CHAPTER 1

# Biorefinery Concepts in Comparison to Petrochemical Refineries

**Ed de Jong**[1], **Gerfried Jungmeier**[2]
[1]Avantium Chemicals, Amsterdam, The Netherlands; [2]Joanneum Research Forschungsgesellschaft mbH, Institute for Water, Energy and Sustainability, Graz, Austria

## Contents



## 1. INTRODUCTION

In recent years, substantial steps into the transition toward a biobased economy have been taken. Multiple drivers, some policy and geographically dependent, are steering an economy where material wastes are minimized, new bioproducts are replacing their fossil counterparts, greenhouse gas (GHG) emissions are reduced; while economic perspectives are developed supported by innovative policies. The recent extreme volatilities in prices (fossil oil, biomass raw materials) and very fluctuating demand ask for robust systems to be competitive in the long run. An economy based on innovative and cost-efficient use of biomass for the production of both biobased products and bioenergy should be driven by well-developed integrated biorefining systems. This will result in large additional volumes of biomass required, possibly causing increasing food and

*Industrial Biorefineries and White Biotechnology*
http://dx.doi.org/10.1016/B978-0-444-63453-5.00001-X

commodity prices, and undesired competition with production of food, feed, wooden products, paper, and so on. It may also have profound environmental implications including loss of (boreal and rain) forests, biodiversity, soil productivity, and (fresh) water availability. Accordingly, reforestation programs, sustainable management, conservation, and sustainable development of all types of forests in the long view cannot be limited to emerging economies such as Algeria ("barrage vert" in the Sahara) or Kenya ("Green Belt Movement" founded by Nobel Price Wangari Maathai) but need to be considered for deforested regions globally, including deforested regions in developed economies. Efficient and sustainable use of biomass resources, which is of paramount importance, can be enhanced by the use of biorefinery processes and their products, which will form the foundation of a future biobased economy. The ultimate goal should not just be to efficiently and sustainably make use of biomass for nonfood applications. It should also encompass increasing availability of biomass for nonfood applications by improved food chain efficiency in industrialized countries.

The integration of agroenergy crops and biorefinery manufacturing technologies offers the potential for the development of sustainable biopower and biomaterials that will lead to a new manufacturing paradigm.[1]

International Energy Agency (IEA) Bioenergy is an organization setup in 1978 by the IEA with the aim of improving cooperation and information exchange between countries that have national programs in bioenergy research, development, and deployment. The IEA was established in November, 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy program. It carries out a comprehensive program of energy cooperation among OECD member countries. Its aims include to promote: systems for coping with oil supply disruptions, rational energy policies, an oil market information system, improved energy supply and demand structures, and integrated environmental and energy policies. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted, and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply while reducing GHG emissions from energy use (http://www.ieabioenergy.com/). For the period 2013–15 there are 10 Tasks operating under the IEA Bioenergy umbrella covering all major aspects of the bioenergy field. The relevance of biorefinery in a successful bioenergy research policy has been acknowledged by the establishment in 2007 of a specific IEA Bioenergy Task 42 on biorefineries, coproducing fuels, chemicals, power, and materials from biomass. The major objective of this Task is to assess the worldwide position and potential of the biorefinery concept, and to gather new insights that will indicate the possibilities for new competitive, sustainable, safe, and eco-efficient processing routes for the simultaneous manufacture of transportation biofuels, added-value chemicals, power and heat, and materials from biomass. This Task is covering an exciting field which can have a large impact both in environmental and technological innovation policies and practices. To open up the biorefinery-related potential, system and technology development is required. Research, development, and deployment (RD&D) programs can link industry, research institutes, universities, governmental bodies, and non-governmental organizations (NGOs), while market introduction strategies need to be developed.

Major outputs of Task 42 (http://www.iea-bioenergy.task42-biorefineries.com/en/ieabiorefinery.htm) include:

- Biorefinery definition and biorefinery classification system[2]
- Country reports describing and mapping current processing potential of existing biorefineries in the participating countries, and assessment of biorefinery-related RD&D programs to help national governments defining their national biorefinery policy goals and related programs.
- Bringing together key stakeholders (industry, policy, NGOs, research) normally operating in different market sectors (e.g., transportation fuels, chemicals, energy, etc.) in multidisciplinary partnerships to discuss common biorefinery-related topics, to foster necessary RD&D trajectories, and to accelerate the deployment of developed technologies.
- Brochures, reports and publications on specific areas such as on Biobased Chemicals "Bio-based Chemicals – Value Added Products from Biorefineries" [3,6], "Green Building Blocks for Biobased Plastics and Biofuel-driven biorefineries [4] and "A Selection of the most Promising Biorefinery Concepts to produce Large Volumes of Road Transportation Biofuels by 2025".[5]
- Development of a "Biorefinery Fact Sheet" to document and report facts and figures of biorefineries in a common and compact format, consisting of a brief description, the classification scheme, mass and energy balance as well as a whole value chain-based sustainability assessment in comparison to conventional systems.[7]

## 2. THE DEFINITION FOR BIOREFINERY

IEA Bioenergy Task 42 has developed the following definition for biorefinery as depicted in Figure 1.1:

> *Biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy.*

This means that biorefinery can be a facility, a process, a plant, or even a cluster of facilities. The IEA Bioenergy Task 42 has produced a brochure that gives an overview of the different kinds of biorefineries.[7] The brochure illustrates at which scale (commercial, demonstration, or pilot) these biorefineries are currently operational.

A main driver for the establishment of biorefineries is the **sustainability** aspect. All biorefineries should be assessed for the entire value chain on their environmental,

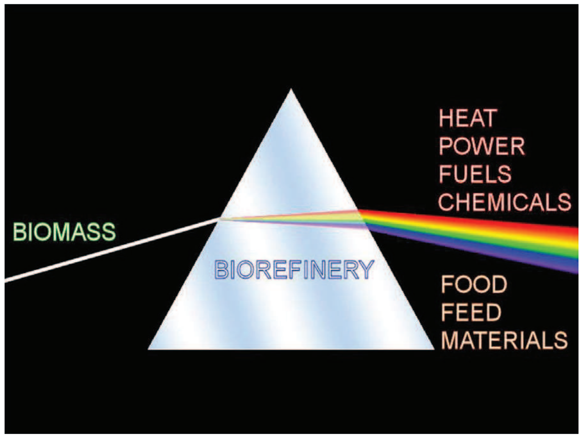


**Figure 1.1** Biorefinery and its role in the transformation of biomass.

economic, and social sustainability covering the whole life cycle (construction—operation—dismantling). This assessment should also take into account the possible consequences due to the competition for food and biomass resources, the impact on water use and quality, changes in land-use, soil carbon stock balance and fertility, net balance of GHGs, impact on biodiversity, potential toxicological risks, and energy efficiency. Impacts on international and regional dynamics, end users and consumer needs, and investment feasibility are also important aspects to take into consideration. As the sustainability assessment is not an absolute number, the sustainability assessment is made in comparison to conventional systems providing the same products and services.

A biorefinery is the integral upstream, midstream, and downstream **processing** of biomass into a range of products. In the classification system IEA Bioenergy Task 42 (described in the next chapter) has differentiated between mechanical pretreatments (extraction, fractionation, separation), thermochemical conversions, chemical conversions, enzymatic conversions, and microbial (fermentation both aerobic, anaerobic) conversions.

A biorefinery can use all kinds of **biomass** from forestry, agriculture, aquaculture, and residues from industry and households including wood, agricultural crops, organic residues (both plant and animal derived), forest residues, and aquatic biomass (algae and seaweeds). A biorefinery is not a completely new concept. Many of the traditional biomass converting technologies such as the sugar, starch, and pulp and paper industry can be (partly) considered as biorefineries. However, several economic and environmental drivers such as global warming, energy conservation, security of supply, and agricultural policies have also directed those industries to further improve their operations in a biorefinery manner. This should result in improved integration and optimization aspects of all the biorefinery subsystems.

A biorefinery should produce a spectrum of marketable products and energy. The **products** can be both intermediates and final products, and include food, feed, materials, and chemicals; whereas energy includes fuels, power, and/or heat. The main focus of biorefinery systems which will come into operation within the next years is on the production of transportation biofuels. The selection of the most interesting biofuels is based on the possibility that they can be mixed with gasoline, kerosene, diesel, and natural gas, reflecting the main advantage of using the already existing infrastructure in the transportation sector. The volume and prices of present and forecasted products should be **market competitive**.

Biorefineries are expected to contribute to an increased competitiveness and wealth of the countries by responding to the need for supplying a wide range of biobased products and energy in an economically, socially, and environmentally sustainable manner. Biorefineries show promises both for industrialized and developing countries. New competences, new job opportunities, and new markets are also expected to elaborate. Furthermore, the development of biorefineries is expected to also contribute to the implementation of several European, North American, and global policies and initiatives. In principle two different motivations for biorefineries are distinguished in IEA Bioenergy Task 42: "product-driven" biorefineries, e.g., pulp and paper and "energy-driven" biorefineries, e.g., road transportation biofuels. The biorefinery definition demands that biorefineries should produce both nonenergetic and energetic outlets and applies to product-driven biorefinery processes that primarily generate biobased products (biomaterials, lubricants, chemicals, food, feed, etc.) and process residues that are almost always used to produce heat and power (for internal use or sale). In energy-driven biorefinery processes the biomass is primarily used for the production of secondary energy carriers (biofuels, power, and/or heat); process residues are used for heat and electricity, or are sold as feed in case of biodiesel and bioethanol in the current situation, or even better are upgraded to added-value biobased products to optimize economics and ecologics of the full biomass supply chain. Both primary products and energy-driven processes are considered as true biorefinery approaches provided that the final goal is the sustainable processing of biomass. Product volumes and prices should be competitive, so their market value should be maximized.

## 3. THE ECONOMIC VALUE OF BIOMASS USING BIOREFINING

The economic value of biomass is determined by the revenue from the various products on the market and the production costs (e.g., capital and operation costs) of the various products. In most of the cases products with a relative high market value are associated with high production costs, and vice versa. In addition, also the size of the market is relevant for the economic feasibility of biorefining. In most of the cases, products with a high market value have a relative small market (e.g., speciality chemicals) and vice versa (e.g., liquid

**Table 1.1** Fossil-derived product substitution options (cost price per GJ end product)

| | **Fossil feedstock cost (€/GJ)** | **Biomass cost (€/GJ end product)** |
|---|---|---|
| Heat | 3 (coal) | 4 |
| Power | 6 (coal) | 22 |
| Transportation fuel | 8 (oil) | 10 |
| Average bulk chemicals | 30 (oil) | 75 |

transportation fuels). Economic values of fossil feedstocks to be possibly substituted by biomass show large differences (Table 1.1). The lowest values are attributed to heat production, whereas the highest values are associated with replacement of fossil-derived bulk chemicals. Because heat is mainly produced from the cheapest fossil fuel (coal), the material costs for the production of 1 GJ of heat will amount to €3 (assuming a 100% conversion efficiency). On the other hand the costs to convert biomass feedstock to heat via combustion are quite low compared to various biorefinery processes. Feedstock costs for power production approximate €6/GJ; fossil transportation fuels feedstock cost being around €8/GJ. Production of 1 GJ of bulk chemicals requires an additional average of 3–4 GJ of conversion energy (usually harvested from fossil oil or natural gas) which may provide considerable cost increases especially when the price of natural gas is linked to that of fossil oil. Consequently, feedstock costs for bulk chemicals are estimated at €30/GJ.[8,9]

Comparing fossil with biomass cost prices reveals that high capital costs are found in power production and chemical synthesis processes. In theory, the former could be circumvented by directly converting biomass to power. Capital costs of producing chemical compounds could be seriously reduced by directly obtaining (most of) the required molecular structures from biomass. In such cases the economic value of biomass feedstocks grossly exceeds the value associated with their caloric value (which is only €3/GJ). They could represent values of up to €75/GJ, provided that components could be obtained in a pure form. Assuming a biomass yield of 10–20 tonnes of dry weight per hectare per year and that the biomass will just be used for its caloric value, this would represent a value of €450–900/ha per year, values that are too low for farmers in Western Europe to make an acceptable standard of living. Things would be different if we could separate biomass into fractions that can be used to produce food, feed, biobased products (chemicals, materials), and/or bioenergy (fuels, power, and/or heat). As we saw above, separated biomass fractions can generate financial returns exceeding their caloric value alone. Assuming that 20% of biomass is suitable to produce chemical compounds, 40% to produce biofuels, and the remainder to produce power and heat, a biomass yield of 10–20 tonnes dry matter per hectare biomass yield potentially could generate €2000–4000/ha, enough for farmers to make an acceptable standard of living.

## 4. CLASSIFICATION OF BIOREFINERIES

In the past, biorefineries were classified based on a variety of different bases, such as:

- Technological implementation status: conventional and advanced biorefineries; first, second, and third generation biorefineries.
- Type of raw materials used: whole crop biorefineries (WCBRs), oleochemical biorefineries, lignocellulosic feedstock biorefineries, green biorefineries, and marine biorefineries.
- Type of main intermediates produced: syngas platform biorefineries, sugar platform biorefineries.
- Main type of conversion processes applied: thermochemical biorefineries, biochemical biorefineries, two platform concept biorefineries.

Examples of those biorefineries can be found in Kamm and Kamm.[10,11] However, an unambiguous classification system was lacking, but in 2008, IEA Bioenergy Task 42 developed a more appropriate biorefinery classification system.[2,12,13] This system is based on a schematic representation of full biomass to end-products chains. The background for this biorefinery classification system is the current main driver in biorefinery development, i.e., efficient and cost-effective production of transportation biofuels, to increase the biofuel share in transportation sector, whereas for the coproduced biobased products additional economic and environmental benefits are gained. The classification approach consists on four main features which are able to identify, classify, and describe the different biorefinery systems, viz.: platforms, products (energy and biobased materials and chemicals), feedstocks, and conversion processes (Figure 1.2). The **platforms** (e.g., C5/C6 sugars, syngas, biogas) are intermediates which are able to connect different biorefinery systems and their processes. Platforms can also be already a final product. The number of involved platforms is an indication of the system complexity. The two biorefinery **product groups** are **energy** (e.g., bioethanol, biodiesel, synthetic biofuels) and **products** (e.g., chemicals, materials, food, and feed). The two main **feedstock groups** are "energy crops" from agriculture (e.g., starch crops, short rotation forestry) and "biomass residues" from agriculture, forestry, trade, and industry (e.g., straw, bark, wood chips from forest residues, used cooking oils, waste streams from biomass processing). In the classification system a differentiation was made between four main **conversion processes**, including: biochemical (e.g., fermentation, enzymatic conversion) (red squares), thermochemical (e.g., gasification, pyrolysis) (yellow squares), chemical (e.g., acid hydrolysis, synthesis, esterification) (blue squares), and mechanical processes (e.g., fractionation, pressing, size reduction) (white squares) (Figure 1.2). The biorefinery systems are classified by quoting the involved platforms, products, feedstocks, and—if necessary—the processes.

Some examples of classifications are the following:

- Oil biorefinery using oilseed crops for biodiesel, glycerin, and feed (Figure 1.7)
- C6 sugar platform biorefinery for bioethanol and animal feed from starch crops

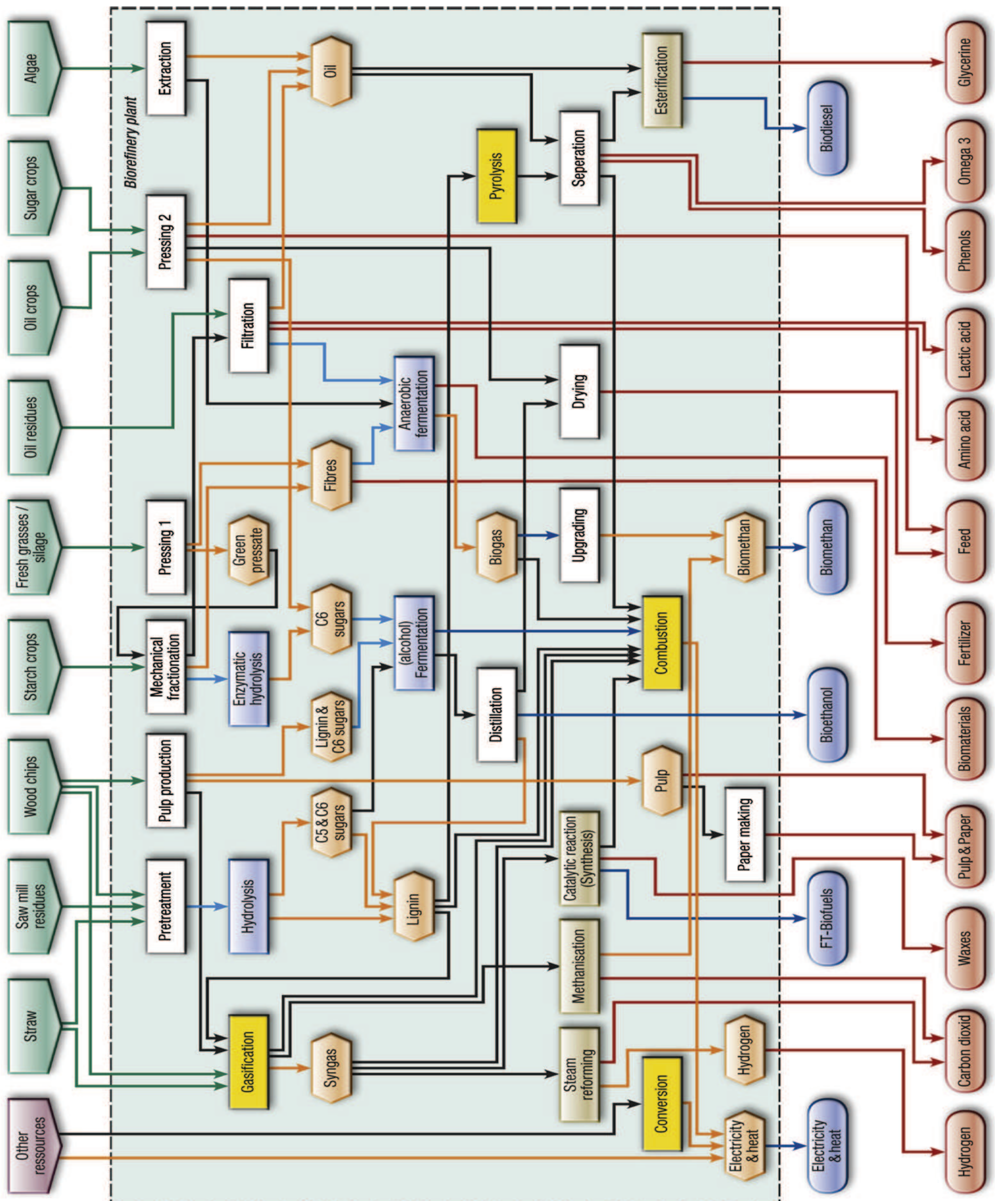


**Figure 1.2** Network on which the biorefinery system classification method is based.

- Syngas platform biorefinery for Fischer–Tropsch (FT) diesel and phenols from straw
- C5 and C6 sugars, electricity and heat, lignin biorefinery using wood chips for bio-ethanol, electricity, heat, and phenols (Figure 1.8)

A full overview of the platforms, products, feedstocks, and conversion processes is given in Figure 1.2.

## 5. CONVENTIONAL BIOREFINERIES

Biorefining is not a new activity: production of vegetable oils, beer and wine requiring pretreatment, separation and conversion techniques developed thousands of years ago, and a Chinese official started paper production around AD 100. Industrial biorefining was initiated by the introduction of steam-driven paper machines in the nineteenth century. Most innovations are, however, related to developments in food production: crystalline sugar, potato starch (early and mid-nineteenth century), wheat and corn starch (early twentieth century) and, recently, soy oil, proteins, and vitamins. Industrial processing techniques, developed in Europe and North America, are applied worldwide and serve as examples of biorefining evolvement. Some are discussed here.

Industrial potato starch production, sparked by the initiatives of the successful Dutch entrepreneur Scholten in 1839, was facilitated by the availability of clean water, good agricultural land and cheap transportation through canals (constructed for peat winning). He copied his first factory over 50 times in Dutch, German, and Polish agricultural areas, to be followed by many competitors including farmers cooperatives suffering from artificially reduced potato prices.[14] Next to (modified) starch, they generated a range of products including thermoplastic starch-based biopolymers. Coproduct development was provoked by factory concentrations following Dutch legislation that demanded wastewater cleaning which thus far was fed into canals causing foam and odor production. The subsequent consolidation into larger plants facilitated the development of coproducts such as high-value protein for human consumption. To achieve this, an innovative process was developed to isolate high-quality native proteins from potato fruit juice. The protein fractions have all novel and unique properties for applications in food, cosmetics, and pharmaceuticals. Potato fibers initially used for animal feed, are now used as feedstocks for the production of higher value food products. Ethanol from fermentation of potato starch (called "Spiritus" or *Kartoffelsprit* in German) has not only been used to make vodka but was also blended up to 25% into transportation fuel until the 1950s.[19]

Modern European sugar production started when a British blockade of Napoleonistic France in 1810, provoked the search for feedstocks to replace sugar imports from the Caraibics. Already in 1801, Franz Achard had processed 250 tonnes of beet into crystalline sugar in Germany, introducing processing steps (extraction, filtration, evaporation, crystallization, centrifugation) that currently still are used.[15] The process also yielded molasses and residual sugar that later served as feedstocks for industrial yeast production after 1840, and still later for ethanol production. Beet pulp continues to serve as a valuable component in cattle feed.

Soybeans gained importance after World War II to substitute protein foods and generate edible oil. Today, soy is a leading crop in the USA, while Brazil, Argentina, and Paraguay are important exporting nations. Oil production starts with the cracking of the beans, adjusting their moisture content, rolling them into flakes, and extracting the oil with hexane. It is subsequently refined and blended, remaining husks being used as animal feed. Soybeans are used in many food products (margarines, butter, vegetarian burgers), as a source of vitamin E, in industrial products (oils, soap, cosmetics, inks, clothing), and—increasingly—as biodiesel feedstock.[9]

## 6. ADVANCED BIOREFINERIES

Additional biorefineries may be introduced in a variety of market sectors in the short term (up to 2020) by the upgrading and extension of existing industrial infrastructures. New biorefinery concepts highlighted in this paragraph are, however, still mostly in the R&D, pilot or small-scale demonstration phase with commercialization being further away. It is expected that these new concepts will be implemented in the market in the medium term (2015–25) in different countries[16] although current economic conditions (relatively low oil prices, credit crisis, and recessions in parts of the global economy) might cause severe delays in their market implementation of some of the biorefinery concepts. The most important concepts of the advanced biorefineries are discussed below.

## 7. WHOLE CROP BIOREFINERY

In a WCBR, grain and straw fractions are processed into a portfolio of end products. It encompasses "dry" or "wet" milling and consequent fermentation and distilling of grains (wheat, rye, or maize). Wet milling starts with water-soaking the grain adding sulfur dioxide to soften the kernels and loosen the hulls, after which it is ground. It uses well-known technologies and allows separation of starch, cellulose, oil, and proteins. Dry milling grinds whole grains (including germ and bran). After grinding, the flour is mixed with water to be treated with liquefying enzymes and, further, cooking the mash to breakdown the starch. This hydrolysis step can be eliminated by simultaneously adding saccharifying enzymes and fermenting yeast to the fermenter (simultaneous saccharification and fermentation). After fermentation, the mash (called beer) is sent through a multicolumn distillation system followed by concentration, purification, and dehydration of the alcohol. The residue mash (stillage) is separated into a solid (wet grains) and liquid (syrup) phase that can be combined and dried to produce "distiller's dried grains with solubles" (DDGS), to be used as cattle feed. Its nutritional characteristics and high vegetable fiber content make DDGS unsuited for other animal species and extension to the more lucrative poultry and pig feed markets continues to be a focus to create extra value for the DDGS fraction. The straw (including chaff, nodes, ears, and leaves) represents a lignocellulosic feedstock that may be further processed (see subsection "Lignocellulosic Feedstock Biorefinery").

## 8. OLEOCHEMICAL BIOREFINERY

An oleochemical biorefinery can be considered as a special example of a WCBR which combines biodiesel production with that of high added value vegetable oil-based products (Figure 1.7). It uses fatty acids, fatty esters, and glycerol from oil crops to produce the so-called platform (basic) chemicals, functional monomers, lubricants, and surfactants.[17,18] Altering lipid profiles by breeding or improved crop management could provide new chemical functionalities thus increasing added value of industrial oilseed crops.

In the long run, oleochemical biorefining might produce renewable feedstocks for fossil-based chemical refineries. The success of a biorefinery will ultimately depend on its integration with its existing fossil counterparts, and building blocks of oleochemical biorefineries are offering a neat interface. The NExBTL process of Neste Oil[19,20] demonstrates how fossil and biorefineries might interact. Precursor feedstocks used to produce vegetable oil-based products also contain substantial amounts of lignocellulosic biomass, which can be used in a lignocellulosic feedstock biorefinery.

## 9. LIGNOCELLULOSIC FEEDSTOCK BIOREFINERY

Lignocellulosic feedstock biorefinery encompasses refining lignocellulosic biomass (wood, straw, etc.) into intermediate outputs (cellulose, hemicellulose, lignin) to be processed into a spectrum of products and bioenergy.[2,21] Lignocellulosic biomass is expected to become the future's most important source of biomass and be widely available at moderate costs showing less competition with food and feed production. Below, different types of lignocellulosic feedstock biorefineries will be discussed.

Lignocellulosic biomass is treated with among others acid or alkaline agents to release cellulose, hemicellulose, and lignin, the former being further converted with (enzymatic) hydrolysis into mainly glucose, mannose (C6), and xylose (C5).[21] These C6 and sometimes C5 sugars are currently predominantly used as feedstock for fermentation to produce biofuels (ethanol, butanol, hydrogen) and/or added-value chemicals, lignin being applied for combined heat and power production to be used internally or sold. Future lignin applications include added-value chemicals such as phenolic components or composites[21,22] while C6 and C5 sugars can also be used as feedstock for chemical catalytic conversions.[3,21] The forest-based biorefinery encompasses full integration of biomass and other feedstocks (including energy) for simultaneous production of pulp (paper) fibers, chemicals, and energy.[23,24] The pulp and paper industry[25] can be considered as the first nonfood biorefinery, value-added coproducts including tall oil, rosin, vanillin, and lignosulfonates. Pulp and paper companies in industrialized countries are currently suffering from decreased demand in some sectors (e.g., newsprint), rising costs and increased competition from emerging countries, and production of value-added coproducts from underutilized streams and waste materials provide a viable survival strategy. The European Forest-based Technology Platform has defined research options for zero-waste wood-based biorefineries,[26] and suggested that pulp mills produce bioproducts and biofuels from forest-based biomass and mill residues using advanced fractionation and conversion followed by sugar or syngas routes. Lignin, the most abundant by-product, has unique prerequisites to produce chemical platforms for renewable polymers, specialty chemicals, materials, and high-quality fuels.

## 10. SYNGAS PLATFORM BIOREFINERY (THERMOCHEMICAL BIOREFINERY)

In this biorefinery type, lignocellulosic biomass is pretreated (size reduction, drying, and/or torrefaction) to allow high-temperature and high-pressure entrained flow gasification into synthesis gas of mainly CO and $H_2$. The syngas is cleaned in a high-temperature gas cleanup system, often applying steam reforming to modify its $CO/H_2$ ratio following downstream synthesis requirements. The clean gas can be used to produce biofuels and/or chemicals (FT diesel, dimethylether), a range of alcohols including bioethanol; and/or a variety of base chemicals (ethylene, propylene, butadiene, etc.) using catalytic synthesis processes.[27]

## 11. NEXT GENERATION HYDROCARBON BIOREFINERY

The essential role of chemistry, chemical catalysis, thermal processing, and engineering in the conversion of lignocellulosic biomass into green gasoline, green diesel, and green jet fuel was stressed in a National Science Foundation and the Department of Energy workshop held in 2007. While it took years of research and design to develop the modern petroleum industry,[27] a similarly expansive and sustained effort is required to develop hydrocarbon biorefineries. Advances in nanoscience provide unprecedented options to control molecular chemistry and promises to accelerate development of biomass-to-fuels production technologies. Expertise of the chemistry, catalysis, and engineering communities—earlier instrumental in the development of fossil refining—is required for the rapid development of cost-effective hydrocarbon biorefineries. However, recent history with the companies Choren, Range Fuels, and Kior has taught that economically scaling up this technology is not straightforward.

Liquid phase catalytic processing is a promising biorefinery process that produces functionalized hydrocarbons from biomass-derived intermediates (e.g., intermediate hydroxymethylfurfural or HMF). Renewable furan derivatives can be used as substitute building blocks for fossil fuels, plastics, and fine chemicals,[28–30] or to develop biofuels based on C5 and C6 carbohydrates (sugars, hemicellulose, cellulose). Currently, Avantium Chemicals in the Netherlands is developing chemical catalytic routes to generate furanics for renewable polymers, bulk and specialty chemicals, and biofuels.[31–33]

## 12. GREEN BIOREFINERY

The use of grassland for cattle production in Europe is on the decline; however, it is felt that continued grass cultivation is essential to preserve valuable grassland landscapes. Green biorefineries, feeding grass or other green/fresh biomass to a cascade of processing stages, offer an innovative alternative. Essential is the mechanical grass ("green biomass") fractionation into a liquid phase containing water-soluble compounds (lactic acid, amino acids) and a solid phase mainly consisting of fibers.[34,35] Overall economic efficiency of the biorefinery is mainly determined by the economic return of the fibers. Green biorefineries can use a wide range of biomass including sugar beet or other leaves, clover, or lucerne to generate a highly diverse range of products. Mixed feedstocks (e.g., fresh and silage grass) sometimes constitute an intermediate between green and lignocellulosic biorefineries. Dutch researchers developed a biorefinery for grass and other leaf material (alfalfa, beet, etc.), costs for grass (€70–80/tonne) exceeding those of leaves (€50–70/tonne). Fibers (representing 30% of the products by weight) were valued at around €100/tonne, other components at an average of €800/tonne of dry grass, making the use of grass in potential very cost-effective.[36] Fractionation of grass appeared, however, to be cumbersome, and therefore costly. So major improvements should be achieved in this area.

The central part of the green biorefinery is a mechanical refiner[37] where leaf material is broken so that fibers can be obtained in a rather pure form (containing less than 11% of the protein). The protein is recovered from the press-juice after heat coagulation and a separation step; the rest of the juice is concentrated by evaporation. Main products are proteins to be used as pig and poultry feed; fibers for building materials, insulation material, plant pots, biocomposites, packaging material and biofuel feedstock; and soluble components like amino acids (polymeric), sugars, organic acids, and minerals. Solubles are concentrated to be used as feed component or fermentation feedstock.[9] European green biorefinery projects are running in Austria, Germany, Ireland, and the Netherlands, most emphasis being put on grass refining.[9,34,35] The starting point is zero-waste and zero-emission extraction of valuable substances, all residues to be used in a biogas plant to realize energetically self-sufficient operation of the plant.

## 13. MARINE BIOREFINERY

The net global primary biomass production is equally divided between terrestrial and aquatic systems. So far, policies have focused mainly on terrestrial biomass, while marine sources like microalgae (diatoms: green, golden, and blue/green algae), and macroalgae (brown, red, and green seaweeds) and their derived products could provide a potential that is still not yet fully known. Diatoms are the dominant phytoplankton life form, probably representing the largest biomass potential on Earth, covering an estimated 100,000 species that often accumulate oils. Algae can, depending on species and growing conditions, accumulate significant amounts of oils, carbohydrates, starch, and vitamins. Green algae are a rich source of starch and oils, golden algae producing oils and carbohydrates. Marine crops have long been recognized for their GHG abatement potential, their ability to absorb $CO_2$ possibly exceeding that of terrestrial species. More recently, they have been recognized as a potential source of biofuel feedstocks.[9] However, cost of production/harvesting of biomass in all marine biorefineries is currently still too high to be a viable option for fuels and bulk chemicals applications.

## 14. CHAIN DEVELOPMENT

Biorefineries can (under certain conditions) disregard economies of scale.[38] Limitations in optimal plant size are caused by feedstock transportation needs: larger plants demanding larger distances to fulfill feedstock requirements year round. Long transportation distances are especially harmful for feedstocks with high concentrations of water (transport of which is expensive but not effective), minerals, or organic components (required to maintain local soil quality). In contrast to fossil feedstocks, that can generally be recovered following the exact timing of its demand (natural gas, often a by-product of oil production, being the exception to the rule), most biomass types (wood being the exception) are harvested only during a relatively short period of the year. Year round biomass availability requires expensive storage facilities, while crops with high water concentrations cannot be stored over long periods.

Biorefinery systems should be designed in such a way that capital intensive operations can continue year round in central plants; collection, separation, and storage can be decentralized. By doing so, minimal investments and energy use are required to recycle minerals and soil components back to the fields. Specific fractions could then be transported to alternative biorefineries, further processing intermediate products derived from a range of crops. This enables robust multi-input single-output systems that can withstand fluctuations in harvested volume as well as price variations, varying the use of given crop components depending on market demand. Decentralized pretreatment units, further, allow efficient waste heat recovery generated by (fossil or) biomass sources, which often is not possible in central power generation facilities, while also offering improved living conditions to rural areas and perspectives for developing economies.[9]

Decentralized preprocessing does, however, require additional capital and labor costs. This drawback can be overcome by improving the overall economics of the production chain by

- Process automatization and telecontrol of the process, limiting labor inputs required for continuous process supervision.
- Some steps are no longer required as mentioned above for recycling of the minerals. In the past this trade-off was never made because the waste products from the traditional biorefineries could be discarded at low cost, often without any treatment. Later governments ordered companies to cope with these environmental problems often at very high economic and energy costs.
- If expensive equipment can be used year round, capital costs per unit product are considerably reduced as compared to seasonal operations such as potato starch, beet sugar, cane sugar, and cassava production.
- Choice of unit operations that have low advantages of economies of scale. In many traditional biorefineries the very large volumes that are processed often result in the duplication of equipment because larger equipment cannot be built because of physical limitations. Sometimes one has the choice to use unit operations that show only small economy of scale benefits such as the usage of membrane processes instead of evaporation using heat for concentration purposes. Another strategy could be to convert the desired components in intermediates that can be recovered by crystallization/precipitation or even to leave the component in the process water and subsequently convert these components to biogas that can be used on site or fed to the grid.

## 15. BIOREFINERY CONCEPTS IN COMPARISON TO PETROCHEMICAL REFINERIES

The production of biobased products could generate US$10–15 billion of revenue for the global chemical industry.[3] The potential for chemical and polymer production from biomass has been comprehensively assessed in several reports and papers. In 2004, the US Department of Energy issued a report which listed 12 chemicals which it considered as potential building blocks for the future.[39] This list was reviewed and updated in 2010.[40] The economic production of transportation biofuels is often a challenge. The coproduction of chemicals, materials, food, and feed can generate the necessary added value. Recently a paper was published highlighting all biobased chemicals with immediate potential as biorefinery "value-added products". The selected products are either demonstrating strong market growth or have significant industry investment in development and demonstration programs.[3]

Often a comparison is made between traditional petrochemical refineries and biorefineries.

Table 1.2 gives an overview of the major similarities and dissimilarities of petrochemical refineries and biorefineries while Figures 1.3 and 1.4 give an overview of the base petrochemicals and their major applications[41] as well as the updated top 12 building blocks derived from biomass.[39,40] Table 1.2 and Figures 1.3 and 1.4 clearly illustrate that starting materials, processes, and products are quite different.

**Table 1.2** Comparison of refineries and biorefineries regarding to feedstocks, building block composition, processes, and chemical intermediates produced at commercial scale

| | Refinery | Biorefinery |
|---|---|---|
| Feedstock | Feedstock relatively homogeneous | Feedstock heterogeneous regarding bulk components e.g., carbohydrates, lignin, proteins, oils, extractives, and/or ash |
| | | Most of the starting material present in polymeric form (cellulose, starch, proteins, lignin) |
| | Low in oxygen content | High in oxygen content |
| | The weight of the product (mole/mole) generally increases with processing | The weight of the product (mole/mole) generally decreases with processing |
| | | It is important to perceive the functionality in the starting material |
| | Some sulfur present | Low sulfur content |
| | Sometimes high in sulfur | Sometimes high in inorganics, especially silica |
| Building block composition | Main building blocks: Ethylene, propylene, methane, benzene, toluene, xylene isomers. | Main building blocks: Glucose, xylose, fatty acids (e.g., oleic, stearic, sebacic) |
| (Bio)chemical processes | Almost exclusively chemical processes | Combination of chemical and biotechnological processes |
| | Introduction of heteroatoms (O, N, S) | Removal of oxygen |
| | Relative homogeneous processes to arrive to building blocks: Steam cracking, catalytic reforming | Relative heterogeneous processes to arrive to building blocks |
| | Wide range of conversion chemistries | Smaller range of conversion chemistries: Dehydration, hydrogenation, fermentation |
| Chemical intermediates produced at commercial scale | Many | Few but increasing (e.g., ethanol, furfural, biodiesel, mono-ethanolglycol, lactic acid, succinic acid, …) |

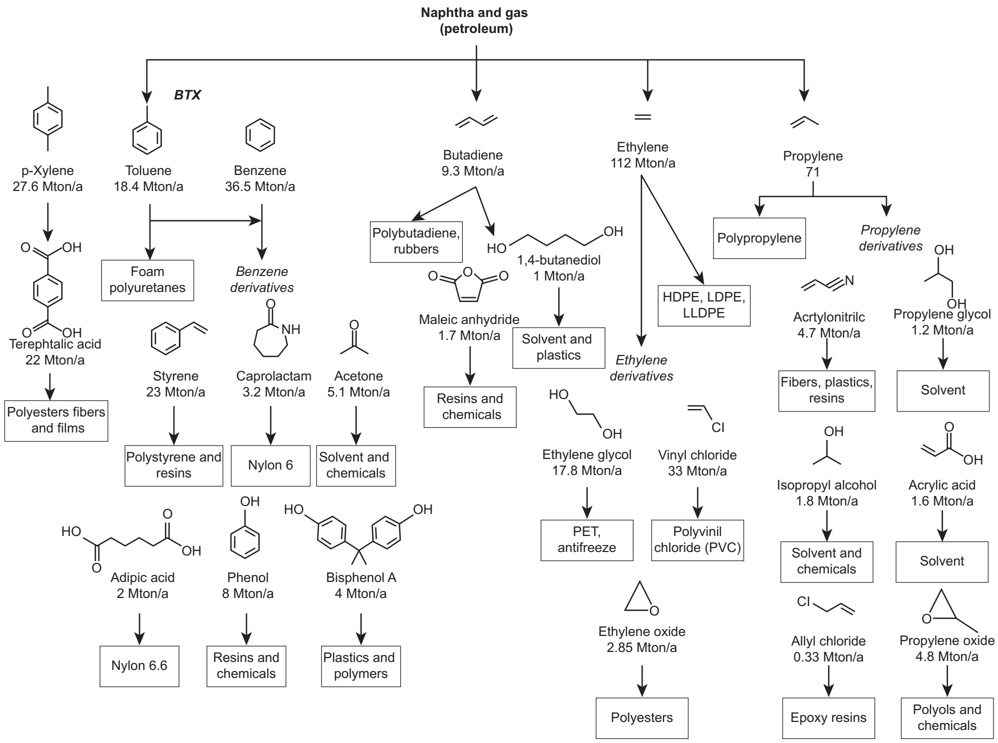


**Figure 1.3** Base petrochemicals, major applications, and global production in 2009.[41]

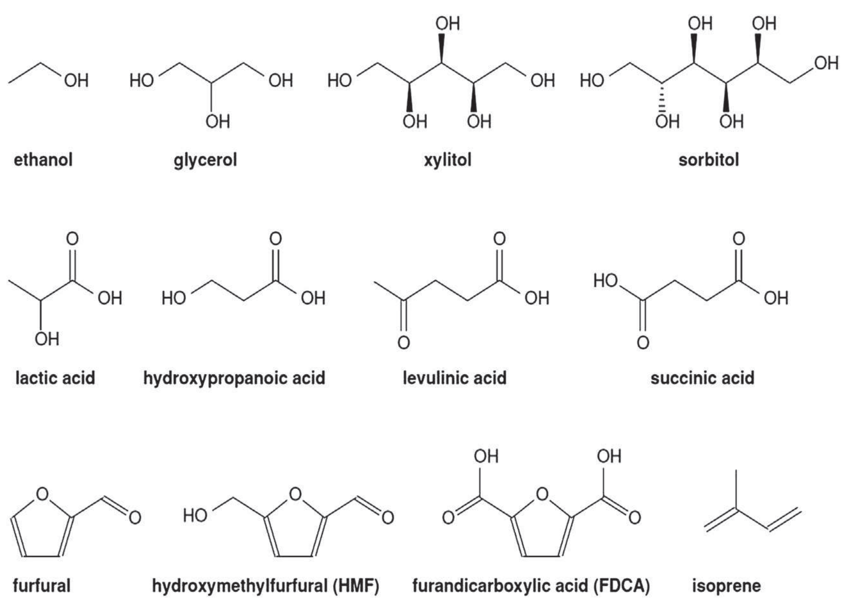


**Figure 1.4** Proposed biobased platform molecules.[39,40]

However, it might be still very attractive to integrate biomass processing in traditional refineries as a way to upgrade conventional refineries and this represents a modern systems version of a retrofit problem. Examples include the production of "green biodiesel," the NExBTL process, and the catalytic cracking of pyrolytic lignin. Green biodiesel (Petrobras/H-BIO, UOP with ENI) is produced widely with the hydrogenation of plant oils (or animal fat) using hydrogen available at the refinery. Fortum Oil Oy uses the proprietary NExBTL process to produce an isoparaffinic fuel (not FAME) by hydrodeoxygenation (or catalytic hydrotreatment of vegetable oils or animal fats) still compatible with existing diesel engines (capacities range from 170 to 800 kT/year).[41] Currently, Fortum Oil produces more than 2 million metric tonnes per year equivalent to 675 million gallons per annum distributed from its three worldwide facilities in Porvoo, Finland; Rotterdam, the Netherlands, and Singapore.[42] The oil and syngas platforms in particular represent a number of opportunities of processing biomass or biomass-derived intermediates by utilizing existing petrochemical facilities, such as oil cracking, hydrotreating, gasification, and chemical synthesis. The resulting products include gasoline, diesel, olefins, alcohols, acids, waxes, and many other commodity chemicals derivable from syngas.[41] The systematic development of such integrated scenarios could use a systems approach to differentiate between available feedstocks (biomass and fossil), processing routes (biomass, petrochemical refinery), and available chemicals. This comparator could produce scenarios for integration badly needed in reviewing the numerous options available in practice.[41]

Insofar biorefineries create a process chain that adds biomass as a resource alternative to coal, crude oil, or natural gas in order to create C2-, C3-, or C4-base chemical platforms.[43] In principle, fossil and renewable resources can substitute each other and historically such replacements, more particularly the substitution of coal by crude oil and natural gas, have occurred. It is also important to keep in mind that crude oil and natural gas differ significantly in composition, depending on the origin (Tables 1.3 and 1.4). The increased usage of shale gas changes the ratio between C2, C3, and C4 building blocks produced and might create extra potential for biomass-derived C4 building blocks (e.g., succinic acid and butanediol).

**Table 1.3** Typical approximate characteristics and properties and gasoline potential of various typical crude oils[44]

| Crude source and name | Paraffins % vol | Aromatics % vol | Naphthenes % vol | Sulfur % wt |
|---|---|---|---|---|
| Nigerian light | 37 | 9 | 54 | 0.2 |
| Saudi light | 63 | 19 | 18 | 2 |
| Saudi heavy | 60 | 15 | 25 | 2.1 |
| Venezuela heavy | 35 | 12 | 53 | 2.3 |

**Table 1.4** Typical approximate composition of natural and oil processing gases (percent by volume[44])

| Type gas | $H_2$ | $CH_4$ | $C_2H_6$ | $C_3H_4$ | $C_3H_8$ | $C_3H_6$ | $C_4H_{10}$ | $C_4H_8$ | $N_{2+}CO_2$ | $C_{5+}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Natural gas | n/a | 98 | 0.4 | n/a | 0.15 | n/a | 0.05 | n/a | 1.4 | n/a |
| Petroleum-associated gas | n/a | 42 | 20 | n/a | 17 | n/a | 8 | n/a | 10 | 3 |
| Oil processing gases | | | | | | | | | | |
| Catalytic cracking | 5–6 | 10 | 3–5 | 3 | 16–20 | 6–11 | 42–46 | 5–6 | n/a | 5–12 |
| Pyrolysis | 12 | 5–7 | 5–7 | 16–18 | 0.5 | 7–8 | 0.2 | 4–5 | n/a | 2–3 |
| Shale gas (typical)[45] | n/a | 74,2 | 15,6 | 5,5 | n/a | 2,1 | n/a | n/a | 2,1 | |

Biomass, compared to fossil feedstock, is first and foremost distinguished by the high content in oxygen (Table 1.5).

The above biobased platform molecules (Figure 1.4) can be synthesized via chemical or biochemical manufacturing technologies. Biochemical technologies often use glucose as nutrient solution. By alcoholic fermentation, glucose is disintegrated yielding the **C2-Platform** molecule ethanol. Fuel-grade bioethanol is rather easily dehydrated to ethylene using an $Al_2O_3$/MgO or a zeolite catalyst in a bioethanol-to-ethylene process. Bioethylene that way becomes an alternative to ethylene sourced from steam cracking of petroleum fractions, natural gas, or shale gas as the point of origin for the C2 product tree (Figure 1.5).

**Table 1.5** CHO composition of crude oil, fats and oils, and lignocellulosic biomass

| | Crude oil | Animal fats and vegetable oils | Lignocellulose (wood) |
|---|---|---|---|
| Carbon | 85–90% | 76% | 50% |
| Hydrogen | 10–14% | 13% | 6% |
| Oxygen | 0–1,5% | 11% | 43% |

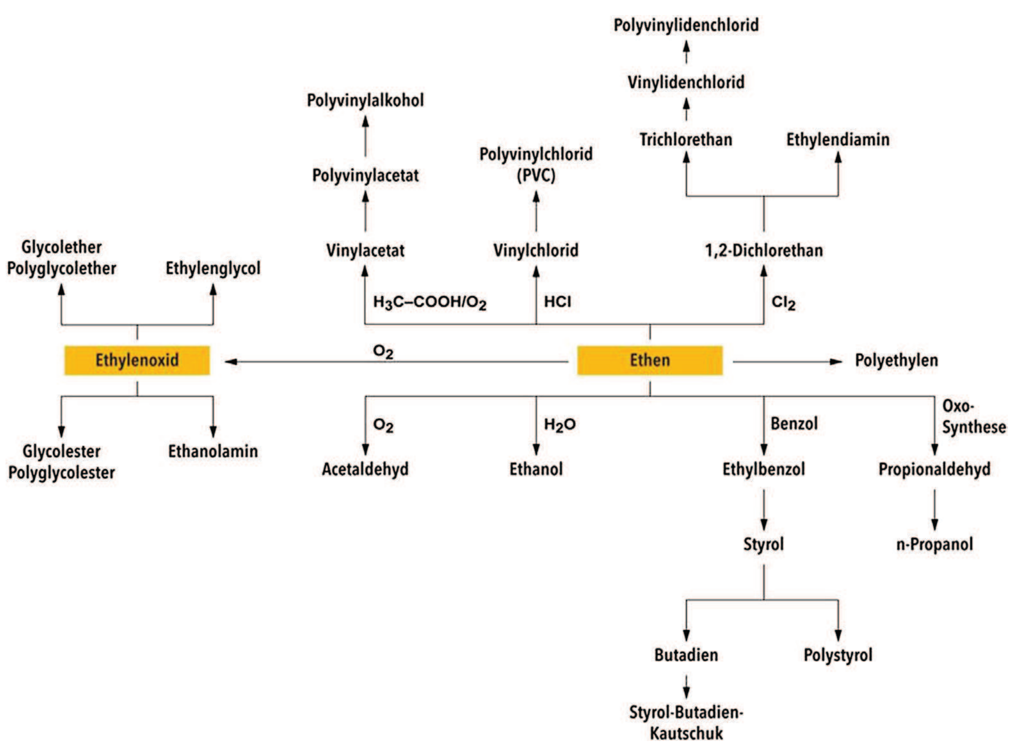


**Figure 1.5** Most important product trees derived from ethylene.[46]

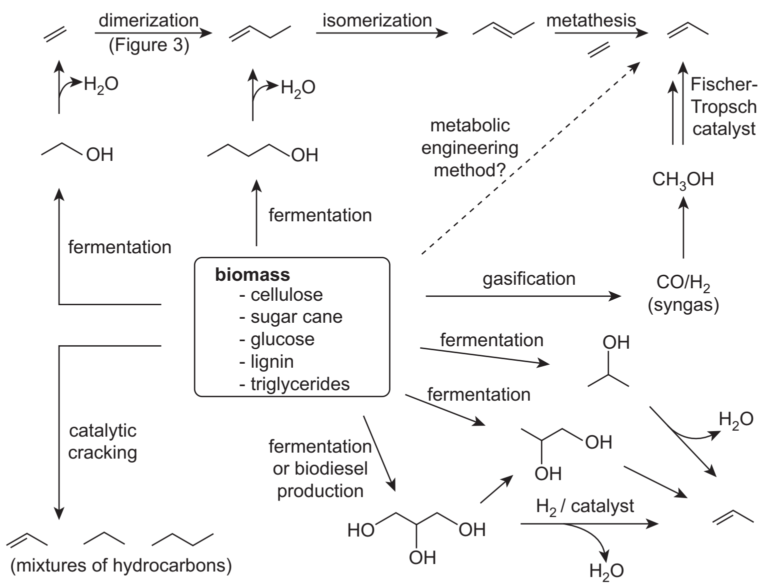


**Figure 1.6** Possibilities for synthesis of propylene from biomass using fermentation, gasification, or cracking strategies.[49]

Starting from renewable raw materials the **C3-Platform** can be accessed both by chemical as well as biochemical routes (Figure 1.6). With biodiesel setup on a firm and permanent basis as transportation fuel glycerol as by-product has become a market-relevant commodity and nucleus of a plethora of value-added chemicals.[3,18,47] Transportation fuel manufacturing by hydrotreatment of vegetable oils and animal fats produces propane as coproduct.[19,20,48] Other manufacturing concepts for biopropylene and biopropane include glycerol dehydration to acrolein,[46] gasification of biomass to produce a syngas followed by synthesis of biomethanol, and methanol-to-olefins technology to produce propylene,[50,51] fermentation of sugars to produce bioethanol, followed by dehydration to bioethylene, dimerization of ethylene to produce normal butenes, which are reacted with bioethylene via metathesis to produce propylene,[52] direct conversion of glucose to propylene using the same artificial metabolic pathway that is used to produce bio-isobutene.[53]

Another important C3 building block, lactic acid, can be produced through both fermentation of carbohydrates and chemical conversion starting from glycerol.[43,54] Lactic acid can be dehydrated yielding acrylic acid, can be reduced to 1,2-propanediol or can undergo polycondensation to polylactic acid.[55]

The **C4-Platform** is accessible by fermentation using corn or sugarcane bagasse as feedstock by acetone–butanol or acetone–butanol–ethanol (ABE) fermentation using *Clostridium acetobutylicum* or *Clostridium beijerinckii* under anaerobic conditions. This process has been industry standard since decades and produces the three solvents in a ratio ABE = 3:6:1.[43,56] More recently, microbial fermentation technologies which genetically alter *Escherichia coli* to generate several higher chain alcohols from glucose, including 1-butanol, 2-methyl-1-butanol, and more particularly isobutanol have been developed. Acid catalyzed dehydration would convert isobutanol into a mixture of $C_4$ olefins (1-butene, *cis*-2-butene, *trans*-2-butene, and isobutene) which then convert to a mixture of unreacted isobutene and 1,3-butadiene in a catalytic dehydrogenation reaction at elevated temperature and low pressure well known from petrochemical process technologies. Carbohydrate-based C4-building blocks do not only substitute crude oil-derived crack C4 intermediates but complement the platform and provide new opportunities for C4-based polymers. This is in particular the case for succinic acid (butanedioic acid). Although the bulk of the actual industrial production of succinic acid is made by hydrogenation of maleic anhydride and subsequent hydration, nearly 0,5 Mio mto biosuccinic acid using sugar-containing feedstock including glucose syrup from hydrolyzed starch, grain sorghum, or corn steep liquor from wet-milling have been established or are under construction.[57,58] A major outlet for succinic acid is its conversion into 1,4 butanediol.

Because of the wide variety of possibilities for a biorefinery configuration a quick preliminary assessment of the (bio)chemical processes at the laboratory stage is very useful.[59] The proposed method enables a review of the processes within a broader sustainability context. It is inspired by green chemistry principles, technoeconomic analysis and some elements of environmental life-cycle assessment. This method evaluates a proposed (bio) chemical process against comparable existing processes using a multicriteria approach that integrates various economic and environmental indicators. An effort has been made to incorporate quantitative and qualitative information about the processes while making the method transparent and easy to implement based on information available at an early stage in process development. The idea is to provide a data-based assessment tool for chemists and engineers to develop sustainable chemistry.[59,60]

## 16. BIOREFINERY COMPLEXITY INDEX

As indicated before, currently many different biorefinery concepts are being developed and implemented. Some of these biorefinery concepts are simple, using one feedstock (e.g., vegetable oil) and producing two or three products (e.g., biodiesel, animal feed, glycerine) with current available commercial technologies. However, other biorefinery concepts are sometimes very complex using many different feedstocks (e.g., algae, miscanthus, and wood chips from short rotation) to coproduce a broad spectrum of different products (e.g., bioethanol, phenol, omega-3 fatty acids, biodiesel) using technologies that still need to become commercial in the upcoming years. It is concluded that each of these different biorefinery concepts has a different degree of complexity, which makes it difficult for industry, decision-makers, and investors to decide, which of these concepts are the most promising options on the short, medium, and long term, and to judge on the technological and economic risks.

Therefore, IEA Bioenergy Task 42 has published a working document to present the current status of an approach to develop a "Biorefinery Complexity Index (BCI)" and to calculate the BCI for some selected biorefinery concepts.[61] The approach was developed since 2010 and started with the analogy to the "Nelson's complexity index" used for oil refineries. The Nelson's (complexity) index was developed by Wilbur L. Nelson and published in the "Oil and Gas Journal" (1960–61) to quantify the costs of the refinery's components. The Nelson's index is an indicator for the investment intensity, the cost index of the refinery, the value addition potential of a refinery, the refinery's ability to process feedstocks, such as high-sulfur crude, into value-added products. The higher the complexity of the refinery the more flexible it is.

Based on the classification system of biorefineries as discussed above and the "Nelson's complexity index" for oil refineries a BCI is under development.

The following basic assumptions on the complexity of a biorefinery are used:

1. The number of different features of a biorefinery influences the complexity. The complexity increases by the number of features in a biorefinery.
2. The state of technology of a single feature influences the complexity. The complexity decreases the closer a technology is to a commercial application, meaning a high "Technology Readiness Level (TRL)" of a feature has lower technical and economic risks, and so a lower complexity.
3. For the products and feedstock the "Market Readiness Level" is applied in analogy to the TRL of the processes and platforms. Therefore only the TRL is used.
4. This leads to the basic assumption for the calculation procedure of the BCI that the complexity is directly linked to the number of features and the TRL of each single feature involved.
5. This means that the complexity of a commercial application, which means that all features are commercially available, is then only determined by the number of features; whereas in noncommercial application the TRL increase additionally the complexity of the biorefinery system.

For each of the four features (platforms, feedstocks, products, and processes) of a biorefinery the TRL can be assessed using level description between 1 ("basic research") to 9 ("system proven and ready for full commercial deployment"). Based on the TRL the feature complexity (FC) for each single feature of a biorefinery is calculated. With the number of features and the FC of each single feature the Feature Complexity Index (FCI) for each of the four features (platforms, feedstocks, products and processes) is calculated. The BCI is the sum of the four FCIs. To simplify the presentation the Biorefinery Complexity Profile (BCP) is introduced. The BCP is a compact format to present the complexity of a biorefinery by giving the BCI and the four FCIs of each feature. The BCP, which includes the BCI and the four FCIs has the following format: BCP: $BCI(FCI_{platforms}/FCI_{Feedstocks}/FCI_{Products}/FCI_{Processes})$, with an example 8 (1/1/3/3) for a 1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin, and feed

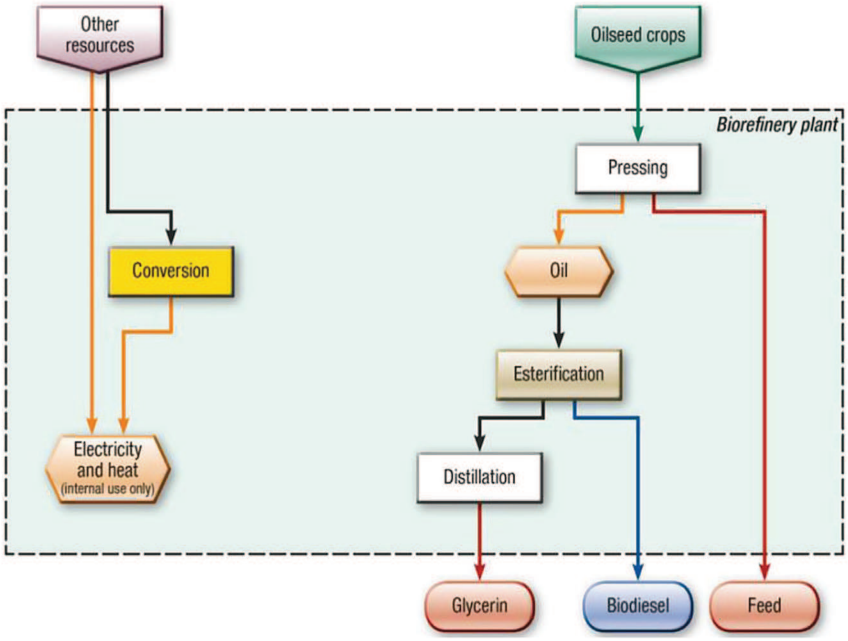


**Figure 1.7** A 1-platform (oil) biorefinery using oilseed crops for biodiesel, glycerin, and feed with a Biorefinery Complexity Profile of 8 (1/1/3/3).

(Figure 1.7). In Figure 1.8 a second generation biorefinery such as 3-platform (C5 and C6 sugars, electricity and heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat, and phenols has a BCP of 29 (8/1/4/16) is shown.[61]

The following conclusions on the BCI and BCP were drawn:

1. They give an indication for the relative comparison of different biorefinery concepts and their development potential.
2. They present a benchmark of the "complexity" of a biorefinery in terms of involved platforms, feedstocks, processes, and products, and their specific and overall "Technology Readiness Level."
3. The higher the BCI the more beyond "state of the art" is the biorefinery.
4. The BCI of a biorefinery producing biodiesel from vegetable oil which is fully deployed, with 8 (1/1/3/3) is a benchmark to compare the complexity of other current and future biorefinery systems.
5. The BCI will change in the future if the TRL has changed, e.g., if a pilot plant, demonstration plant, and/or first-of-a-kind commercial plant will go into operation.
6. The BCP shows the most relevant features contributing to the complexity of a biorefinery.
7. The BCP of a biorefinery gives an indication on the technological and economic risks.

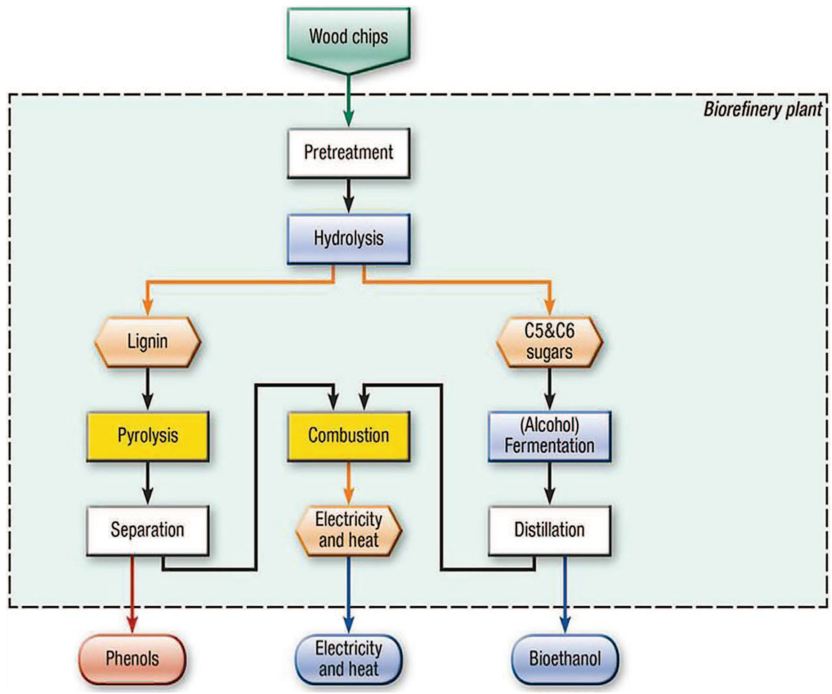


**Figure 1.8** A 3-platform (C5 and C6 sugars, electricity and heat, lignin) biorefinery using wood chips for bioethanol, electricity, heat, and phenols with a Biorefinery Complexity Profile of 29 (8/1/4/16).

The first results and conclusions of a critical review by the country representatives in IEA Bioenergy Task 42 show that the "Biorefinery Complexity Index" adds additional relevant information on the assessment and comparison of different biorefinery systems. It was concluded that the results are potentially relevant for industry, decision-makers as well as investors as additional information is generated to assist them in their strategies to implement the most promising biorefinery systems by minimizing technical and economic risks.

## 17. DISCUSSION AND CONCLUSIONS

Successful market implementation of integrated biorefineries requires reliable processing units combined with environmentally acceptable and economically profitable production chains. Development and implementation of the biorefinery concept should include crop cultivation and the selection of crops that maximize full chain performance.

Table 1.6 gives an overview of the different biorefineries and their development stage. It should be mentioned that although the sugar and starch biorefineries are in full-scale operation, their development will get a new input due to the biobased economy demands for new products and certainly for reduction of costs. Further biorefinery improvement

**Table 1.6** Overview of the main characteristics of the different biorefineries

| Concept | Type of feedstock | Predominant technology | Phase of development | Products (selection) |
|---|---|---|---|---|
| Conventional biorefineries | Starch (corn, wheat, cassava) and sugar crops (sugarcane, sugar beet), wood | Pretreatment, chemical and enzymatic hydrolysis, catalysis, fermentation, fractionation, separation | Commercial | Sugar, starch, oil, dietary fibers, pulp and paper |
| Whole crop biorefineries | Whole crop (including straw) cereals such as rye, wheat and maize | Dry or wet milling, biochemical conversion | Pilot plant (and Demo) | Starch, ethanol, distiller's dried grains with solubles |
| Oleochemical biorefineries | Oil crops | Pretreatment, chemical catalysis, fractionation, separation | Pilot plant, Demo, commercial | Oil, glycerin, cattle feed |
| Lignocellulosic feedstock biorefineries | Lignocellulosic-rich biomass: e.g., straw, chaff, reed, miscanthus, wood | Pretreatment, chemical and enzymatic hydrolysis, catalysis, fermentation, separation | R&D/Pilot plant (EC), Demo (USA) | Cellulose, hemicelluloses, lignin |
| Green biorefineries | Wet biomass: green crops and leaves, such as grass, lucerne and clover, sugar beet leaf | Pretreatment, pressing, fractionation, separation, digestion | Pilot plant (and R&D) | Proteins, amino acids, lactic acid, fibers |
| Marine biorefineries | Aquatic biomass: microalgae and macroalgae (seaweed) | Cell disruption, product extraction and separation | R&D, pilot plant and Demo | Oils, carbohydrates, vitamins |

is expected to generate more feedstocks, technologies, and coproducts, inevitably offering all kinds of economic opportunities. Research and development will speed up agricultural and rural development, increase industrial development, and open existing and newly created markets. It can be foreseen, however, that biorefinery technologies will develop gradually over time, because the more fractions are obtained the more markets should be served. All these markets dictate that raw materials and intermediates are available at a rather constant supply and therefore prices. The build up of this raw material supply will take time.

The current status of biorefineries is exemplified in a strengths, weaknesses, opportunities, and threats analysis of biorefineries are presented in Table 1.7.

**Table 1.7** Strengths, weaknesses, opportunities, and threats (SWOT) analysis on biorefineries

| **Strengths** | **Weaknesses** |
|---|---|
| • Adding value to the sustainable use of biomass.<br>• Maximizing biomass conversion efficiency—minimizing raw material requirements.<br>• Production of a spectrum of biobased products (food, feed, materials, chemicals) and bioenergy (fuels, power, and/or heat) feeding the full biobased economy.<br>• Strong knowledge infrastructure available to tackle both nontechnical and technical issues potentially hindering the deployment trajectory.<br>• Biorefinery is not new, in some market sectors (food, paper…) it is common practice. | • Broad undefined and unclassified area.<br>• Involvement of stakeholders of different market sectors (agro, energy, chemical…) over full biomass value chain necessary.<br>• Most promising biorefinery processes/concepts not clear.<br>• Most promising biomass value chains, including current/future market volumes/prices, not clear.<br>• Studying and concept development instead of real market implementation.<br>• Variability of quality and energy density of biomass. |
| **Opportunities** | **Threats** |
| • Makes a significant contribution to sustainable development.<br>• Challenging national, European and global policy goals—international focus on sustainable use of biomass for the production of bioenergy.<br>• International consensus on the fact that biomass availability is limited so that the raw materials should be used as efficiently as possible—i.e., development of multipurpose biorefineries in a framework of scarce raw materials and energy.<br>• International development of a portfolio of biorefinery concepts, including composing technical processes.<br>• Strengthening of the economic position of various market sectors (e.g., agriculture, forestry, chemical, and energy). | • Economic change and drop in fossil fuel prices.<br>• Fast implementation of other renewable energy technologies feeding the market requests.<br>• No level playing field concerning biobased products and bioenergy (assessed to a higher standard).<br>• Global, national, and regional availability and contractibility of raw materials (e.g., climate change, policies, logistics).<br>• (High) investment capital for pilot and demo initiatives difficult to find, and existing industrial infrastructure is not depreciated yet.<br>• Fluctuating (long-term) governmental policies.<br>• Questioning of food/feed/fuels (land use competition) and sustainability of biomass production.<br>• Goals of end users often focused upon single product. |

Biorefineries can provide a significant contribution to sustainable development, generating added value to sustainable biomass use and producing a range of biobased products (food, feed, materials, chemicals, fuels, power, and/or heat) at the same time. This requires optimal biomass conversion efficiency, thus minimizing feedstock requirements while at the same time strengthening economic viability of (e.g., agriculture, forestry, chemical and energy) market sectors. As biomass availability is limited, it should be used efficiently, effectively producing materials and energy in multi-purpose biorefineries. The use of the "Biorefinery Complexity Index/BCI" might add additional relevant information on the assessment and comparison of different biorefinery systems. It is concluded that the BCI is potentially relevant for industry, decision makers as well as investors as additional information is generated to assist them in their strategies to implement the most promising biorefinery systems by minimizing technical and economic risks. The perceived conflict between energy and food production can be allayed by developing technologies based on lignocellulosic materials but it was discussed before that this currently results in a much higher BCI. Biorefining requires further innovation but offers opportunities to all economic sectors. Building a biobased economy can help to overcome present difficulties while laying the foundation of an environmentally benign industry.

One of the key prerequisites of a successful biorefinery is to invite key stakeholders from separate backgrounds (agriculture/forestry, transportation fuels, chemicals, energy, etc.) to discuss common processing topics, foster necessary R&D trajectories and stimulate deployment of developed technologies in multi-disciplinary partnerships. Optimal economic and environmental performance can be further guaranteed by linking the most promising biobased products, that is, food, feed, (fiber-based) added-value materials and (functionalized and platform) chemicals with bioenergy production.

## REFERENCES

1. Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, et al. The path forward for biofuels and biomaterials. *Science* 2006;**311**:484–9.
2. Cherubini F, Jungmeier G, Wellisch M, Willke T, Skiadas I, van Ree R, et al. Toward a common classification approach for biorefinery systems. *Biofuels Bioprod Bioref* 2009;**3**(5):534–46.
3. de Jong E, Higson A, Walsh P, Wellisch M. Product developments in the bio-based chemicals arena. *Biofuels Bioprod Bioref* 2012;**6**:606–24.
4. de Jong E, Langeveld H, van Ree R. *IEA Bioenergy Task 42 biorefinery*. 2009. http://www.iea-bioenergy.task42-biorefineries.com/upload_mm/8/5/4/2e500e0f-d19a-4f7f-9360-4e9d5e580b75_Brochure%20Totaal_definitief_HR%5B1%5D.pdf.
5. Jungmeier G, Hingsamer M, van Ree R. *Biofuel-driven biorefineries. A selection of the most promising biorefinery concepts to produce large volumes of road transportation biofuels by 2025*. 2013. http://www.iea-bioenergy.task42-biorefineries.com/upload_mm/b/6/4/8d4294a1-9021-4360-adb3-a76c8b309519_Biofuel-driven%20Biorefineries%20Report%20LR%20February%202013.pdf.
6. de Jong E, Higson A, Walsh P, Wellissch M. Bio-based chemicals, value added products from biorefineries. In: *IEA Bioenergy Task 42 report*. 2012. http://www.ieabioenergy.com/wp-content/uploads/2013/10/Task-42-Biobased-Chemicals-value-added-products-from-biorefineries.pdf.
7. Jungmeier G, Stichnothe H, de Bari I, Jørgensen H, Van Ree R, de Jong E, et al. A biorefinery fact sheet for the sustainability assessment of energy driven biorefineries. Efforts of IEA Bioenergy Task 42 "biorefining". In: *Conference proceedings of the 21st European biomass conference, Copenhagen, Denmark*. June 2013.
8. Sanders J, Scott E, Weusthuis R, Mooibroek H. Bio-refinery as the bio-inspired process to bulk chemicals. *Macromol Biosci* 2007;**7**:105–17.
9. de Jong E, van Ree R, Sanders JPM, Langeveld H. Biorefineries: giving value to sustainable biomass use. In: Langeveld H, Meeusen M, Sanders J, editors. *The biobased economy: biofuels, materials and chemicals in the post-oil era*. London: Earthscan Publishers; 2010. (Chapter 7) p. 111–30.

10. Kamm B, Kamm M. Biorefinery – systems. *Chem Biochem Eng Q* 2004;**18**(1):1–6.
11. Kamm B, Kamm M. Principles of biorefineries. *Appl Microbiol Biotechnol* 2004;**64**:137–45.
12. Cherubini F. *Life cycle assessment of biorefinery systems based on lignocellulosic raw materials – concept development, classification and environmental evaluation* (PhD thesis). Austria: University of Technology at Graz; 2009.
13. Jungmeier G, Cherubini F, Dohy M, de Jong E, Jørgensen H, Mandl M, et al. Definition and classification of biorefinery systems? The approach in IEA Bioenergy Task 42 biorefineries. In: *Presentation held at the biorefinery course adding value to the sustainable utilisation of biomass. Ghent, Belgium*. June 12, 2009.
14. Ekhart J. Van Groningen tot Oekraïne. Verslag van een speurtocht naar de tien buitenlandse fabrieken van Willem Albert Scholten. In: *Dutch, 'From Groningen to the Ukrain. Report of a search to the ten foreign factories of Willem Albert Scholten'*. Groningen: Egbert Forsten & Profiel; 1999.
15. Wolff G. Franz Karl Achard, 1753–1821, A contribution to the cultural history of sugar. *Med Monatsschrift* 1953;**7**(4):253–4.
16. Wagemann K, Benzing T, Böhland T, Fritsche UR, Fröhling M, Gröngröft A, et al. *Biorefineries roadmap*. Gülzow: Agency for Renewable Resources (FNR); 2012. http://www.bmbf.de/pub/BMBF_Roadmap-Bioraffinerien_en_bf.pdf
17. Kazmi A, editor. *Advanced oil crop biorefineries*. Cambridge: RSC Green Chem. No.14, RSC Publ.; 2012.
18. Abraham TW, Höfer R. Lipid-based polymer building blocks and polymers. In: Matyjaszewski K, Möller M, editors. *Polymer science: a comprehensive reference*. McGrath JE, Hickner MA, Höfer R, editors. *Polymers for a sustainable environment and green energy*, vol. 10. Amsterdam: Elsevier; 2012. p. 15–58.
19. Dinjus E, Arnold U, Dahmen N, Höfer R, Wach W. Green fuels – sustainable solutions for transportation. In: Höfer R, editor. *Sustainable solutions for modern economies*. Cambridge: RSC Green Chem. No 4, RSC Publ.; 2009. p. 125–63.
20. Egeberg RG, Michaelsen NH, Skyum LHT. *Novel hydrotreating technology for production of green diesel*. Technical Info Haldor Topsøe. http://www.topsoe.com/file/novel-hydrotreating-technology-production-green-diesel. January 01, 2009.
21. de Jong E, Gosselink RJA. Lignocellulose-based chemical products. In: Gupta VK, Kubicek CP, Saddler J, Xu F, Tuohy MG, editors. *Bioenergy research: advances and applications*. Amsterdam (The Netherlands): Elsevier; 2014. p. 277–313, ISBN: 978-0-444-59561-4.
22. Windeisen E, Wegener G. Lignin as building unit for polymers. In: Matyjaszewski K, Möller M, editors. *Polymer science: a comprehensive reference*. McGrath JE, Hickner MA, Höfer R, editors. *Polymers for a sustainable environment and green energy*, vol. 10. Amsterdam: Elsevier; Oxford: Waltham; 2012. p. 255–65.
23. Chambost V, Stuart PR. Selecting the most appropriate products for the forest biorefinery. *Ind Biotechnol* 2007;**3**(2):112–9.
24. Chambost V, Eamer B, Stuart PR. Forest biorefinery: getting on with the job. *Pulp Pap Can* 2007;**108**(2):18–22.
25. Mleziva MM, Wang JH. Paper. In: Matyjaszewski K, Möller M, editors. *Polymer science: a comprehensive reference*. McGrath JE, Hickner MA, Höfer R, editors. *Polymers for a sustainable environment and green energy*, vol. 10. Amsterdam: Elsevier; Oxford: Waltham; 2012. p. 397–410.
26. Axegård P, Karlsson M, McKeogh P, Westenbroek A, Petit-Conil M, Eltrop, et al. *A bio-solution to climate change. Final report of the biorefinery taskforce to the forest-based sector technology platform*. 2007. http://www.forestplatform.org/.
27. Huber GW. *Breaking the chemical and engineering barriers to lignocellulosic biofuels: next generation hydrocarbon biorefineries*. National Science Foundation. Chemical, Bioengineering, Environmental, and Transport Systems Division; 2008. http://www.ecs.umass.edu/biofuels/Images/Roadmap2-08.pdf.
28. Huber GW, Chheda JN, Barrett CJ, Dumesic JA. Production of liquid alkanes for transportation fuel from biomass-derived carbohydrates. *Science* 2005;**308**:1446–50.
29. Román-Leshkov Y, Chheda JN, Dumesic JA. Phase modifiers promote efficient production of hydroxymethylfurfural from fructose. *Science* 2006;**312**:1933–7.
30. Zhao H, Holladay JE, Brown H, Zhang ZC. Metal chlorides in ionic liquid solvents convert sugars to 5-hydroxymethylfurfural. *Science* 2007;**316**:1597–600.
31. de Jong E, Vijlbrief T, Hijkoop R, Gruter G-JM, van der Waal JC. Promising results with YXY diesel components in an ESC test cycle using a PACCAR diesel engine. *Biomass Bioenergy* 2012;**36**:151–9.

32. van Putten R-J, van der Waal JC, de Jong E, Rasrendra CB, Heeres HJ, de Vries JG. Hydroxymethylfurfural, a versatile platform chemical made from renewable resources. *Chem Rev* 2013;**113**:1499–597.
33. de Jong E, Dam MA, Sipos L, Gruter G-JM. Furandicarboxylic acid (FDCA), a versatile building block for a very interesting class of polyesters. In: Smith PB, Gross R, editors. *ACS symposium series "biobased monomers, polymers and materials"*. 2012. p. 1–13. http://dx.doi.org/10.1021/bk-2012-1105.ch001.
34. Mandl MG. Status of green biorefining in Europe. *Biofuels Bioprod Biorefining* 2010;**4**:268–74.
35. Schaffenberger M, Ecker J, Koschuh W, Essl R, Mandl MG, Boechzelt HG, et al. Green biorefinery – production of amino acids from grass silage juice using an ion exchanger device at pilot scale. *Chem Eng Trans* 2012;**29**:505–10.
36. Sanders JPM. *Renewable resources and biorefineries*. September 19, 2005. Gent http://www.rrbconference.ugent.be/presentations/sanders%20Johan.pdf. [accessed 15.06.09].
37. Hulst AC, Ketelaars J, Sanders J. Separating and recovering components from plants. US patent 6740342; 1999.
38. Sanders JPM, Van der Hoeven DA, Van Dijk C. *Voorwaartse integratie in de akkerbouw*. Utrecht (the Netherlands): InnovatieNetwerk; 2008. ISBN: 978-90-5059-352-6.
39. Werpy T, Petersen G. *Top value added chemicals from biomass, volume 1 results of screening for potential candidates from sugars and synthesis gas*. 2004. [Online 2004]. Available at: http://www1.eere.energy.gov/biomass/pdfs/35523.pdf.
40. Bozell JJ, Petersen GR. Technology development for the production of biobased products from biorefinery carbohydrates – the US Department of Energy's "Top 10" revisited. *Green Chem* 2010;**12**:539–54.
41. Kokossis AC, Yang A. On the use of systems technologies: a systematic approach for the synthesis and design of future biorefineries. *Comput Chem Eng* 2010;**34**(9):1397–405.
42. Neste Oil. *NExBTL® Renewable diesel singapore plant tallow pathway description*. http://www.arb.ca.gov/fuels/lcfs/2a2b/apps/neste-aus-rpt-031513.pdf [accessed 17.08.14].
43. Pascault J-P, Höfer R, Fuertes P. Mono-, di, and oligosaccharides as precursors for polymer synthesis. In: Matyjaszewski K, Möller M, editors. *Polymer science: a comprehensive reference*. McGrath JE, Hickner MA, Höfer R, editors. *Polymers for a sustainable environment and green energy*, vol. 10. Amsterdam: Elsevier; Oxford: Waltham; p. 59–82.
44. Kraus RS. Exploration, drilling and production of oil and natural gas. In: Kraus RS, editor. *75. oil exploration and distribution*. J.M. Stellman, editor-in-chief. *Encyclopedia of occupational health and safety*. Geneva: International Labor Organization; 2011.
45. Klaber KZ. Natural gas production in the Marcellus and Utica shales. In: *Pittsburgh chemical day (Sept. 25) with reference to pace Global's NiSource Gas Transmission and Storage presentation to WVONGA (May 6, 2010)*. 2012.
46. Bader HJ, Horn S, Fehrenbacher U, Grosshardt O, Kowollik K, Pohsner U, et al. *Informationsserie Nachwachsende Rohstoffe* 2009. 64 p. https://www.vci.de/vci/Downloads-vci/textheft_farbig.pdf.
47. Pagliaro M, Rossi M. *The future of glycerol*. 2nd ed. Cambridge: RSC Green Chemistry No. 8, RSC Publ.; 2010.
48. Huber GW, O'Connor P, Corma A. Processing biomass in conventional oil refineries: production of high quality diesel by hydrotreating vegetable oils in heavy vacuum oil mixtures. *Appl Cat A Gen* 2007;**329**:120–9.
49. Brandin J, Hulteberg C, Nilsson AL. *Bio-propane from glycerol for biogas addition*. Malmö: Rapport SGC 198, Svenskt Gastekniskt Center; 2008.
50. Keim W. C1 chemistry: potential and developments. *Pure Appl Chem* 1986;**58**:825–32.
51. Bare SR. Methanol to olefins (MTO): development of a commercial catalytic process. In: *Modern methods in heterogeneous catalysis research, FHI lecture Nov. 30*. 2007. http://www.fhi-berlin.mpg.de/acnew/department/pages/teaching/pages/teaching__wintersemester__2007_2008/bare_mto_301107.pdf.
52. Mathers RT. How well can renewable resources mimic commodity monomers and polymers? *J Pol Sci A Pol Chem* 2012;**50**:1–15.
53. Chayot R. Direct fermentation for isobutene, butadiene and propylene production: a highway to renewable plastics, synthetic rubber and fuels. In: *AIChE proceedings metabolic engineering X*. 2014. http://www3.aiche.org/proceedings/Abstract.aspx?PaperID=354187.
54. Chen L, Ren S, Re XP. Lactic acid production from glycerol using CaO as solid base catalyst. *Fuel Process Technol* 2014;**120**:40–7.

55. Haas T, Kircher M, Köhler T, Wich G, Schörken U, Hagen R. White biotechnology. In: Höfer R, editor. *Sustainable solutions for modern economies*. Cambridge: RSC Green chemistry, No. 4, RSC Publ.; 2010. p. 436–74.
56. Qureshi N, Blaschek HP. Recent advances in ABE fermentation: hyper-butanol producing *Clostridium beijerinckii* BA101. *J Ind Microbiol Biotechnol* 2001;**27**:287–91.
57. de Guzman D. *Chemical industry awaits for bio-succinic acid potential*. ICIS Chemical Business; 2012. http://www.icis.com/resources/news/2012/01/30/9527521/chemical-industry-awaits-for-bio-succinic-acid-potential/.
58. Cok B, Tsiropoulos I, Roes AL, Patel MK. Succinic acid production derived from carbohydrates: an energy and greenhouse gas assessment of a platform chemical toward a based economy. *Biofuels Bioprod Bioref* 2014;**8**:16–29.
59. Patel A, Meesters K, den Uil H, de Jong E, Blok K, Patel M. Sustainability assessment of novel chemical processes at early-stage: application to biobased processes. *Energy Environ Sci* 2012;**5**:8430–44.
60. Patel AD, Meesters K, den Uil H, de Jong E, Patel MK. Early stage comparative assessment of novel biobased processes. *ChemSusChem* 2013;**6**:1724–36.
61. Jungmeier G. *The biorefinery complexity index*. 2014. http://www.iea-bioenergy.task42-biorefineries.com/upload_mm/6/2/f/ac61fa53-a1c0-4cbc-96f6-c9d19d668a14_BCI%20working%20document%2020140709.pdf.