production of bio-based material products in addition to bioenergy is still underdeveloped</td>
</tr>
<tr>
<td>→ Strong research and development well established in Germany for the conversion of vegetable oils</td>
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<tr>
<td>→ Raw materials for long-chain fatty acids available in Germany, Europe and globally</td>
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<tr>
<td>→ Technologically well-developed primary refining for the vegetable oil platform</td>
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<tr>
<td>→ Experiences available on the chemical and biotechnological conversion of vegetable oils</td>
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<tr>
<td>→ Further development into integrated biorefinery sites via a bottom-up development scenario at existing sites in the vegetable oil processing industry (e.g. oil mills)</td>
<td>→ Relocation of production of oleochemical intermediates to non-European countries close to resources; biorefineries with short-chain fatty acids as platform are developing in raw material-originating countries</td>
</tr>
<tr>
<td>→ Additional value creation through the integration of chemical and biotechnological processes and products on the basis of glycerol and fatty acids</td>
<td>→ Shortage of raw materials due to increasing demand for vegetable oils from the food industry and for provision of bioenergy; alternative sources of raw materials (e.g. algal lipids, microbial lipids) are not yet market ready</td>
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<tr>
<td>→ Export opportunities for German technologies and systems, and for process chemicals for the processing of vegetable oils</td>
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3. Lignocellulosic biorefinery and green biorefinery

a) Lignocellulosic Biorefinery

For reasons of quality- and quantity-related availability, above all agricultural residues (cereal- and corn straw) and wood (forest wood, poplar short rotation wood) are relevant at this time in Germany; annual and perennial grasses could also play a role in the future, however. Cellulose, hemicellulose and lignin, or mixtures thereof, are available as raw materials for further processing after completion of primary refining. There are two basic paths for secondary refining: (a) The direct production of fermentable carbohydrates for further biotechnological conversion and (b) the further isolated processing of the individual fractions, as well as combinations of both pathways. Mostly cellulose and hemicellulose fractions are used in the production of fermentable carbohydrates. The enzymatic conversion into corresponding monomeric carbohydrates (e.g. glucose, xylose) results in one material flow of fermentable sugars and one material flow of lignin. The fermentable sugars can pass directly into biotechnological production. (b) During the isolated processing, the cellulose, hemicellulose and lignin fractions are processed separately. Incidental cellulose can be further processed, e.g. into glucose as a fermentation- or chemical feedstock. The separated hemicellulose fraction contains more or less digested carbohydrates and various monomeric C6- and C5 carbohydrates. From this, monomeric carbohydrates (e.g. xylose) can be separated and then refined, for example by fermentation or chemical methods. The separated hemicellulose fraction contains various other re-usable materials (e.g. acetic acid, furfural), which can be extracted and processed in the chemotechnical area. Lignin from the decomposition paths (a) or (b) can in principle be used directly as a feedstock, but current applications are limited, and usually create little value.

Table: SWOT analysis of algal lipid biorefinery

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<tr>
<td>→ Strong research and development in Germany in the area of microalgae</td>
<td>→ The climatic conditions are not optimal for the cultivation of microalgae in Germany</td>
</tr>
<tr>
<td>→ Research-intensive SMEs in the area of cultivation and utilisation of microalgae, including technology development (e.g. photobioreactors, processing technologies)</td>
<td>→ Circulation and recirculation of nutrients is not yet resolved</td>
</tr>
<tr>
<td>→ Strong German systems engineering in the relevant areas</td>
<td>→ Inadequate strategies for the problem of high microalgae productivity being associated with low concentrations</td>
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<td>→ Product development and refinement is under-developed, especially for products aimed at high added value</td>
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<td>→ Only closed photobioreactors are applicable in Germany; biomass production and processing remains highly complex and cost-intensive</td>
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<tr>
<td>→ Development of a new biomass resource that can be produced independently of arable land</td>
<td>→ In comparison to other global locations, Germany is geographically disadvantaged in the cultivation of microalgae</td>
</tr>
<tr>
<td>→ In comparison to land plants, high photosynthetic efficiency in microalgae enables relatively high biomass production</td>
<td>→ Strong, competitive research and development outside of Germany</td>
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<tr>
<td>→ Creation of value through new products with new functionalities and utilisation options</td>
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The straw-based lignocellulosic biorefinery will be tested at demonstration scale as of 2012 (4,500 tonnes straw/1,000 tonnes ethanol). A potential industrial capacity of 280 thousand tonnes of straw/year is anticipated. At an assumed cost of provision for straw of around 75 €/t and capital expenditure of around €70 million, the production costs correspond to around 680 €/t (about 54 €-ct/l) of ethanol. This means that prices for bioethanol are currently in the same order of magnitude as trade prices for gasoline (spot market: Rotterdam, May 2012). The decisive factor here is the price of the raw material. Under specific conditions, calculated savings of 98% in greenhouse gases would result in comparison with the fossil reference system. Nevertheless, it is still not possible to speak of general ecological benefits, as an ecological assessment would be incomplete at this time due to a lack of data.

Table: SWOT analysis of lignocellulosic biorefinery

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<td>→ Innovative chemical and biotechnology companies are established; it will be possible to build on existing structures in the fermentation industry</td>
<td>→ Competition situations in the utilisation of native forest timber, taking into account the multifunctional demands on the forest, can restrict the availability of raw materials</td>
</tr>
<tr>
<td>→ Well-developed German pulp industry</td>
<td>→ Synthesis gas- and lignocellulosic biorefineries require access to the same raw material base</td>
</tr>
<tr>
<td>→ Strong, already globally-oriented German machinery- and systems engineering in the relevant areas</td>
<td>→ Lignin utilisation is underdeveloped with respect to products with high value creation</td>
</tr>
<tr>
<td>→ Strong research and development in place in Germany in the area of chemical and biotechnological conversion of carbohydrates and their further refinement</td>
<td>→ Utilisation of pentoses from the hemicellulose not yet mature</td>
</tr>
<tr>
<td>→ Lignocellulosic raw materials in principle available in Germany, Europe and globally; unused potential lignocellulosic residues from agriculture and forestry</td>
<td>→ Activities towards biorefinery concepts for the German pulp industry are generally underdeveloped</td>
</tr>
<tr>
<td>→ No direct resource competition for food and feedstuff production in the utilisation of lignocellulosic raw materials from agricultural residues and forest wood</td>
<td>→ Integration of the individual elements of the lignocellulosic biorefinery and their validation in conjunction is not yet mature</td>
</tr>
<tr>
<td>→ Experience available for decomposition processes for lignocellulose, and for chemical and biotechnological conversion of carbohydrates</td>
<td>→ Demonstration is pending of the technologies in application on an industrial scale</td>
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<tr>
<td>→ First pilot- and demonstration plants for lignocellulosic biorefineries are in operation or under construction in Germany</td>
<td>→ Connection with the value chain of the chemical industry is underdeveloped</td>
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<td>→ Development of new growth markets through a top-down development scenario (concept for fermentable carbohydrates)</td>
<td>→ Competing utilisation options for lignocellulosic biomass</td>
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<tr>
<td>→ Improvement of the competitiveness and further development of existing sites of the pulp industry through diversification and new products via a bottom-up development scenario (concept for pulp)</td>
<td>→ Strong, competitive research and development outside of Germany (US, Scandinavia, among others)</td>
</tr>
<tr>
<td>→ Export opportunities for German lignocellulose-based technologies and systems in the establishment of lignocellulosic biorefineries in other countries</td>
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Table: SWOT analysis of green biorefinery

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| → Globally leading research in the area of biogas production  
→ Strong, already globally oriented German machinery and systems engineering in the relevant areas  
→ Preservation of cultural landscapes | → Only realiseable in regions that have corresponding grassland potential  
→ As a concept, only commercially feasible with a biogas plant  
→ Quality level of the products often not sufficient or only difficult to attain; value creation of the products not sufficient to date  
→ Concepts based on fresh green biomass can be operated only seasonally |

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<th>Opportunities</th>
<th>Risks</th>
</tr>
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</table>
| → Further development through diversification of current biogas plant sites, via a *bottom-up* development scenario  
→ Opportunities for technology exports | → Alternative means of access exist for bio-products (e.g. fibres, lactic acid, proteins)  
→ Limited export opportunities to countries with corresponding grassland potential |

A pilot plant for a wood-based lignocellulosic biorefinery is currently under construction at the Leuna site. The orders of magnitude of a possible industrial implementation are anticipated to be around 300,000 to 500,000 tonnes of wood (bone dry) processed per year. The economic feasibility of the process depends strongly on a range of factors. Alongside the integration into an existing industrial complex and the provision of the raw materials, standing in the foreground are the validation of the assumptions and the implementation on an industrial scale of the yields previously achieved in the laboratory- and pilot plant scale, as well as the high quality material utilisation of the three product fractions glucose, (oligo) pentose (in particular xylose), and above all of lignin. Other particularly relevant cost positions are the provision of energy, solvents and enzymes. If the technical conditions and a high-quality utilisation of lignin – not yet possible today – are achieved the economic feasibility of the process appears to be possible.

An ecological assessment of the chain from raw material to factory gate was carried out for the products glucose, xylose (fermentable sugar) and lignin. In all three considered impact categories, the comparison with reference processes (manufacturing of cane juice from sugar beet and phenol from cumene via the Hock process) demonstrated the significant benefits of the process (a total of ca. 40% fewer CO₂ equivalents, ca. 55% fewer SO₂ equivalents, ca. 65% fewer PO₄ equivalents). Also here, further investigation is required to provide general statements on the ecological benefits.

**b) Green biorefinery**

In a green biorefinery, moist biomass in green or ensiled form, such as annual and perennial grasses, is used as a raw material. Grass juice and raw grass fibres are available as raw product following primary refining. A green biorefinery is typically coupled with a biogas plant. This is because a part of one or both fractions (grass juice and grass fibre) is always utilised as a cosubstrate for technical/procedural reasons. The grass juice either goes directly into the biogas plant, or its ingredients (for example, lactic acid, acetic acid, proteins, amino acids) are separated. The grass fibre can be directly processed into animal feedstuff, or can serve as a raw material, e.g. for insulation, cellulose fibres or fibre-reinforced synthetics.

On the basis of experimental results, the present calculations on the economics and ecology assume a system capacity of 91,000 tonnes/year (20% dry matter content) of green waste and silage. Such a biorefinery would need circa 2,300 hectares of grassland for raw material supply. Capital expenditure of approximately €15 million is expected for the implementation of this system. The wide range of possible products – white proteins, feedstuff, lysine lactate and fermentation media – play a major role in the assessment. High-priced sales opportunities
are conceivable for such products, although there are major uncertainties both in terms of market size and of attainable revenues. With regard to both cost and to environmental impacts, a further elaboration of the technical concept, the definition of reference products, as well as more detailed evaluation studies would be required for further statements and a comparison with existing reference systems.

4. Synthesis gas biorefinery
In Germany, above all agricultural residues (cereal straw) and wood (forest wood, poplar short rotation wood) are of significance. A specific feature of a synthesis gas biorefinery is that the individual components are not separated during primary refining; instead, all organic ingredients and components of the biomass are broken down, creating synthesis gas as raw product. The advantage of this is flexibility for product manufacturing, which can be either fuels, methanol, higher alcohols or chemicals, and even polymers. Processing and purification is followed by the synthesis step, in which carbon monoxide and hydrogen from the synthesis is further chemically processed, either directly into chemical intermediates (e.g. methanol or dimethyl ether (DME)), into fuels (e.g. so-called biomass-to-liquid fuel), into bio-based hydrogen, or into chemical products. Direct energetic use via a stationary motor is also possible.

### Table: SWOT analysis of the synthesis gas platform

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Strong research and development of biomass gasification in Germany</td>
<td>→ High demand for raw materials due to requirement of large systems</td>
</tr>
<tr>
<td>→ Experience with coal gasification and its scale-up are available, and can be incorporated</td>
<td>→ Competition situations in the use of domestic forest timber, taking into account the multifunctional demands on the forest, can restrict the availability of raw materials</td>
</tr>
<tr>
<td>→ Strong, already globally oriented German machinery and systems engineering in the relevant areas</td>
<td>→ Synthesis gas- and lignocellulosic biorefineries require access to the same raw material base</td>
</tr>
<tr>
<td>→ Raw materials for gasification are in principle available in Germany, Europe and globally</td>
<td>→ Construction of systems is extremely capital intensive</td>
</tr>
<tr>
<td>→ Lignocellulosic raw materials in Germany, Europe and globally in principle available; unused potential of lignocellulosic residues from agriculture and forestry is present</td>
<td>→ Integration of the individual elements of the synthesis gas biorefinery and their validation in interaction has not yet reached maturity</td>
</tr>
<tr>
<td>→ No direct resource competition for food and feedstuff production in the utilisation of lignocellulosic raw materials from agricultural residues and forest wood</td>
<td>→ Demonstration is pending of the technologies on an industrial scale</td>
</tr>
<tr>
<td>→ Experiences available on the chemical conversion of synthesis gas</td>
<td>→ Potential product diversity not yet exhausted</td>
</tr>
<tr>
<td></td>
<td>→ Biotechnological conversion of synthesis gas is underdeveloped to date</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ The concept inherently allows the almost complete utilisation of the biomass</td>
<td>→ Competing utilisation options for lignocellulosic biomass</td>
</tr>
<tr>
<td>→ High possible range of synthesis gas-based products</td>
<td>→ Strong, competitive research and development outside of Germany (US, Austria, among others)</td>
</tr>
<tr>
<td>→ Development of new industries via a top-down development scenario</td>
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</table>
As of 2010, the German federal government has the conception of practicable and sustainable systems. Products from primary- and secondary refining, as well as raw materials, optimisation of the processes and products from primary- and secondary refining, as well as the conception of practicable and sustainable systems. As of 2010, the German federal government has pledged funding totalling €2.4 billion over a period of six years (project funding and institutional support) as part of the ‘National Research Strategy BioEconomy 2030’. The promotional activities also include the utilisation of biomass for industrial material- and energetic purposes. This includes support for biorefinery concepts. Around half of the supported projects for the conversion and material- and energetic utilisation of biomass in the BMELV ‘Renewable Resources’ funding programme can be regarded as projects for the support and technology development of biorefineries. Added to this are activities funded by a range of other funding programs, particularly by the BMBF, but also by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and by the Federal Ministry of Economics and Technology (BMWi). With the 2010 legislation for the establishment of the ‘Energy and Climate Fund’ investment fund, the German federal government is providing further means of funding for research and development in the area of bioenergy, among other areas.

Also here, it should be mentioned that more in-depth economic and ecological classifications (see unabridged version) are first estimates, and are subject to corresponding data uncertainties.

Conclusions, further steps and prospects

The ‘Biorefineries Roadmap’ is a robust demonstration of the opportunities presented by biorefineries for climate protection, value creation and resource efficiency. First and foremost, this is thanks to the possibilities presented by the complete utilisation of biomass. Nevertheless, this will not involve the replacement of traditional biomass uses. On the contrary: i.e. biogas plants will retain their importance specifically because of the various advantages of decentralised organisation.

However, the assessment of the individual biorefinery concepts clearly shows that considerable research is required before commercial practical applications can be fully realised. Here, special attention should be given to the integration of various methods for the creation of coherent technical concepts, the upscaling from laboratory to industrial scale, the provision of raw materials, optimisation of the processes and products from primary- and secondary refining, as well as the conception of practicable and sustainable systems. As of 2010, the German federal government has pledged funding totalling €2.4 billion over a period of six years (project funding and institutional support) as part of the ‘National Research Strategy BioEconomy 2030’. The promotional activities also include the utilisation of biomass for industrial material- and energetic purposes. This includes support for biorefinery concepts. Around half of the supported projects for the conversion and material- and energetic utilisation of biomass in the BMELV ‘Renewable Resources’ funding programme can be regarded as projects for the support and technology development of biorefineries. Added to this are activities funded by a range of other funding programs, particularly by the BMBF, but also by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and by the Federal Ministry of Economics and Technology (BMWi). With the 2010 legislation for the establishment of the ‘Energy and Climate Fund’ investment fund, the German federal government is providing further means of funding for research and development in the area of bioenergy, among other areas.

As stated above, a growing importance is attached to the subject of biorefineries in the European programs. As far as possible, as in the other EU funding programs, it will be important to secure funding for projects for the development of biorefineries in Germany. The economic and ecological classification of biorefinery concepts will play a key role, both in terms of the comparability of individual platforms with each other, and of comparability with other biomass utilisation paths. It is evident from the roadmap that gaps remain with respect to knowledge and data. Such a classification is nevertheless urgently needed to help making decisions regarding future research and research funding, amongst others for pilot- and demonstration plants, and to effectively focus scarce private and public research budgets. While the focus on environmentally beneficial approaches is a requirement of environmental- and climate protection, the economic potential will decide whether a concept will be developed up to a commercial scale and eventually enters the market. It will therefore also be necessary in the near future to implement projects focusing in-depth economic and ecological assessment of biorefinery concepts, both between themselves and in comparison to other biomass utilisation paths.

Overall, to support and accompany corresponding efforts from the private sector, the German federal government must also continue to support research and development on the subject of biorefineries – throughout the development chain, in a clearly visible manner, and to the required extent. The path to
realisation on an industrial scale is long, and requires a long-term time frame. The time line from specific concept via pilot plant to large-scale production is more than ten years. This will demand considerable efforts from the industrial sector, including the necessary deployment of risk capital.

In the consideration of individual platform concepts it has become apparent that, in all cases, the long-term assurance of the required biomass (whether imported or locally produced) at satisfactory prices is a decisive factor for the feasibility of the concepts. A central challenge thereby is to increase the efficient and sustainable production and supply of biogenic raw materials. Here too, the government should continue to provide support to corresponding research and development. Of interest thereby are new forms of land use such as short rotation plantations. It will also be crucial to make other sources of raw materials accessible along the lines of increased raw material production. In addition to the utilisation of waste materials and facilitation of imports (as with the fossil and mineral sector), for example, partnerships with the key raw biomass-producing countries will play a stronger role in the future. At the same time, the materially utilised biogenic raw materials must meet sustainability requirements. This goal was also formulated in the coalition agreement, and confirmed by the BMELV in the ‘Charter for Agriculture and Consumers’. The German federal government is thus funding a number of projects that are oriented strongly towards the voluntary willingness among industry stakeholders to exclusively utilise sustainably produced raw materials, also for material use.

In addition, it has become evident that considerable technological advancement and innovation is necessary for the presented biorefinery concepts to be operated commercially and on an industrial scale. Both the nature and extent of the required developments may differ in detail between the concepts, but it can generally be seen that there is a comprehensive need for the integration of various process steps and sub-concepts into coherent overall concepts, as well as into product development and product refinement – two key areas for the economic viability and establishment of biorefineries. A challenge for the implementation of all concepts is upscaling to industrial scale from the previous development stages. Alongside a variety of research projects on specific aspects of biorefineries, experimental facilities will also be needed in order to answer many of the questions related to these topics. The first of such systems are already under construction, also with the support of the German federal government. Worthy of mention in this context is the facility at Süd-Chemie in Straubing, the Fraunhofer Society’s Chemical-Biotechnological Process Center in Leuna, and the pilot plant for the bioliq process at the Karlsruhe Institute of Technology (KIT).

Overall, the roadmap demonstrates that biorefineries represent a promising approach for an efficient utilisation of renewable resources. Biorefineries will enable not only the increased substitution of fossil carbon sources in the production of a range of common chemicals and energy carriers, but will also result in new products as part of new value creation chains. At the same time, there is high interest in these technologies on the side of industry. However, it remains clear that the current state of knowledge leaves many questions unanswered, and that considerable research is still needed. The roadmap is set to be updated by 2020, at which time the technical developments and the level of knowledge again will be assessed, and where applicable, additional measures will be identified towards the acceleration of practical implementation of the most promising platforms.
1 Motivation

The major challenges of the future are closely tied to a growing world population and to meeting the rights of all people to basic requirements such as food, housing, energy, and mobility. The resultant requirements are intensified by the fact that ever more people will be hoping to meet these needs according to the standards of modern industrialised countries. Added to this is the knowledge that the Earth’s fossil resources are finite, and that their overall consumption must be reduced for reasons of climate- and resource protection. The subsequent growing role of renewable carbon sources for the production of energy and materials is reinforced by a shift away from nuclear energy, not least in response to the Fukushima reactor catastrophe in Japan.

As a result, the use of biomass for nutrition and food-stuffs – as well as to supply energy and raw materials – is seeing an increase in importance. While other renewable energy sources are available in the area of energy for the provision of electricity and heat, in the chemical industry and in other sectors, biomass represents the only non-fossil source of carbon – along-side CO₂ – in the area of the industrial production of materials and products, including fuels.

Biomass is renewable but remains limited because of the restricted availability of suitable cultivation areas. This issue and moreover competition with other land uses, such as for food, feed and industrial production, energy supply and nature conservation, requires – alongside sustainable increase in yields – a highly efficient utilisation of the scarce resource of biomass. This resource efficiency is key to realising the described opportunities, provided that simultaneous consideration is paid to principles of sustainable management. Together with the value creation that comes with increased use of biomass and the associated creation and securing of jobs, the emphasis throughout will be on minimum environmental impact. These advances also open up opportunities for the sustainable development of rural areas, both in Germany and globally.

By pursuing an approach that integrates different processes and which ensures the largely waste-free and sustainable utilisation of renewable resources, biorefineries promise high levels of resource efficiency whilst also giving due consideration to economics and ecology. With a view to the export potential of technologies from resource-rich countries, important roles in biomass production lie ahead for agriculture, forestry and for the chemicals industry with regard to new products, but also for the development of new conversion processes and machinery- and plant construction.

Alongside the systematic documentation of the current situation, this roadmap is intended to provide an analysis of the strengths and weaknesses – as well as opportunities and risks – of various future biorefinery concepts. In the process, it will also investigate issues of economic and ecological evaluability and provide concrete recommendations for the necessary R&D efforts, with the aim of the development and operation by 2030 of the most efficient, responsive and environmentally advantageous biorefineries as possible.
Biorefineries Roadmap

2 Biorefineries in the context of biomass utilisation

2.1 Biorefineries in the political context

The increased use of biomass combined with the challenges associated with limited availability of biomass can be overcome only by the joint efforts of all societal stakeholders from industry, science, and academia, as well as consumers and politicians.

The German federal government has made a clear commitment to the expansion of renewable energy, including bioenergy and the industrial use of renewable resources. The targets arise in large part from the EU’s package of measures on the set of issues of climate change and energy, the Lead Market Initiative on bio-based products in the EU, the European strategy for a European bioeconomy for Europe, the German federal government’s national research strategy for a knowledge-based bioeconomy, the federal government’s energy concept, the climate protection initiative from the federal government, and the federal government’s national research strategy for a knowledge-based bioeconomy.

It is important to reinforce Germany’s current technological leadership in the utilisation of biomass for the production of chemicals, materials and energy, including biofuels. However, increased efforts will be essential against the backdrop of current international and European developments. The federal government has firmly set the course with the ‘National Biomass Action Plan for Germany – Biomass and Sustainable Energy Supply’; the ‘The Federal Government Action Plan for the Use of Renewable Raw Materials’; the ‘High-Tech Strategy 2020 for Germany’; the ‘Research Strategy BioEconomy 2030’, as well as the national sustainable development strategy and the rules for management contained therein.

The ‘Biorefineries Roadmap’ is a further element in the German federal government strategy for the use of biomass and for the development of a bioeconomy, where Germany will be able to take a vital position. This strategy rests on numerous pillars. The underlying principle is a broad-based, interdisciplinary research environment that above all comprises biotechnological research as the important engine of innovation. On the economic side, alongside agriculture and forestry the bioeconomy takes in sectors of manufacturing and supply industries such as the chemicals-, plastics-, pharmaceutical- and cosmetic industries, the automotive industry, the energy and fuel-producing industries, the food processing industry, sugar and starch industry, oilseeds- and natural fibre-processing industry, pulp and paper industry, mechanical and plant engineering, as well as parts of the service sector.

The contents and objectives of the ‘Biorefineries Roadmap’

The ‘Biorefineries Roadmap’ is a comprehensive and integrated roadmap for the period up to 2030. The purpose of the roadmap is to create an essential foundation for the formulation of a strategy towards the development and implementation of biorefineries. Thereby, and also taking into account developments that are already in progress, this will involve the identification of future development paths incorporating both market demand and technology push, and where sustainability will serve as a model. The goal of the ‘Biorefineries Roadmap’ is the analysis and preliminary assessment of future developments in the field of action of biorefineries.

Raw materials, products, technologies and markets are put into a greater overall context in this roadmap, which also encompasses the relationship between biorefineries and other biomass utilisation paths (Section 2.2). A systematic compilation of the various concepts (Section 3) and a technological- (Section 4) as well as economic- and environmental analysis (Section 5) will serve as the basis for a SWOT analysis (Section 6) and the derivation of short-, medium- and long-term needs for action for biorefineries (Section 7).

The development of the ‘Biorefineries Roadmap’ took place with the close involvement of representatives from industry, research, and a variety of associations. An emphasis has been placed on broad societal consensus.
2.2 Biorefineries in the context of other biomass utilisation paths

Today, the term ‘biorefinery’ is used for many concepts, processes and approaches that bear some relation to the utilisation of biomass. Often, the term biorefinery is understood to mean any processing plant for biomass that does not belong to the food and feed sector. However, the term biorefinery cannot be applied either to this or to individual biomass conversion processes.

Instead, a biorefinery is characterised more by an explicitly integrative, multifunctional overall concept that uses biomass as a diverse source of raw materials for the sustainable and simultaneous generation of a spectrum of different intermediates and products (chemicals, materials, bioenergy/biofuels), whilst including the fullest possible use of all raw material components. The co-products can also be food and/or feed. By closing material cycles and through cascade utilisation and recycling, efforts are also made to prevent resource loss. Along the entire biorefinery value chain, all processes for the treatment and conversion of biomass should be resource efficient in terms of the use of materials and energy and in the consumption of media (e.g. water) and auxiliaries, and should avoid adverse environmental impacts. From the perspective of resource efficiency, goods and products of long lifetime are also of particular value.

Biorefinery concepts are characterised by a multitude of integrative and multifunctional features that are realised at a raw material-,. process-, product- and industry level (Table 1).

Biorefineries are a further building block in the utilisation of biomass, and complement the range of biomass utilisation options (Figure 1) with an additional path.

Current approaches in the use of biomass will be expanded and not replaced by future biorefineries. All biomass utilisation paths, including both established and innovative approaches to biomass conversion, are regarded as important and will be the subject of increased research and development efforts in the future. Through the use of all raw material components, biorefinery concepts carry greater potential than the reference system for high economic and environmental benefits. This is true both in a comparison with a fossil reference system as well as with other concepts for biomass utilisation aimed towards decoupled use of biomass and/or biomass components without simultaneous production of numerous other material and/or energetic products.

Table 1: Levels of integration and multifunctionality already realised in biorefineries

<table>
<thead>
<tr>
<th>Level</th>
<th>Integrational and multifunctional features</th>
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<tbody>
<tr>
<td>Raw material</td>
<td>→ Utilisation of all biomass components&lt;br/&gt;→ Processing of the various raw material components – in parallel and where appropriate in linked processes&lt;br/&gt;→ Optimally flexible use of raw materials in primary refining</td>
</tr>
<tr>
<td>Process</td>
<td>→ Linking of primary- and secondary refining&lt;br/&gt;→ Successive process steps along the value chain&lt;br/&gt;→ Connected product trees</td>
</tr>
<tr>
<td>Product</td>
<td>→ Simultaneous production of chemicals, materials and energy, and where appropriate co-products food and feed&lt;br/&gt;→ Simultaneous production of various materials and/or simultaneous production of different energy carriers&lt;br/&gt;→ The linking of conversion and refining</td>
</tr>
<tr>
<td>Industry</td>
<td>→ Incorporation into existing value chains&lt;br/&gt;→ Selection of location according to biomass generation and availability, where appropriate including&lt;br/&gt;- Integration into existing biomass processing locations&lt;br/&gt;- Integration into existing chemical parks respectively Verbund-Sites</td>
</tr>
</tbody>
</table>
With rising demand for biomass for competing uses, the construction and design of biorefinery concepts must take into account the limited domestic potential of biomass, likewise the consequences of biomass importation and of biomass production in the countries of origin. A further important aspect is the exportability of this high technology; in countries with corresponding biomass volume, biorefineries can be designed as complete systems or as system components, and could thus contribute greatly to the sustainable production of materials and energy, including biofuels.

The integrated processing of biomass in a single location, i.e. a biorefinery with combined production of materials and energy, offers a major opportunity for synergies. The benefits of combining processing- and product trees, of coupling energy and heat, and of joint water-, wastewater- and waste management, fixed costs reductions, and economies of scale also make up a part of the picture. On the other hand there are also challenges arising from the production of biomass and the decentralised and sometimes seasonal supply of raw materials. The logistical requirements and, where necessary, conditioning of the raw materials should also be mentioned here. Likewise, it will be necessary to ensure a long-term sustainable supply of raw materials of the appropriate quality and quantity, and at acceptable costs. A characteristic feature of a biorefinery is co-production. This refers to the combined production of several products that, for natural or technical reasons, are jointly produced in a single process. Here, the emphasis is on the production of energy and of marketable and ecologically advantageous products – at competitive costs and using all biomass components. A further characteristic of a biorefinery is the integration of numerous individual processes for production and refining. In contrast to the frequently highly selective biotechnological conversion, chemical processes in biorefineries often feature an internal recirculation of unreacted starting materials. The result of this integration is a complex vertical and horizontal integration of elements, encompassing both individual production processes as well as combinations of various processes. An integrated, networked system demands effective management as well as high levels of coordination and adjustment. Here, in terms of process safety and efficiency, consideration must be given to the potential issues that can occur as a result of an operational fault or loss of a subsystem in the integrated overall system.

It will be the task of the biorefinery sector to find its place in a complex environment. Only when all of these factors and challenges are taken into account will it be possible to see whether, when and at which locations the integrated, coupled/uncoupled production of chemicals, materials and biofuels or other forms of bioenergy will be meaningful and indeed sustainable.
3 The definition and classification of biorefineries, the state of the technology and the starting position

3.1 Definitions and differentiations

The biorefinery process chain consists essentially of system components for the pre-treatment and preparation of biomass, as well as for the separation of biomass components (primary refining) and the subsequent conversion/processing steps (secondary refining). The biorefinery process chain is outlined schematically in Figure 2:

The primary refining in a biorefinery involves the separation of biomass components into intermediates (e.g. cellulose, starch, sugar, vegetable oil, lignin, plant fibres, biogas, synthesis gas), and usually also includes the pre-treatment and conditioning of the biomass. While component separation takes place at the biorefinery, one or more pre-treatment/conditioning processes can also be decentralised where need be.

In secondary refining, further conversion and processing steps create a larger number of products from the intermediates. Thereby, in a first conversion step the intermediate materials are fully or partially processed into precursors, as well as into more intermediates; in further value creation at the site of the biorefinery, these are then fully or partially refined into products. The products from biorefineries can be both finished or semi-finished.

The by-products\(^6\) that occur as a result of primary- and/or secondary refining are used to supply process energy or, where applicable and in compliance with statutory requirements, they are further processed into food or feed.

Systems with the following characteristics will not be classified as biorefineries:

\(\rightarrow\) Plants for biomass conversion where no primary refining takes place either locally or regionally, or where absolutely no secondary refining is carried out.

Examples: An individual fermentation plant or paper mill with no attached pulp mill (no primary refining), or a simple starch factory with no connected processing plants or oil mill for oilseed processing (no secondary refining).

\(\rightarrow\) Systems for the conversion of biomass where there is no separation of components, but where the biomass is unchanged, modified slightly, or used only minimally.

Examples: A wood-processing mill or a facility for the manufacture of natural fibre insulation.

\(\rightarrow\) A plant for the conversion of biomass that generates only a single major product\(^6\) by direct conversion following primary refining, or where the main product clearly predominates in quantity.

Examples: Biodiesel production (main product: biodiesel) or an agricultural biogas plant (main products: electricity & heat).
Seen in isolation, these plants are not regarded as biorefineries but as components or subsystems of a biorefinery concept.

The features and characteristics of biorefineries are described and explained in the VDI guidelines “Quality Criteria for Biorefineries”, which is currently in preparation.

**Definition of terms for biorefineries**

A biorefinery is characterised by an explicitly integrative, multifunctional overall concept that uses biomass as a diverse source of raw materials for the sustainable generation of a spectrum of different intermediates and products (chemicals, materials, bioenergy/biofuels), whilst including the fullest possible use of all raw material components. Co-products can also be food and/or feed. These objectives necessitate the integration of a range of different methods and technologies.

The biorefinery process chain consists essentially of the pre-treatment and preparation of biomass, as well as the separation of biomass components (primary refining) and the subsequent conversion and processing steps (secondary refining).

**3.2 Sustainable biomass for biorefineries**

The biomass used in biorefineries must be provided and utilised in sustainable manner. Irrespective of geographical location, this directly concerns the means of production, the mode of trade, and the processing and/or utilisation. The reduction of greenhouse gases and use of fossil resources is also hugely important, while a simultaneous emphasis is placed on the maintenance of economic viability through products with high added value intensity. Further assessment factors apply here; these will be discussed in detail in Section 5.

Among other factors, the extent to which biomass will be able to replace fossil resources depends greatly on its availability and on the competing uses. The expansion of the use of renewable raw materials in biorefineries in Germany must be accompanied by the provision of qualitatively and quantitatively sufficient, as well as sustainably- and competitively produced, raw materials. Thereby, the secure production of foodstuffs takes clear precedence.

To some extent, the use of plant and animal biomass for industrial purposes also competes with use as a source of energy. Furthermore, there is occasional competition with use as a food or feed, and with the concerns of environmental and natural protection. On the other hand, there are many synergies between the different biomass pathways, such as the generation of animal feed co-products (e.g. as with vegetable oils) or material re-use of residual materials from food/feed production (e.g. straw). Biorefineries and the strengthened use of cascading can contribute greatly to mitigating potential competition, particularly between material- and energy recovery. Moreover, the use of biomass must encompass approaches that exhaustively pursue the ecologically sustainable expansion of the raw material base. Here, there is great potential in a more efficient use of existing land. There must be an improved mobilisation in compliance with nutrient sustainability of agricultural and forestry residues and biogenic waste materials; this is alongside the two main sources of renewable raw materials, agricultural biomass and timber. Aquacultures such as algae could also serve as a source of raw material in the future.

A particular focus is on the sustainable provision of domestically produced raw materials; there is great potential in Germany for expansion in this area. In plant cultivation above all, expectations centre on further yield increases and stagnant domestic demand for foodstuffs; worldwide, however, demand for foodstuffs is expected to increase. Nevertheless, farmers will make their planting decisions according to the extent of cultivation, which is ultimately determined by the competitive situation for the respective crop. There also appears to be potential for the additional use of biomass from the forestry sector, although a differentiated picture emerges when species and type of wood, as well as region and location, are taken into account (e.g. soil type). Here, appropriate measures in the context of sustainable and a forest management are necessary for the development and mobilisation of unused capacity.

Depending on the type, domestic biomass carries cost disadvantages over imported raw materials. However, commodity prices on the domestic and world markets have moved ever closer as part of the progressive liberalisation of the increasingly globalised agricultural markets. This can be seen above all for cereal crops, but also for sugar. Whether the requirements of industry for these commodities will be covered increasingly by imports in the future
depends on a number of factors, the most important being production costs, the exchange rate, transport-/haulage costs, transportability, the quality/quantity of the required raw material, and security of supply. Not all qualities are available domestically for some commodities (e.g. vegetable oils with short-chain fatty acids), and in such cases it will be necessary to fall back on imports.

The same rules of good practice and statutory regulations apply for domestic agricultural production of renewable raw materials as for the cultivation of food and feed crops. For wood production in Germany, sustainable forest management is ensured by the German Federal Forest Act and the legal provisions of the German State Forest Acts. The international certification systems FSC and PEFC for sustainability standards for forests also apply globally. Compliance with these rules assumes due consideration to concerns of environmental protection, independent of utilisation. To some extent, this cannot be guaranteed for the production of raw materials in third countries. For example, alongside negative effects on local populations and food security, adverse environmental effects cannot be excluded during the cultivation of tropical plants, in particular with regard to CO₂ emissions, biodiversity, and soil and water concerns.

Life-cycle assessments (LCA) are of central importance for the sustainability assessment of products, intermediate products or energy from biomass. Many existing LCAs have differing reference values, use differing methodological approaches, or are based on different principles; this affects above all the consideration of possible land use changes following cultivation. In some cases the expansion of agricultural and forestry production, including the increased cultivation of renewable raw materials, can result in adverse direct and indirect changes to land use, such as the deforestation of tropical rain forests for additional acreage. This can contribute increased CO₂ emissions, declining biodiversity, and the destruction of ecosystems. Appropriate precautions must be taken to avoid such negative outcomes and effects.

The assessment of biomass-based products is made more difficult by regional variations in environmental impact weighting for biomass crops, and there is a lack of regional-specific data at this time that can be used to evaluate biomass production in a specific region/country. A further methodological challenge in the assessment process is the consideration of time components and resource needs, e.g. water and phosphorus.

There is also a lack of internationally comparable LCAs for many bio-based products and biorefinery concepts; here, standards for assessments must be established on an international basis. Furthermore, appropriate instruments to promote positive climate- and environmental effects must be developed in the medium- and long term, while appropriate utilisation of products and energy from renewable raw materials must involve an improved understanding of their effects. The opportunities and risks of increased biomass use must be weighed on the basis of clear and objective criteria and parameters. This is also true for the assessment of biorefinery concepts, where the first approaches have already been implemented. If sustainability is not guaranteed, the acceptance of bio-based products and bioenergy in general, and of biorefineries in particular, will be at risk. This also means that the provision of biomass for biorefineries featuring coupled and simultaneous production of chemicals, materials and bioenergy, as well as for enclosed current and future methods and technologies, should demonstrate the highest possible cost- and resource efficiency.

3.3 Classification

A wide range of highly differing concepts is contained within the term ‘biorefinery’ and there are many approaches to the systematisation of biorefinery concepts. In terms of classification, no uniform approach has emerged to date for the area
of biorefineries. Depending on the viewpoint, the classification of various biorefineries focuses more or less systematically on a range of aspects. In the spotlight thereby are either:

→ the **raw material** (for example cereal crops biorefinery, grass biorefinery, straw biorefinery, wood biorefinery, forest-based biorefinery, whole crop biorefinery, algae biorefinery),

→ the **intermediate** (for example, synthesis gas biorefinery, lignocellulosic biorefinery, vegetable oil biorefinery, two-platform biorefinery),

→ the **process** (e.g. thermochemical biorefinery, biotechnology biorefinery), or

→ the product(s) (e.g. bio-ethanol biorefinery, fuel biorefinery).

The groundwork for a classification system for biorefineries – with a systematic approach and with a controlled vocabulary – was first developed as a part of IEA Task 42.11 This classification system focuses on the intermediate as the biorefinery platform, whilst orienting itself along the lines of the chemical industry with respect to the value chain. This allows for greater flexibility in the allocation of raw materials and products, and leads to a manageable number of platforms.

The systematisation proceeds according to four structural elements: raw material, platform, products and processes. The central element of the system is comprised of intermediate(s) that arise in primary refining, and which serve as a **platform** for the biorefinery for secondary refining. The terms **raw materials** and **products** are subsequently assigned to this platform. A connecting element is the **processes**. A polyhierarchical classification scheme is used here, shown in modified form in the following Figure 2. The sub-groups of the four structural elements are not conclusively determined; a final allocation is pending.

### Table 2: The elements of biorefinery classification

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Agricultural biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>→ Oil crops</td>
</tr>
<tr>
<td></td>
<td>→ Starch crops</td>
</tr>
<tr>
<td></td>
<td>→ Sugar crops</td>
</tr>
<tr>
<td></td>
<td>→ Grasses</td>
</tr>
<tr>
<td></td>
<td>→ Wood</td>
</tr>
<tr>
<td></td>
<td>→ Woody biomass</td>
</tr>
<tr>
<td>Aquatic biomass</td>
<td>→ Algae</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biogenic residual- &amp; waste materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Agricultural and forestry residues</td>
</tr>
<tr>
<td>(e.g. straw, manure, wood residues, fruit peel, slurry)</td>
</tr>
<tr>
<td>→ Biogenic residual materials from processing</td>
</tr>
<tr>
<td>(e.g. whey, pulp, stillage, spent grains)</td>
</tr>
<tr>
<td>→ Biogenic waste materials</td>
</tr>
<tr>
<td>(e.g. yellow grease, waste wood)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Platform</th>
<th>→ Low molecular weight carbohydrates (e.g. lactose, sucrose)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>→ Polymeric carbohydrates (e.g. starch, inulin, pectin)</td>
</tr>
<tr>
<td></td>
<td>→ Lignocellulose components (lignin/cellulose/ hemicellulose)</td>
</tr>
<tr>
<td></td>
<td>→ Proteins</td>
</tr>
<tr>
<td></td>
<td>→ Plant fibres</td>
</tr>
<tr>
<td></td>
<td>→ Vegetable oils, lipids</td>
</tr>
<tr>
<td></td>
<td>→ Pyrolysis oil</td>
</tr>
<tr>
<td></td>
<td>→ Press juice</td>
</tr>
<tr>
<td></td>
<td>→ Biogas</td>
</tr>
<tr>
<td></td>
<td>→ Syngas</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Products</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>→ Chemicals</td>
</tr>
<tr>
<td></td>
<td>→ Materials</td>
</tr>
<tr>
<td></td>
<td>→ Feedstuff*</td>
</tr>
<tr>
<td></td>
<td>→ Foodstuff*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bioenergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Solid, liquid, gaseous sources of bioenergy</td>
</tr>
<tr>
<td>→ Electricity</td>
</tr>
<tr>
<td>→ Heat</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processes</th>
<th>→ Physical, including mechanical processes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>→ Thermochemical processes</td>
</tr>
<tr>
<td></td>
<td>→ Chemical processes</td>
</tr>
<tr>
<td></td>
<td>→ Biotechnological processes</td>
</tr>
</tbody>
</table>

* as a co-product
Table 2 provides an overview of theoretical possibilities, without reference to technical and economic feasibility. A graphic representation of classification is shown in the schematic in Figure 3.

In this classification of biorefinery plants, the platform and raw material are used for designation; where applicable, the main products are named when either material or energetic products predominate. This is elucidated and schematically illustrated in Figure 4.

The four main elements (raw materials, platform, products and processes) underlying the classification scheme for biorefineries will be described and explained in more detail in the following. The following depictions of the structural elements of raw materials, products and processes are not unique to biorefineries, but also apply fully or in part to other biomass conversion pathways.

### 3.3.1 Biorefinery platforms

The term biorefinery platform refers to the intermediate products that arise during primary refining, and which serve as the raw product for subsequent secondary refining. The biorefinery platform thus takes a central position in the overall system, and is consequently the main element in the classification of biorefineries. The intermediate(s) result from the direct conversion of the biomass, which involves a separation of the biomass components. In some cases, however, these components are only produced in-situ, and are degraded to low molecular weight compounds in the same process step; these are then available as intermediates for further conversion in secondary refining. Here, the intermediates are further modified and/or converted. Thereby, conversion into one or more intermediate products (e.g. glucose, fructose, fatty acids, glycerol, amino acids, hydrogen) can proceed as a first step; these products then serve as precursors for subsequent further processing. Finally, one or more secondary refining steps results in finished or semi-finished products for commercialisation.

The raw products that are in principle obtained as intermediates from primary refining, and which can constitute a biorefinery platform, are listed in Table 2. However, for technological and economic reasons, as well as with respect to location conditions, not all
intermediates represent a suitable biorefinery platform basis within an integrated production network of primary- and secondary refining.

3.3.2 Raw materials for biorefineries
The raw materials for biorefineries are biogenic raw materials that are based on biomass. Summarised under the term biomass are all organic materials occurring or generated in the Holocene (denoting the present epoch). Biomass either remains in the ecosystem or is used by humans as raw material for nutrition purposes, in the material conversion industry, or for the production of energy.

Plant biomass formed through the photosynthetic fixation of carbon dioxide represents the bulk of the terrestrial primary production of biomass; algae and other primary producers take on this role in aquatic systems. The biomass formed by primary producers is then further converted by consumers – above all into animal biomass. In terms of volume, terrestrial plant biomass is the most significant biogenic raw material.

From a chemical perspective, biomass is a very complex mixture of mainly organic compounds. Alongside abundant organic carbon, it is proportionally rich in oxygen, although relatively poor in hydrogen. Nitrogen, sulphur and other elements are also present in small quantities. Besides organic compounds, small amounts of inorganic compounds (e.g. salts, minerals, trace elements) are also found in biomass. Water is an exception here, as this can be present in larger quantities.

Although biomass is highly complex, it can be essentially broken down into four classes of compounds, which make up the bulk of the organic components:

→ Carbohydrates
→ Lipids
→ Proteins
→ Lignins

These major components can vary depending on the origin of the biomass, or in some cases can be missing entirely. There are many other organic compounds that can be present in biomass. With respect to organic components, plant biomass consists above all of carbohydrates, fats and lignin, whereas animal biomass consists primarily of proteins and fats.

Because of the importance of plant biomass, a more detailed consideration will be given to the main components. Carbohydrates are the main component of plant biomass, serving predominantly as structural- and storage carbohydrates, but also as transport carbohydrates and in glycoconjugates. Quantitatively, the most important natural carbohydrates are cellulose, hemicellulose and starch, and to a lesser extent pectins, inulin and sucrose. Cellulose is the most commonly occurring natural substance. These natural carbohydrates are predominantly made up of polymeric and oligomeric compounds. Here, glucose is the most important monomer, making it most abundant organic compound on earth. Examples of carbohydrate-rich plant parts are sugar beet, sugar cane and cereal grains.

Fats are plant storage substances, and are found primarily in seeds or fruits. Fat-rich plant parts include canola- and sunflower seeds and palm pulp.

Lignins accumulate in the plant cell wall as structural substances. Lignins are three-dimensional polymeric networks of aromatic building blocks that are variously connected. In addition, many phenolic groups are also present. After cellulose, lignin is the second most abundant natural product. All woody plant parts, for example, are lignin-rich.

Alongside chemical composition, there are also other important biomass characteristics, including physical raw material properties such as density, water content, ash content, trace element content, particle size, heat value, and other properties. Also relevant are volume, yield, availability, time of harvest, purity, transportability, storage life, storage stability, and long-term quality.

There are diverse types of biogenic raw materials. They are cultivated specifically as industrial or energy crops, or arise during primary production either as plant- or animal residues or as co-products. They can also arise in the industrial processing steps of secondary refining, or as waste after the usage phase of the finished products (Figure 5).

These can be approximately divided into the following groups:
1. **Renewable resources**, i.e. biomass from agriculture and forestry that is not used as food or feed. In addition to agricultural biomass, this also includes aquatic biomass.
2. **Biogenic residual materials from agriculture and forestry**, i.e. the residues generated as a result of agricultural and forestry production (e.g. straw, beet leaves, wood residues, manure), e.g. biogenic residues obtained in primary refining (e.g. beet pulp, rapeseed cake, potato pulp, corn cobs, animal by-products, black liquor, algal biomass).
3. **Industrial biogenic residual materials**, i.e. processing- and production residues that result from industrial processing, such as residual biomass from fermentation (e.g. slurry, fermentation residues), or biogenic residual materials from food production (e.g. whey, spent grains, fruit peels).

4. **Biogenic waste materials** that arise in the usage phase of the finished product (e.g. waste fats from food, waste from food consumption, bio-based oils, bio-based plastic packaging materials, used wood).

The sustainable, secure and cost-effective production and supply of biomass in the required quality and quantity is a decisive factor for the operation of a biorefinery. The provision of biomass is divided into a number of phases (Figure 6).

The cultivation together with the harvesting and recovery as well as collection of biogenic residue- and waste materials represents the production- or mobilisation phase. Soil and plant cultivation factors, site conditions, and operational and market-economic aspects all play a role in the yields and quality of the biomass. The quantity and quality of biogenic residue- and waste materials is also dependent on the production-, recovery- and collection procedures.

The production- and mobilisation phase is followed by the conditioning- and logistics phase, which bridges the time and the distance between the generation of the biomass and its utilisation. Transport, storage and preparation processes are conducted in this post-harvesting phase. In principle, such steps can take place over the entire supply chain, and thus also at the site of material and energy conversion; they can also be carried out at different times, or multiple times (e.g. transport processes). Since they take place at the site of the conversion facilities, some of these storage, transportation and loading processes are often regarded as an internal part of the conversion plant, among other things also because they must be adapted to include the respective plant engineering.

In the production and provision of bio-based raw materials, consideration is given both to quantity...
and to the respective characteristics, including the delivered quality. In the cultivation phase, this concerns above all the chemical composition and the material characteristics (e.g. type and amount of substance, the structure of the biomass), whereas the physical properties are in the foreground in the subsequent deployment phase. This results in a spectrum of different properties, enabling optimisation within a specific framework of the respective bio-based raw material towards the desired process; where appropriate, the process can also be adapted to the bio-based raw material.

The procurement options for biogenic raw materials are diverse. Alone for agricultural biomass or for woody biomass deriving from forests, there are a wide range of supply chains up to the point of use. These are complemented by numerous potential supply chains for biogenic residual materials and biogenic waste materials.

Suitable for use in biorefineries above all are bioogenic raw materials, which are available in sufficient and consistent quality and quantity, and allow year-round operation. Indeed, the commercial operation of a biorefinery is greatly hindered if these conditions are not satisfied.

### 3.3.3 Products from biorefineries and their markets

**Products**

Biorefineries are characterised by the provision of a wide range of semi-finished and finished products. These are parallel produced in secondary refining and/or in successive conversion- and processing steps. These products can be preliminary- and intermediate products for other production processes, or finished products for end use. In biorefineries it is possible to distinguish between two major user groups: bio-based chemicals and materials as products for material utilisation, and secondary energy carriers for energetic utilisation. The most important product groups are listed below:

- Bio-based chemicals and materials
  - Base chemicals and chemical intermediates
  - Fine- and specialty chemicals (e.g. pesticides, pharmaceutical raw materials, dyes)
  - Bio-based polymers, materials and composite materials
  - Bio-based synthetic fibres, natural fibres
  - Natural fibre- and wood fibre-reinforced materials and composite materials
  - Adhesives, lacquers and paints
  - Detergent- and body care products
  - Fertilisers

- Bioenergy carriers
  - Electricity
  - Heat
  - Biofuels (e.g. ethanol, biodiesel, biomass to liquid (BtL) fuels, biomethane, hydrogen)

Biorefineries always feature the coupling of different material and energetic utilisation paths. However, the development of a biorefinery is generally driven forward either on a material or energetic basis, i.e. the biorefinery is oriented primarily towards the production of bio-based, technical products, or is oriented primarily towards the generation of bio-based secondary energy carriers.

In addition to bio-based technical products and bio-based secondary energy carriers, a biorefinery can in some cases, and assuming suitability and compliance with legal requirements, also generate co-products that can be further processed into food and feed. Here, in alternative uses, the risks associated with specific by-products must be considered in the concept development. This applies above all in cases of use as a food or feedstuff, where safety must be ensured. The option to use by-products as a food and/or feed is only considered if the co-products directly result as a raw material from the input of renewable raw materials or biogenic residual materials (as defined by the classification in Section 3.3.1). If biogenic waste materials are used as raw material, the use of the subsequent co-products is possible only in the technical area. In a biorefinery, the co-products that are used as food or feed arise only as by-products. Moreover, prior to the further processing of co-products, a separation of production streams takes place to ensure that food or feed is not produced in plants that simultaneously produce materials for technical purposes.

### Product orientation of biorefineries

**Materials-driven biorefineries:** In terms of volume and/or value creation, the biorefinery is focused primarily on the production of a range of chemical- and material products. Co-products and residual materials are utilised for the production of bioenergy and food/feed.

**Energy-driven biorefineries:** In terms of volume and/or value creation, the biorefinery is orientated primarily towards the production of one or sometimes multiple bioenergy carriers. Proportionally, only a small amount chemicals and materials are generated. Co-products and residual materials are utilised for the production of chemicals, materials and food/feed.
**Market**
In terms of volume, fossil-based products and energy currently greatly outweigh the use of bio-based chemicals/materials and bioenergy.

In 2008, approximately 4% of all fossil raw materials in Germany (crude oil, natural gas, coal) and about 14% of the oil in the chemical industry was materially utilised, with the remainder (electricity, heat, fuels) utilised for energy provision (Figure 7).

To date, the application of biogenic raw materials has been on a much smaller scale than of fossil fuels.

**Bio-based chemicals and materials.** In 2008, approximately 3.6 million tons of renewable raw materials (excluding raw wood) were materially utilised for the production of bio-based chemicals, bio-based materials and other bio-based products. About 2.7 million tonnes flowed into the chemical industry, i.e. about 13% of the organic raw materials here were renewable and were processed into bio-based products. Around 0.9 million tonnes were consumed outside of the chemical-pharmaceutical sector, above all in the paper starch- and natural fibre-processing industries. Added to this are imported chemical intermediates/semi-finished products and finished products based on renewable agricultural raw materials. Furthermore, in 2008 the wood processing industry required considerable quantities (around 72 million cubic meters, ~36 million tonnes) of woody raw materials. Added to this are waste paper and imported semi-finished and finished wood products. Only preliminary data are available for 2009 and 2010, but they can be assumed to be of a similar magnitude.

**Bioenergy.** According to the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), in 2010 the final energy consumption for bioenergy lay at around 196 TWh, corresponding to around 7.9% of final energy consumption in Germany of 2496 TWh. Bioenergy thus takes the largest share of renewable energies. Overall, around 71% of all renewable energy was produced from biomass, with the following proportions achieved in the individual renewable energy sub-sectors: 33% in the electricity sector, 92% in the heat sector, and 100% in the fuel sector.

The markets for material products are open and unprotected, and market access is determined largely by technical suitability and price. A differentiated view should be applied for the market situation for energetic products. Overall, the market for bioenergy (as one part of the renewable energies) is shaped more strongly by policy requirements and subsidies at a national and European level. As an energetic product, electricity thus partially operates in a protected, subsidised market. The framework conditions for biofuels have not been stable in recent years, and this has hindered long-term planning and market penetration. Heat recovery requires the use of heat collectors, which are not always available in the coupled production of electricity and heat, and in terms of quantity, the material utilisation of renewable materials in the chemical industry is low compared to energetic utilisation. However, the proportion of

---

**Figure 7: Portion of material utilisation in the chemical industry and of energetic utilisation of fossil raw materials in Germany in 2008**

- **Use of fossil raw materials in Germany**
  - **Mineral oil**: 109 Mt
  - **Fuels**: 4.1 Mt
  - **Material utilisation in chemical industry**: 13 Mt
  - **Energetic utilisation**: 83 Mt

- **Total fossil raw materials**: 456 Mt
renewable resources in the total consumption of organic raw materials in the chemical industry is considerably larger than the proportion of biogenic raw materials in the total consumption of energetic raw materials (a comparison for 2008 shows a 13% share of biomass in organic raw materials in the German chemical industry, and 6.4% for bioenergy for total final energy consumption in Germany).

The European Commission considers the market for bio-based products to be one of the six most promising future markets. The EU Commission expects sales in the six emerging markets to grow strongly by 2020, and for many related jobs to be created in the EU area. The federal government is taking part in the implementation of the European Lead Market Initiative. This initiative is also aimed at supporting business in the establishment of a sustainable, bio-based economy.

### 3.3.4 Processes and technologies for biorefineries

A wide range of technologies and processes is required for both primary and secondary refining, as well as for the preparatory provision of biomass. There are essentially no specific developments involved in biorefineries; instead, the emphasis is on the innovative adaptation of fundamentally well-known production techniques to specific biomass characteristics. In turn, this demands the development of new and specific processes and methods, as well as intelligent technical solutions for the provision, conditioning and conversion of biomass. It is possible to distinguish between four main groups, to which the following processes can be assigned (no claim is made here to comprehensiveness):

- **Physical processes**, including mechanical
  - Basic operations to change material properties (e.g. milling, drying, heating, cooling, compacting)
  - Cleaning and separation processes (e.g. filtration, distillation, extraction, crystallisation, adsorption, sieving)
  - Extraction processes

- **Thermochemical processes**
  - Combustion
  - Gasification
  - Pyrolysis
  - Thermolysis
  - Hydrothermal processes

- **Chemical processes**
  - Basic operations for material transformation (e.g. oxidation, hydrogenation, esterification, etherification, isomerisation, hydrolysis, polymerisation)
  - Chemically catalysed conversions

- **Biotechnological processes**
  - Enzymatically catalysed conversions
  - Fermentation and decomposition processes

These processes can also be operated in an integrated sense, e.g. through the combination of separation and reaction technologies, or the combination of chemical and biotechnological procedures.

A process encompasses more than just products and reactants. All processes require additional additives/media and energy, which must be considered in the process development and balancing for a biorefinery. Moreover, waste, wastewater and emissions are additional factors that must be taken into account in process development and balancing.

Further factors (such as nutrient cycling and competing uses for biomass) must also be given due consideration in the utilisation of biomass. The assessment of a process, a technological development and a utilisation path can only take place once a comprehensive material and energy balance for a biorefinery has been carried out, in combination with general and specific location factors and a sustainability analysis.

### 3.4 Biorefinery value chain versus petrochemical value chain

A comparison between the biorefinery value chain and the petrochemical value chain shows some similarities at first glance. At second glance, however, it is possible to recognise that although there are overall similarities, there are also a large number of significant differences.
Both value chains share the principle of separation of components, the principle of primary and secondary refining, as well as a wide range of products in the form of product trees. The differences arise from:

- the type of raw material components, the raw material composition, and the complexity of the raw material;
- the nature and process of primary refining;
- the principles and core processes of secondary refining;
- the product spectrum with regard to combined production of food and feedstuffs.

The following Table 3 illustrates in detail the similarities and differences between the two value chains. It is possible to see here that in a biorefinery value chain with a synthesis gas/biogas gas platform, there are more commonalities than in a biorefinery value chain with a solid/liquid intermediates platform.

The fundamental differences in composition between fossil and biogenic raw materials are exemplified by a comparison of the important fossil raw material naphtha with the biogenic raw materials cellulose, hemicellulose, and lignin (Figure 8).

### 3.5 Biorefinery concepts

Alongside the main elements, the classification scheme outlined in Section 3.3 features numerous sub-elements. This opens up a range of options for biorefinery platforms and related biorefinery concepts. From these, a few particularly promising biorefinery paths have emerged from the biorefinery concepts:

1. Sugar biorefinery and starch biorefinery
2. Vegetable oil biorefinery and algal lipid biorefinery
3. Lignocellulosic (cellulose, hemicellulose and lignin) biorefinery and green biorefinery
4. Synthesis gas biorefinery
5. Biogas biorefinery

These biorefinery paths differ according to platform, i.e. by the intermediate formed at component separation.

<table>
<thead>
<tr>
<th>Value chain</th>
<th>Biorefinery (Platform: solid or liquid intermediates)*</th>
<th>Petrochemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td>→ Biomasses: Very complex mixture of organic compounds → Carbon and heteroatoms (poor in hydrogen, rich in oxygen) → Contains inorganic compounds → Hydrous</td>
<td>→ Mineral oil, natural gas: Mixture of hydrocarbons → Carbon and hydrogen (only few hetero atoms, poor in oxygen) → Contains virtually no inorganic compounds → Waterless</td>
</tr>
<tr>
<td>Primary refining</td>
<td>→ Mechanical, chemical and biochemical decomposition into complex molecules</td>
<td>→ Distillation and thermal and thermocatalytic cleavage into simple molecules</td>
</tr>
<tr>
<td>Secondary refining</td>
<td>→ Conversion and decomposition of complex molecules (top-down principle) → Use of the complex molecules of the raw materials</td>
<td>→ Build-up of complex molecules from simple precursors (bottom-up principle)</td>
</tr>
<tr>
<td>Processes</td>
<td>→ Thermochemical and chemocatalytic processes → Biotechnological processes</td>
<td>→ Thermochemical, thermocatalytic and chemocatalytic processes</td>
</tr>
<tr>
<td>Product classes</td>
<td>→ Chemicals and materials → Combustibles and fuels → Food and feedstuff</td>
<td>→ Chemicals and materials → Combustibles and fuels</td>
</tr>
</tbody>
</table>

*Examples: Starch platform, vegetable oil platform, lignocellulose—platform (cellulose, hemicellulose, lignin)
ration. The platforms thus differ initially according to the nature of primary refining. The spectrum of products is nevertheless broad and diversified, meaning that further subdivision is not useful. The above-named biorefinery paths are subject to a detailed analysis and assessment in chapters 4 and 5 of this roadmap.

3.6 Development approaches

A further question that naturally arises is: How is a biorefinery developed? In principle, there are two basic approaches for the implementation of a biorefinery concept. Bottom-up and top-down (Figure 9).

**Bottom-up approach**

If the biorefinery concerns the expansion of an existing biomass processing facility (e.g. sugar, starch, plant pulp mill, oil mill, ethanol plant), it is referred to as a bottom-up approach. Here the aim is to achieve an expanded range of products and/or an increase of usable biomass fractions through the connection of additional processes and technologies in an integrated primary- and secondary refining.

An example of such a system is the grain-based starch biorefinery in Lestrem (France). The plant was originally a simple starch factory that was later supplemented by corn- and wheat starch production. This was followed by a gradual expansion of the product spectrum (starch derivatives and starch modifications, chemicals, fermentation products).

**Top-down approach**

In contrast to bottom-up, the term top-down is used when the emphasis is on newly conceptualised, highly integrated systems designed for the use of various biomass fractions and the (zero-waste) generation of a variety of products for different markets. Thereby, there is no linking to existing biomass conversion processes; instead, systems for primary and secondary refining are specifically developed towards the biorefinery platform-based production of a range of products.

<table>
<thead>
<tr>
<th>Value chain</th>
<th>Biorefinery (Platform: solid or liquid intermediates)</th>
<th>Petrochemical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Raw materials</strong></td>
<td>→ Biomasses: Very complex mixture of organic compounds &lt;br&gt;→ Carbon and heteroatoms (poor in hydrogen, rich in oxygen) &lt;br&gt;→ Contains inorganic compounds &lt;br&gt;→ Hydrous</td>
<td>→ Mineral oil, natural gas: Mixture of hydrocarbons &lt;br&gt;→ Carbon and hydrogen (almost no hetero atoms, poor in oxygen) &lt;br&gt;→ Contains virtually no inorganic compounds &lt;br&gt;→ Waterless</td>
</tr>
<tr>
<td><strong>Primary refining</strong></td>
<td>→ Thermal and thermocatalytic (syngas) as well as biochemical (biogas) cleavage into simple molecules</td>
<td>→ Distillation and thermal and thermocatalytic cleavage into simple molecules</td>
</tr>
<tr>
<td><strong>Secondary refining</strong></td>
<td>→ Build-up of complex molecules from simple precursors (bottom-up principle)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Processes</strong></td>
<td>→ Thermochemical, thermocatalytic and chemocatalytic processes</td>
<td>-</td>
</tr>
<tr>
<td><strong>Product classes</strong></td>
<td>→ Chemicals and materials &lt;br&gt;→ Combustibles and fuels</td>
<td>-</td>
</tr>
</tbody>
</table>

* Examples: Synthesis gas platform, biogas platform
Figure 8: Comparison of fossil raw material naphtha with the biogenic raw materials cellulose, hemicelluloses and lignin, with regard to molecular weight and oxygen/carbon ratio

An example of this approach is the wood-based synthesis gas biorefinery in Güssing (Austria). This demonstration plant produces heat and electricity for commercial purposes and also conducts tests on a variety of synthesis gas uses (e.g. Fischer-Tropsch synthesis, Bio-SNG synthesis, synthesis of alcohols, hydrogen production).

Both the bottom-up and top-down development approaches can be implemented centrally at a new site ('greenfield') or at an existing industrial site ('brownfield'). In the latter case, this takes place preferably via integration into an existing industrial- or chemistry park, or as an extension of existing biomass conversion systems. It is also conceivable for components of primary refining (e.g. biomass conditioning) to be decentralised, giving rise to a hybrid structure.

As already described in Section 3.3, a coupling of various energetic and material utilisation paths takes place in biorefineries. Nevertheless, a biorefinery is typically either materially oriented or energy oriented, i.e. either the biorefinery is predominantly based on the production of bio-based technical products or predominantly based on the generation of bio-based secondary energy carriers. Moreover, development and expansion usually proceeds incrementally. In addition to primary refining, the secondary refining is frequently implemented into only one or into a quantitatively predominant primary product. An expansion into a biorefinery through the integration of additional conversion within the secondary refining process takes place only later (this is exemplified in the following box with a scenario for the development of a straw-based lignocellulosic biorefinery).

What is the development status of biorefinery concepts? Bottom-up approaches for biorefinery concepts are implemented only on an industrial
scale, albeit in very few plant complexes. Examples are the grain-based starch biorefinery in Lestrem (France) and the corn-based starch biorefinery in Decatur, Illinois (USA), as well as the wood-based lignocellulosic biorefineries in Lenzing (Austria) and Sarpsborg (Norway). Even here, however, there is a great need for research. Top-down biorefinery concepts have not yet been fully implemented to date and remain at the research-, development- and demonstration stages. The first pilot and demonstration plants are based or are currently being constructed in Europe (including Germany), the US, and in other countries.

3.7 Development of biorefineries in Germany – classification in the international context

There has been a continuous growth of the development (predominantly technology-driven) of the utilisation of biomass in the past ten to fifteen years in Europe, the USA and in a number of other industrialised countries, with a corresponding development of biorefineries over the past five years. The following analyses refer to biorefineries in the sense of the explicitly integrated, multi-functional concepts described in Section 3.1 for the sustainable, coupled generation of a spectrum of different products (chemicals, materials, bioenergy, food/feedstuffs) from biomass.

In Europe, the development of biorefineries has gathered momentum in the last five years. While developments in some countries (e.g. Germany, France, Netherlands, Scandinavia) have already
been in progress for a decade, the EU level first began to seriously engage with the topic of biorefineries about three years ago. The envisaged financial resources are comparatively modest, both in comparison to the national expenditures of member states and to the funding resources of non-European players (e.g. the US). While the topic of biorefineries played an extremely minor role in the 6th EU Research Framework Programme (FP6) and its predecessor programs, the current 7th EU Research Framework Programme (FP7) has for the first time included comprehensive funding totalling over €70 million for the explicitly integrated biorefinery concepts as defined in 3.1. The contents of the explicitly integrative biorefinery projects are extremely varied and for the most part encompass the development of new biorefinery processes and products, the optimisation and upgrading of existing conversion processes, and the industrial-scale demonstration of research results. An extensive project in the area of ‘Research Coordination’ was also provided with support through Star-COLIBRI (Strategic Targets for 2020 – Collaboration Initiative on Biorefineries). The goal of Star-COLIBRI was to stimulate cooperation between complementary research projects at the European level, which would promote progress in this area and counteract the fragmentation of research activities and results. The ‘Biorefinery Research Agenda 2020’ and ‘Biorefinery Vision for 2030’, both of which are aimed at providing a framework for the development of the biorefinery sector in Europe, have also been drawn up during the course of this project. In Germany, the Agency for Renewable Resources (FNR), the German Biomass Research Centre (DBFZ) and the Technical University of Dresden are all engaged in Star-COLIBRI. Beyond the explicitly integrative R&D projects, there are also a wealth of research projects supported at the EU level that deal with one or more (potential) aspects of the topic of biorefineries or of the conversion of biomass. Future subsidies are likely to be in the same order of magnitude.

In the US, under the heading of ‘Biorefineries’, the utilisation of biomass is supported by high financial resources totalling several hundred million dollars. This is aimed at research, development and demonstration, although the majority of projects to date have not fallen under the definition of explicitly integrated biorefinery concepts as described in 3.1. The funding is oriented above all towards the area of cellulosic bioethanol. The first construction of production-scale reference plants is now underway in the US. There have been advancements in the utilisation of biomass in the past two years, and the area of biofuels and above all cellulosic bioethanol will continue to receive strong support; bio-based chemicals and materials are also moving into the spotlight. There are two significant reasons for this overall trend: On the one hand, a number of past predictions about the US biofuel sector have proven unrealistic; on the other, researchers and investors have increasingly come to realise that bio-based materials and chemicals carry high potential for value creation. The latter applies for both the singular production of bio-based chemicals and materials, and for the additional integrated production of biofuels. This biofuels production in particular leads to the development of biorefineries (in line with the above-described definition), meaning that strengthened development efforts in the United States towards explicitly integrated biorefineries can be expected in the future.

By way of comparison, the development of the utilisation of biomass in most emerging and developing countries is raw materials-driven, resulting in numerous plants for biomass conversion, which in some cases will evolve into biorefineries in the future. The relatively good agricultural structure and competitiveness of biomass in some emerging and developing countries (e.g. Brazil, India, Thailand) has attracted large agricultural-, chemical- and energy companies from the developed countries. Cooperations between national and international companies play a crucial role here, with particular engagement from North American, British, and French companies, while German companies are only sporadically active in these countries.

In Germany, the utilisation of biomass has been pushed forward since about fifteen years, and explicitly integrated biorefinery concepts have already been pursued for a number of years. For example, a range of activities aimed at investigating and developing diverse biorefinery paths are in various stages of realisation:

- Sugar/starch biorefinery on the basis of cereal crops/sugar beet from the company Südzucker/CropEnergies in Zeitz (Saxony-Anhalt)
- Wood-based lignocellulosic biorefinery operated by a consortium coordinated by DEHEMA as part of the Fraunhofer Society’s Chemical Biotechnological Process Center at the chemical site in Leuna (Saxony-Anhalt)
- Lignocellulosic biorefinery based on straw from the Süd-Chemie company in Munich and Straubing (Bavaria)
Grass silage-based green biorefinery from the company Biowert in Brensbach (Hesse)\(^3\)
Grass-based green biorefinery from the company Biopos in Selbelang (Brandenburg)\(^3\)
Straw-based synthesis gas-based biorefinery from KIT in Karlsruhe (Baden-Württemberg)\(^3\)

The research and development involved in biorefineries is extremely complex. Alongside research projects with focus on integrated biorefinery concepts, there is also a variety of research projects that deal with one or more aspects or potential components within the overall topic of biorefineries, or which contain fundamental research of relevance for the various biomass utilisation pathways, but which do not apply to biorefineries. Furthermore, it is not possible for basic research (e.g. for plants or sustainable agricultural production) to be allocated

Table 4: Analysis of the development of biorefineries in Germany

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>➔ internationally competitive industry and energy sector</td>
<td>➔ the opportunities of a shift in raw materials toward the use of biomass is not yet sufficiently recognised in all parts of industry</td>
</tr>
<tr>
<td>➔ effective agriculture and forestry sector</td>
<td>➔ further improvement of sustainable biomass production and the sustainable provision of biomass is essential</td>
</tr>
<tr>
<td>➔ outstanding infrastructure and favourable geographic location</td>
<td>➔ basic research and applied research is not sufficient in some areas of the decomposition and conversion of biomass</td>
</tr>
<tr>
<td>➔ many years of practical experience in the conversion of biomass as well as in the establishment and operation of systems for processing biomass</td>
<td>➔ market orientation of public funding for biomass utilisation pathways and biorefinery pathways are not present in all application-oriented funding programs</td>
</tr>
<tr>
<td>➔ leading role in industrial and energetic utilisation of biomass in European and global comparison</td>
<td>➔ few flexible and open-access pilot and demonstration plants</td>
</tr>
<tr>
<td>➔ strong scientific-, engineering-, agricultural- and forestry research landscape</td>
<td>➔ high investment costs for complex systems</td>
</tr>
<tr>
<td>➔ strong German chemical and biotechnology industries</td>
<td>➔ social acceptance is not present for all areas of biomass cultivation</td>
</tr>
<tr>
<td>➔ high-performance machinery-, apparatus- and plant construction</td>
<td></td>
</tr>
<tr>
<td>➔ positive political framework conditions in Germany and Europe for bio-based products and renewable energies</td>
<td></td>
</tr>
<tr>
<td>➔ positive public opinion towards bio-based products and renewable energies</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>➔ a shift in the industrial raw materials base towards sustainability and resource efficiency</td>
<td>➔ competition distortions due to globally differing sustainability standards</td>
</tr>
<tr>
<td>➔ a strengthening of the competitiveness of the German industrial- and energy sectors with respect to foreign competitors</td>
<td>➔ limited availability of biomass</td>
</tr>
<tr>
<td>➔ a strengthening of the competitiveness of German agriculture and forestry, as well as improvements to the development of rural areas in Germany in comparison to foreign competitors</td>
<td>➔ amplification of possible land use conflicts</td>
</tr>
<tr>
<td>➔ export of bio-based products and of systems for biomass processing and -conversion</td>
<td>➔ stronger international competition between industrialised and emerging countries</td>
</tr>
<tr>
<td>➔ construction of refineries abroad with German know-how</td>
<td></td>
</tr>
<tr>
<td>➔ an improvement of agricultural structures in emerging and developing countries opens up market opportunities for the domestic/local processing and refining of biomass, and of participation in international biomass trading</td>
<td></td>
</tr>
</tbody>
</table>
to the respective application areas in the food or non-food sectors.

Around half of the supported projects for the conversion and material- and energetic utilisation of biomass in the BMELV 'Renewable Resources' funding programme can be regarded as projects for the support and technology development of biorefineries, despite of issues with classification and demarcation. Also underway are activities funded by a range of other support programs, particularly by the BMBF, but also by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Federal Ministry of Economics and Technology (BMWi). The 2010 legislation for the establishment of the 'Energy and Climate Fund' investment fund will provide further means of funding in the future for the federal government, among other things for research and development in the area of bioenergy.

From 2010, funding totalling €2.4 billion (project funding and institutional support) has been pledged over a period of six years as part of the 'National Research Strategy BioEconomy 2030' which summarises the research promotion activities of the individual departments associated with the use of biological resources. The funding activities encompass developments in the area of nutrition (including sustainable agricultural production and safe-and healthy foodstuffs), as well as the utilisation of biomass for material and energetic purposes. This includes support for biorefinery concepts.

Moreover, the Fraunhofer Center for Chemical and Biotechnological Processes (CBP) is currently under construction at the chemical site in Leuna (Saxony-Anhalt). After completion in 2012, this will function as a 'biorefinery development centre' aimed at providing the appropriate framework for connections between research and industry in the context of ambitious projects. The CBP Leuna will be financed by the German federal government (BMBF, BMELV, BMU), the state of Saxony-Anhalt, and the Fraunhofer Society.

The priority area for German R&D activities towards integrated biorefinery concepts will be to emphasise the top-down development approaches of lignocellulosic biorefineries (including the green biorefinery) and synthesis gas biorefineries. Work here will be spread out over a number of major projects. Bottom-up development approaches are being pursued for the sugar/starch biorefinery and the vegetable oil biorefinery, while the lignocellulosic biorefinery, which is based on existing structures in the pulp industry in Germany (e.g. in contrast to the Scandinavian countries), has played almost no role in this area to date. There have been comparatively few activities in the context of major projects with the bottom-up approach to development, as these often expand on existing structures in the sugar-, starch- or vegetable oil industries. For this reason, the dominant projects here are oriented towards providing support for such biorefineries, or are concerned with aspects of these biorefineries and/or with the conventional conversion of sugar, starch and vegetable oils into bio-based products or bioenergy.

The SWOT analysis of the development of biorefineries in Germany with regard to internal strengths and weaknesses, and with a view of external international developments and resulting opportunities and risks, is aggregated in Table 4. The analysis shows that Germany is well situated in a European and global context, and occupies an outstanding starting position. Under no circumstances should international developments be overlooked, however. In this context, it will be important to maintain and where appropriate to expand Germany’s leadership. Here, it will be possible to fall back on a very good starting basis.
4  Technological description and analysis

The promising biorefinery concepts named in Section 3.5 are described and discussed in general terms with regard to the four elements ‘Platform’, ‘Primary Refining’, ‘Secondary refining’, and ‘Products’. One or more specific biorefineries will be also illustrated and discussed in detail as examples for all the described biorefinery concepts. Specifically, these encompass the biorefinery concepts shown in Table 5.

Table 5: The biorefinery concepts considered in the roadmap

<table>
<thead>
<tr>
<th>Group</th>
<th>Biorefinery concept*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sugar biorefinery</td>
</tr>
<tr>
<td></td>
<td>Starch biorefinery</td>
</tr>
<tr>
<td>2</td>
<td>Vegetable oil biorefinery</td>
</tr>
<tr>
<td></td>
<td>Algal lipid biorefinery</td>
</tr>
<tr>
<td>3</td>
<td>Lignocellulosic (cellulose/hemi-cellulose/lignin) biorefinery</td>
</tr>
<tr>
<td></td>
<td>(a) Production of fermentable carbohydrates</td>
</tr>
<tr>
<td></td>
<td>(b) Production of pulp</td>
</tr>
<tr>
<td></td>
<td>Green (green fibre/green juice) biorefinery</td>
</tr>
<tr>
<td>4</td>
<td>Synthesis gas biorefinery</td>
</tr>
<tr>
<td>5</td>
<td>Biogas biorefinery</td>
</tr>
</tbody>
</table>

* Platform(s) in bold

The following criteria were used for selection:

→ the provision of raw materials for the platform is possible and sustainable
→ a coupling of primary and secondary refining with the platform as nexus is deemed to be technically and economically feasible within the forecast horizon
→ the platform provides sufficient technical and economic opportunities for the production of marketable material- and energetic products
→ the biorefinery concept is broadly applicable and also provides opportunities for the export of resource-efficient technologies for biorefineries and bio-based products

The following selected examples serve to illustrate and clarify the respective general biorefinery concepts. It should be noted that they do not necessarily represent an optimal or most mature solution in each case. The studies reflect the current state of development; in selected cases, sufficient valid data for a detailed dimensioning and evaluation are already available.

There are also numerous other examples and variants for all of the promising biorefinery concepts. Whether a specific biorefinery concept is technologically, economically and environmentally feasible must be considered on a case-by-case basis. In view of this fact, no direct comparison of the following examples is possible (see also Section 5).

4.1 Sugar and starch biorefinery

Sugar biorefinery

Platform: In a sugar biorefinery, the component separation in primary refining results in sucrose, known colloquially as sugar. Sucrose thus constitutes the platform of the sugar biorefinery (Figure 10).

Raw materials: A variety of plants can serve as a raw material base for sugar production. The two most important sugar-producing plants worldwide are sugar cane and sugar beet. However, sugar produced in Germany is made exclusively using local sugar beet. The sugar beet forms a root body, which stores the sugar, in the growing season from spring to late September. The plant is harvested from September to November. Deliveries to the sugar factories are carried out for the most part using lorries. Here, by tilting or aided by water, the beets are unloaded and are processed either immediately or after storage.

Primary refining: The primary refining is divided into juice production, juice purification, juice thickening, and crystallisation. For the juice extraction, the washed beets are crushed in cutting machines. The cuttings are heated to 70°C and turned into a slurry in a vessel with an agitator. The sugar is then extracted in extraction towers, where the cuttings are desugared with hot water in a counter-current process. The extracted cuttings are dried and used as animal feed. As well as sugar, the raw juice from beet extraction also contains non-sugar materials. The raw juice is mixed with lime water for purification. Together with the non-sugar materials, the excess calcium carbonate is then precipitated and used as fertiliser. The filtrate is a clear, pale yellow, thin sugar
Sugar, which is then concentrated (syrup) to a dry matter content of 70–75% in a multi-stage evaporator unit. The syrup juice is further concentrated up to formation of crystals in steam-heated evaporation crystallisers. The separation of the sugar crystals from the syrup takes place in centrifuges. The produced white sugar is dried and undergoes fine and coarse screening before storage in large silos. The separated syrup is subjected to two further crystallisation stages (raw sugar and second product). The result of the last crystallisation stage is molasses.

Raw juice, thin juice or juice concentrate, as well as high purity crystal sugar, are available for further processing into bio-based products and/or the production of bioenergy. The exploitation of the mentioned intermediate products is closely linked to process concepts, microbiological stability, and also transport properties. Syrup and crystalline sugar are particularly suitable as substrates that are available all year round.

Sugar-containing molasses as well as the extracted cuttings are incurred as co-products.

Secondary refining/Products: The sugar syrup is for the most part processed into sugar, but can also be used as a fermentation raw material (e.g. for bioethanol, chemical intermediates).

Granulated sugar is used as table sugar in the food industry, or finds application in the commercial sector. In the chemotechnical area, it serves as a fermentation raw material, or can be used as precursor for chemical intermediate- or finished products (e.g. surfactants).

Molasses is for the most part utilised as fermentation raw material (for instance as feed yeast, bioethanol, chemicals), or for the production of feedstuffs. Molasses can also be further desugarised for the production of crystalline sugar. Alongside sugar, molasses also contains other ingredients (organic acids, betaine, vitamins, inorganic salts), which can be isolated and further processed.

The chemical intermediates and/or fermentation products (e.g. amino acids, lactic acid, citric acid, gluconic acid, and the esters and salts of these organic acids) are then either also chemical intermediates or are further processed into finished products.

The extracted cuttings are dried and then typically pelleted and molassed. Molassed beet cuttings is a popular animal feedstuff.

Example: As a detailed example for the sugar biorefinery, a concrete biorefinery pathway has been technologically illustrated and is shown schematically in Figure 11.

Example 1:
The concept encompasses the configuration of a sugar beet-based sugar biorefinery for the production of ethanol, carbon dioxide, fusel oils, glucose, fructose and gluconic acid, with molassed sugar beet shreds and vinasse as co-products.

Sugar beet syrup is then extracted from the sliced beet using the procedure described above. A part of the syrup is then separated for sucrose inversion, while the majority is used as a fermentation raw material for ethanol production.

The sucrose in the separated syrup is inverted using acid catalysis. The result following hydrolysis is a 1:1 mixture of glucose and fructose. The separation of glucose and fructose proceeds via chromatography. The purified glucose solution is placed in a stirred tank reactor, adjusted to a pH of 9, and pressurised with oxygen. Selective oxidation to sodium gluconate takes place at 40°C in the presence of a gold
catalyst. The water must then be separated in order to obtain pure sodium gluconate. In an optional process, the sodium salt can also be converted by ion exchange into pure gluconic acid, which also necessitates the later separation of water.

For ethanol fermentation, a suitable sugar concentration is adjusted by addition of syrup to the fermenter, and yeast is added. After a few hours, a part of the fermentable substrate is fermented, and this is predominantly used for yeast propagation. When yeast propagation decreases and finally ceases, the slurry – under strong CO₂ formation – begins primary fermentation, which is achieved at temperatures of 30°C and higher. The alcohol concentration in the fermented slurry amounts to 10–12%. The CO₂ gas formed during fermentation is fed a scrubber column, washed and liquefied.

The ethanol fermentation is followed by distillation, which produces a residual stillage. The stillage is evaporated, resulting in a protein-containing vinasse, which is used as an animal feedstuff. A rectification column removes by-products from the alcoholic distillate, and molecular sieves are used to remove the residual water from the alcohol. The subsequent dehydrated bioethanol has a purity of 99.7%. The fusel oils separated in rectification are marketed as a raw material for the chemical industry.

Starch biorefinery
Platform: In a starch biorefinery, the component separation in primary refining results in starch⁷, which thus constitutes the platform of the starch biorefinery (Figure 12).

Raw materials: A variety of plants can serve as a raw material base for starch production. The most important starch crops worldwide are cereal crops (corn, wheat, rice), potatoes and cassava. Above all potatoes and cereal crops (wheat and corn) are used in Germany for starch production. Corn and wheat are annual crops; the starch is contained in the grains. Potatoes are root crops, and starch is contained in the tubers.
Primary refining: The first processing steps for the cereal grains is the soaking and expansion of the grains (where appropriate after grinding), germ separation, grinding, and sieving. After cleaning, the potatoes are mashed. The subsequent processing continues along similar lines; the starch is dissolved out and fibres and protein separated. The starch slurry is then cleaned and dried, so that pure starch results. The extraction of starch can be carried out using either local grains and potatoes, or imported grain.

Native potato starch, wheat starch or corn starch can be used as raw products for further processing into bio-based products and/or the production of bioenergy. The separated proteins and fibre residues are incurred by-products.

Secondary refining/Products: Native starch is used in the food and chemo-technical industries, where it is either directly further processed or converted to starch modifications and starch saccharification products. Chemotechnical utilisation is the manufacturing of paper and cardboard, the further processing into chemotechnical products (e.g. adhesives) and the manufacturing of finished products (e.g. tyres).

Native starch is modified chemically or physically for the production of starch modifications. The resulting starch modifications (e.g. starch esters, starch ethers, dextrins) and starch mixtures are then further processed for use as thickening agents in the food industry, as an additive in paper production, or as an intermediate product in the cosmetics industry.

Starch saccharification products (e.g. dextrose, glucose caused) result from the degradation of the polymeric starch into low molecular weight products. The hydrolysis of starch provides three product groups that differ in their degree of hydrolysis and which are used as feedstock for the production of other starch sugar derivatives: Maltodextrins (starch hydrolysates with a DE content of less than 20), glucose syrup (starch hydrolysates with DE content of more than 20 and less than 80), dextrose syrup (starch hydrolysates with DE content of more than 80). These three product groups are either utilised directly or are further processed. The dextrose syrup is used, for example, for the production of the sugar alcohol sorbitol and for the synthesis of surfactants (so-called alkyl polyglycosides, APG). Glucose and starch hydrolysates can also be used as fermentation raw materials. The fermentation products (e.g. amino acids, lactic acid, citric acid, gluconic acid, and the esters and salts of these organic acids) are then either also chemical intermediates or are further processed into finished products. Further processing into other chemical products is also conceivable.

The separated proteins can be used in the animal feedstuff sector. The corn protein gluten can be used as a binder and adhesive in the food industry, and in the chemotechnical area.

The separated fibre residues are commonly used for animal feedstuffs.

Examples: As an example for the starch biorefinery, two concrete biorefinery pathways are technologically illustrated in detail, and shown schematically in Figure 13.

**Example 2:**
The concept encompasses the configuration of a wheat-based starch biorefinery for the production of A starch, bioethanol, with gluten, wheat bran and DDGS as co-products.

![Figure 12: Schematic of a starch biorefinery](image)
Wheat flour is used as the raw material; this is processed to a suspension through continuous machine mixing and the addition of warm water. The ingredients are dissolved from the gluten matrix and then separated by means of the input of mechanical energy. Separation into a heavy phase of primarily A starch and some gluten, a light fraction containing the pentosans and gums, and a middle phase containing B starch, fibre, and again gluten, proceeds via a 3-phase decanter. The rapidly clumping gluten is separated from both the middle and the heavy phase. The gluten is washed and subsequently dewatered to a dry substance content of around 40%.

**Example 2**

![Wheat biorefinery pathway diagram](image)

**Example 3**

![Corn biorefinery pathway diagram](image)

Figure 13: Examples of starch biorefinery pathways
The A starch is separated from the heavy phase and, depending on the quality requirements, is again sieved to separate out small fibre fractions, before being mechanically pre-dried and then finally dried in heated air.

The remaining middle phase is combined with the light phase, which contains the pentosans and mucilages, and this is fed to fermentation. The resultant suspension from starch refining is further processed to ethanol in secondary refining. Depending on the process, up to 80% of the A starch fraction is likewise fed to fermentation. The starch suspension is first mixed with liquefying enzymes and then saccharifying enzymes, thereby converting the available starch into glucose. The product of the hydrolysis is a glucose-containing slurry, which also contains monomeric carbohydrates from the hemicelluloses and pentosans. For ethanol fermentation, the slurry is pumped into a fermenter and yeast is added. Strong alcohol formation then begins under anaerobic conditions. The alcoholic fermentation proceeds similarly as described for the sugar biorefinery, and encompasses the same process steps. The result after treatment is dehydrated bioethanol with a purity of 99.7%.

For homofermentative lactic acid fermentation, the slurry is pumped into a fermenter and *Lactobacillus* sp. is added. Lactic acid formation then begins under anaerobic conditions. A pH value in the weakly acidic range is maintained using calcium carbonate. The cell biomass is then separated from the fermentation broth using ultrafiltration. Lactic acid is present as calcium lactate in the solution, and is released by acidification with sulphuric acid. This process produces calcium sulphate, which is filtered off. The lactic acid that is separated after processing is treated with deionised water, before being decolourised and concentrated.

4.2 Vegetable oil- and algal lipid biorefinery

**Vegetable oil biorefinery**

**Platform:** In a vegetable oil biorefinery, the component separation in the primary refining produces vegetable oil, which thus constitutes the platform for the vegetable oil biorefinery (Figure 14).

**Raw materials:** The precursors for the production of vegetable oil are oil seeds and -fruits, whereby oil is present together with other lipids. The most important oil seeds worldwide are rape seeds, soybeans, sunflower seeds, cottonseed and peanuts. The most significant global oil crops are oil palm fruit and -kernels, coconuts and olives. Rape is by far the most important oil plant in Germany, and linseed and sunflowers are also cultivated over large areas. The selection of raw materials is also influenced by the intended products – not every vegetable oil is suitable for a specific application. Short-chain and long-chain fatty acid content is of particular significance for later application. Oil seeds and -fruits that serve as a source of short-chain fatty acids are not cultivated in Germany.

**Primary refining:** The oil-containing seeds or fruits are cleaned and shredded. The vegetable oils are then separated by pressing (cold or hot) or by extracting (in rare cases by centrifugation). The extraction of vegetable oils that serve as a source of short-chain
Fatty acids generally take place in the tropical countries of origin, meaning that primary refining does not take place in Germany. Palm kernels can in principle be imported. The extraction of vegetable oils that serve as a source of long-chain fatty acids proceeds using both domestic oilseeds (rapeseed, sunflower seeds, linseed) as well as imported oilseeds and -fruits (e.g. soybeans).

Crude vegetable oil (fats and oils) are available as a raw product for further processing. Meal extract or presscake incur as co-products.

**Secondary refining/Products:** The vegetable oil can be used either in the food area or in the technical area. In the technical area, native vegetable oil is on the one hand used in virgin form (or following transesterification in the form of biodiesel) as a fuel or for the production of electricity and heat, for instance in combined heat and power plants (CHP). The native vegetable oil is purified before utilisation or further processing. On the other hand, vegetable oil is a valuable raw material for the oleochemical industry or for the production of lubricants. Here, the vegetable oil can be used directly (e.g. as a solvent), or is cleaved to obtain fatty acids and glycerol. In turn, fatty acids are precursors for a whole raft of chemical products, and after processing can be found in cosmetics, surfactants, lacquers and dyes, among other products. Glycerin also has a range of applications; further processing produces pharmaceutical grade glycerine, and subsequent conversions and chemical reactions provide further chemical intermediates and products. Glycerol can also be used as a fermentation raw material. In turn, the fermentation products are either chemical intermediates or are further processed into finished products. A technical utilisation or combustion of co-products, meal extract or presscake would be possible in principle, but utilisation as feedstuff produces more value, and in the case of livestock production (above all through use as manure) makes a contribution to the closing of the nutrient cycle on the field.

**Examples:** As an example for the vegetable oil biorefinery, two concrete biorefinery pathways are technologically illustrated in detail, and shown schematically in Figure 15.

**Example 4:**
The concept encompasses the configuration of a rapeseed-based vegetable oil biorefinery with vegetable oils of predominantly long-chain and unsaturated fatty acids. It is oriented towards the production of biodiesel, lubricants and specialty chemicals, with rapeseed press cake and rapeseed extraction meal as co-products.

Through pressing and solvent-aided extraction, crude rapeseed oil and presscake, as well as meal extract, are obtained from the rapeseed. Because of their high protein content, presscake and meal extract are used above all for animal feedstuffs. In so-called oil refining, the associated materials contained in the crude rapeseed oil are separated by various physical and chemical processes.

Via hydrolysis, cleavage processes produce so-called fission fatty acids and glycerol from the refined rapeseed oil. Through subsequent distillation or fractionation, the mixture of fatty acids gives rise to a variety of predominantly unsaturated and long-chain fatty acids with narrowly defined specifications, which can serve as base materials for further processing. Synthesis esters, which form the base component for lubricants, are produced via esterifi-
cation of the fatty acids with special alcohols. The refined rapeseed oil is also used to manufacture biodiesel. In this catalytic transesterification procedure, rapeseed oil with methanol is converted into fatty acid methyl esters and glycerol.

Glycerol from hydrolytic fat cleavage or from biodiesel production is used as a raw material for the production of specialty chemicals. 1,3-propanediol, which can be used among other things for the production of polyesters, is synthesised in a
Example 5:
The concept encompasses the configuration of a palm kernel-based vegetable oil biorefinery with vegetable oils of predominantly short-chain and saturated fatty acids for the production of fatty acids, surfactants, and specialty chemicals.

Crude palm kernel oil and meal extract are extracted from the palm kernels via solvent-aided extraction. The meal extract is used as an animal feedstuff. The associated materials contained in the crude palm kernel oil are separated by various physical and chemical processes.

Via hydrolysis, cleavage processes produce so-called fission fatty acids and glycerol from the refined palm kernel oil. Through subsequent distillation or fractionation, the mixture of fatty acids gives rise to a variety of predominantly saturated and short-chain fatty acids with narrowly defined specifications. These can be used as base materials for further processing, e.g. esterification with special alcohols to form synthetic esters as base components for lubricants.

Fatty acid methyl esters can be produced through the catalytic transesterification of palm kernel oil with methanol. Following fractionation, the fatty acid methyl esters are hydrogenated into fatty alcohols in fixed bed reactors with hydrogen, according to the length of the carbon chains of the fatty acids. The fatty alcohols are precursors for the production of surfactants, which require above all short-chain and saturated fatty acids. Fatty alcohol sulfates are produced through the conversion of fatty alcohols, e.g. with sulphuric acid. These can also be applied in the textile industry for the production of detergents, and for dispersing- and emulsifying agents in cosmetics. The acid-catalysed conversion of fatty alcohols with glucose or starch hydrolysates produces polyglycosides, used for the production of detergents, dishwasher detergents, and cleaning agents.

Algal lipid biorefinery

Platform: In an algal lipid biorefinery, component separation in primary refining results in algal lipids and algal biomass, which constitute the platform of the algal lipid biorefinery (Figure 16).

Raw materials: The precursor in the production of algal lipids is microalgae. Microalgae are single- or few-celled creatures that conduct photosynthesis but do not belong to the actual plant. They are found in saltwater and freshwater. Upon arresting of growth i.e. via lack of nitrogen with simultaneous supply of CO₂ and light, many microalgae are known to become enriched in lipids in the form of oil droplets in the cells.

Primary refining: The wet, oily algal biomass is concentrated to 15–20% bio dry matter content through the separation of water and algal biomass via centrifugation, flocculation or filtration. Depending on the strain and the extraction method, the algal biomass must undergo decomposition, using a high-pressure homogeniser or bead mill, for example. Microwaves or ultrasound can be used to directly support extraction, if required. The degraded, wet algal biomass must then undergo drying. After drying – usually spray-drying – the algal biomasses are storable. Today, algae oil is extracted from previously dried and degraded algae biomass using a variety of solvents, the best results being achieved with hexane. An advantage of the use of supercritical fluids for extraction is that neither the crude algal oil nor the residual biomass contain any solvent residues that could interfere with further processing. The solvent is separated and fed back to the process.

Algal lipids (algae oil) and the largely oil-free algal biomass are available as a raw product for further processing.

Secondary refining/Products: Alongside triglycerides and polar membrane lipids, the algae crude oil contains other lipophilic algae ingredients such as carotenoids, chlorophyll and phytosterols, which can be selectively extracted and modified in secondary refining. The triglycerides can be used either in the food industry or in the technical area. In the technical sector, the triglycerides can either be used (following transesterification) as a fuel in the form of biodiesel, or as native vegetable oil for the production of electricity and heat, e.g. in CHP. Triglycerides are also a potential raw material for the chemical industry. In the chemotechnical area, triglycerides can be used directly, or fatty acids and glycerol extracted via cleavage. In turn, fatty acids are precursors for a whole raft of chemical products, and after processing can be found in cosmetics, surfactants, lacquers and dyes, among other products. Glycerol also has a range of applications: Further processing produces pharmaceutical grade glycerine or – via subsequent conversions and subsequent chemical reactions
– further chemical intermediates and products. Glycerol can also be used as a fermentation raw material. In turn, the fermentation products are either chemical intermediates or are further processed into finished products.

After drying, high-protein feedstuff is produced using the deoiled algae biomass, or the algal biomass can be converted as cosubstrate into biogas through anaerobic decomposition.

**Example:** Because it offers a much higher level of photosynthetic efficiency, the use of microalgae as feedstock in biorefineries carries more promise than the use of traditional biomass crops. Under optimum growing conditions, microalgae can convert up to 5% of solar energy into chemical energy; land plants on the other hand can only manage 0.5%–1%. One disadvantage is that microalgae can only be cultivated cost-effectively in high latitudes, with daily and continuous sunlight all year round, and with suitable day- and night temperatures.

At this time, reliable data and indicators are not sufficiently available to provide concrete technological details for the lipid algal biorefinery. Nevertheless, three promising options have emerged.

→ the integrated extraction of high value chemicals, such as polysaccharides, lipids, and lipophilic substances. The production of biodiesel can be based on the main part of the lipid fraction. The residual biomass (in the sense of biogenic residual materials, see Section 3.3.2) is used for energy recovery, e.g. in a biogas plant. This concept is economically viable, but it should be noted that the plant capacity must be aligned to a market volume for high-priced re-usable materials, which is considerably smaller than the one of fuels.

→ Alignment with wastewater treatment. In turn, the resulting biomass can be used for the production of chemicals and energy carriers. One advantage is that there are no expenses for the production as well as circulation of nutrients; in particular, the high economic and energy requirements of current wastewater treatment systems can be credited to algae production. However, low nutrient concentrations in existing treatment plants limits algal productivity. Due to the use of wastewater, however, guidelines restrict the spectrum of commercialisable re-usable materials. In addition, there are still unclarities concerning an all-year-round operation and alternative organisms that can be separated in an easier way (e.g. duckweed).

→ The production of energy carriers with high volatility. Ethanol is a possibility here, for example. An advantage of this concept is that no energy-intensive harvesting of biomass is required; instead, the energy is produced continuously, while thermodynamics favour the separation of materials. However, closed systems are required for collection of the product.

Only laboratory and pilot plant data are available for many algal lipid biorefinery sub-processes, whereby the current level of data does not enable viable and economically efficient technological design. For this reason, the following will concern itself only with general statements; a possible lipid algae biorefinery is shown schematically in Figure 17. Thereby, a pos-

![Figure 16: Schematic of an algal-lipid biorefinery](image-url)
Example 6

The concept is oriented towards the extraction of fatty acids and glycerol from algal lipids and from useful lipophilic substances. The deoiled algal biomass is utilised as energy in a biogas plant, producing digestate as a co-product.

The lipid content in microalgae rises from 10–15% (w/w) in growing cultures to 60–70% (w/w) in growth-limited cultures. The rate of lipid formation depends largely on the light supply for the algal cells. In growing cultures, lipids are present above all in the form of polar membrane lipids of different lipid classes. After growth limitation, triglycerides are produced as storage lipids. While the membrane lipids contain a high proportion of polyunsaturated C16 and C18 fatty acids, the storage lipids (strain-specific) contain high proportions of saturated C16 and mono-unsaturated C18 fatty acids.

Worldwide, however, oil-rich algae have to date only been produced only on a pilot scale (<< 1 ha) in open ponds or in closed photobioreactors. Due to the high light requirements and short production times, the production of lipid-rich algal biomass (> 30% fatty acid content) is likely to be only possible in Germany during the summer months. For this reason, only closed photobioreactors can come into consideration. In months with low light intensity, the energy cost of production is higher than the energy content of the produced biomass; fatty acid composition also tends more strongly towards unsaturated fatty acids due to the lower triacylglyceride content.

The treatment of the algal biomass from the photobioreactor is technically possible, but further optimisation is necessary with regard to economic efficiency and above all energy consumption. Furthermore, the processes for the separation of lipophilic materials from the crude algal oil are far from fully developed. No methods have been described to date for selectively separating carotenoids and chlorophyll from the algal oil. Previously ap-
plied procedures for carotenoid extraction make immediate use of the algal biomass, and the resulting carotenoid-oil mixture is directly utilised without separation. After chromatographic separation and transesterification, omega-3 fatty acids, which are found exclusively in polar membrane lipids of some algae, can be separated and purified into ethyl esters with supercritical carbon dioxide.

Lipophilic substances, which alongside triglycerides can also be obtained as products from algae oil, are carotenoids (such as β-carotene, lutein, fucoxanthin) as pigments and antioxidants, chlorophyll and omega-3 fatty acids (such as eicosapentaenoic acid for the food industry).

4.3 Lignocellulosic biorefinery and green biorefinery

Lignocellulosic Biorefinery

Platform: In a dry-biomass-based lignocellulosic biorefinery, the component separation in the primary refining produces the lignocellulosic components cellulose, hemicelluloses, and lignin[45], which thereby constitute the platform for the lignocellulosic biorefinery[21] (Figure 18).

Raw materials: Lignocellulosic biomass as a raw material can derive from a variety of sources, such as agricultural residues (e.g. straw, bagasse, corncobs), energy crops (e.g. annual and perennial grasses), wood, and biogenic waste (e.g. paper waste). In Germany, for reasons of quality- and quantity-related availability, above all agricultural residues (cereal- and corn straw) and wood (forest wood, poplar short rotation wood) are significant at this time; annual and perennial grasses could also play a role in the future, however.

Primary refining: The pre-treatment of the relatively robust lignocellulosic biomass is essential, and initially entails a mechanical process step (milling or grinding). Decomposition is conducted by means of pressure and temperature, with or without chemical agents. Decomposition can alternatively be conducted by means of concentrated acid. The lignin can be separated either extractively during pre-treatment, or from the remaining solution as an insoluble component.

Depending on the mode of decomposition, cellulose, hemicelluloses and lignin are available for further processing as raw materials, as are raw product mixtures.

Secondary refining/Products: There are two basic paths for secondary refining: (a) the direct production of fermentable carbohydrates for further biotechnological conversion, and (b) the further isolated processing of the individual fractions, as well as combinations of both pathways.

(a) Mostly cellulose and hemicellulose fractions are used in the production of fermentable carbohydrates. The enzymatic conversion into corresponding monomeric carbohydrates (e.g. glucose, xylose) results in one material flow of fermentable sugars and one material flow of lignin. The fermentable sugars can be sent directly to biotechnological production, such as the production of ethanol and other higher-chain alcohols, biopolymers, organic acids, amino acids or other biotechnological products.

(b) The cellulose, hemicellulose and lignin fractions are processed separately via isolated processing. Depending on the objective of the decomposition, the cellulose obtained in decomposition can be processed into paper- or chemical pulp or, after enzymatic hydrolysis, processed into glucose as a fermentation- or chemical raw material. The separated hemicellulose fraction contains more or less decomposed carbohydrates and various monomeric C6- and C5 carbohydrates. From this, monomeric carbohydrates (e.g. xylose) can be separated and then refined, for example by fermentation or chemical methods. Through the degradation of the original hemicelluloses, the separated hemicellulose fraction contains a range of other useful substances (e.g. acetic acid, furfural), which can be extracted and further processed in the chemotechnical section.

In principle, lignin from the decomposition paths (a) or (b) can be used directly as a feedstock, although current applications have been limited to date, and usually create little value-added. There are two options for higher value creation from lignin. Firstly, lignin is used as material, whereby the lignin is refined by polymer- and material-oriented technologies. On the other hand, with its aromatic structure, lignin offers the possibility of (selective) degradation to monomeric- and dimeric aromatic compounds (e.g. phenols). An alternative possibility is the use of lignin and/or a lignin/hemicellulose solution for energy production. This can be carried out either by incineration or by gasification.

Example: As an example for the lignocellulosic biorefinery, two concrete biorefinery pathways are technologically illustrated in detail, and shown schematically in Figure 19.
Example 7:
The concept encompasses the configuration of an agricultural residue-based lignocellulosic biorefinery (cereal straw) for the production of ethanol, biogas and lignin.

Here, the cereal straw is hydrothermally pre-treated to prepare the raw material for subsequent enzymatic hydrolysis. In the hydrolysis step, enzyme systems are used to transfer the polymers cellulose and hemicelluloses into monomeric fermentable carbohydrates. In this concept, the enzyme systems used for hydrolysis, which are specifically tailored to the particular raw material, are produced in the biorefinery in a process-integrated manner. After separation of the solid lignin phase, the dissolved hexoses and pentoses are simultaneously converted via fermentation to ethanol with yeast. Strong alcohol formation then begins under anaerobic conditions. The alcoholic fermentation proceeds similarly as described for the sugar biorefinery, and encompasses the same process steps. The separation and purification of the ethanol proceeds via a newly developed adsorption technology. Further purification is carried out via subsequent rectification. The end result is a azeotropic ethanol/water mixture (96%). Molecular sieves are used to remove the residual water from the alcohol. The subsequent dehydrated bioethanol has a purity of 99.7%. The remaining stillage from the ethanol fermentation is converted into biogas, which can be used for energy production together with the separated lignin. This process-integrated energetic utilisation is sufficient for the supply of full process energy. Alternatively, the biogas can be fed in or the lignin materially utilised.

Example 8:
The concept encompasses the configuration of a forest wood-based lignocellulosic biorefinery for the production of glucose, xylose and lignin via ethanol/water decomposition and enzymatic hydrolysis. Forest wood in the form of beech wood chips is digested with ethanol/water under pressure and temperature. The liquid phase, which comprises the lignin and the (degraded) hemicelluloses as main components, is subsequently separated. The remaining solid phase contains the cellulose as a main component, in the form of the wood fibre fraction.

The enzymatic two-step hydrolysis of the cellulose is carried out after the cleaning of the fibre fraction. The reclaimed glucose solution is either fed directly into fermentation for further processing in the biorefinery, or is commercialised as a product.

The extraction of the lignin proceeds via precipitation of the wood pulp from the liquid phase. The end result after washing is pure sulphur-free lignin. The clean lignin can now be further processed in the biorefinery or commercialised.

The remaining solution from the lignin precipitation contains the degraded components of the hemicelluloses in the form of monomeric carbohydrates (in particular xylose). The result after concentration and purification is a 5% xylose solution, which is available for further processing in the biorefinery.

Green biorefinery
Platform: In a green biorefinery, component separation in primary refining results in press juice and cellulosic fibres, which thus constitute the platform of the green biorefinery (Figure 20).
Figure 19: Examples of lignocellulosic biorefinery pathways
Raw materials: Moist biomass in green or ensiled form, such as annual and perennial grasses and cereals, is used as raw material in a green biorefinery.

Primary refining: The green or ensiled biomass is cleaned and crushed and the liquid components are separated by compression. All soluble components remain in the grass juice. The remaining solid grass fibre presscake is freed from adhesions.

Grass juice and grass fibre are available as raw products for further processing.

Secondary refining/Products: A green biorefinery is typically coupled with a biogas plant. This is because a part of one or both fractions (grass juice and grass fibre) is always utilised as a cosubstrate for reasons of process technology. For economic purposes, the water-/heat flows from the grass processing plant and the biogas plant are coupled.

The grass juice either goes directly into the biogas plant, or its ingredients (for example, lactic acid, acetic acid, proteins, amino acids) are separated. Also conceivable is the use of grass juice (with or without separation of ingredients) as raw material, or to supplement or fermentations.

The grass fibre can be processed directly into animal feedstuff or used as raw a material for fibre-based products. Examples of fibre-based products are insulation materials, cellulose fibres and fibre-reinforced polymers. After decomposition and hydrolytic degradation/saccharification, the grass fibre fraction can also be of interest as a fermentation raw material. The hydrolysate-based fermentation products are then either chemical intermediates or are further processed into finished products. Residues from grass fibre processing are then utilisable for the biogas plant as a co-substrate.

Example: As a detailed example for the green biorefinery, a concrete biorefinery pathway has been technologically designed and is shown schematically in Figure 21.

Example 9: The concept encompasses the configuration of a grass-based green biorefinery for the production of lysine lactate, proteins, lactic acid, acetic acid and biogas, producing digestate as a co-product. The concept encompasses a mode of operation with both winter and summer operation.

For winter operation, grass cuttings are ensiled, creating silage. In the first processing step, silage is extracted and pressed in a screw press. The result is silage press juice (green juice) and silage presscake (green fibre). Lactic acid and acetic acid are chromatographically separated from the silage press juice, and the other juice components are added to the lysine fermentation medium. The silage presscake is subjected to enzymatic hydrolysis in order to hydrolyse the carbohydrates (saccharification); together with the residual phase, this is then consolidated in a complete fermentation medium for lysine production. The lysine is stored for summer operation.

For summer operation, fresh grass is extracted and pressed in a screw press. The pressed juice is fractionally heated and the white proteins are membrane-separated from the green proteins. This results in an aqueous residual phase (brown juice), which is added to the medium for lactic acid fermentation. The presscake is subjected to a AFEX extraction and enzymatic hydrolysis in order to monomerise the contained carbohydrates (saccharification); together with the residual phase, this is then consolidated in a full fermentation medium for lactic acid production. Neutralisation with lysine (from the winter operation) gives lysine lactate.
The residual biomass from the fermentation can be processed to biogas throughout the year, where appropriate also together with co-substrates. The resulting digestate co-product is used as fertiliser.

### 4.4 Synthesis gas biorefinery

**Platform:** In a synthesis gas biorefinery there is no separate component separation during primary refining; instead, all organic constituents and biomass components are broken down in such way to produce the raw product synthesis gas \(^48\) (Figure 22). The advantage is the flexibility for product manufacturing; products range from fuels, such as Fischer-Tropsch diesel and methanol, to higher alcohols and chemicals, and even synthetics.

**Raw materials:** Numerous lignocellulosic biomasses from around the world were taken into consideration as sources of raw material: dry agricultural residues (e.g. straw, bagasse, peels and husks, corn cobs), energy crops (annual and perennial grasses), wood and woody biomass, dry biogenic residues, and waste materials (e.g. paper waste, lignin). For reasons of quality- and quantity-related availability, above all agricultural residues (cereal straw) and wood (forest wood, poplar short rotation wood) are of significance in Germany.

**Primary refining:** The first step in primary refining is the pre-treatment and drying of the biomass. With the strength varying according to process variant, this is followed by thermal cleavage of the biomass at high temperatures, and sometimes also under pressure. The heat cleaves the long molecular chains. The result is numerous different liquid and gaseous hydrocarbons with shorter chain length, and later in progression, increased carbon monoxide, carbon dioxide, carbon, hydrogen and water. The composition of the gas mixture and the character of the pyrolysis products can be influenced by the process conditions of temperature, pressure and time of exposure in the reactor, as well as by added chemical agents and catalysts. Variations and intermediate steps are possible depending on the applied procedure. This
initially produces a pyrolysis slurry, which is thermally gasified or is subjected to upstream torrefication. Different technologies also exist for gasification. A necessary last step is the post-treatment and purification of the synthesis gas.

Crude synthesis gas is available as a raw product for further processing.

**Secondary refining/Products:** The gas composition of the crude synthesis gas depends on a range of process parameters, and also determines subsequent use. At any rate, comparatively elaborate and complex gas treatment and cleaning, which must also be adapted to the later conversion, is required for subsequent syntheses. The following step is the synthesis step, in which carbon monoxide and hydrogen from the synthesis is further chemically processed, either directly into chemical intermediates (e.g. methanol or dimethyl ether (DME)), into fuels (e.g. so-called biomass-to-liquid fuel), into bio-based hydrogen, or into chemical products. Direct energetic use via a stationary motor is also possible (to generate electricity and heat), or as a motor fuel for mobile use.

The remaining ash and other solid elements are not required to be considered as recoverable by-products. The utilisation of interesting nutrients from the remaining residues for agriculture and forestry, including possible treatment and recirculation, will be the subject of future development of separation and purification procedures.

**Example:** As an example for the synthesis gas biorefinery, three concrete biorefinery pathways are technologically illustrated in detail, and shown schematically in Figure 23.

**Example 10:**
The concept encompasses the configuration of a wood-based synthesis gas biorefinery for the production of methanol via rapid pyrolysis and entrained-flow gasification.

Beechwood chips, which are introduced into the respective screw reactor of two pyrolysis systems, are used as input for the synthesis route. At temperatures of ca. 500°C, the biomass pyrolysis is converted via rapid pyrolysis into pyrolysis vapours and coke. The subsequent condensation of the pyrolysis vapours into pyrolysis oil and admixing of the coke results in a flowable and energy-rich suspension known as bioslurry. Together with oxygen, this is injected into the entrained flow gasifier at over 1200°C and up to 80 bar. The crude synthesis gas is then cooled and cleaned via gas scrubbing, and is prepared for CO-shift conversion. After treatment/purification, the subsequent methanol synthesis produces pure methanol, which can then be directly or further processed as a chemical or fuel in the chemotechnical area.

**Example 11:**
The concept encompasses the configuration of an agricultural residue-based (straw, bagasse where applicable) synthesis gas biorefinery for the production of methanol via biomass torrefaction and entrained-flow gasification.

The feedstock for the synthesis route is straw, which is introduced to two roasting devices; these produce roasted biomass at 200 to 300°C and with a residence time of 10-30 minutes. Through a dense phase conveyor and a lock system, the roasted, fine-grain biomass is fed into the entrained flow gasifier. The thus-produced crude synthesis gas is purified via gas scrubbing and prepared for CO-shift conversion. After treatment/purification, the subsequent methanol synthesis produces pure methanol, which can then be directly or further processed as a chemical or fuel in the chemotechnical area.

![Figure 22: Schematic of a synthesis gas biorefinery](image-url)
Processes for respective alcohol syntheses are not illustrated in detail.

Figure 23: Examples of synthesis gas biorefinery pathways
Example 12:
The concept encompasses the configuration of a poplar short rotation wood-based synthesis gas biorefinery for the production of ethanol via biomass drying and fluidised bed gasification.

The poplar wood chips are dried and processed under high pressure and low temperature. Dry wood chips combined with oxygen are then fed into a fluidised bed gasifier at 870°C and 30 bar. The produced crude synthesis gas is treated and subsequently fed into alcohol synthesis. Ethanol and higher alcohols are derived from the alcohol distillation.

4.5 Biogas biorefinery

Platform: In a biogas biorefinery there is no separate component separation in primary refining; instead, a large proportion of the organic ingredients and components of the biomass are removed (with the notable exception of lignin), producing raw biogas (Figure 24).

Raw materials: Diverse types of biomass are suitable as a raw material base, as long as they are not highly lignified. Moist biomass above all is well suited to biogas production. Among others, this includes organic residues from agriculture (animal excrement such as slurry and solid manure, crop residues such as beet leaves), organic residual materials from the food processing industry (fruit and vegetable residues, stillage, spent grains), as well as municipal biogenic waste (organic waste, food waste, green waste, landscaping greenstuff) as well as agricultural biomass grown specifically for energy production (so-called energy crops such as grain crop silage, corn silage, perennial grasses).

Primary refining: In a biogas plant, the applied substrate is subjected to anaerobic microbial degradation (fermentation). A variety of types of microorganisms use the complex biomass compositions (mainly carbohydrates, fats and proteins) as a source of nutrients and energy. The main degradation products are methane and carbon dioxide. Because these are gaseous, they separate from the fermentation substrate and form the main components of the biogas.

The biogas and digestate are subsequently available as a raw product for further processing.

Secondary refining/Products: The gas composition of the biogas depends on a range of parameters, first and foremost the substrate composition and the mode of operation of the fermentation container. The methane content is typically around 50–70%. The energy content of biogas means that it can be used diversely for the provision of electricity and heat in cogeneration processes, for pure energy recovery (condensing boiler), or as vehicle fuel. Due to gas network requirements, the processing of the biogas into biomethane is necessary for feed-in to the existing natural gas network; alongside the drying and desulphurisation of the gas, this primarily involves the removal of carbon dioxide (CO2). The utilisation of biogas can therefore either take place directly at the biogas plant, e.g. via a cogeneration plant (CHP) for the production of electricity and heat, or indirectly – after comprehensive biogas treatment – via the feeding-in to the gas grid or the use of biomethane as fuel.

While the digestate can be used materially and energetically, it is nevertheless usually deployed as a fertiliser in agriculture in order to ‘re-close’ the nutrient cycle.
Example: At this time, reliable data and indicators are not yet available to provide concrete technological details for the biogas biorefinery. In addition to the described energetic utilisation, a direct material utilisation of biomethane on-site would be necessary for a biorefinery as described in 3.1. However, there are currently no commercial utilisation options available that could be implemented in a manageable period for a direct material utilisation of biomethane in the sense of an integrated, local biorefinery concept. Utilisation at another location via injection in the gas network is possible and straightforward. For this reason, the following will concern itself only with general statements; a possible biogas biorefinery is shown schematically in Figure 25. The data is based on the available scientific- and technical data and studies for a possible future biogas biorefinery.

Example 13: Biomethane is available as a natural gas substitute for both material and energetic utilisation via feed-in to the natural gas network or on site. Moreover, material utilisation of the carbon dioxide separated from the biogas during processing to biomethane is in principle feasible as a base material for the chemical industry. However, this is not currently considered an economic use option as there is a general assumption that relevant quantities cannot be made available on location and/or utilised in any meaningful magnitude for industrial purposes, and because the market value for carbon dioxide is low. Nevertheless, methane is generally available as a fermentation raw material if appropriate microorganisms are present. In turn, the fermentation products are then either chemical intermediates or are further processed into finished products. In principle, methane can also be chemically converted into other chemical intermediates, which are then further processed into finished products. The extent to which methanol production from synthesis gas based on biogas or methanol from the fermentation of biogas by methylotrophic organisms will be considered as a viable process for material utilisation of biomethane beyond the 2030 time frame cannot be estimated at this time.

Figure 25: Schematic example of a biogas biorefinery pathway
5 Economic and ecological Aspects

As described in the previous chapters, the development of new biorefinery concepts is expected to offer both environmental and economic benefits in comparison to fossil or mineral-based value chains, but also in comparison to the traditional use of biomass. There is a overall requirement for the characterisation and assessment of the developed concepts with respect to economic and ecological aspects. This is in order to realise potential opportunities, to become established in the market, and to find broad public acceptance. In the early phase of development, it will also enable indications to be made for sustainable design processes, as well as support government bodies and companies in the identification of the most promising processes. Moreover, such an analysis can also serve as the basis for the assessment, communication and discussion of the concepts in the public realm.

This chapter will first outline the most relevant economic and ecological aspects of the considered generic biorefinery concepts (see Section 4), even if these do not always specifically apply to biorefineries. General issues encountered in the assessment of biorefineries will be dealt with in Section 5.1. Section 5.2 addresses assessment aspects of the cultivation, provision and transportation of the raw materials. Specific concepts are discussed in more detail in Section 5.3. Given the early stage of development of many of the biorefinery concepts, there is often a lack of adequate data available for more detailed considerations. There are also a number of methodological issues. For this reason, these chapters will put forward predominantly qualitative and variously detailed observations. It should be noted thereby that the statements refer to the specific generic concepts, and that other forms can result in deviations. Further statements regarding the potential and limits of these processes will be made via a first quantitative economic and ecological consideration of two concepts: a lignocellulosic biorefinery via hydrothermal decomposition following the ‘sunliquid’ method (Example 7) and a synthesis gas biorefinery via pyrolysis (Example 10). Finally, in Section 5.4 the results will be discussed, conclusions will be drawn, and further research requirements will be outlined.

5.1 General aspects of the analysis and assessment of biorefineries

For a profound ecological and economic analysis and assessment of production- and processing methods, the entire value creation chain should be considered, from the respective raw material provision, to preparation and further processing, and up to final provision of products in the various plants, also including co-products and disposal of residual materials. This applies both to biorefinery concepts as well as to alternative production processes for bio-based and non-renewable products. A comparison of material utilisation with the direct energetic utilisation of biogenic raw materials shows significant differences, as an extension of the value chain through the material utilisation enables recycling and cascade uses, at the very end of which can stand an energy recovery process. The methodological challenges of comparing different reference designs also require the validation of anticipated advantages of biorefinery concepts opposite (partially established) system concepts for the production of individual products.

In the analysis and assessment of the biorefineries, the various development stages of the concepts must be given due consideration. This can encompass technologies, which can be positioned anywhere between laboratory-, technical-, pilot-, demonstration-, and reference plant scale, and even up to the scale of successful commercial operation. This can also apply to the utilisation of various crops that to date have been bred primarily for high yields for use as food and feedstuff. Some of the ‘new’ crops are yet to reach a comparable level of breeding, although improvements are possible in the future with the use of modern plant breeding and the responsible application of biotechnological methods, focusing on recoverable components. Further progress can also be made for short-rotation plantations (SRP) and energy grasses, and advancements are possible as well as necessary with respect to cultivation- and harvesting technologies. The end result of all this is variable availability, and different levels of detail and data quality, making robust comparisons more difficult.

Logistical issues are also very significant. Different biorefinery concepts also allow for a temporal and
spatial decoupling of sub-processes, both of which offer economic and ecological benefits. These can be met by capacity balancing or a reduction of required transportation of respective raw materials, e.g. as a result of seasonal accumulation or low transportability (see Section 5.2). The same applies to the possibility of establishing a ‘greenfield’ biorefinery in a top-down approach, or at an existing industrial site in a bottom-up approach (see section 3.6). Alongside the general economies of scope that are associated with integration into an existing industrial site, this also opens up the possibility of the reduction of transportation costs, either on the raw materials side, e.g. integration into a large-scale lumber mill, or on the product side through the direct further processing of products.

Analysis and assessment issues can also arise via changes to the calculation basis, such as the underlying data for an economic assessment. Among other factors, competition between various existing but also in-development uses of biomass, sometimes with the same product lines on the market, can reduce the choice on offer and raise prices. Conversely, saturation effects and improvements to conventional products can lead to a stabilisation of prices for biogenic raw materials. As with all other bio-based applications, the realisation of a biorefinery requires the sustainable, long-term securance of the required quantities and quality of the respective resources, and a predictable price basis. Adjuvants such as enzymes and catalysts will be advanced, and alongside an increase in conversion rates can be achieved; this could influence the analysis and assessment results both economically and ecologically. Advantages of biorefinery concepts in comparison to other conversion processes for biogenic raw materials can be provided by the more comprehensive and sometimes higher quality utilisation of raw material components, as well as higher process efficiencies.

The offer of larger product quantities can greatly influence the existing markets for these products. For existing products, it should also be taken into account that these are often significantly further in development and can thus be produced more economically. There are frequently no reliable estimates for market sizes and obtainable prices for new products. In addition, the classification and assessment of these products is significantly hindered by the fact that the potential target products for individual biorefinery concepts remain unfixed; there are also no comparable products and/or a comparative basis must first be drawn up.

Government subsidies also play a role in individual investment decisions; these can lead to greatly differing estimates in the economic assessment of material utilisation concepts, above all in comparison to pure energy utilisation concepts.

Alongside the previously discussed points, there are also other methodological challenges in the ecological analysis and assessment. This concerns above all the consideration of the relevant environmental aspects. It is common practice to give consideration to the effects of acidification, eutrophication and resource consumption, e.g. the land use or the cumulative non-renewable energy consumption. The significance of other important criteria such as ozone depletion and smog are non-controversial, and there are no specific methodological shortcomings with regard to bio-based products. However, there are methodological deficiencies with regard to the aspect of land use changes. Direct land use changes (dLUC) and associated environmental impacts, for example on biodiversity and greenhouse gas emissions, are usually relatively well determinable as a function of the commodity- and capacity choice for a biorefinery type. A broadly accepted scientific accounting methodology would be required for any indirect land use change (iLUC) relating to displacement effects caused by biomass cultivation. Moreover, an important aspect from a specifically regional perspective is water use; to date, this has
been given inadequate consideration in the environmental analysis and assessment.

The choice of appropriate functional units is also important. Here, in analogy to direct energetic utilisation, for some products of biorefinery concepts it is possible to use the energy content. However, this is not always meaningful for all material uses, and it will be expedient to define other appropriate units. As a basic principle, it is useful to draw upon a comparison with reference systems with the same product spectrum as a biorefinery and encompassing equal quantities.

In general, the data basis for many areas of the economic and environmental analysis and assessment of biorefinery concepts is insufficient and poorly validated. There is frequently lacking reliable data on catalysts and enzymes to complement data on the cultivation and provision of raw materials, and on technological processes. Furthermore, in some cases the environmental impacts of biomass crops and biorefineries depend considerably on local conditions, such as air, water and soil. This necessitates efforts towards the regionalisation of assessment methods.

Against this background, the following will undertake a closer examination of the examples of generic biorefineries discussed in this roadmap. Raw materials provision will be dealt with separately because of its relevance for an examination of all biorefinery concepts. In order to make the first, predominantly qualitative statements on economic and ecological contextualisation, and on relevant aspects of economic efficiency and environmental impacts, the discussed concepts will be analysed on the basis of the technical characterisations (see Section 4) and the existing literature. Unless otherwise indicated, comments refer to data collection in the context of the Roadmap process.

5.2 Economic and ecological aspects of the cultivation, provision and transportation of raw materials

The cultivation and provision of raw materials are of central importance for the analysis and assessment of biorefinery concepts. Thereby, and taking due consideration of plant size of the biorefinery type, it can generally be assumed that with increasing size (i.e. larger quantities of free-to-plant raw material, whereby a sustainable supply of raw materials should be investigated in each case) there is a corresponding increase in complexity for the logistics concepts for biomass supply, with a concomitant increase in the proportion of raw materials purchased on international markets.

The following initially deals with aspects relating to the availability of agricultural- and wood raw materials, as well as of green biomass. Aspects relating to the harvesting, transportation and logistics of raw materials are subsequently outlined in Section 5.2.2, while Section 5.2.3 deals with specific assessment issues. The potential of marginal yields and sparse areas, as well as of contaminated sites – highly relevant in Europe and around the world – will not be given consideration here as it is of low significance for Germany.

5.2.1 Raw material availability and prices

**Agricultural raw materials**

The raw material base for the different biorefinery types encompasses starchy (e.g. cereal crops, potatoes) and sugar-containing agricultural products (e.g. sugar beet, sugar cane) as well as various oil crops (e.g. rape, soy, oil palm). This also includes agricultural biogenic residual materials. The quality of the individual raw materials depends on the required product characteristics (different starch levels, fatty acid composition, purity, etc.) and the subsequent direction of utilisation. In 2009/10 the level of self-sufficiency in Germany for these products was between 43% (vegetable oils) and 136% (potatoes and sugar), giving an indication that under the given economic and locational conditions, availability is partially limited at the national level.

The availability of land, and with this the aforementioned raw materials for use in refineries, can be narrowed or improved by various national and European factors:

- Competing uses (e.g. nutrition, feedstuff, material and energetic use, nature conservation and ecosystem services) affect both national and European raw material availability.
- Political decisions on the future of the European Common Agricultural Policy (CAP) and European environmental policy can have a positive or negative impact on the availability of land for production.
- Moderate yield increases can be expected for food and feedstuff production in Germany.
- In the coming years, the domestic consumption of food is anticipated to slightly decline as a result of demographic change in Germany and of changes in eating habits. Following rationalisa-
tion pressure and changing dietary habits, the domestic consumption of feedstuffs for meat- and milk production is likely to decline as a result of reduction in livestock numbers. The German food industry is nevertheless striving for further expansion of export opportunities.

- Coupling products such as stillage, oilseed extraction meal etc. generated by material and/or energetic utilisation of renewable sources can be at least partially used as animal feedstuff, whereby synergies are possible.
- Domestic demand may rise slightly through increased organic farming surface and other extensification of agricultural production.
- National objectives for nature and landscape protection as well as the domestic development of residential- and traffic areas must be taken into consideration.

Due to the complexity of all these factors, it is impossible to make a precise statement on whether additional land for biomass production will be made available in Germany in the future.

From a global perspective, consideration must also be given to rising demand for agricultural commodities for use as food and feedstuff, above all due to population growth and changes in eating habits in favour of animal products, as predicted by the Food and Agriculture Organisation (FAO). In parallel with improvements in yields and reductions in losses, this necessitates a significant expansion of global arable land for food and feedstuffs.

Future demand for agricultural raw materials for the production of biofuels, electricity and heat will significantly depend on the political conditions (including future amendments to the EEG and German international targets for renewable energies), and the price developments of CO₂ in the context of emissions trading and the relative prices of fossil fuels and/or other renewable energy sources. Over the past ten years, the industrial utilisation of cereal crops has already risen ten times quicker than demand for foodstuffs.

Provided that it fulfils the required product properties, industrial producers, including the operators of biorefineries, buy the raw material at the best available price – either on the EU internal market or the global market. As a consequence of spatial and economic conditions, some raw materials with desirable product characteristics (e.g. fatty acid chain length, above all in coconut (oil) and palm (kernel) oil) are not cultivated in Germany, but must be imported. To ensure the long-term raw material base, it can therefore be assumed that raw materials must be sourced from different markets. Nevertheless, farmers will produce only those products that they can sell profitably. As soon as German industry sends out clear signals to farmers regarding the resources required in the medium- and long term and regarding the quantities as well as product characteristics for further processing, and when acceptable prices for farmers can be fixed, it can be assumed that farmers will respond with corresponding offers. Appropriate and already successfully applied instruments to achieve these goals – alongside acquisition – are multi-year supply contracts as well as contract farming for selected raw materials. Especially in cases of a narrow range of offers, increased demand will lead to higher prices and thus also increase the attractiveness of these products among farmers. Nevertheless, the cultivation of foodstuffs must take priority, while giving simultaneous consideration to the effects on the price structure for food and feedstuffs.

Aside from framework conditions that require a specific raw material base, companies will only switch from fossil- or mineral-based raw materials to renewable resources to a significant extent (assuming technical ability) when there is an economic incentive – either on the side of raw materials procurement or of the commercialisation of subsequently derived products.

Because raw materials are an important production cost factor, the market prices play an important role. World market prices for agricultural commodities have been exposed to strong fluctuations in recent years, which have passed over to domestic prices to a large extent. As a consequence of increasing liberalisation of agricultural markets, even more price volatility can be expected in the future than in the past. 2007/08, agricultural commodity prices were at historically high levels (see Figure 26). This was due to a range of complex factors, among others increased oil prices, poor harvests in key producing countries, increased demand as a result of globally strengthened biofuel production, historically low stock levels, and – at least temporarily – price speculation. In 2009 prices fell significantly, triggered by the global financial and banking crisis, only to rise again relatively quickly to new highs in early 2011. Alongside the indexes for German producer prices for feed wheat, grain corn, rape and sugar beet, Figure 26 also shows indexes for German import prices for oils and fats, providing indications on the prices for imported palm- and soy oil (both incl. sales tax).
If prices for raw materials do increase, it can be assumed that the prices of principal- or co-products from specific production processes will likewise increase (e.g. ethanol), with a corresponding interval. The FAO and OECD anticipate rising commodity prices in real terms in their agricultural price projections up to 2030.

In addition to the above-discussed raw materials for biorefineries, targetedly cultivated ‘new’ crops such as miscanthus or perennial energy grasses could increase domestic biomass potential in Germany in the future. Here, the mentioned land availability, as well as the compatibility with nature and landscape conservation, must be given due consideration.

In addition, the establishment of perennial crops means higher costs and higher investment risks for farmers, as the revenues from these cultures are delayed. Furthermore, unless ensured by long-term contracts, obtainable prices are difficult to calculate in advance under these market conditions. As a rule, however, the annual expenditure following establishment is generally lower for perennial crops.

**Straw**

Crop residues such as straw from cereal crop- and grain corn production – with an estimated 35.4 million tonnes produced in Germany in 2010 – are potential raw materials for biorefineries. The demands that this will make on the maintenance of humus content depends on many factors, such as soil type and quality, climate, etc. Between 20% and 40% of the resulting straw is available for energetic and material utilisation, although the sustainable available recovery rates, as well as aspects of crop rotation and the greenhouse gas balance, are also significant. In individual cases, higher recovery of straw can help to ensure sustainable land management.

The regional availability of straw varies greatly; in contrast to Denmark, for example, there is no established straw market in Germany. In addition to alternative uses, the main reason for this high variability is the fact that straw has low transportability due to its low energy density. In consequence, the current price structure makes it likely that no supra-regional market for straw is emerging, and competing users should be considered more from a regional perspective. This can represent an advantage – in terms of provision for biorefineries, as regionally limited trading can greatly reduce the competition situation. Thus, for selected biorefineries, straw should be regarded as an important agricultural, biogenic residual material, also as one of the few renewable resources to date that has failed to achieve optimal utilisation.

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*Figure 26: Producer price indices including sales tax for selected agricultural raw materials, 1980–2010*
'Green' biomasses
While generally dependent on use intensity, green biomasses, such as growths from permanent grasslands or field grass from arable land, are cut up to 3 to 4 times during the growing season (April to October), and can thus achieve total returns of between 7 to 10 tonnes of dry matter per hectare per year. Nevertheless, intensive use can be associated with undesirable effects on the environment and nature (e.g. soil, water, biodiversity). The milk quota will end as of 2015, after which time farmers will be able to produce as much milk as they can sell on the market. Assuming higher agricultural prices for arable crops in the long term, it can be expected that farmers in agricultural regions will concentrate on the production of crops, and that due to low milk prices, less profitable milk production will concentrate predominantly on grassland regions.

The future extent of real demand for green waste for animal production and as substrate in biogas plants remains open, meaning that it is not possible to draw robust conclusions on displacement effects (iLUC). In theory, green waste is available as a raw material for material and energetic utilisation in biorefineries. In 2010 in Germany, approximately 31 million tons of dry matter green biomass was grown on just over 4.8 million hectares (29% of agricultural arable land). It should be noted, however, that due to gradients and soddenness, an estimated one-third of grassland areas is not well mechanisable, and is therefore of only partial economic use. Fresh biomass must be either processed directly or conserved as silage. Silage enables year-round operation, with 'green' biomass as a raw material. Large-scale utilisation concepts for green biomass can cause logistical as well as presumably acceptance problems among the general public and farmers. An important and sustainable alternative to green waste, which also comes with higher provisioning prices – may be 'conservation grass' and residual materials from landscape maintenance.

However, the low transportability of green biomass is a limiting factor, and could risk an overestimation of economic potential. The processing of 'green' biomass should be carried out regionally, in direct combination with existing agro-industrial infrastructure (vegetation drying units, silage production, biogas plants for waste material processing).

Wood from forests and short rotation plantations
In terms of volume, wood is the most important renewable resource worldwide. Due to its chemical, physical and even mechanical properties, wood is used in a variety of ways, both materially and energetically. A total of approximately 3.4 billion cubic meters of raw wood was utilised in 2008. Of this, approximately 53% was used for energetic purposes. This is predominantly for food preparation and heating in the less developed countries, i.e. Africa, Asia and South America. In Germany, use is predominantly material. Mantau et al (2009) estimate for Germany that about 57% of total volume of wood is used materially and 43% is used energetically. The sawmill industry is the largest total raw wood consumer in Germany, followed by private households and power plants, which use wood for the production of heat and electricity. The wood composite-, paper- and pulp industries are the remaining large consumers of wood.

The extent of the raw material base for raw wood-based biorefineries in Germany will depend on market conditions and utilisation competition, likewise the safeguarding of nutrient sustainability, technical, legal and administrative restrictions, the availability of sustainably utilisable woody biomass generation in Germany, and on the import and export of wood and wood products. In Germany, estimates, for the year 2020 agree that theoretically annual sustainably available wood biomass from forests will reach ca. 100–140 million cubic meters. Given the climate change targets for 2020 and the associated promotion of renewable energies, demand for wood will increase significantly by this time, and the supply of wood for utilisation in some application areas will become increasingly scarce. Differentiated location analyses show, however, that there is still untapped potential that would be available as a feedstock for lignocellulosic biorefineries.
So-called short-rotation plantations could serve as an additional source of raw materials. This concerns the cultivation on agricultural land of fast growing tree species such as poplars and willows. In a relatively short time, these can produce large quantities of wood without requiring substantial fertilisation or irrigation. At this time, 8 to 12 tonnes of dry matter per hectare per year can be assumed. The Agency for Renewable Resources currently estimates that there are around 5,000 hectares of short-rotation plantations in Germany.

In contrast to most agricultural raw materials, there is no global market price for raw wood. The reason for this is that the value of raw wood is determined by a variety of criteria such as tree species, size, quality and application possibilities, and is therefore not traded over commodity exchanges. Raw wood prices thus vary greatly regionally, not only for the above named reasons.

The prices for industrial timber are a good indicator of raw material costs because the raw material requirements of a wood-based lignocellulosic or synthesis gas biorefinery are comparable to that of a large sawmill or a pulp industry operation, and because industrial timber could also be processed in a lignocellulosic biorefinery.

Figure 27 shows the development of producer price indexes including sales tax for the industrial timbers beech, oak, spruce and pine in Germany for the period 1980–2010. After a price high in the 1980s, the prices for industrial timber fell until the mid 1990s, after which they remained at a comparatively low level until the middle of the last decade. Rising prices can again be observed since the middle of the last decade. Further price increases are likely in the medium term due to generally anticipated higher demand for wood.

5.2.2 Harvesting, transportation and logistics

Opposite most non-renewable fossil raw materials, the transportation and logistics for renewable raw materials are characterised by a number of specific features. By far the most striking is that the emergence of renewable raw materials is predominantly determined not by technical but by natural factors such as climate, weather, season, soil, size, and spatial distribution of cultivation areas. Harvesting, transportation and logistics must take these factors into account, and adapt appropriately.

In the relatively short harvesting periods, the agricultural harvesting and transport systems must be able to harvest and transport comparatively large, decen-trally-distributed quantities, and be able to store/stock them appropriately – as much as the agricultural raw materials allow. Powerful harvesting techniques and machines can be used in the intensive agriculture of developed countries, where appropriate standardised to the respective raw materials. Crop performance

![Producer price for industrial timber](image-url)

Figure 27: Producer price indices including sales tax for industrial timber, 1980–2010
thus differs only to a small extent, regardless of where a particular agricultural raw material is cultivated. The transportability and storage life of agricultural raw materials varies greatly. While grains (such as cereal crops and oilseeds) can be transported and stored almost without restriction, the transportation of beets, root vegetables and green waste/silage content is only economic over short distances due to high water content. In suitable storage conditions, silage can be stored for longer periods of up to 12 months, and beets for up to 6 months if it is well stocked and carefully covered. Although potatoes can be stored in refrigeration for up to a year, transportation is laborious due to their relative pressure sensitivity.

After harvesting, cereal straw can be stored both at the field breaks or in warehouses, and is thus available for supply all year round. However, due to the low (energy-) density, it is transportable only at a regional level.

With some restrictions, forest wood can be harvested all year round. Thereby, the choice of wood harvesting and transport processes proceeds according to the age, dimensions, and other characteristics of the wood, as well as the selection to be harvested. Although there are highly mechanised harvesting methods in the agricultural sector, the performance varies from crop to crop; unlike fields, forests are more diverse and less uniform. While harvesting is carried out by fully mechanised harvesters in younger crops, predominantly motor-manual methods are used for older crops with very large trees. The transportation and storage life of raw wood is comparable to that of grain. Transportation is less economical over long distances when the product line is more humid and less dense (wood chips, sawdust). If it is dry enough and protected from pests, the shelf life of wood is almost unlimited.

The harvesting of short rotation plantations can be compared with that of other agricultural commodities because the harvesting season is also possible in winter, although only during a very short period, as with other raw materials. Modified agricultural machinery and transport logistics can be used for wood chips production. Special forest harvesting techniques are required for the harvesting of round timber. Both agricultural and forestry techniques are used to transport wood chips, whereby the storage life is equivalent to that of forest wood.

Various conditioning procedures (e.g. pelletisation, torrefaction, pyrolysis, hydrothermal conversion) with the objective of increasing energy density and hence the transportability, while simultaneously improving the raw material properties for conversion, are known, or in some cases remain in the pilot- or demonstration stages.

5.2.3 Assessment factors for raw materials provision

The assessment methodology is also always dependent on the objective, such as the optimal utilisation of a particular raw material, optimal land use, and best process route to specific products. From this it can already be seen that not all raw materials for various biorefinery types are comparable, and also other requirements must be made of respective assessment methodologies. It is therefore important that the existing methodological challenges and data gaps are worked out in the context of specific questions and then formulated as research needs for medium-term development of appropriate and viable assessment methods.

A site-specific discussion of environmental effects with respect to raw material provision, and encompassing the various site options, is a prerequisite for the proper assessment on site as well as for the assessment of Germany and globally. The forest- and agricultural raw materials purchased both nationally and internationally will have to meet sustainability criteria if the much-discussed expansion of sustainability requirements are implemented for biomass utilisation for energetic use. Here, a sustainable provision of raw materials should at the very least (i) have a positive climate balance over the entire life cycle from cultivation to waste material recycling, (ii) not cause any deterioration of soil condition, (iii) exhibit tolerable material input and output across all paths, and (iv) have closed material cycles for residues.

Forest production is characterised by both limited use of fossil energies and by low use of other production factors, i.e. no fertilisers and very limited use of pesticides. On the raw material side, this ultimately results in a very small environmental impact through greenhouse gases, acidifying, or eutrophying inputs in the soil, water and air. Among other ecosystem services, forests remove atmospheric CO₂ and store it for decades.

Short rotation plantations (SRP) are agricultural crops that are farmed relatively extensively. Thereby, there is less intensive use of machines during the investment period than in conventionally farmed land, and less use of pesticides and mineral fertilisers. Both greenhouse gas emissions as well as inputs in soil and water are relatively minimal. During the
lifetime of the SRP, the long ground rests associated with the cultivation of short rotation plantations results in improved soil structure, nutrient enrichment, formation of a humus layer, and reduced soil erosion. For this reason, SRPs could be used to recuperate degraded soils; depending on the initial situation, they can also have a positive effect on the diversity of species. The water requirements of SRPs is generally higher than of conventional agricultural crops under similar location conditions, while the clearing of the SRP can have a negative impact on the environment and natural balance if the land is not subsequently used for agricultural purposes.

Cultivated plants (cereal crops, oilseeds, sugar beet, etc.) are grown primarily for utilisation as a food or feedstuff. The use of fertilisers and pesticides that have been connected to undesirable effects on the environment and nature is required to achieve the highest possible yield per area. During cultivation, lignocellulosic agricultural waste by-products that are not suitable for food production are incurred as by-products for primary use. The provision of crops causes a higher environmental impact per unit area than the provision of timber; however, agricultural products can be more easily converted into high-quality products. This is due to the fact that the raw material components are either used directly (e.g. sugar or vegetable oil) or require only minimal conversion (e.g. starch). A conversion of lignocellulosic agricultural waste materials into valuable products and energy appears to make economic sense, and the first approaches have demonstrated technical and economic feasibility. There is need for investigation into the influence of tillage on environmental impact, particularly the change in soil carbon content and C/N interaction in the soil, as well as for soil erosion and compaction. The utilisation of agricultural products as raw material for biofuels has triggered an intense debate about direct and indirect land use changes; the generation of biomass (be it, for example, from agricultural and forestry production) is in principle limited to available area, and thus conflicts may arise between the different utilisation options. Here, crop residues can represent an advantage, as with their utilisation no additional land use occurs because of the primary crop use as food and feed. It is therefore possible to achieve an optimal production of food and feedstuff in combination with lignocellulose-based products.

Life-cycle assessments (LCA) are recommended in the EU lead market initiative as assessment instruments in the identification of bio-based products that are both economically and ecologically advantageous. However, significant methodological challenges remain in the environmental assessment, particularly with regard to the sustainable cultivation of soil, for example with respect to:

- the determination of humus in the soil for maintenance of fertility, as well as nitrous oxide (N₂O) and ammonia emissions by biogenic substances remaining on or returned to the field,
- the quantification of water requirements (water footprint) for the manufactured products,
- direct and indirect land use changes,
- the biodiversity and ecosystem services,
- the time measurement framework (annual, crop rotation, harvesting period, or 100 years in accordance with the greenhouse effect),
- regional-specific impact assessment methods and
- the sustainability assessment, e.g. through the combination of Life Cycle Assessment and Life Cycle Costing, and where applicable the Social Life Cycle Assessment.

Moreover, disaggregated background data for the relevant conversion and treatment processes for renewable resources are lacking in the existing LCA databases, as well as regional- and seasonal-related material flow analyses for organic residual materials in Germany.

5.3 Economic and ecological aspects of the considered biorefinery concepts

In the following, the economic and ecological aspects for the different biorefinery types will be discussed on the basis of the thirteen different concepts considered in this roadmap (see Section 4). Reflecting the development status and available data, most
examples are, if anything, more likely to be contextualised in a qualitative sense, and particularly relevant factors and issues are outlined for economic and ecological perspectives in cases of implementation on a commercial scale. First quantitative assessments will be made using the example of a lignocellulosic biorefinery (Example 7) and a synthesis gas biorefinery (Example 10).

5.3.1 Sugar and starch biorefinery
The concepts for sugar- and starch-biorefineries presented in the context of this roadmap (see Section 4.1) are based on a bottom-up approach (see Section 3.6) and expand the product range of existing biomass processing plants with newly integrated processes.

The requirement for sugar beet for the possible sugar biorefinery identified in this roadmap as Example 1 is likely to be met domestically. Market potential already exists for all of the products of the sugar-biorefinery, for example glucose, fructose, carbonic acid and gluconate in the food industry, and bioethanol as a fuel.

The provision of cereal flour as a raw material for a wheat- (Example 2) and corn-based (Example 3) starch biorefinery can be met domestically and independent of season. The transportation and storage costs for cereal crops/-flour are therefore assumed as low. On the sales side, corresponding markets exist in the food and feed industry, in the transportation sector, and in the chemicals industry.

The economic feasibility of sugar- and starch biorefineries is dependent on a number of factors. In addition to the cost of providing the resources (raw materials, enzymes, other), the major cost components are primarily energy supply costs. Fluctuating raw material prices as well as rising energy prices can thus impact heavily on economic efficiency, although this can be improved by an integrated approach, in which the various sugar- and starch biorefineries are operated in one plant complex. In comparison to conventional biomass processing, the revenues from the various new products can likewise contribute to the economic efficiency of these biorefineries. The investment required for a wheat-based starch biorefinery (in accordance with Example 2) with a capacity of 200,000 tonnes of wheat/a is in the order of €120 million. A more far-reaching economic assessment will require more detailed studies into more specific configurations. This also applies for ecological aspects, as the data are not sufficient for such an undertaking. Along-side the production of raw materials, the provision of energy and resources such as enzymes and chemicals appears to be of particular relevance for environmental impact considerations. A number of chemicals that can be produced more cheaply from biomass than from fossil fuels are already produced in sugar and starch biorefineries. Nevertheless, there are numerous equivalent products for many products from sugar- and starch-based biorefineries, i.e. there is difficulty in defining appropriate systems with functional and qualitative equivalence. A comparison with (fossil-based) reference systems is made more difficult for the reasons mentioned.

In view of this fact, there is a requirement here on the one hand for further work on the standardisation of accounting methods, both for the cultivation of raw materials as well as their conversion, and on the other hand for the provision of data for the conversion processes in order to be able to make secure and quantitative economic and environmental statements.

5.3.2 Vegetable oil- and algal lipid biorefinery

Vegetable oil biorefinery
The concepts for vegetable oil refineries presented in the context of this roadmap represent a combination of already industrially applied processes as well as processes that are still in the development stages. To this extent they concern bottom-up developments. Oleochemical plants are for the most part integrated into the network of chemical industry and are generally sited in locations that also pursue fossil raw material-based production. Systems for biodiesel production are either stand alone or integrated in oil mills. These processes for material and energy use have thus been largely developed in a decentralised manner. The first approaches for a commercial vegetable oil biorefinery in the manner described here can be found in Southeast Asia.

Example 4 is a vegetable oil biorefinery on the basis of rapeseed for the production of biodiesel, lubricants and specialty chemicals. Processing dimensions of approximately 530,000 tonnes of rapeseed per year can be assumed to be realistic, using the capacity of oil mills in Germany as a basis. An investment in the order of €100 million is to be expected for the integration of such a plant into an existing industrial park. The main product would be rapeseed methyl ester as a fuel, which would contribute to more than half of the total turnover of the biorefinery. At current price conditions, a further 15% would be accounted for in the form of rapeseed meal, and a little less than a third of turnover by the
higher-value products triacetin, 1,3-propanediol and lubricants.

Example 5 is a vegetable oil biorefinery for the palm kernel-based production of fatty acids, surfactants and specialty chemicals. Likewise, a circa 100 million-euro investment can be expected for integration into an existing industrial park, with a raw material processing capacity of 400,000 tonnes of palm kernels per year. At about 75%, fatty alcohol sulphate would represent by far the largest share of revenue in the considered configuration. Fatty acids, alkyl polyglycosides, glycerol triacetate and glycerol as other main products would provide for a diversified product portfolio. In addition, the by-product of palm kernel cake could also be commercialised.

The environmental impacts of vegetable oil-based biorefinery concepts are determined above all by the ecological profile of the raw material, but also by the organisation of transport routes, the process conditions, and the feedstock used for conversion to finished products. An ecological assessment of the processes in an integrated vegetable oil biorefinery is still pending. For this reason, it is currently not possible to make reliable statements regarding the environmental impacts of these concepts.

In a vegetable oil biorefinery constituting the current or near-future state of the technology, the main products produced would be those that are already manufactured today on the basis of renewable raw materials. In the context of existing structures in Germany, future research on the assessment of vegetable oil refineries should thus concentrate on the analysis of integrated concepts that utilise all raw material components. Thereby, the objective should be to include the entire value chain, also encompassing raw material production and product use, with identification of cost savings and consideration in the analyses of oleochemical process- and product innovations.

**Algal lipid biorefinery**

Algae and cyanobacteria produce many secondary metabolites, meaning that they are suited not only to the production of non-toxic and biodegradable fuels, but also to the preparation of chemicals and polymers, suitable as a feedstuff for fish, among other uses.

Practical experience is available on a large scale for the industrial production of material products, for instance of β-carotene (e.g. in Australia) in open ponds, as well as for the production of nutritional supple-

ments in closed photobioreactors (e.g. in Klötze/Germany). Three demonstration projects for the production of energy carriers are currently supported at the EU level; these envision the cultivation of microalgae over 10 hectares. The aim of this project is to replace fossil fuels with bio-based equivalents. There are also a variety of projects in the laboratory scale.

Since algae can be grown on non-fertile land, their use for the production of fuels is associated with smaller land use competition than conventional first-generation biofuels. Taking the high yields as their basis, the first studies of potential have shown that fuels made from algae could theoretically replace fossil fuels entirely. Life cycle assessment studies show that the energy balance of algae fuels can be negative, however. The main factors are the cultivation system, the use of fertiliser and carbon dioxide, as well as the choice of conditioning or conversion technique.

Frequently, considerations of the economic and energy balance also neglect the fact that the microalgae build up mass in the daytime and shed this again at nighttime, and that lipid production takes place only during growth limitation, i.e. when biomass production does not reach the known maximum values. One to-date not detailed cost factor is the cleaning and preparation of equipment, which varies greatly depending on equipment and nutrient supply. The use of wastewater as a source of nutrients also appears to represent an energetically advantageous approach.

As a result of these considerations, the majority of concepts with production aimed primarily towards fuels cannot be meaningfully assessed from an ecological or economical perspective. The remaining basic options are described in Section 4.2.

There is still a great need for research, both from a technical perspective and with regard to the ecological and economic assessments.

**5.3.3 Lignocellulosic biorefinery and green biorefinery**

**Lignocellulosic Biorefinery**

Of all the detailed examples of process types for lignocellulosic biorefineries considered in this document (cf. Section 4.3), the following will deal with the utilisation of straw via hydrothermal decomposition according to the ‘sunliquid’ method (Example 7) and then of wood via organosolv extraction (Example 8). While a first quantitative assessment
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will be conducted for Example 7, only a qualitative consideration will be conducted for Example 8.

Example 7 – a crop residue-based lignocellulosic biorefinery – will undergo testing in demonstration scale in 2012. 4,500 tonnes of raw materials will be utilised annually for the production of approximately 1,000 tonnes of ethanol. The concept is developed in a top-down approach, i.e. the aim is an independent facility constructed close to the raw material source. Crop residues such as wheat straw will be used as raw material; this will be transported in unconditioned form to the biorefinery location from an average of about 50 km distance. The main products of this biorefinery concept are ethanol and the lignin contained in the raw material, which will be thermally utilised; the resulting energy will be used for the plant’s own requirements. Mineral fertiliser is produced as a co-product. The possible orders of magnitude for the envisioned industrial plants are expected to be 250,000 to 750,000 tonnes (dry matter) of raw materials per year.

In the following, a first quantitative economic and environmental assessment will be carried out for the described implementation scenario. It should be noted that, depending on the development stage, this involves considerable uncertainty with respect to data. Based on an investment estimate for the entire plant, a production cost estimate for the main product will be carried out, in which investment-dependent cost elements (depreciation and interest, maintenance, cleaning and maintenance, repair, administration, insurance and other unforeseen expenses) will be statically estimated as a percentage of total investment. Consumption-dependent cost elements for raw materials, auxiliary- and operating materials, water, energy and waste will also be considered. In order to arrive at a conservative estimate for production costs, no revenues for co-product mineral fertilisers will be considered. Likewise, possible extensive (material) recycling of further excess quantities of lignin, following further developments and process improvements, will also not be considered. The corresponding calculation bases and calculations can be found in the appendix in Table 1 to Table 3.

Capital expenditure in the range of €70 million can be expected for the realisation of this future optimised production plant concept, encompassing the utilisation of e.g. 280,000 tons/year of straw. For the main product of ethanol, this would result in production costs of circa 680 €/t (see above for calculation), corresponding to 2.5 €cents/MJ. Ca. 65% of production costs will be attributable to the provision of raw materials, auxiliary and operating materials, and other material flow-dependent costs (waste-water). At more than 50%, the largest share of total costs is represented by the provision costs for straw, which are assumed to be 75 €/t. The remaining costs consist of capital-related costs (interest and depreciation 23%) and other costs (11%) (see Figure 28). A variation in the provision price illustrates the huge influence of this parameter: A straw price of 50 €/t dry matter gives production costs of 562 €/t of product; at 100 €/t it is 797 €/t of product. A comparison with the current European market conditions is given. The prices for ethanol from Rotterdam of around 750–800 €/t in 2011 enables a classification of these production costs in the current European market conditions.

### Specific productions costs of example 7

![Figure 28: Composition of the specific production costs for ethanol in a straw-based lignocellulosic biorefinery (Example 7)](image-url)
A benchmark for these production costs is the reference system ‘gasoline provision and 100% utilisation in a mid-sized car with a gasoline engine.’ For 2010, this gives a provision price of 4.2 €cent/MJ end energy (equivalent to 1,722 €/t gasoline). This means that the price of bioethanol is currently at the same level as the trading price of gasoline in Rotterdam.

For an initial ecological consideration, the presented concept is likewise compared with the provision and use of gasoline. A first assessment will be carried out for environmental effects (midpoints) with respect to global warming potential (GWP100) and acidification, as well as for the cumulative non-renewable energy consumption (non-renewable CEC) as an indicator of resource consumption of non-renewable primary energy sources. Attention will be paid to the entire value chain, from cultivation to provision of the raw material, its conversion in the biorefinery, up to the use of the ethanol as a fuel in the vehicle.

For the production of bioethanol, it is assumed that emissions occur solely during the provision of auxiliary and operating materials (harvesting and transportation of the raw material (50 km), water supply, provision of chemicals). No further emissions result from fossil fuels because the full process energy can be met by the energetic utilisation of the lignin. Compared to the reference system, savings of 98% of greenhouse gas, 40% of acidifying emissions and 96% of non-renewable CEC can be achieved under these conditions (see Figure 29).

Compared with existing uses of biomass, the process enables an almost complete utilisation of the raw material, with the substantial use of the cellulose and hemicellulose fractions as well as a process-integrated, energetic utilisation of the lignin fraction for the provision of process energy. There are almost no additional costs and emissions for the provision of process energy. Furthermore, no direct land use changes occur because the straw is produced as crop residue material.

In summary, this analysis on the one hand demonstrates that, with regard to the price of ethanol, the process exhibits the potential to compete commercially with gasoline when the currently valid tax exemption remains in place. The decisive factor is the raw materials supply. Thereby, through the relatively small size and the concept of a standalone system, the processes under consideration carry the advantage of production in close proximity to the raw materials. The first assessment of environmental effects have shown significant potential for environmental relief in the presented impact categories of global warming potential, acidification, and non-renewable energy consumption. No conclusion can be drawn for general ecological benefits as an environmental assessment could currently provide only incomplete results. In order to realise the demonstrated potential, the underlying assumptions with regard to scale-up must be met. These developments may also serve in the production of other products based on cellulose- and hemicellulose components, as well as in the material or energetic utilisation of lignin and the commercialisation of the mineral fraction.

Example 8 for a lignocellulosic biorefinery, i.e. the process path via organosolv decomposition and enzymatic hydrolysis, is also yet to be implemented on
an industrial scale. After a pilot project, the further development of the process and the construction of a pilot plant at the Fraunhofer CBP in the chemical park Leuna is currently underway. Nevertheless, through the pilot project and its continuation, data are available regarding the economic and environmental assessment of an industrial plant of this process type. The following considerations are essentially based on these data.

In comparison to conventional pathways for biomass utilisation, the process aims at the fullest possible utilisation of wood for to-date not-yet fully utilised ranges, and provides an alternative path for the provision of sugars as a fermentation raw material. Alongside the substitution possibilities for fossil-based products and fermentation processes, the sulphur-free lignin should provide an alternative to fossil-based material pathways, such as aromatics.

The plant concept envisages integration into an existing industrial complex for the further processing of the partly solution-based product streams. Such an integration and the secure provision of raw wood (safeguarding the quantity, price and transportation distance) are therefore key success factors for the realisation of the process type. The orders of magnitude of such an industrial implementation are anticipated to be around 300,000 to 500,000 tonnes of wood (dry matter) processed per year.

The economic feasibility of the process depends strongly on a range of factors. Alongside the previously discussed integration into an existing industrial complex and the provision of the raw materials, standing in the foreground are the validation of the assumptions and the implementation on an industrial scale of the yields previously achieved in the laboratory- and pilot plant scale, as well as the high quality material utilisation of the three product fractions glucose, (oligo) pentose (in particular xylose), and above all of lignin. Other particularly relevant cost factors are the provision of energy, solvents and enzymes. The economic feasibility of the process appears to be possible if the technical conditions and a high-quality utilisation of lignin are achieved.

An ecological assessment of the chain from raw material to factory exit (cradle-to-gate analysis) with regard to the impact categories of climate change, acidification and eutrophication using life cycle assessment methods (ISO 14040 and ISO 14044) for CML was carried out for the products glucose, xylose (fermentable sugar) and lignin. In all three considered impact categories, the comparison with reference processes (manufacturing of cane juice from sugar beet and phenol from cumene via the Hock process) demonstrated the significant benefits of the procedure (a total of ca. 40% fewer CO₂ equivalents, ca. 55% fewer SO₂ equivalents, ca. 65% fewer PO₄ equivalents). The main contributions to the observed climate effects are due to the provision of steam and electricity. With regard to acidifying effects, the most important factor is the provision of operating materials, above all solvents and enzymes before electrical energy is allocated. The provision of operating materials, particularly enzymes, also dominates the eutrophying effects. Also here, further investigation is required to provide general statements on the ecological benefits.

**Green biorefinery**

In the context of the preparation of this document, a combined process for the treatment of 91,000 t/year (20% dry matter content) of green waste silage was worked out on the basis of experimental results (see Section 4.3, Example 9).

Such a system would typically be built close to the raw material source on the site of a biogas plant, on the one hand to take advantage of existing infrastructure and on the other to be able to exploit the resulting residual materials. Such a biorefinery would require about 2,300 hectares of grassland, based on an average yield (8 t dry matter/hectare and year), 50% fresh biomass for processing and 50% ensiled biomass (assuming 10% ensiled loss). A large intake radius can be expected as not only grassland but also better soils for cereal crop cultivation are likely to be found in the area surrounding a biorefinery. This is associated with logistical challenges as a result of the multiple harvests per year.

Capital expenditure in the order of magnitude of approximately €15 million can be expected for the implementation of a green biorefinery. Thereby, the provision of raw materials and energy are the main cost drivers. The wide range of possible products – white proteins, feedstuff, lysine lactate and fermentation media – play a major role in the assessment. High-priced sales opportunities are conceivable for such products, although there are major uncertainties both in terms of market size and of attainable revenues. With regard to both cost and to environmental impacts, a further elaboration of the technical concept, the definition of reference products, as well as more detailed evaluation studies would be required for further statements and a comparison with existing reference systems.
5.3.4 Synthesis gas biorefinery

Synthesis gas biorefineries for the production of biomass to liquid (BtL) fuels and chemicals are not currently present on the market on a commercial scale. The production of BtL fuels and chemicals requires complex and cost-intensive technologies, meaning that production takes place in larger systems. This is to take advantage of economies of scale and to retain overall economically feasibility. The plant capacity will be limited first and foremost by the transportability of the applied biomass types. Orders of magnitude of 500,000 to 2,000,000 tonnes of biomass input per year are under discussion, respective of version. The capital expenditure for systems in this order of magnitude can move between €250 million and €1,000 million. The decoupling and decentralisation of several smaller systems for the preparation of biomass are being discussed in order to combine the advantages of small systems (i.e. lower transportation costs) with the advantages of economies of scale of larger systems. Compared to traditional biomass uses for material and energetic purposes, this method carries the advantage of the near complete use of the biomass, as well as the utilisation of residual materials.

The following is a more detailed quantitative analysis of the example 10 of a synthesis gas biorefinery from Section 4.4. Here, pyrolysis and gasification is based on the bioliq concept, which can utilise diverse biomasses such as straw and wood. The most important qualitative differences of this example in comparison to examples 11 and 12 will be subsequently examined. It should be noted at this point that these first estimations of quantitative economic and environmental calculations are an initial assessment, and due to the development stage, there are corresponding data uncertainties.

The scenario considered in Example 10 for the synthesis gas biorefineries for the production of methanol features a capacity of about 450,000 tonnes (dry matter) of beechwood chips per year. With the exception of the two pyrolysis plants, the applied system components for this capacity are already commercially available, albeit with fossil fuels as feedstock. The adaptation of the facilities to biomass/beech wood chips as raw material brings about no fundamental process changes to the gasification and downstream process steps, although the practical technical implementation of biomass-based conversion products is likely to be a challenge. The greatest uncertainty is the pyrolysis plant, as no plants with the considered capacity are in operation. Furthermore, uncertainties exist with respect to raw material supply. This applies in particular to the size of the catchment area required to supply the two pyrolysis plants with biomass of about 225,000 tonnes of dry matter per year, and to the average prices at which they can be supplied. The following will assume provision costs freely to pyrolysis plants of around €75 per tonne of dry matter.

For such a synthesis gas biorefinery, capital expenditure totalling €250 million can be expected for the construction of an industrial facility. The two pyrolysis plants would be responsible for the largest proportion, followed by the entrained flow pressurised gasifier, the Rectisol wash technology, air separator, methanol synthesis, and CO-shift reactor.

<table>
<thead>
<tr>
<th>Specific production costs for example 10</th>
</tr>
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<tbody>
<tr>
<td>Imputed interest 10 %</td>
</tr>
<tr>
<td>Depreciation 13 %</td>
</tr>
<tr>
<td>Contingencies 2 %</td>
</tr>
<tr>
<td>Insurance 2 %</td>
</tr>
<tr>
<td>Administration 1 %</td>
</tr>
<tr>
<td>Maintenance and cleaning 8 %</td>
</tr>
<tr>
<td>Repairs 6 %</td>
</tr>
<tr>
<td>Personnel costs 6 %</td>
</tr>
<tr>
<td>34 % Raw material</td>
</tr>
<tr>
<td>1 % Auxiliary and operating materials</td>
</tr>
<tr>
<td>16 % Electrical energy</td>
</tr>
<tr>
<td>1 % Water</td>
</tr>
</tbody>
</table>
Analogous to the process for the straw-based lignocellulosic biorefinery (see Section 5.3.3), the production costs for the main product of methanol can be estimated on the basis of investment estimates. In addition to the investment-related cost elements (cf. Section 5.3.3.), the consumption-related costs will also be considered for the raw materials beechwood chips, auxiliary and operating materials, e.g. catalyst, sand, methanol, sodium carbonate, as well as for water, electricity and natural gas. Personnel requirements will be estimated as a function of biomass input capacity. The corresponding calculation bases and calculations can be found in the appendix in Tables 9 to 11.

The result of the production cost estimate for the main product of methanol is shown in Figure 30 in the form of the cost components of specific production costs. The main product of the considered synthesis gas biorefinery is methanol with an annual production volume of approximately 150,000 tonnes, on the basis of an assumed 680 € per tonne. At more than 30%, the provision of the raw material beechwood chips represents the largest share of production costs. The material flow-dependent costs account for a total of ca. 18% of production costs. This is followed by the individual investment-dependent cost elements and personnel. It should be noted that, following this first rough estimate of the cost of production for biogenic methanol, it can not be competitively produced in comparison with conventional methanol; This is currently traded at market prices of between €300 and €400 per tonne, making it around 50% cheaper. Here too, it is possible to see the major impact of raw material costs. On the basis of €50 per tonne of dry matter, this comes to €600 per tonne; at €100 per tonne of dry matter, however, the cost is €755 per tonne.

For a first quantitative consideration of the ecological effects of the synthesis gas biorefinery, a comparison will be made between Example 10 with wood as a raw material and with the reference system ‘fossil methanol’ in the categories of global warming potential, acidification potential and cumulative non-renewable energy consumption (non-renewable CEC). The procedure and data basis is analogous to the straw-based lignocellulosic biorefinery (see Section 5.3.3, Example 7). The emissions (CO₂ equivalents), formed in the material conversion of wood
to methanol are regarded as biogenic and will not be included in this assessment. Likewise, the influence of catalysts will not be considered. The required thermal energy is provided by the process. Energy for the generation of the various required pressures of nitrogen and steam, as well as for the water demineralisation, is contained in the electrical energy.

The results of the first quantitative consideration are shown in Figure 31. 75% of the global warming potential (GWP) of the pyrolysis synthesis gas biorefinery derives from the supply of electrical energy. It is possible to save 45% of greenhouse gas emissions. A total saving of 85% of greenhouse gases arises if methanol is thermally utilised in a further product cycle.80

A comparison of non-renewable cumulative energy consumption of the synthesis gas biorefinery with a conventional production method shows savings of 75%; in a biorefinery, the non-renewable raw material of natural gas is replaced with renewable resources (Figure 31).

In the category of acidification potential, the biorefinery gives indications to a savings potential of over 40% for SO₂-equivalents compared to the reference system (Figure 31). 80% of air pollutants is the result of provision of energy.81

In the following, the central differences between the various synthesis gas biorefinery concepts considered in this roadmap will be briefly examined from an economic and ecological perspective.

The most important variable in the choice of raw materials as possible feedstock in a synthesis gas biorefinery – between wood, i.e. wood residues, wood from short rotation plantations, or agricultural residues, i.e. cereal straw – is the price of the biomass from the field or forest. As a result of transport properties (see Section 5.2.2), there are strong regional variations in the cost of procurement for input materials. The relatively small differences in the individual process steps of transport, drying, as well as pyrolysis and gasification, can only be examined more closely when these are secured by long-term contracts. Compared to straw, there are slight advantages on the side of wood in the cost of transportation. The higher volumetric energy density of the wood means that it has higher transportability. Additional costs on the part of wood arise mainly through the drying upstream of pyrolysis, as the wood usually contains more water than straw at the beginning of the process chain (about 50% water content in the wood as opposed to 15% water content in the straw is assumed).

In the synthesis gas biorefinery concept, pyrolysis and torrefaction (see Example 11) will be considered as an alternative possible first conversion step for biomass into a feedstock for gasification. In the case of the torrefaction of straw, this technically less complex alternative approach could save costs. However, some of this cost advantage could again be balanced out by more complex technology for biomass separation in the entrained flow pressurised gasifier, and by the lower quality of the straw in comparison to wood. A detailed comparison of process alternatives is required in order to make a final statement.

In the gasification step, the fluidised bed gasification (see Example 12) can only be implemented on a small scale in comparison to entrained flow gasification pressure, and therefore does not benefit to the same extent from the economies of scale effects. However, fluidised bed gasification is not as technically demanding as entrained flow gasification.
pressure. In comparison to entrained-flow pressure gasification, the lower gasification temperature in fluidised bed gasifiers produces lower quality synthesis gas, which as a rule must undergo more extensive processing if it is to be used in the same synthesis processes.

The flexibility with regard to application of the end product methanol brings marketing advantages, as methanol can serve as a base chemical both for fuels and for other chemical base materials, and has already found widespread application.

Methanol can be added directly to gasoline. With over 100 octanes, it features the benefit of improving the octane number. It can also be used in the form of converted MTBE. Methanol is a basic chemical, and routes to propylene itself and thus to polypropylene should be possible in the production of ‘green plastic’.

From an ecological perspective, with identical feedstock and with regard to most environmental effects, the different process types in the three examples for synthesis gas biorefineries generally behave correspondingly to the respective energy efficiency. This means that a process that is advantageous from an energetic point of view is also advantageous in this respect.

Thus, alongside the configuration of the conversion process, the differences in the ecological profiles of the process paths are first and foremost defined by the choice of feedstock.

5.4 Discussion and conclusion

The economic and ecological assessment of biorefinery concepts will play a key role in process development, investment decisions, societal acceptance and funding policies. Using the methods of material flow analysis, economic feasibility calculations and life cycle assessments, also in comparison to reference systems, appropriate assessments can be made. Here, however, the specific characteristics of the biorefineries must be given due consideration. Complete and valid data bases for (future) raw material production, the technical processes and reference systems for comparison, as well as comparisons of analytical results are frequently lacking. Also methodologically, other aspects come to the fore, for example in energetic biomass utilisation concepts. Thus, so far only limited statements can be made for many biorefinery concepts, particularly with regard to environmental impacts. The considerations in this section of the roadmap can for this reason provide only a first overview and discussion of key economic and ecological assessment aspects.

The analysis and assessment of biorefinery concepts must take into account the relevant aspects of the supply chains of the systems. In addition to the technical system, a comparison of potential biorefineries must encompass feedstock production and provision systems, as well as the utilisation and end of life cycle of the products. Given the large number of concepts, a comparison of the different concepts between each other and with the reference systems in relation to raw materials, logistical configuration, technologies, products and markets, performance classes and development levels, is ultimately hindered. In view of this fact, the results of individual assessments are not readily transferable to other biorefinery concepts, and further considerations will be essential. Against this background, the discussion of general assessment aspects, the treatment of raw material production and the various individual biorefinery concepts provide the first indications on key aspects with regard to the economic- and ecological potential for success of the processes.

Similarly to other biomass conversion facilities, a critical factor for most biorefinery concepts is the sustainable securing of the raw material base, namely the provision of raw materials, sustainably produced and in the required quantity and quality, and at reasonable prices. Playing an important role here is competition with existing uses, as well as various processes still in development for the same
utilisation of raw material potentials. The discussion surrounding biorefineries and the securing of the necessary raw material base thus also concerns the discussion of an efficient allocation of available agricultural and forestry land, also taking into account possible competition for food and feed production. Other factors, which vary according to concept, are integration into existing chemical facilities, energy costs, as well as costs for the provision of auxiliary and operating materials, in particular solvents, enzymes and catalysts. In the upscaling from previous development stages, it is also important to achieve and to improve upon intended process efficiencies (product yields, enzyme- and solvent recovery etc.) at the industrial scale. The high-quality material utilisation of all product streams is required in if the processes – in some cases considerably more complex than conventional biomass utilisation – are to be operated economically. For basic chemicals such as alcohols, there is the advantage that corresponding markets already exist. However, competition from existing conventional process routes should be classified as tendentially strong. The market is therefore sometimes difficult for concepts that are still in development. In some cases, the production of fine chemicals may offer better opportunities for selling products at higher prices. As a rule, however, the markets are usually much smaller, and thus the scale-up of product streams can appear problematic at times. Here, the development of suitable new product trees and product portfolios will be crucial.

For new biorefinery concepts, the fact that the first commercial systems are on the one hand associated with increased investments and not-yet-achieved consumption- and conversion rates must be taken into account. To achieve economic competitiveness, the process must therefore find more widespread application in order to gain learning- and experience curve effects.

The observations for biorefinery concepts with respect to the named factors demonstrate very large differences, even within the variants of the generic concepts. In this respect, a more detailed analysis of the individual concepts will be useful – also taking location-related factors into account. This would enable a quantitative assessment of process concepts, could provide indications on the further development of the process, and through the comparison with reference systems, also help make statements on the benefits in comparison to existing value chains.

This will require extensive further studies, both with respect to the data basis and to the methodology. In the area of the analysis and assessment of environmental aspects, unified accounting standards are required more for the material utilisation of biomass than for energetic utilisation, in order for ecological data to be comparable.

With respect to the data basis, only rough estimates of incoming and outgoing material- and energy flows are available to date for some of the concepts. Here, further elaborations and development of plant concepts and processes, as well as experimental confirmation of material and energy flows at larger scales, will be required in order to obtain valid data. Moreover, disaggregated background data for the relevant conversion and treatment processes for renewable resources are lacking in the existing LCA databases, as well as regional- and seasonal-related material flow analyses for organic residual materials in Germany. In general, consideration must be paid to the sometimes considerable uncertainty associated with the data on technical processes, on the provision of raw materials, and on the economic calculation variables.

To obtain statements on profitability, both in relation to existing utilisation concepts for biogenic raw materials and fossil-/mineral-based value chains, it will be necessary to define suitable reference systems and to procure the corresponding data, above all for material products and their future development up to 2020 and 2030 in order to estimate the extent to which biorefinery concepts can provide contributions to solutions for reducing greenhouse emissions and securing raw materials in the context of limited natural resource- and area potential and the resulting competition, the time-related variations of the characteristic data from reference systems (dynamics) as well as regional, national and international aspects must be taken into account.

Despite the complexity of the observable factors, there are methodological challenges in the analysis and assessment in keeping the to-be-compared systems simple enough to allow interpretations to be drawn. It is thus necessary to ensure that the conflicts of interests that can be expected in many cases (e.g. through the use of multicriteria assessment- and decision support processes) are taken into account, as the number of considered criteria, factors and concepts can become very large. Furthermore, the requirements of various stakeholders should be included in the assessments. Various methodological developments are also required with regard to the appraisal of environmental aspects, for example to take sufficient account of aspects of land use.
changes or the (regionalised) water requirements. In general, approaches are required for proper consideration of data uncertainties and bandwidths, in particular with respect to processes still in development.

One approach to solving the mentioned problems is an exemplary consideration of selected biorefinery concepts in further studies, using detailed standardised methods and basic data. This can provide a more comprehensive assessment of the advantages of the proposed concepts in comparison to fossil raw material-based value chains, but also in comparison to traditional uses of biomass. This would also contribute to the further development of material reference data. A complete assessment and analysis will be costly but indispensable; however, a two-stage procedure (1. hotspot analysis, 2. detailed assessment) could reduce these costs and make a contribution to solving the outlined problems. To these ends, aggregate indicators must be selected for the hot spot analysis that are suitable for the identification of economic key performance indicators and the ensuing environmental effects, such as carbon footprint, water footprint, and nitrogen footprint. After comparison with relevant reference systems, the focus and the course of action for a detailed assessment would be derived from this, taking into account the national sustainable development strategy. Appropriate case studies that take a more detailed look at the example concepts considered in this roadmap – in particular with regard to the key variables identified in the hotspot analyses, the issues of the importance and influence of various factors such as catalyst and enzyme use, water use or land use changes – could be given exemplary treatment, and solutions developed and discussed. This would also contribute to the harmonisation of the methodologies. The data collected in the context of such detailed studies could also serve as the basis for regional, national and international system studies; these would be used to estimate the potential economic and ecological contributions of biorefinery concepts and of other use concepts for biogenic raw materials. This could also build on the results from completed and ongoing research projects (e.g. BioCouple82, Bioraffinerie202128,77) and the ongoing analyses for EU projects86 (e.g. StarColibri27, KACELLE83). However, a valid foundation for the temporal development of fossil and mineral reference systems is yet to be developed.

Furthermore, in the development and implementation of the various biorefinery concepts, an early-stage monitoring of environmental and socio-economic effects that also takes into account all stages of development must be incorporated in order to make undesirable developments visible and correctable as soon as possible.

The informational value of the assessment depends on the extent to which the described aspects are taken into account, and to which solutions are developed. In general, however, the uncertainties associated with the assessment will only permit estimates of a certain bandwidth.

Likewise, the current state and possible development directions of the various funding instruments for the material utilisation of biomass – in comparison with and in the context of the funding of energetic use concepts – should also be subject to discussion.
6 Challenges in the establishment of biorefineries – SWOT analysis

In the two previous sections (Sections 4 and 5), the biorefineries underwent technological, economic and ecological contextualisation. On this basis, this chapter will undertake a strengths, weaknesses, opportunities and threats analysis (SWOT analysis) for the individual biorefineries, as well as an assessment of the opportunities and risks, and an addressing of future challenges and problems. In the next chapter (Section 7), this will serve as the basis for the derivation of the actions required for the development and establishment of biorefineries.

The degree of maturity of the biorefinery concepts, both between themselves and with respect to the different sub-concepts, is very heterogeneous. The development statuses for the different biorefinery concepts are shown relative to each other in Figure 32, based on the TRL concept.

Thereby, it should be ensured that all biorefinery concepts can be implemented in a variety of process- and technology concepts, so that the development status for the resulting variations can deviate from the general development status presented here. Moreover, sub-components can already be in a further state of development, or be more technologically mature as a single process outside of biorefinery concepts.

Furthermore, the technological maturity of the various elements of the biorefinery (including their integration) should be regarded on a similarly differentiated basis. Extensive questions remain with regard to product development, especially in the refining of chemicals, pharmaceuticals, polymers and functional materials. Biorefineries will enable not only the substitution of fossil carbon sources in the production of a range of common chemicals and energy carriers, but will also result in new products as part of new value creation chains. A selection of possible products from biorefineries is illustrated in Figure 33.

A detailed analysis of the various biorefinery concepts with regard to the current state of development and
6.1 Sugar and starch biorefinery

The processing of sugar and starch crops and the production of sugar- and starch-based products has a long tradition, utilises mature technologies, and has been established in Germany for decades. On the other side, technologies for the chemical-technical or biotechnological conversion of carbohydrates (for instance glucose, sucrose and starch) are to some extent present in the chemical industry. The sugar and starch industry also already produces derivatives in existing sugar and starch factories on the basis of the platforms sucrose and starch. Further recovery areas could be opened up by research activities (e.g. in biotechnological conversion). The first biorefinery concepts – in simple form, with a relatively small range of products, and often implemented with minimal degree of refinement – have been realised or are underway (e.g. in Lestrem in France). The current development status of the sugar and starch biorefinery is illustrated in Figure 34.

**Strengths:**
- can build on already existing structures in the sugar and starch industry
- the German sugar and starch industry is already established in Europe
- strong, already globally oriented German machinery- and systems engineering in the relevant areas
- strong research and development in Germany in the biotechnological conversion of carbohydrates
raw materials are available in Germany, Europe and globally
→ generation of surpluses in Germany is possible for the raw materials sugar beet and wheat
→ technologically well advanced primary refining for the platforms sucrose and starch
→ experiences are available in the chemical and biotechnological conversion of carbohydrates, whereby the range of intermediates from secondary refining must be expanded

Weaknesses:
→ product diversification not yet sufficient; refinement of intermediate products into new products requires improvement
→ integrated production of bio-based products and bioenergy is capable of expansion
→ connections between sugar/starch industry and chemical industry are underdeveloped

Opportunities:
→ further development at existing sites in the sugar/starch industry into integrated biorefinery sites via a bottom-up development scenario
→ additional value creation through the integration of other chemical and biotechnological processes and products

realisation of synergy effects through coupled processes
→ export opportunities for German sugar- and starch-based technologies and systems in the establishment abroad of sugar and starch biorefineries

Risks:
→ German sugar and starch industry poorly positioned globally in relevant locations (Brazil, US, Southeast Asia)
→ Competition from globally active, forwards-integrated agro-industrial companies, or from backwards-integrated chemicals companies
→ shortage of raw materials due to increased demand for sugar and starch from the food industry

In the future, it will be important to expand integrated approaches where various sugar/starch processing- and refining processes are combined into one complex system, and to operate these as integrated biorefineries. Playing a key role here are the combination of primary and secondary refining and the development of new, high-value products. In the future, this path of diversification and of higher or additional value will have to be consistently pursued. This will improve the economic efficiency (e.g.

Figure 34: Technology readiness level (TRL) of the sugar and starch biorefinery
as a consequence of cost reductions through process integration and revenues from various products). The most important objective is to guarantee high creation of value under European framework conditions.

As a result, most of the sites in the sugar and starch industry will be converted into sugar and starch biorefineries by 2030. This development has already begun – also in Germany; examples of this are the integrated sites in Zeitz (sugar biorefinery) and Krefeld (starch biorefinery).

### 6.2 Vegetable oil- and algal lipid biorefinery

**Vegetable oil biorefinery**

The processing of oil crops and the manufacturing of vegetable oil-based products for material or energetic utilisation are long established in industry in Germany, which can fall back on mature technologies. On the other hand, alongside the use of technical oils in the oleochemical industry, there has been large-scale production of rapeseed oil methyl ester (biodiesel) in recent years in the chemical and technical conversion of vegetable oils (e.g. in fatty alcohol production). Thereby, primary refining was for the most part separated from secondary refining. However, a trend towards integrated systems can be observed in recent years, which connects vegetable oil extraction with the manufacturing of a product (e.g. biodiesel or fatty acids). These integrated systems are currently the standard for new installations.

With respect to domestic raw materials (rapeseed, sunflower seeds, and where applicable other oilseeds such as camelina seeds), primary refining provides exclusively long-chain fatty acids.41 Because they contain short-chain fatty acids, palm kernel oil and coconut oil are also important raw materials for the oleochemistry area. These raw materials must be imported from tropical countries (e.g. Malaysia, Indonesia). In such cases, the primary refining is carried out in the countries of origin. The current development status of the vegetable oil biorefinery is illustrated in Figure 35.

**Strengths:**

- Can build on already existing structures for vegetable oil production and -processing
- already globally established German vegetable oil industry, as well as globally active companies working in Germany
- strong, already globally well positioned German machinery- and systems engineering in the relevant areas
- research-intensive SMEs available for material conditioning of vegetable oils
- strong research and development well established in Germany for the conversion of vegetable oils
- raw materials for long-chain fatty acids available in Germany, Europe and globally
- technologically well-developed primary refining for the vegetable oil platform
- experiences available on the chemical and biotechnological conversion of vegetable oils

**Weaknesses:**

- raw materials for short-chain fatty acids are not available in Germany and Europe; only in tropical and subtropical countries
- commercial production of secondary products from glycerol rather underdeveloped in comparison with production of fatty acids
- primary refining and secondary refining frequently not yet integrated in one site86
- integrated production of bio-based products in addition to bioenergy is still underdeveloped

**Opportunities:**

- Further development into integrated biorefinery sites via a bottom-up development scenario at existing sites in the vegetable oil processing industry (e.g. oil mills)
- Additional value creation on the basis of glycerol and fatty acids through the integration of chemical and biotechnological processes and products
- Export opportunities for German technologies and systems, and for process chemicals for the treatment of vegetable oils

**Risks:**

- Globally active agro-industrial companies, covering the entire process chain from raw material to product
- Relocation of production of oleochemical intermediates to non-European countries close to resources; biorefineries with short-chain fatty acids as platform can develop in raw material-originating countries
- Shortage of raw materials due to increasing demand for vegetable oils from the food industry and for the provision of bioenergy: alternative sources of raw materials (e.g. algal lipids, microbial lipids) are not yet market-ready

Against the backdrop of existing structures in Germany, there will be a focus in the future on the...
Technology readiness level (TRL)

- **Technology readiness level (TRL):**
  - TRL 1
  - TRL 2
  - TRL 3
  - TRL 4
  - TRL 5
  - TRL 6
  - TRL 7
  - TRL 8
  - TRL 9

**Vegetable oil biorefinery (left) and algal lipid biorefinery (right)**

**Raw material, supply**

**Primary refining, decomposition**

**Primary refining, purification**

**Secondary refining, intermediates**

**Secondary refining, refining**

**Integration**

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**Figure 35:** Technology readiness level (TRL)\(^{44,45}\) of vegetable oil- and algal lipid biorefinery

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development of integrated biorefinery concepts with vegetable oils of predominantly long-chain fatty acids. Here, new oleochemicals must be developed through the refining of intermediates.

Oleochemical plants for the refining of vegetable oils are for the most part integrated into the network of chemical industry and are generally sited in locations that also pursue fossil raw material-based production. Here, oleochemical precursors are often ordered from external suppliers, and this is expected to continue. For this reason, biomass utilisation pathways with separate primary and secondary refining will remain in the oleochemical industry. Where sensible, however, integrated primary and secondary refining can take place in a biorefinery concept (such as already in place in Düsseldorf).

For vegetable oils with short chain fatty acids, the more appropriate option is a decoupled production using biomass components in different locations (e.g. Germany: palm kernel oil; land of origin: palm flesh, residual materials from palm kernels) or the establishment of vegetable oil biorefineries in the raw material-producing countries. The first approaches for commercial vegetable oil biorefineries of the latter kind exist in South East Asia, for example.

As a result, a differentiated development will take place up to 2030, which will encompass both integrated paths (and thus biorefinery concepts) and also geographically separate biomass utilisation paths.

**Algal lipid biorefinery**

For the case of the algal lipid biorefinery, it is currently evident that the potential of this algae-based concept is not (yet) commercially viable. Indeed, there are major challenges in both primary and secondary refining. The use of components from algal biomass is commercially successful in only exceptional cases where the product can be marketed with high value added and relatively low tonnage. The current development status of the vegetable oil biorefinery is illustrated in Figure 35.

**Strengths:**

- strong research and development in Germany in the area of microalgae
- Research-intensive SMEs in the area of cultivation and utilisation of microalgae, including technology development (e.g. photobioreactors, processing technologies)
- strong German systems engineering in the relevant areas
Weaknesses:
- the climatic conditions for the cultivation of microalgae in Germany are not optimal
- Only closed photobioreactors are applicable in Germany; biomass production and processing currently highly complex and cost-intensive
- Circulation and recirculation of nutrients is not yet resolved
- Inadequate strategies for the problem of high microalgae productivity being associated with low concentrations
- Product development and refinement is underdeveloped, especially for products aimed at high added value

Opportunities:
- Development of a new biomass resource that can be produced independently of arable land
- In comparison to land plants, high photosynthetic efficiency in microalgae enables relatively high biomass production
- Creation of value through new products with new functionalities and utilisation options
- Commercialisation of products with high added value
- Export opportunities for German technologies and systems for the cultivation and (further-) processing of microalgal biomass

Risks:
- In comparison to other global locations, Germany is geographically disadvantaged in the cultivation of microalgae
- Strong, competitive research and development outside of Germany
- Easier access to R&D funding and venture capital in North America and Asia in the pre-competition phase

The future challenges evidently lie in the basic- and applied research and development, and in a more long-term time horizon. Major gaps to be closed remain in both microbiology and molecular biology, and in cultivation and bioprocess engineering in general. The most important objectives are on the one hand to increase the productivity of algae and on the other to significantly increase processing efficiency with the aim of improving economic efficiency. Only when these challenges have been fundamentally solved can the development take place of integrated concepts for coupled material- and energetic production of materials and energy on the basis of algae.

As a result, improvements to the technology maturity will be made up to 2030, also encompassing technical validation and demonstration. A complete assessment of algal lipid biorefinery concepts will be possible on the basis of the subsequent findings. In addition, extensive experience will be available from established materials-driven algal lipid biorefineries.

6.3 Lignocellulosic biorefinery and green biorefinery

Lignocellulosic Biorefinery

In the case of the lignocellulosic biorefinery, a differentiation must be made in the assessment of the development status for the components cellulose/ hemicellulose between the objective of pulp production and the objective of production of fermentable carbohydrates.

The best demonstrated available technology is pulp production, which can fall back on mature technologies. The lignocellulosic biorefinery concept is already implemented for sulphite process-based pulp production, (e.g. in Sarpsborg in Norway and in Lenzing in Austria). For pulp production using the Kraft process, which in 2010 accounted for over 90% of pulp production worldwide and around 40% in Germany, the development status is considerably lower with regard to the biorefinery concepts, despite the high potential.

The concept of the production of fermentable carbohydrates on the basis of cellulose and/or hemicellulose was already realised in the middle of the 20th Century, but was not technologically and economically mature enough to compete against emerging petrochemical competitors. The lignocellulosic decomposition was for the most part optimised for pulp production, but not for the subsequent hydrolysis to fermentable carbohydrates. However, this is not completely new ground, and there are previous experiences to draw upon. Indeed, the biotechnology industry has made tremendous progress in recent years. The current development status of the lignocellulosic biorefinery is illustrated in Figure 36.

Strengths:
- Innovative chemical and biotechnology companies are established; it will be possible to build on existing structures in the fermentation industry
- Well-developed German pulp industry
- Strong, already globally well positioned German machinery- and systems engineering in the relevant areas
- Strong research and development in place in Germany in the area of chemical and biotech-
Biorefineries Roadmap

Biological conversion of carbohydrates and their further refinement

- Lignocellulosic raw materials in principle available in Germany, Europe and globally; unused potential of lignocellulosic residues from agriculture and forestry are present
- No direct resource competition for food and feedstuff production in the utilisation of lignocellulosic raw materials from agricultural residues and forest wood
- Experiences available for decomposition processes for lignocellulose, and for chemical and biotechnological conversion of carbohydrates
- First pilot- and demonstration plants for lignocellulosic biorefineries are in operation or under construction in Germany

Weaknesses:
- Competition situation in the utilisation of native forest timber, taking into account the multifunctional demands on the forest, can restrict the availability of raw materials
- Synthesis gas- and lignocellulosic biorefineries require access to the same raw material base
- Lignin utilisation is underdeveloped with respect to products with high value creation
- The exclusive utilisation of pentoses from the hemicelluloses is at the very earliest stages of development
- Activities towards biorefinery concepts for the German pulp industry are generally underdeveloped
- Integration of the individual elements of the lignocellulosic biorefinery and their validation in conjunction not yet mature
- Demonstration is pending of the technologies in application on an industrial scale
- Connection of the value chain with the chemical industry is underdeveloped

Opportunities:
- Development of new growth markets through a top-down development scenario (concept for fermentable carbohydrates)
- Improvement of the competitiveness and further development of existing sites of the pulp industry through diversification and new products via a bottom-up development scenario (concept for pulp)
- Export opportunities for German lignocellulose-based technologies and systems in the establishment of lignocellulosic biorefineries in other countries
- Development of a new source of fermentable carbohydrates

Risks:
- Competing utilisation options for lignocellulosic biomasses
- Strong, competitive research and development outside of Germany (US, Scandinavia, among others)
- Easier access to R&D funding and venture capital in North America and Asia in the pre-competition phase
- Massive promotion of technologies for energy-driven lignocellulosic biorefineries for bioethanol production in North America up to production scale; thus a possible loss of European technology lead

Also in the assessment of future development, a differentiation must be made between the lignocellulosic biorefinery concept for pulp on the one hand and fermentable carbohydrates on the other.

The two main aims in the lignocellulosic biorefinery for pulp are higher value-creation from black liquor (for example lignin-based materials, black liquor gasification) and the utilisation of by-products. The latter can be achieved by upstream (e.g. pre-extraction, prehydrolysis) or downstream (e.g. extraction of the waste streams) processes. Here, the future challenge lies in the generation of additional value from to-date unexploited components, or components that have only been used to generate electricity and heat.

The lignocellulosic biorefinery for fermentable carbohydrates has already been extensively studied for various types and products, also as a result of their potential use as lignocellulosic residues. However, there are high R&D requirements for many variants in both primary and secondary refining. Cost-effective lignocellulose decomposition is an important goal in this context. Furthermore, the value-added utilisation of all components must be ensured, whereby particular attention must be paid to higher value creation for lignin and hemicellulose in secondary refining.

As a result, by 2030 many sites in the pulp industry in Europe will be converted to sites with a diversified product range. This development has already begun in Scandinavia. Lignocellulosic biorefinery concepts with a focus on fermentable carbohydrates will demonstrate improved technology maturity by 2030. A technical validation and demonstration will take place, and the first reference plants have been built. This will result in a medium- to long-term investment need for the construction and operation of industrial reference
plants. An in-depth assessment will be possible on the basis of the subsequent findings. In Germany, this will apply in particular to lignocellulosic biorefinery concepts with an emphasis on fermentable carbohydrates. This is already visible in Germany with the pilot (Leuna) and demonstration projects (Straubing) that are currently under construction.

**Green biorefinery**

To date, all variants have only been studied in sub-components and not implemented as integrated concepts. Furthermore, past developments show that these sub-components have always been designed together with a biogas plant. Outside the laboratory, validation has taken place for the most part as an ancillary facility operated on a significantly smaller scale. An exception here is the implementation of the green biorefinery in Brensbach in Hessen; a demonstration in application on an almost industrial scale is underway – a world first. For the commercial operation of a green biorefinery, a biogas plant is a necessary precondition in the vast number of concepts – but is not sufficient on its own. The current state of development of the green biorefinery is illustrated in Figure 36.

**Strengths:**
- Globally leading research in the area of biogas production
- Strong, already globally well positioned German machinery- and systems engineering in the relevant areas
- Preservation of cultural landscape and of ecologically valuable areas

**Weaknesses:**
- Only feasible in locations and regions with unused grassland
- As a concept, only commercially realisable with a biogas plant
- Cost of downstream processing remains too high
- Quality level of the products often not sufficient or only difficult to attain; value creation of the products is not sufficient to date
- Fresh green biomass-based concepts can be operated only seasonally

**Opportunities:**
- Further development through diversification of current biogas plant sites, via a bottom-up development scenario
- Opportunities for technology exports
Risks:
→ Alternative means of access exist for bio-products (e.g. fibres, lactic acid, proteins)
→ Export opportunities to countries with pasture surplus are limited

The future development of green biorefineries is difficult to predict because they can be implemented in very different ways. There are thus greatly differing challenges to solve for both primary and secondary refining, giving a highly differentiated overall picture of challenges. Decisive here is the utilisation path of the fibre fraction of the presscake; this can either be predominantly material or chemical-technical. A common challenge is how to address the commercial implementation of the green biorefinery. The use of partial streams or residual materials in a biogas plant poses no technical hurdles, although in some cases R&D would be advisable for technological optimisations or for improvement of economic feasibility.

In 2030, extensive experiences from the implementation of the green biorefinery in Brensbach as well as knowledge from other locations (e.g. Utzenaich in Austria and Selbelang in Germany) will be available for an assessment of the viability of the green biorefinery.

6.4 Synthesis gas biorefinery

The synthesis gas refineries are currently not present on the market on a commercial scale. To date, efforts have focused on the conversion of synthesis gas into a main product (e.g. electricity, heat or biofuels). The technical implementation of the provision of electricity and heat via biomass gasification has been carried out at reference system scale (e.g. in Guessing in Austria87). Furthermore, the production of biomass-to-liquid (BtL) fuels and chemicals on the basis of the syngas platform also carries great potential for development. The development is driven above all by the objective of substitution of petrochemical fuels with biofuels. The synthesis gas biorefinery is thus an energy-driven biorefinery concept. The current development status of the synthesis gas biorefinery is illustrated in Figure 37.

Strengths:
→ Strong research and development of biomass gasification in Germany
→ Experience with coal gasification and its scale-up are available and can be incorporated
→ Strong, already globally well positioned German machinery- and systems engineering in the relevant areas

Weaknesses:
→ Raw materials for gasification are in principle available in Germany, Europe and globally
→ Lignocellulosic raw materials in principle available in Germany, Europe and globally; unused potential lignocellulosic residues from agriculture and forestry are present
→ No direct resource competition for food and feedstuff production in the utilisation of lignocellulosic raw materials from agricultural residues and forest wood
→ Experiences available in the chemical conversion of synthesis gas

Opportunities:
→ The concept inherently allows the almost complete utilisation of the biomasses
→ High possible range of synthesis gas-based products
→ Development of new industries via a top-down development scenario
→ Export opportunities for German technologies and systems in the construction of synthesis gas biorefineries abroad
→ Simpler and global access to value creation chain of chemicals industry
→ Synthesis gas as an alternative source of carbon for fermentations

Risks:
→ Competing utilisation options for lignocellulosic biomass
→ Strong, competitive research and development outside of Germany (US, Austria, among others)
→ Easier access to R&D funding and venture capital in North America and Asia in the pre-competition phase
The future implementation of synthesis gas refineries is closely associated with the applied gasification technology, meaning that primary refining represents a principle challenge. The technical challenges in the individual process steps and their interaction, including biomass gasification and conditioning for gas cleaning, have not been resolved. The most important objective is to further improve the efficiency of production of synthesis gas to the requisite quality, and to improve its economic feasibility. There are also challenges in the integration with subsequent secondary refining steps. The conversion of synthesis gas to a main product will be further pursued. The provision of electricity and heat will be joined by the production of individual products (e.g., biofuels). Thus, in a first step, integration into existing value chains will take place (e.g., black liquor gasification in the pulp industry). Moreover, for fuel-driven approaches, an important driver is the possibility of the manipulation of fuel characteristics (gasoline, diesel, jet fuel) through process control, whereby the prospect of production of jet fuel is particularly attractive.

Integrative concepts for the production of chemicals and energy will use an intermediate product (e.g., methanol) as the basis for the creation of a chemical product tree. Since the production of fuels and chemicals requires complex and expensive technologies, production will take place in large plants (orders of magnitude 500,000 to 2,000,000 tonnes of biomass input per year), in order to take advantage of economies of scale.

In the time horizon up to 2030, firstly systems for biomass gasification and synthesis gas production will be established; these will initially focus on either the generation of electricity and heat or the production of BtL fuels and chemicals. These concepts do not initially count as biorefineries. The development of integrated concepts for combined material and energetic production of materials and energy on the basis of synthesis gas can only be addressed when the basic challenges are resolved and the gasification technology on the basis of biomass is well established. However, only a few synthesis gas biorefineries featuring a broad range of materials and energetic products can be expected by 2030.

### 6.5 Biogas biorefinery

For the area of the biogas biorefinery, it is currently evident that the potential of this platform is not (yet) commercially viable. For biogas, the focus at this time is not on the biogas biorefinery but on the conventional generation of electricity and heat, as well as the
feed-in or use of biomethane fuel following biogas treatment. Germany is world-leading here, and is traditionally well established.

The subsystem biogas production (either for the production of electricity and heat or for the production of biomethane for feed-in to the gas network) is in itself – regardless of the suitability of biogas as a platform for integrated material and energetic utilisation – an independent and promising biomass utilisation path. This also applies to the production of biogas as biorefinery components for the utilisation of biorefinery residual materials. For the biogas biorefinery concepts, the biogas production, and with this the primary refining, essentially correspond to the state of the technology. The realisation of secondary refining is limited to energetic utilisation – either the use of biogas for the provision of electricity and heat, or of biomethane for fuel. The material utilisation of biogas at the site of the biogas plant is not currently underway. At this time, only the feed-in of biomethane into the natural gas grid is in progress for these purposes. This allows further processing at all locations with a pipeline connection, and avoids potential bottlenecks as a result of limited, location-related biogas production capacity. With the energetic utilisation (electricity, heat, fuel) of biogas, the best demonstrated available technology is already well advanced, so that improvements and developments stand in the focus; these can also be considered independently from a biorefinery concept. The current development status of the biogas biorefinery is illustrated in Figure 37.

The future development towards a biogas biorefinery requires first of all the solving of fundamental- and applied research questions with regard to material utilisation of biomethane in secondary refining. Experiences from natural gas processing can be of assistance here. A major obstacle in connecting biogas production and secondary refining lies in the reconciliation of plant capacities. The most important goal here is to develop material applications that are adapted to the local biogas production capacities, and which are economically feasible. To this extent, the matter of whether it might be a better option to have a complete utilisation of the biomass via the platform biogas across different various sites for chemicals/materials on the one hand, and for bioenergy on the other, remains an open question. For this reason, there is little research and development to date on coupled energetic and material utilisation of biogas. A detailed SWOT analysis will not be carried out due to the low technological maturity.

From today’s perspective, a biogas biorefinery is possible only under very limited framework conditions. Such a case would be the integration of a conventional biogas plant in a chemical park (e.g. for the exploitation of biogenic residues and waste materials) with the option of integration into the local value chain (e.g. fermentation with biomethane as a carbon source into an intermediate required on site). The integration of a material utilisation of biogas/biomethane into an existing biogas plant at a stand-alone location does not appear to make sense economically nor technologically, considering the state of the art.

An updated assessment and SWOT analysis for the biogas biorefinery is scheduled for 2030 based on the by-then attained technological maturity.
7 Need for action

The development, establishment and market penetration of biorefineries requires extensive research, development and innovation, as well as accompanying measures. The solving of correlated challenges will require longer time frames, and can only be achieved through the joint efforts of all stakeholders. To achieve this, competencies in science and business will be bundled, and will be geared towards common strategic objectives. Conversely, it is the responsibility of business to drive forward its own research and development work, and to lead innovative process techniques and products to the marketplace. Government intervention can only be effective in a supporting sense.

With regard to the general material and energetic use of biomass, the German federal government has already described and set forth guidelines for funding and support via the relevant action plans and the National Research Strategy BioEconomy 2030. Here, biorefinery concepts are highlighted as potentially interesting biomass utilisation paths, with which – where possible and appropriate – biomass efficiencies could be realised through the use of integrated coupling. The technological, economic and environmental analyses, as well as estimates and explanations in the previous chapters, illustrate the potential of biorefineries. To exploit this potential there is both a higher-level need for action for biorefineries as a whole, as well as a need for action for individual elements of the biorefinery. Included therein is the identification and prioritisation of important and necessary research areas and fields of action, as well as other activities and measures. The time frame is determined by the maturity of the biorefinery concepts (see Section 4.6 and Figure 32).

Naturally, the need for action for biorefineries also encompasses requirements and measures relevant for various other biomass utilisation paths, and thus affects not only biorefineries. Furthermore, aspects of basic research (e.g. plant breeding or sustainable agricultural production) are important for both the food and non-food sector.

The need for action described in the following is aimed at decision makers in universities and other non-academic research institutions, companies, research funding organisations, associations, and in public administration.

7.1 Need for action for research, development and implementation

The overarching need for action for biorefinery concepts in general and for individual biorefinery elements, including accompanying measures, can be summarised as follows:

**Biorefineries generally:**
Biorefineries represent a promising approach for an efficient utilisation of renewable resources. Here, strengthened application-oriented basic research towards the development of appropriate biorefinery concepts and their rapid conversion into commercial systems is of major importance, also in order to successfully take continued advantage of Germany’s internationally strong starting position in this area. There is a need for investment in the construction and operation of industrial reference plants in Germany in cases of high technological maturity of biorefinery concepts. The ‘Biorefineries Roadmap’ developed in conjunction with representatives from government, academia and business, identifies promising development paths for biorefineries. The priority fields of action are:
The intensification of research, development and innovation along the entire biorefinery value chain, from raw materials to the procedures and processes of primary and secondary refining, up to finished product.

The conversion and refitting of existing, suitable biomass conversion plants into biorefineries with integrated material and energetic utilisation of renewable resources.

The consolidation of biorefinery development lines with the objective of developing technically available, sustainable integrated concepts that take changing framework conditions into account.

The transferring of sustainable biorefinery concepts from the research stages to technical-, pilot-, demonstration- and production scale, with the objective of ‘series production’ in commercial facilities.

A strengthening of research collaborations towards the development of biorefineries at a European and international level.

Support in the creation of uniform standards and a consistent data basis for environmental life cycle analyses for biorefineries.

The development and implementation of appropriate communication strategies to safeguard the social acceptance of biorefineries.

**Biorefinery – raw materials:**
The sustainable increase of yields is of high importance in order to safeguard the resource base. All responsible and appropriate approaches towards the reduction of use- and land competition should be pursued. Particularly eligible are integrated approaches that intelligently combine material and energetic utilisation in terms of the optimum sustainable use of raw materials, such as utilisation cascades in biorefineries. The application of utilisation cascades should be supported by the research, development and testing of regulatory measures. The priority fields of action are:

- The safeguarding and expansion of the raw material base in Germany, as well as sustainable total yield optimisation on available space.
- The quantification of regional and seasonal availability of biomass, above all organic residual materials in Germany, in terms of sustainability, conflicting aims between material and energetic use, and of the primacy of food security.
- The development and improvement of industrial processes for the provision of high quality and cost-effective biomass for biorefineries.
- The development and high-quality utilisation of new or alternative sustainable sources of raw material sources, including the utilisation of biogenic residues and waste materials in a biorefinery.
- The creation of new biorefinery systems based on new or alternative sources of raw materials.

**Biorefinery – processes and products for primary and secondary refining:**

- Improvement of component separation and of the decomposition of biomass in biorefineries, as well as the optimisation of the required chemical, biotechnological, thermal and mechanical processes, including combinations thereof.
- The development of new and optimised thermo-chemical, chemocatalytic and biotechnological conversion processes (including combinations thereof) of agricultural, forestry and marine raw materials, as well as biogenic residues and waste materials for biorefineries.
- The adaptation and optimisation of downstream processing and recycling processes for products (e.g. for biopolymers).

**Biorefinery – sustainability:**
Ensuring the sustainability of material uses requires efforts towards the setting of norms and standards at a European level and the creation international sustainability standards. This also includes standards for life cycle analyses on the climate- and environmental effects. Medium- and long-term instruments must be developed in order to strengthen the positive protective effects of microeconomic incentives. The priority fields of action are:

- The development of methods for the sustainability assessment of biorefineries, above all with respect to the sustainable provision and conversion of biomass, but also the identification and quantification of conflicting aims such as land use change, resource competition, price pressure on foodstuffs, water scarcity etc., and subsequent issues.
- The quantification of stored carbon in bio-based products and of energy savings through their use, as well as the contributions of bio-based products to the objectives of the German federal government’s sustainability strategy.
- Identification and quantification of conflicting aims and subsequent issues:
  - Price pressure on foodstuffs
  - Water scarcity
  - Land use changes
  - Resource protection
  - Nature/biodiversity protection
  - Social compatibility.
7.2 Research policy needs for action, improvement of framework conditions

With the ‘High-Tech Strategy 2020’, the ‘National Research Strategy BioEconomy 2030’ and the renewable resources funding program, the German federal government has created a suitable framework for research, development and innovation in Germany, describing in detail current and also future biomass- and biorefinery-oriented announcements and calls for proposals from the individual government departments. A modern biorefinery research centre will be erected at the chemical park Leuna (Saxony-Anhalt) in Germany’s traditional chemical triangle of Halle-Bitterfeld-Leipzig, and demonstration plants will be constructed in Straubing and Karlsruhe, jointly funded by federal and state governments. Procedures for the utilisation of biomass for the integrated production of chemicals, fuels, electricity and heat will be developed in the framework of the projects. This will include cooperation partners from business and academia in the immediate vicinity, as well as from other parts of Germany and abroad.

To drive biorefinery technologies forward towards practical implementation, it will be essential for the federal government to continue to support basic- and application-oriented research and development into the material and energetic utilisation of biomass. For the purposes of clarity in the funding environment, the federal government departments should continue to closely calibrate their respective funding activities and priority areas.

Biorefineries that can produce multiple products from various raw materials are still in their infancy in terms of development. The further development of concepts will require research promotion. Thereby, the entire development chain from basic research up to process-, technology- and product development in biorefineries, must be given support. To demonstrate the first use of new technologies that have already been successfully tested on a smaller scale, the promotion of demonstration- and pilot projects for the development of production technologies is necessary in the context of collaborative research or innovation alliances between industry and science. Moreover, research promotion in agriculture and forestry is required in order to strengthen the necessary integration between biomass producers and customers.

Alongside process- and technology development, biorefineries also need good framework conditions to be successful on the market in Germany and internationally. Above all, these must be well integrated into the value chain: This relates to the provision of biomass and the downstream value added, i.e. the processing of biorefinery products in the chemical and other industries, as well as plant construction. Ideally, the biorefinery products should be integrated into existing and proven process chains in industry. In addition, there are opportunities for the development of new product lines.

Biorefineries can process a variety of raw materials (e.g. wood, straw, green material, fats, organic wastes), whereby a prerequisite for commercial production is the technical feasibility of the treatment and refining. Furthermore, the availability must be ensured of sustainably produced renewable raw materials in sufficient quantity and quality, and at competitive prices. Here, competing uses (e.g. nutrition, feedstuff, material and energetic utilisation, nature conservation and ecosystem services) as well as framework conditions for biomass use (such as the action plans for material and energetic utilisation of biomass) must be given due consideration. This must be consistent with the priority provision of adequate healthy and safe foodstuffs.

The German federal government’s ‘National Research Strategy BioEconomy 2030’ and the ‘National action plan for substance recovery from renewable raw materials’ is intended, among other things, to provide support for research and development in plant breeding, with the ultimate aim of strengthening the use of biomass in Germany. The breeding of optimised raw material crops to increase biomass yield and for the optimisation of substances will require input from all the methods of modern plant breeding and crop production, including plant biotechnology. These offer, among other things, new opportunities for the provision of renewable raw materials and of biomass. Thereby, the attainable volume increase and the specific production of required raw materials with a predetermined composition both play a role. To these ends, a factual approach to the potential of green genetic engineering and a responsible use of genetically modified plants will be required.

An increase in agricultural production is necessary for the adequate supply of raw materials. This must be achieved using efficient and resource-friendly management, the handling of which must be in line with the challenges posed by climate change, envi-
Biorefinery products stand in competition with petroleum-based products with respect to quality, economic efficiency and product characteristics. Competitive products from biorefineries must be further processed and refined. The chemical industry and its customer industries will only be able to achieve this more substantial added value in Germany with the appropriate framework conditions. The safeguarding of reliable industrial policy framework conditions for a competitive Germany is expected on the part of the German federal government. Thereby, appropriate conditions for research, the training of qualified young talents, a competitive sustainable supply of energy and raw materials, the resource-efficient development of infrastructure, and the reduction of trade barriers at home and abroad are of central importance. It will be desirable to achieve a balance in the general situation with regard to the material and energetic utilisation of biomass.

The federal government is advised to review the regulatory requirements with regard to the removal of obstacles to innovation and of market entry barriers along value creation chains, with a continuous balancing of economic, social and environmental concerns.

As models and pioneers, the public order processing- and procurement bodies at the federal-, state- and local level can significantly contribute to an increase in the demand for bio-based products. The German federal government through the Federal Ministry of Economics and Technology is supporting the export potential of business for bio-based products and technologies, for example through the foreign market development program and the ‘Renewable Energy Export Initiative’. Furthermore, through the BMU, the federal government is supporting research activities in the area of the sustainability assessment of biorefineries. Here, the guiding principle is the federal government’s sustainability strategy and the management regulations contained therein.

Alongside the lacking competitiveness, a scarcity of information is a key barrier to market entry for bio-based products and technologies. For this reason, ongoing measures from the German federal government and business will be continued and strengthened. Via the Agency for Renewable Resources and other communication channels of the BMELV and BMBF, the German federal government provides numerous advisory and information services on renewable raw materials, bio-based products and technologies, as well as biorefineries, which – in cooperation with the private sector – should be continuously developed and circulated. The federal government should support the development of networks for information exchange and for the strengthening of technology transfer between industry and research.
8 Prospects

Against the background of increasing globalisation of industry and its services, and of the subsequent requirement for flexibility, it is essential that special consideration is paid to interdisciplinarity and high innovation in the area of research funding. This includes the material and energetic utilisation of biomasses, and also encompasses the implementation of biorefinery concepts. Only through the joint and focused efforts of all stakeholders can these ideas be translated into innovations and thus contribute to the strengthening of the business location Germany.

As a highly technology-oriented country, Germany is particularly dependent on innovation. In terms of new technologies and new products, the utilisation of renewable raw materials and biogenic residual and waste materials has a high potential for innovation. This is associated with high added value through the production, processing and utilisation of biomass. Furthermore, the sustainable use of renewable raw materials and biogenic residues and wastes makes important contributions to climate protection, to the security of raw material supplies, and to resource conservation in Germany. It also ultimately helps to avoid wastes, which are frequently expensive to dispose of.

Large areas of industry, accustomed for decades to processing fossil fuels, must unlock the benefits of renewable resources. Technologies for the application of biogenic residues and waste materials must be further developed as well as optimised. For new technologies, reference systems must be created to ensure successful launch. Conventional processing methods must be adapted and new ones developed – a worthwhile task given the environmental benefits, but also given the interesting markets for biomass-based products. From an innovation-political perspective, the concept of plants as a source of raw materials has been identified as one of the most important future fields. Today, German industry – above all the chemical industry – processes significant quantities of agricultural- and forestry raw materials. In addition, the wood processing industry is a significant branch of industry, and one that is aimed at high value creation from wood raw materials. At the present time, bioenergy is a mainstay among the renewable energies, and the material utilisation of renewable materials is an important aspect of sustainable raw materials supply. Both traditional utilisation, for example in timber construction or in the paper industry, as well as innovative new products can contribute to climate protection, conservation of fossil resources, ensuring the supply of raw materials, and to maintaining and increasing value added and employment. Renewable resources represent the only renewable carbon source, making it of great interest for the carbon-containing raw material-dependent chemicals industry.

The action plans ‘National Biomass Action Plan’ for the energetic utilisation of biomass and the “The federal government action plan for the use of renewable raw materials”, both adopted in 2009, provide important impetus to drive forward both the energetic and material use of biomass.1 The action plans form an integrated concept – for a significant and sustained increase of the biomass content in the industrial and energy sectors, as well as to improve the efficiency of biomass utilisation in raw materials provision in Germany in accordance with the objectives and requirements of sustainability. This should also protect and enhance Germany’s leading international role in the utilisation of renewable resources. As part of the German federal government action plans, the ‘Biorefineries Roadmap’ is a building block towards a bio-based economy, and thus constitutes a part of the ‘National Research Strategy BioEconomy 2030’.3

Research and development remain extremely important in the use of renewable raw materials. This will be continued at a high level along the entire value creation chain, whereby it is the role of the Biorefineries Roadmap to identify priority issues. Current gaps, especially with regard to knowledge-oriented basic research, must be closed.

For all discussions surrounding biorefineries, it must be clearly emphasised that the path towards realisation of industrial-scale biorefineries – above all for the top-down approach to plant design – remains a long one. The implementation of existing fundamental knowledge in a concept realised on a small scale, from pilot plant via large-scale production up to greater than 100,000-tonne scale, requires a long-term time frame. The roadmap shows that the time window from concept to implementation is greater than five to ten years.

Furthermore, it must be emphasised that biorefineries are just one variation of biomass conversion, and
that they complement and do not replace existing approaches. ‘Classical’ and other new innovative approaches for biomass conversion will continue to retain their significance. In the future, all biomass utilisation pathways will take parallel focus in research and development efforts. Their advantages and disadvantages will be evaluated, opportunities and risks analysed, and where it is meaningful, biorefineries or other biomass utilisation pathways will be implemented.

Thereby, sight should not be lost of the fact that even biomass is not available in unlimited quantities. Here, the different variants of biomass utilisation will stand in economic and ecological competition. The sustainable supply of raw materials remains a fundamental and increasingly important challenge. Thus the question of an exploitation of additional sources of biomass (among others SRC, landscaping timber, biomass from reclaimed land, imports) are equally as important as the question of an efficiency increase in the use of biomass (e.g. light construction, utilisation cascades according to the principle of material- before energetic application). Biorefineries offer interesting perspectives also with a view to the intensification of utilisation cascades.

The ‘Biorefineries Roadmap’ will lay the foundation for the development and implementation of biorefineries. Challenges, as well as priority fields of action and solution measures, will be extracted on the basis of a technological, economic and environmental analysis. The analysis has also shown that adjustments to current developments will be essential at regular intervals. The roadmap, which is based on the current – or currently foreseeable – framework conditions, serves as a guideline for decision makers in politics and industry, but also for industrial and public research. These conditions might change in the medium term, e.g. through changes to ‘fuel demand’ as a result of electric mobility, changes in the consumption- and eating habits of consumers, or alternative types of electricity production (Desertec). Consequently, the roadmap should be periodically evaluated and clarified/adapted according to the changed framework conditions and newly gained insights. Thus, a comprehensive review and adaptation of the roadmap will be required in the period from 2015 to 2020, whereby the current time frame of 2030 will also be re-examined. Due to the long-term nature of research, development and innovation for biorefineries, this ‘Biorefineries Roadmap’ represents the first step towards these goals.
Explanatory notes

1 'National Biomass Action Plan for Germany - Biomass and Sustainable Energy Supply', BMU, 2009,
http://www.erneuerbare-energien.de/inhalt/45556/4593/

2 Action plan of the German federal government on material usage of renewable resources, BMELV, 2009
http://www.bmelv.de/cln_182/SharedDocs/Standardartikel/Landwirtschaft/Bioenergie-NachwachseneRohstoffe/NachwachsendeRohstoffe/AktionsplanNaWaRo.html

3 'National Research Strategy BioEconomy 2030’ – Our route towards a bio-based economy, Federal Ministry
of Education and Research, 2010,

4 ‘Perspectives for Germany’,

5 This can be useful products or residual materials.

6 A main product is a substance that is the result of a production process that aims at the production of this
substance. A by-product is a substance that is the result of a production process that does not predominant-
ly aim at the production of this substance. Co-products or coupling products are two or more substances
that inevitably occur at the same time in the same production process.

7 VDI-Guideline 6310 ‘Quality Criteria for Biorefineries’ (working title), in preparation, draft planned for
2012,
http://www.vdi.de/44392.0.html

8 Position Paper ‘Use of renewable raw materials in the chemical industry’, DECHEMA, 2008,

9 Wuppertal Institute for Climate, Environment and Energy, Eco-Institute, Fraunhofer Institute for Envi-
ronmental, Safety and Energy Technology – Environmental, Safety project on behalf of the BMU ‘Coupling
material and energetic utilisation of biomass’: ‘Analysis and assessment of concepts and integration into
existing provision and utilisation scenarios’ (BioCouple),

10 IEA Bioenergy Task 42 ‘Biorefineries: Co-production of Fuels, Chemicals, Power and Materials from Biomass’,

11 F. Cherubini, G. Jungmeier, M. Wellisch, T. Willke, I.Skiadas, R. Van Ree, E. de Jong „Toward a common clas-
sification approach for biorefinery systems’, Biofpr 3 (2009) 534 - 546

12 Through the Agency of Renewable Resources (FNR), modified and updated elements from the schematic
for IEA Task 42 on the classification of biorefineries.

13 The case of biomass encompasses a recent time period of a few hundred years, and thus does not overlap
with the term fossil.

14 ‘Leitfaden Bioenergie’ (Bioenergy Guidelines), FNR, 2005,

15 Known as materials-driven biorefinery or energy-driven biorefinery.

16 The great majority of production of food or feedstuff does not concern biorefineries, but plants can be clas-
sified in the area of food and feedstuff although not belonging to the technical field.

17 German Chemical Industry Association e.V. (VCI), as of February 2010, percentage based on tons of raw
material.

18 Renewable resources in industry, FNR, 2008,
http://www.fnr-server.de/ftp/pdf/literatur/pdf_228-bro_nr_industrie_dt_15072010_02_klein.pdf,
(http://mediathek.fnr.de/broschuren/fremdsprachige-publikationen/english-books/renewable-resources-
in-industry.html) (as of July 2010).
19 In ATR (absolutely dry tonne), conversion factor $m^3/t = 0.5$


21 Due to the three involved platforms, the biorefinery type is actually described systematically as a cellulose/hemicellulose/lignin biorefinery, although the simplified term of lignocellulosic biorefinery has fallen into common use. Here, the term lignocellulosic is not referring explicitly to the raw material, but is synonymous as a collective term for the three separated components of cellulose, hemicellulose, and lignin.

22 This type of biorefinery is more specifically described as a plant fibre/press juice biorefinery after the involved platforms and crops, although it is commonly referred to as a green biorefinery.


25 SNG is a natural gas substitute produced on the basis of coal (SNG) or biomass (bio-SNG) via synthesis gas (SNG = Synthetic Natural Gas).

26 http://cordis.europa.eu/search/index.cfm

27 http://www.star-colibri.eu


31 http://www.biowert.de/


33 http://iwrwww1.fzk.de/bioliq/

34 This is true even though the term ‘biorefinery’ is used in a less specific sense internationally and is more broadly applied than in the characterisation and classification described in Section 3.1. The term biorefinery often refers to any processing plant for biomass that does not belong to the area of food/feedstuffs.

35 The term sugar is a synonym for sucrose in agriculture and industry. Sucrose is a disaccharide composed of glucose and fructose. Sugar plants are therefore plants that contain sucrose. In the industrial, chemotechnical sense, sugar secondary products refer to sucrose and its secondary products. Here, sugar does not refer to carbohydrates as is generally the case in the field of chemistry.

36 Some processes have been omitted from the schematic diagram for simplicity.

37 Starch is the most abundant storage carbohydrate in the plant world, and is a mixture of the polysaccharides amylose (10–30%) and amylopectin (70–90%).

38 The degree of hydrolysis in the starch is specified in dextrose equivalents (DE). Dextrose is an older name for glucose that is still used in the starch industry to refer specifically to glucose-rich syrups (> 80%).

39 DDGS = Dried Distillers Grains with Solubles (dry stillage). Dry stillage is produced through the evaporation, drying, and pelletisation of the protein-containing stillage.
The two starch fractions are grouped according to the size of the starch granules. Starch granules with a diameter of 25–50 µm are termed A-starch, those with 2–15 µm as B-starch; the latter also contains pentosans and hemicelluloses.

DDGS = Dried Distillers Grains with Solubles (Dry stillage); Dry stillage is produced through the evaporation, drying, and pelletisation of the protein-containing stillage.

Vegetable oils can be liquid or solid. Vegetable fat refers to vegetable oils that are solid at room temperature.

Short-chain fatty acids = fatty acids with length of 6–14 carbon atoms, long-chain fatty acids = fatty acids with chain length of 16–24 carbon atoms.

It cannot serve as platform for a biorefinery in Germany (see Section 3.1) if the extraction of vegetable oils, i.e. the primary refining, takes place abroad.

Lignocellulose comprises the three main components cellulose (30–60%), hemicelluloses (20–40%) and lignin (10–30%). While lignin is a phenolic polymer, the carbohydrates cellulose and hemicellulose are polysaccharides.

The hexoses are derived from cellulose and are monomeric carbohydrates with six carbon atoms; pentoses are derived from the hemicelluloses and are monomeric carbohydrates with five carbon atoms.

AFEX = Ammonia Fibre Explosion

Synthesis gas is a gas mixture with the main components carbon monoxide and hydrogen.

Here, the roadmap horizon takes the period up to 2030 as a manageable period of time.

Excepted here is the change of use of grassland, for example to cultivate perennial grasses.

'Statistisches Jahrbuch über Ernährung Landwirtschaft und Forsten' (Statistical Yearbook on Food, Agriculture and Forestry) BMELV, 2011

From a global perspective, the described potential should include only those areas that do not compete for food and feed production in the cultivation of renewable resources. Perennial crops can offer long-term rehabilitation for such frequently degraded areas, whereby the cost of cultivation of renewable resources on these areas is substantially higher than traditional agricultural areas.

Federal Statistical Office, GENESIS-Online Database, as of 12.01.2012


B. Osterburg, persönliche Mitteilung, vTI Braunschweig, 2011


Federal Statistical Office, series 17, series 1, as of 12.01.2012
Due to the high complexity of material utilisation, this would require adaptations to the existing certification systems.


The preferred location for the processing of the fruit pulp and of seeds from oil palm fruits is presently regions that dominate in the cultivation and harvesting of palm fruits, in particular Malaysia and Indonesia. In contrast to the pulp, the palm kernels are extremely hard and thus suited for storage, meaning oil extraction need not take place at the place of harvesting. Only the processing of imported palm oil and palm kernel oil takes place in Germany at present.

Dry matter

€ 680/t ethanol corresponds to about 54 €cents/litre of ethanol.

The stated straw prices are not be understood as estimates of the lower and upper limits, but to illustrate the influence of prices on outcomes.

Ethanol fuel grade T2 FOB Rotterdam (monthly average values), ‘Collection of statistical data on prices of renewable resources’ (FKZ 22,024,507) on behalf of the BMELV.


Reference system ‘Benzinbereitstellung und 100%-Nutzung in einem Mittelklasse-Pkw mit Ottomotor’ (cf. GEMIS Version 4.8, www.gemis.de)

The categories are chosen as examples to provide indications on significant environmental impacts (climate change, air pollution and resource consumption). The consideration of other categories would be desirable; in light of the available data, however, this is currently not possible (cf. further comments in Section 5)

Functional unit is MJ

The calculations are based on the course of action and impact models from the IPCC 2007, the UNECE (for acidification potential) and GEMIS Version 4.8 for non-renewable CEC

The data base for the preceding chains and the use of products is the Global Emission Model for Integrated Systems (GEMIS), Version 4.8 (see GEMIS 2012). The plant emissions were estimated in the context of this roadmap. The other significant assumptions are provided in the text.

Method of the Environment Institute (Centrum voor Milieukunde) at the University of Leiden


Provision of methanol at the ex works

Methanol from a synthesis gas biorefinery is regarded as biogenic, and CO₂-equivalents from the combustion reaction do not count as greenhouse gas emissions. The chemical reaction here is considered without accounting of further emissions, e.g. from the necessary electrical energy.

Other issues in the synthesis gas biorefinery arise through the provision of the catalysts, but are not taken into consideration in light of the available data.

‘BioCouple – Coupling of the material and energetic utilisation of biomass.’ Final report on the research project of the same name funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). FKZ 03 KB 006 A-C. Wuppertal Institut, Fraunhofer institute for environmental, safety and energy technology, Öko-Institut, Wuppertal, Oberhausen, Darmstadt, 2011

Kalundborg Cellulosic Ethanol Project (KACELLE), http://www.inbicon.com/Projects/KACELLE/Pages/KACELLE_Project.aspx
84 Technology Readiness Level (TRL) Classification based on ‘European Commission, High Level Expert Group (HLG) on Key Enabling Technologies (KET), Final Report, June 2011’, 

85 Development status of a fully integrated biorefinery concept, respective phase (component parts may have already developed further).

86 Plants for the production of biodiesel are either stand-alone or integrated in oil mills, but are not usually connected to additional secondary refining of material products. The processes for material and energetic use of vegetable oils have largely been developed in a decentralised manner, and do not represent the implementation of biorefinery concepts in a single location, taking the raw material as starting position.

87 A corresponding plant is in construction in Germany (HKW Senden demonstration project), 
http://www.swu.de/privatkunden/energie-wasser/waerme/waermegewinnung/holzgas-heizkraftwerk.html

88 ‘Förderprogramm Nachwachsende Rohstoffe’ (renewable resources funding program) BMELV, 2008, 
http://www.nachwachsenderohstoffe.de/fileadmin/fnr/pdf/Brosch_Foerderprogramm7_BMELV.pdf


90 Graphics modelled on ‘Research and Innovation in Germany’, diagram on page 14, BMBF, 2010, 
http://www.bmbf.de/pub/forschung_und_innovation_fuer_deutschland.pdf

91 Full provision through thermal utilisation of by-products

92 Assumption of Süd-Chemie AG
## Appendix

### Lignocellulosic biorefinery (Example 7)

#### Table 6: Capital-dependent costs for Example 7, the straw-based lignocellulosic biorefinery

<table>
<thead>
<tr>
<th></th>
<th>€</th>
<th>€/t product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>63,000,000</td>
<td>1.056</td>
</tr>
<tr>
<td>Planning</td>
<td>7,000,000</td>
<td>117</td>
</tr>
<tr>
<td><strong>Total investment</strong></td>
<td>70,000,000</td>
<td>1.173</td>
</tr>
<tr>
<td>Depreciation (20 years)</td>
<td>3,500,000</td>
<td>59</td>
</tr>
<tr>
<td>Imputed interest (8 %)</td>
<td>5,600,000</td>
<td>94</td>
</tr>
<tr>
<td><strong>Total capital-dependent costs</strong></td>
<td>9,100,000</td>
<td>153</td>
</tr>
</tbody>
</table>

#### Table 7: Consumption-dependent costs for Example 7, the straw-based lignocellulosic biorefinery

<table>
<thead>
<tr>
<th>Material and energy</th>
<th>Unit/a</th>
<th>€/unit</th>
<th>€/a</th>
<th>€/t product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>280,731 t/a</td>
<td>75</td>
<td>21,057,075</td>
<td>353</td>
</tr>
<tr>
<td>Auxiliary and operating materials</td>
<td>33,745 t/a</td>
<td>151</td>
<td>5,095,495</td>
<td>85</td>
</tr>
<tr>
<td>Water (cooling, ...)</td>
<td>376,400 m³/a</td>
<td>0.14 €/m³</td>
<td>52,696</td>
<td>1</td>
</tr>
<tr>
<td>Electrical energy</td>
<td>25,200 kWh/a</td>
<td>0 €/kWh</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wastewater</td>
<td>37,600 m³/a</td>
<td>2 €/m³</td>
<td>752,000</td>
<td>13</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>26,957,266</td>
<td>452</td>
</tr>
</tbody>
</table>

#### Table 8: Other costs for Example 7, the straw-based lignocellulosic biorefinery

<table>
<thead>
<tr>
<th>Factors</th>
<th>€/a</th>
<th>€/t product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel costs (4 shifts of 8 persons)</td>
<td>50,000 €/a per person</td>
<td>1,600,000</td>
</tr>
<tr>
<td>Maintenance and cleaning</td>
<td>2 % of the total investment/a</td>
<td>1,400,000</td>
</tr>
<tr>
<td>Administration</td>
<td>0.5 % of the total investment/a</td>
<td>350,000</td>
</tr>
<tr>
<td>Insurance</td>
<td>1 % of the total investment/a</td>
<td>700,000</td>
</tr>
<tr>
<td>Contingencies</td>
<td>0.75 % of the total investment/a</td>
<td>525,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4,435,000</td>
<td>74</td>
</tr>
</tbody>
</table>
**Synthesis gas biorefinery (Example 10)**

### Table 9: Capital-dependent costs for Example 10, the wood-based synthesis gas biorefinery

<table>
<thead>
<tr>
<th></th>
<th>€</th>
<th>€/t product</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Investment I₀</strong></td>
<td>255,099,000</td>
<td>1,173</td>
</tr>
<tr>
<td><strong>Depreciation (20 years)</strong></td>
<td>12,754,950</td>
<td>86,52</td>
</tr>
<tr>
<td><strong>Imputed interest (8 % I₀)</strong></td>
<td>10,203,960</td>
<td>69,22</td>
</tr>
<tr>
<td><strong>Total capital-dependent costs</strong></td>
<td>22,958,910</td>
<td>156</td>
</tr>
</tbody>
</table>

### Table 10: Consumption-dependent costs for Example 10, the wood-based synthesis gas biorefinery

<table>
<thead>
<tr>
<th>Material and energy</th>
<th>Unit/a</th>
<th>€/unit</th>
<th>€/a</th>
<th>€/t product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>447,930 t/a</td>
<td>75 €/t\text{atr}</td>
<td>33,594,750</td>
<td>227,88</td>
</tr>
<tr>
<td>Auxiliary and operating materials</td>
<td></td>
<td></td>
<td>1,021,112</td>
<td>6,93</td>
</tr>
<tr>
<td>Water (cooling-, ...)</td>
<td>3,553,524 m³/a</td>
<td>1.5 €/m³\text{77}</td>
<td>573,000</td>
<td>3,89</td>
</tr>
<tr>
<td>Electrical energy</td>
<td>101 GWh/a</td>
<td>0.12 €/kWh\text{77}</td>
<td>16,480,000</td>
<td>111,79</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>51,669,162</td>
<td>350</td>
</tr>
</tbody>
</table>

### Table 11: Other costs for Example 10, the wood-based synthesis gas biorefinery

<table>
<thead>
<tr>
<th>Factors</th>
<th>€/a</th>
<th>€/t product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel costs (30 employees)</td>
<td>50,000 €/a per person\text{77}</td>
<td>5,750,000</td>
</tr>
<tr>
<td>Repairs</td>
<td>6,377,475</td>
<td>43,26</td>
</tr>
<tr>
<td>Maintenance and cleaning</td>
<td>7,652,970</td>
<td>51,91</td>
</tr>
<tr>
<td>Administration</td>
<td>1,275,495</td>
<td>8,65</td>
</tr>
<tr>
<td>Insurance</td>
<td>2,550,990</td>
<td>17,30</td>
</tr>
<tr>
<td>Contingencies</td>
<td>1,913,243</td>
<td>12,98</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>19,142,698</td>
<td>173</td>
</tr>
</tbody>
</table>
Working group ‘Biorefineries Roadmap’

Drawn up and developed by a temporary working group, chaired by Prof. Dr. Kurt Wagemann, Society for Chemical Engineering and Biotechnology, Frankfurt am Main

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