Chapter 5.

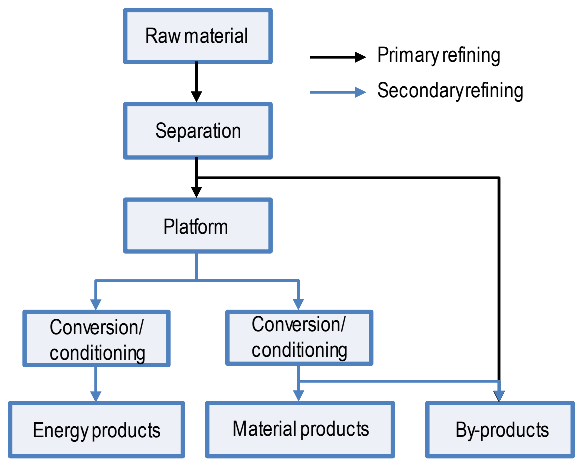
What is a biorefinery:
Definitions, classification and general models

This chapter explores biorefinery models and their status, setting the stage for later chapters that focus more on public policy. Biorefinery models have evolved according to needs from the first ethanol mills using food crops as feedstocks to more complex (and more expensive) models using feedstocks other than food crops. The ultimate goal is the widespread application of the integrated biorefinery that can use multiple feedstocks and generate multiple products (fuels, chemicals, materials, electricity). However, these are still not ready for the market and are seen as high-risk investments. Building the first-of-kind flagship plants is proving difficult. Meanwhile, marine biorefineries, which offer similar advantages, remain difficult to design and build. And other yet more novel biorefinery concepts are arising.

Introduction

Definitions of a biorefinery are important for gathering data, observing trends and investing public funds. It is necessary then, to identify what actually happens in a generalised model of a biorefinery and then explore the different models and definitions. Figure 5.1 is a schematic of general processes and the order in which they occur.

Figure 5.1. **General schematic of a biorefinery**



Source: Peters (2011), "The German biorefinery roadmap".

Box 5.1. **Examples of definitions of biorefinery**

The term "green biorefinery" has been defined as "complex systems based on ecological technology for comprehensive (holistic), material and energy utilization of renewable resources and natural materials using green and waste biomass and focalising on sustainable regional land utilization". The term "complex systems" can now be regarded as "totally integrated systems" (Kamm et al., 1998).

According to Kamm et al. (2007, 2006), the US Department of Energy (DOE) uses the following definition: "A biorefinery is an overall concept of a processing plant where biomass feedstocks are converted and extracted into a spectrum of valuable products. Its operation is similar to that of petrochemical refineries".

The US National Renewable Energy Laboratory (NREL) uses the following definition: "A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power and chemicals from biomass. The biorefinery concept is analogous to today's petroleum refineries, which produce multiple fuels and products from petroleum. Industrial biorefineries have been identified as the most promising route to the creation of a new domestic biobased industry".

The International Energy Agency (IEA) describes the biorefinery as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)". This means that biorefinery can be a concept, a facility, a process, a plant or even a cluster of facilities.

A future definition of biorefinery could include processes that use living organisms to convert waste products from non-biogenic sources, including CO_2 from fossil fuel combustion.

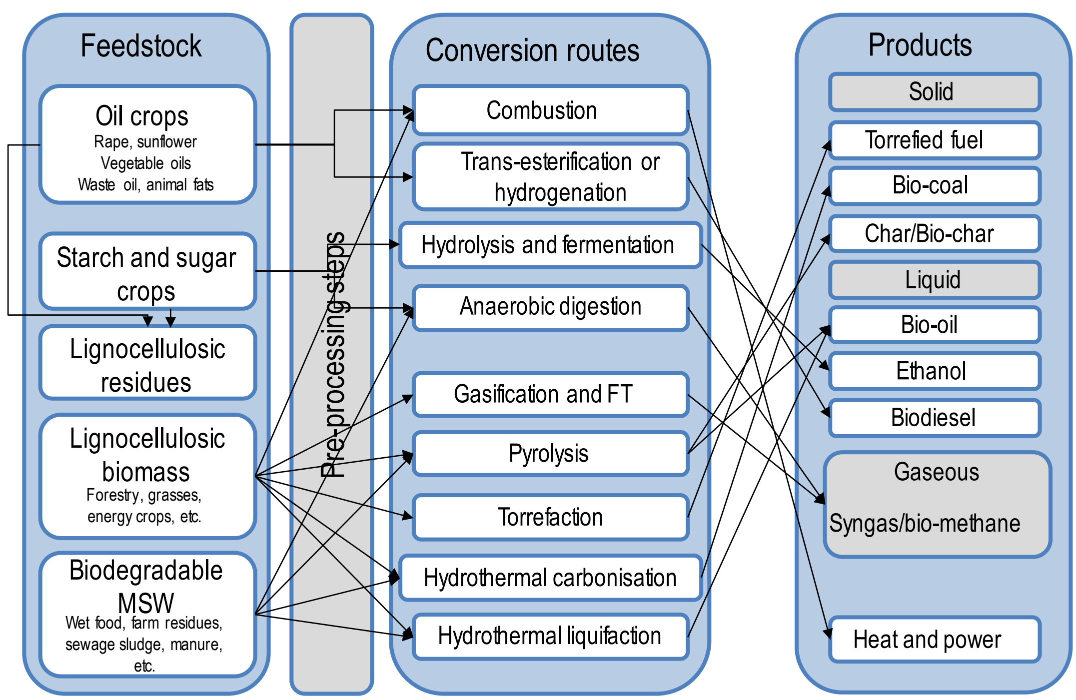
Sources: Kamm, B. et al. (2007), "Biorefineries – industrial processes and products"; Kamm, B. et al. (2006), "Biorefinery systems – an overview"; Kamm, B. et al. (eds.) (1998), "Die grüne Bioraffinerie"; Schieb, P.-A. et al. (2015), *Biorefinery 2030: Future Prospects for the Bioeconomy*, http://dx.doi.org/10.1007/978-3-662-47374-0.

The International Energy Agency (IEA Bioenergy Task 42 Biorefinery, 2012) described a biorefinery as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)". This definition suggests that biorefineries should produce both non-energetic and energetic outputs, and applies to product-driven biorefinery processes. Both primary products and energy-driven processes are considered as true biorefinery approaches provided the final goal is the sustainable processing of biomass (de Jong and Jungmeier, 2015). Some existing definitions of "biorefinery" are shown in Box 5.1.

The IEA biorefinery classification system is useful in clarifying different models in operation and under development. The widespread adoption of the IEA system would help clarify several issues. Its classification approach consists of four main features that can identify, classify and describe the different biorefinery systems: platforms, products (energy and bio-based materials and chemicals), feedstocks and conversion processes.

The raw material or feedstock has a highly varied range of organic materials (containing carbon).[1] Feedstocks can be grouped. Energy crops from agriculture (e.g. starch crops, short rotation forestry) constitute the major feedstocks. Biomass residues from agriculture, forestry, trade and industry (e.g. straw, bark, used cooking oils, waste streams from biomass processing) form another major category; these biorefineries are the most promising for future progress. Even less conventional feedstocks include municipal solid waste (MSW) and waste industrial gases such as CO and H_2 from the steel-making process.

Figure 5.2 **Conversion processes in a fuel biorefinery**



Note: MSW = municipal solid waste.

Concerning conversion processes, the IEA classification system identifies four main groups: biochemical (e.g. fermentation, enzymatic conversion); thermochemical (e.g. gasification, pyrolysis); chemical (e.g. acid hydrolysis, steam explosion, esterification);

and mechanical processes (e.g. fractionation, pressing, size reduction).Energy products can be usually considered as liquid fuels (e.g. ethanol, biodiesel, bio-based jet fuel), but biogas is also possible. Wood chips, pellets and lignin are possible solid fuel outputs. Material products could be any of a large number of bio-based chemicals, plastics and textiles. Energy products might also be residues at the end of the process that can be burned to generate electricity and/or heat. By-products could include animal feed and soil conditioners.

The diversity of biorefineries is already large, and Figure 5.2, showing different feedstocks and conversion processes, testifies to this diversity.

The IEA Biorefinery Complexity Index

All current models of biorefineries are high-risk investments, and even Brazilian ethanol mills have gone through difficult times. The industry has had a spate of bankruptcies, a problem caused by the global financial crisis, adverse weather and low sugar prices (Soybean and Corn Advisor, 2015). Biorefineries range from single feedstock-single product operations to multiple feedstock-multiple products. In other words, the complexity of biorefineries varies greatly. Arguably, prospects for economic viability mount in tandem with complexity. When conditions dictate, one feedstock can be replaced by another, and the product stream can be changed.

However, different degrees of complexity make it challenging for industry, decision makers and investors to identify the most promising short-, medium- and long-term options, including their technological and economic risks. In response, IEA Bioenergy Task 42 published a Biorefinery Complexity Index (BCI) that can help calculate the complexity of some selected biorefinery concepts (Jungmeier, 2014). It bears a strong resemblance to the Nelson Index used in petro-refineries. The Nelson Index is an indicator for the investment intensity, cost index and value addition potential of the refinery, and the refinery's ability to process feedstocks into value-added products (Wikipedia, n.d.). As the refinery becomes more complex, it is also considered to be more flexible.

The number of features in the biorefinery – used to calculate the "Feature Complexity Index" (FCI) – and the "Technology Readiness Level" (TRL) make up the essence of the BCI calculation. With each new feature in a biorefinery, the complexity increases. A high TRL of a feature has lower technical and economic risks, and so a lower complexity. Thus, the number of features determines the complexity of a commercial application, in which all features are commercially available. Conversely, in non-commercial applications, the FCI and TRLs both increase the complexity of the biorefinery system.

The TRL can assess each of a biorefinery's four features (platforms, feedstocks, products and processes) using standard descriptions from 1 (lowest) to 9 (highest, with the system proven and ready for full commercial deployment (see also Chapter 8). The feature complexity (FC) for each single feature of a biorefinery is calculated based on the TRL. Once the number of features and the FC of each single feature are known, the FCI for each of the four features can be calculated. The BCI is the sum of the four FCIs. The Biorefinery Complexity Profile (BCP) is introduced to simplify the presentation. Jungmeier (2014) provides details of how to make the appropriate calculations.

Equation 5.1. The biorefinery complexity profile

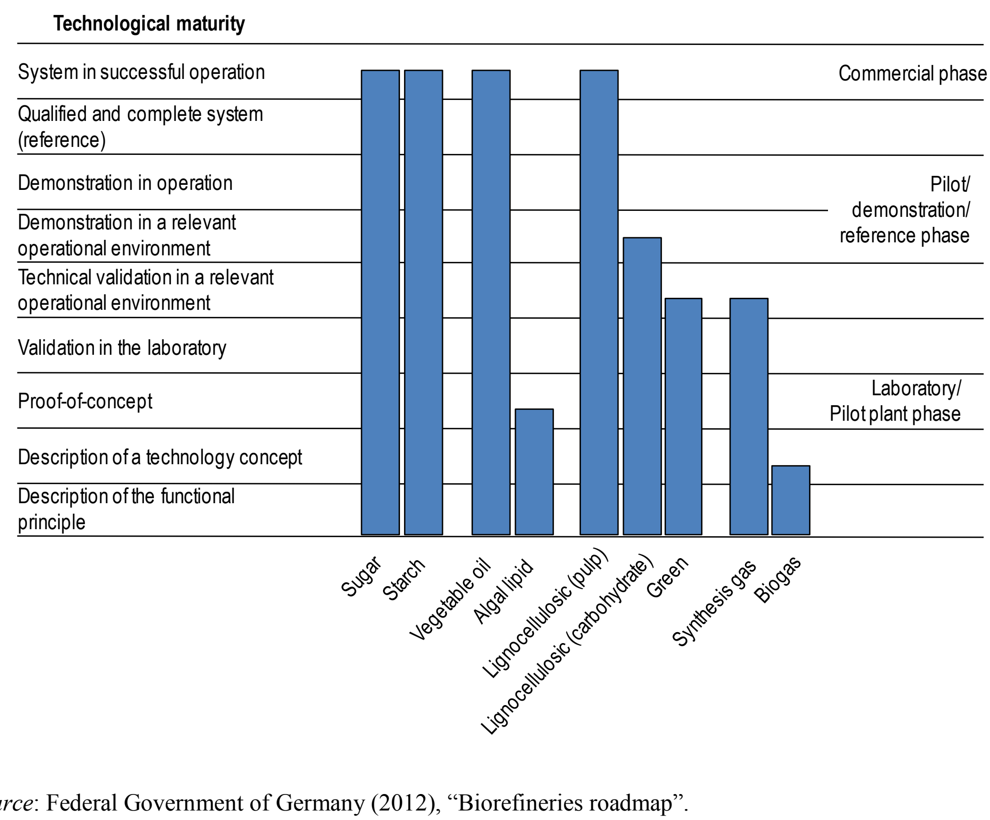
$$BCP = BCI \text{ x } (FCI_{Platforms}/FCI_{Feedstocks}/FCI_{Products}/FCI_{Processes})$$

The BCP and the BCI arguably can compare different biorefinery concepts and their development potential. As the BCI increases, the biorefinery moves increasingly beyond "state of the art". Furthermore, this system is flexible as it can consider changes in TRL of features through research and development. It can therefore help address the economic and technical risks for any given biorefinery project or concept. This, in turn, will help public- and private-sector investors make decisions.

Biorefinery types: A brief description

There are myriad different concepts arising for different biorefineries. However, these are concentrated into a small number of what can be seen as biorefinery "types". Many are described in the literature, such as The Biorefinery Roadmap (2012) (Federal Government of Germany, 2012). Excellent unit process descriptions are found in the Star-COLIBRI (2011) European Biorefinery Joint Strategic Research Roadmap. The former is especially helpful (Figure 5.3) as it also estimated the status of technological development at the time of publication. Things have moved on since 2012, but this status has not really changed significantly. Changes, too, can be described.

Figure 5.3. **Development status of various biorefinery models**

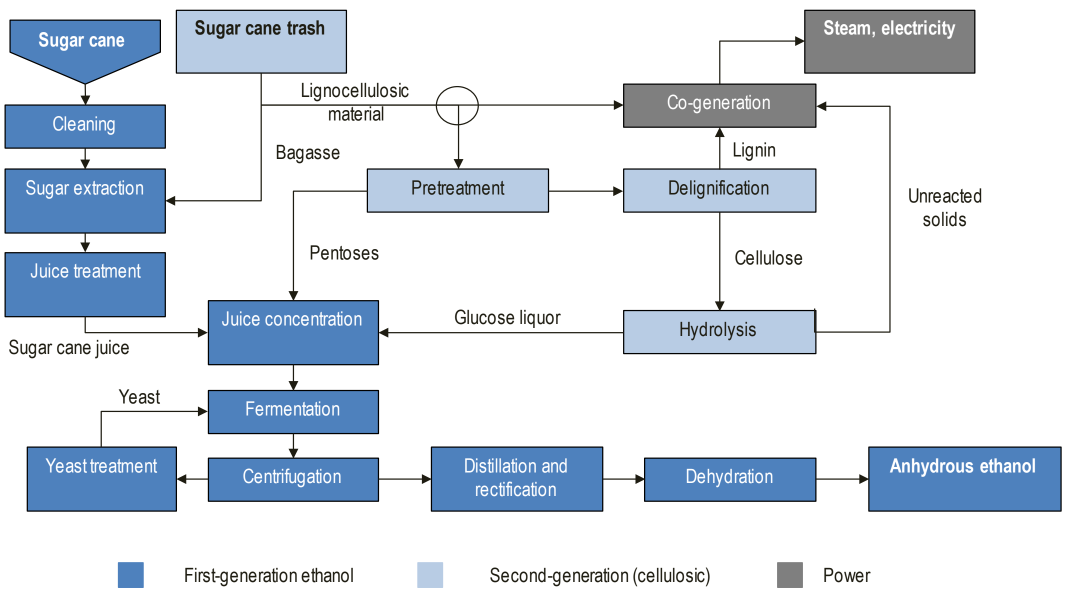


Source: Federal Government of Germany (2012), "Biorefineries roadmap".

The typical sugar cane biorefinery

In terms of economic sustainability, Brazilian sugar cane is the most favoured feedstock for biorefineries at present (e.g. UK Bioenergy Strategy, 2012). As of 2011, Brazil had 490 sugar cane ethanol plants and biodiesel plants (BRBIOTECH-CEBRAP, 2011). As of mid-2016, for various reasons, this number had declined to somewhere around 300 operational sugar cane/ethanol plants, with some of the closures permanent. Figure 5.4 shows the first-generation bioethanol production process from sugar cane. The typical Brazilian ethanol mill has a processing capacity of 500 tonnes of sugar cane per hour (wet basis), equivalent to 2 million tonnes per year. At the industrial level, most sugar cane in Brazil is processed through an integrated production chain, allowing sugar production, industrial ethanol processing and electricity generation from by-products. The typical steps for large-scale, highly optimised production of sugar and ethanol include milling, electricity generation, fermentation, distillation of ethanol and dehydration.

Figure 5.4. **Integrated first- and second-generation ethanol production from sugar cane**



Source: Dias et al. (2013), "Biorefineries for the production of first- and second-generation ethanol and electricity from sugar cane".

In the Brazilian sugar cane industry, large amounts of lignocellulosic materials, especially bagasse, are readily available, typically as by-products of sugar and ethanol. Most of the bagasse produced in the mills, where sugar cane juice is separated from the fibre, supplies energy for the bioethanol production process in cogeneration systems. It is commercially and technically feasible in Brazil to sell sugar cane lignocellulosic fractions to the grid as fuels in electricity production (Cardona et al., 2010). If electricity prices are favourable, more lignocellulosic material may be diverted for production of steam and electricity (see the circle on Figure 5.4). The opposite occurs when ethanol prices are more attractive (Dias et al., 2013).

Lignocellulosic or cellulosic biorefinery

Lignocellulose is composed of carbohydrate polymers (cellulose, hemicellulose), and an aromatic polymer (lignin). It is the most abundant raw material for biorefining as it contains large amounts of fermentable sugars. However, the sugars needed for fermentation are tightly bonded within the lignocellulose. This becomes a barrier to using lignocellulose from biomass in biorefining. Much of the technical effort to unleash this vast bounty for biorefining is related to overcoming this recalcitrance of the feedstock; the "conversion" has been the bottleneck.

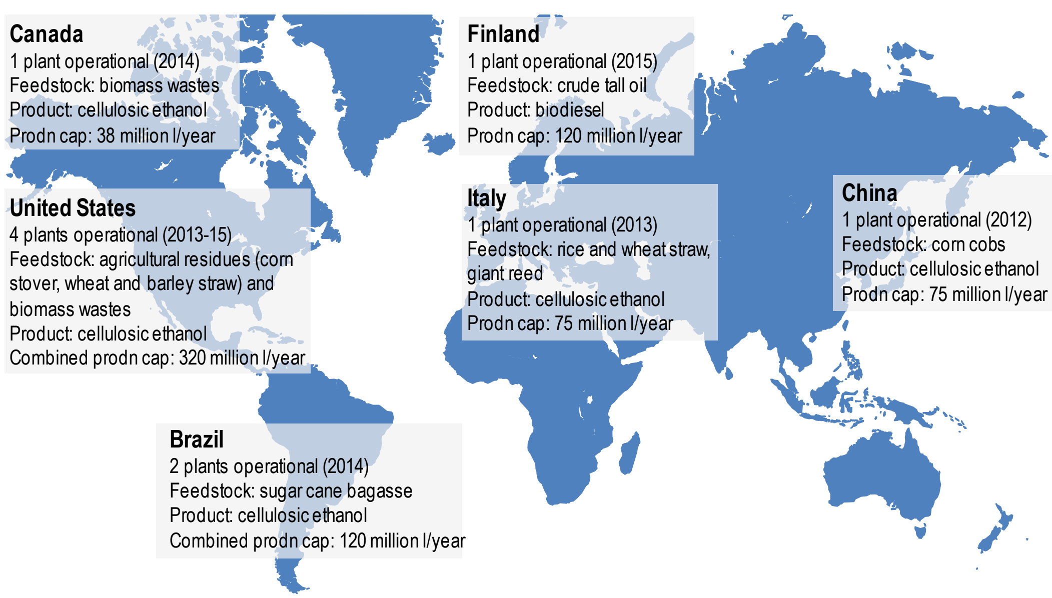
Lignocellulosic biomass can be grouped into four main categories (Tan, Yu and Shang, 2011):

1. agricultural residues (e.g. corn stover and sugar cane bagasse)
2. dedicated energy crops
3. wood residues (including sawmill and paper mill discards)
4. municipal paper waste.

Costs vary between types of plants. Second-generation biofuel plants may have capital costs five times greater than starch ethanol plants (Wright and Brown, 2007). For first-generation bioethanol, the most significant cost was feedstock (Carriquiry et al., 2011). About 40-60% of the total operating cost of a typical biorefinery is related to the feedstocks chosen (Parajuli et al., 2015). However, the most significant cost for second-generation cellulosic biofuels may be conversion of woody biomass into fermentable sugars.

A crisis of sorts has arrived in cellulosic biorefining. Through its Renewable Fuels Standard (RFS), the US Environmental Protection Agency (EPA) is enforcing 230 million gallons of cellulosic biofuel blending for 2016. The RFS statute, however, nominally requires 4.25 billion gallons, which represents a 95% reduction. Technical problems surrounding conversion have proven so intractable that only a handful of these biorefineries have become commercially viable (Figure 5.5).

Figure 5.5. **Global capacity in cellulosic biorefining**



Note: prodn cap = production capacity; l = litre.

As a result of these technical barriers and policy uncertainty, investments in these biorefineries have been drastically reduced. A new one was approved for construction in July 2016 in Renfrew, Ontario, Canada. However, it may be the only commercial-scale cellulosic biofuel project that has gained approval anywhere in the world over the past two years. Financing for the Renfrew plant is overwhelmingly from the public sector. It will convert forestry waste into Ensyn biocrude for further processing in oil refineries. The California Air Resources Board granted key regulatory approvals to Ensyn pursuant to the low-carbon fuel standard on the company's application for its biocrude renewable fuel oil. California oil refineries will use it in co-processing (Biodiesel Magazine, 2016).

Waste biorefineries: Rubbish to bio-based products and electricity

Although they can be categorised as lignocellulosic biorefineries, domestic waste biorefineries are treated separately here to highlight their future potential. The use of domestic waste materials as feedstock for biorefineries promises to be the most sustainable approach, provided waste materials are collected efficiently. A large amount of waste is available for feedstock, but political will is needed to create incentives for its collection.

Using municipal waste not only reduces the amount of waste going to landfills, it also breaks the link between food crops and bioethanol production. At full production, the waste biorefinery in Vero Beach, Florida, for example, (INEOS, 2013) is expected to produce 8 million gallons of advanced cellulosic bioethanol and 6 megawatts (gross) of renewable power. It uses renewable biomass including yard, vegetative and agricultural wastes. The waste material goes through a gasification process to create synthesis gas (syngas). Syngas can then be used to manufacture a range of chemicals, either through synthetic chemistry or fermentation (Latif et al., 2014). The heat recovered from the hot syngas is fed into a steam turbine and used to generate renewable electricity. The renewable electricity powers the facility; the excess electricity is expected to power as many as 1 400 homes in the Vero Beach community. A relatively small facility, it has 60 full-time employees and provides USD 4 million annually in payroll to the local community.

The Vero Beach project is also a good example of a public-private partnership (PPP). These are deemed to be a way to get high-risk biorefineries built in the absence of substantial interest from venture capital investors. Ineos Bio and New Planet Energy, Florida, in a PPP with the US Department of Energy (USD 50 million cost-matched grant) and the US Department of Agriculture (USD 75 million loan guarantee), have constructed this waste biorefinery.

Algal biorefineries

Both micro- and macroalgae are extremely promising feedstocks for future biorefineries for a variety of reasons (IEA Bioenergy Task 39, 2011). First, the land requirement for algae is much less than for terrestrial crops, thus alleviating pressure on food crops. Second, they grow rapidly and have a higher solar conversion efficiency than most terrestrial plants. Third, they can be harvested batch-wise or continuously almost all year-round. Fourth, they can use waste CO_2 sources, thereby potentially mitigating the release of GHGs into the atmosphere. Finally, they could generate a vast amount of oil compared to terrestrial crops (Table 5.1); the differences are of magnitude orders.

However, of all the road transport biofuels reviewed by Accenture (2009), algal technology was deemed to be the most difficult and will take the longest to achieve commercial scale. Nonetheless, some companies claim that the first commercial plants will be available soon in various parts of the world, including Australia, Europe, the Middle East, New Zealand and the United States (Pienkos and Darzins, 2009). That prediction of 2009 remains accurate, as marine biorefining still presents large technical challenges. The design and engineering principles for marine biorefining are in their infancy compared to biorefineries for terrestrial crops. The development of stable cultivation technologies – harvesting, product extraction and biorefinery processes – represent the main challenges of algal biotechnology for production of high-value or bulk products.

Genetic engineering for strain improvement and higher product yields, and the need to gain market and regulatory acceptance of such organisms, are other major challenges (Sayre et al., 2013).

Table 5.1. **Oil yields from various terrestrial plants compared to algae**

Crop	Oil yield (gallons/acre)
Corn	18
Cotton	35
Soybean	48
Mustard seed	61
Sunflower	102
Rapeseed	127
Jatropha	202
Oil palm	635
Algae	10 000

Source: Pienkos (2009), "The promise and challenges of microalgal-derived biofuels".

The seaweed (macroalgae) industry is small but mature, and has plenty of scope for expansion. Nearly 7.5-8 million tonnes of wet seaweeds are harvested worldwide per year (Subba Rao and Mantri, 2006), but the treatment of spent seaweed is challenging. Apart from the oil, macroalgae contain various higher-value chemicals, such as plant proteins, alginates and phenolics. Moreover, fermentation of seaweed hydrolysates can produce many by-products, such as glycerol, organic acids (e.g. acetate, succinate), biomass protein and other minor products (Wei et al., 2013). And because seaweed biomass does not contain lignin, residuals after fermentation can be used as animal feed or a feed supplement. Therefore, there is great scope for cascading use of biomass with algae and cyanobacteria (Ducat et al., 2011). For example, a study has examined the production of ethanol from spent biomass generated from the seaweed processing industry using baker's yeast. The process has potential for converting galactose and alginate monomers to bioethanol through fermentation (Sudhakar et al., 2016).

Certain caveats must be invoked when discussing the potential of algal technologies, especially microalgal technologies. Several comprehensive analyses study the design and economics of microalgal processes, but they leave the actual species undetermined. By doing so, the assumptions of the analyses may be inaccurate. With this in mind, the need for rapid, accurate and defendable taxonomic identification of microalgae and cyanobacteria strains is paramount for culture collections, industry and academia, particularly when addressing issues of intellectual property and biosecurity (Emami et al., 2015).

Similarly, there are locations with sufficient year-round levels of sunlight close to plenty of water. Further, they are not far from carbon-intensive industries that can supply inexpensive CO_2. And they have access to developed road and rail networks that can support distribution of raw materials and end products. But these locations are by no means commonplace (Klein-Marcuschamer et al., 2013).

The National Marine Bioenergy Research Centre, in collaboration with the department of Biological Engineering of the Inha University at Incheon, Korea, has tested an experimental algae production system. Algae are produced in semi-permeable membranes in the sea. In this system, no energy for the culturing needs to be added as the sea movement keeps the culture moving. Further, as seawater contains more nutrients than fresh water, no extra nutrients need to be added; they are taken up through the semi-permeable membrane.

The experimental set up produced bioethanol up to three times higher from red or brown algae than from sugar beet or sugar cane, the best performing land energy crops. For production of biodiesel, the yield was even up to ten times higher from microalgae than from oil palm, which is the best performing biodiesel production crop on land. This production system has, in fact, passed all government criteria. The oil produced has better quality than palm biodiesel.

Waste gas and syngas biorefineries

Gas fermentation offers an opportunity to use resources as diverse as industrial waste gases, coal and municipal solid waste (after gasification) to produce fuels and chemicals. A 1995 demonstration at the laboratory scale showed the feasibility of converting gases to bioplastics (Tanaka et al., 1995). Hydrogen, oxygen and CO_2 were converted to a bio-based, biodegradable plastic in the absence of another source of carbon. Other bio-based products have been shown to be feasible at laboratory scale. For example, the steel mill off-gas CO and syngas can be fermented into a variety of useful products, such as ethanol and 2,3-butanediol (Köpke et al., 2011).

However, taking gas fermentation technology to commercialisation has taken a long time. LanzaTech, a waste gas-to-fuel and -chemicals start-up founded in New Zealand, converted steel mill waste gases to ethanol at demonstrator level in 2013. It produced roughly 380 cubic metres (m^3) of ethanol per year at a steel mill near Shanghai in the People’s Republic of China (hereafter “China”) (Pavanan et al., 2013). In 2014, the company closed a USD 60 million investment from the New Zealand Superannuation Fund, a sovereign wealth fund, to develop the technology further.

A system to be built at an ArcelorMittal steel mill in Ghent, Belgium would be about 30 times larger than the Shanghai plant, producing some 47 000 tonnes of ethanol a year (Clark, 2015). It will cost EUR 87 million to install, and the project has received EUR 10 million in EU research funding. If the system at Ghent proves to be commercially viable, ArcelorMittal, the world’s largest steel maker, hopes to install it across its operations. This move could eventually produce up to 10% of Europe’s bioethanol a year.

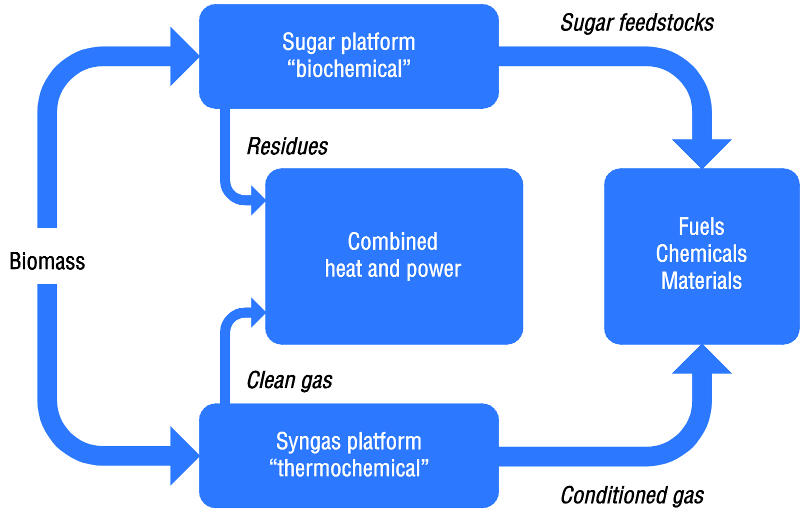
The steel industry has long struggled to deal with its emissions (OECD, 2015). The top three industrial GHG emitters are steel, cement and chemicals. This biorefining technology would help steel makers reduce emissions, and also add value to their core business. It also does not compete for land or interfere with food as no crops are required.

The integrated chemical and biological biorefinery concept

The integrated biorefinery (Figure 5.6) would make full use of all the components of multiple feedstocks (particularly cellulosic). It would produce value-added multiple co-products including energy (electricity and steam) and various bio-based chemicals and plastics, along with fuel-grade ethanol or other fuels. It might even be able to create other products such as paper.

In this concept, chemicals and fuel production are integrated within a single operation where high-value products become an economic driver. These products provide higher margins to support low-value fuel, leading to a profitable biorefinery operation that also exhibits an energy impact. This is how many petrochemical oil refineries operate – the 7-8% of crude oil for chemical production results in 25-35% of the annual profits of integrated petrochemical refineries (Bozell, 2008). Many configurations are possible depending on the choice of chemicals to be manufactured on-site.

Figure 5.6. **Schematic of a generalised integrated biorefinery**



Source: OECD (2017), *The Next Production Revolution*, http://dx.doi.org/10.1787/9789264271036-en.

Such a biorefinery is obviously technically complex, even more so than a petrochemical facility. But it has some advantages compared to single feedstock, single product biorefineries that make this model particularly attractive. First, it can switch between feedstocks and products when, for example, one particular feedstock is too expensive; switching between feedstocks helps cope with seasonal availability (Giuliano et al., 2016). Integration avoids the low-margins trap of producing high-volume fuels (OECD, 2014). Specifically, there is less fractional market displacement required for cost-effective production of high-value co-products as a result of the economies of scale provided by the primary product (Lynd et al., 2005); the economies of scale provided by a full-size biorefinery lower the processing costs of low-volume, high-value co-products. In addition, biorefineries maximise value generated from heterogeneous feedstock, making use of component fractions. Common process elements are involved, lowering the need for equipment duplication, with subsequent decreases in capital cost. Co-production can provide process integration benefits (e.g. meeting process energy requirements with electricity and steam co-generated from process residues). Finally, it can operate like a "waste exchange".

A lesson can be observed from US biodiesel production from soybean oil. Over 2005-08, the price of soybeans doubled. Many biodiesel production plants halted production, delaying construction of new plants (Starkey, 2008). Such issues may be avoidable if low production volume, higher value-added products can also be made at the same site. The integrated biorefinery also gives the flexibility to use different feedstocks if one feedstock is unavailable.

The benefits notwithstanding, several defining challenges are proving difficult to overcome (Cheali et al., 2015). For example, it is difficult to achieve maximum efficiency with improved designs or to expand by integration of conversion platforms or upstream and downstream processes. Other challenges relate to accounting for a wide range of feedstock, processing paths and product portfolios (Tsakalova et al., 2015). Whereas fossil fuel-based processes (i.e. local supply and value chains) formulate local/regional solutions, biorefineries develop solutions on a global basis. Finally, design challenges relate to feedstock characteristics, feedstock quality and availability; trade-offs between energy consumption for feedstock and product distribution, production and product market prices).

Real examples of truly integrated biorefineries are not yet available. This is not the result of low oil and gas prices, but rather due to technical challenges in perfecting processes with waste materials as feedstocks. One suitable candidate is the ARD-BRI complex in northern France, although the feedstocks are food crops (Box 5.2).

Wood biorefineries

Again, there is much cross-over between cellulosic and integrated biorefineries. Some issues are identical, especially the conversion technologies. Wood biorefining makes sense in many countries that have a long history of pulp and paper-making. The relatively high energy density of wood is attractive for transportation purposes. An advantage enjoyed by pulp and paper mills in biorefining stems from the perfected kraft processing of wood. The kraft process converts wood into wood pulp, which consists of almost pure cellulose fibres, the main component of paper. The process treats wood chips with a hot mixture of water, sodium hydroxide and sodium sulphide, known as white liquor; this breaks the bonds that link lignin, hemicellulose and cellulose.

Unlike cellulosic biorefineries, wood contains much more lignin than, say, agricultural residues. Lignin is challenging to biorefine, but remains a major potential source of all manner of aromatic compounds. Aromatics are extremely important industrial chemicals, and bio-based drop-ins or alternatives are not easy to produce. The interest in lignin as a source of chemicals or materials is increasing; processes for lignin isolation from kraft processes are being installed.

The potential of lignin is not just in drop-in alternative chemicals; it is a polymer that can be derivatised for various applications. Lignin epoxide, for example, can be used for printed circuit board, segmented polyurethane plastics and others. The new wood biorefinery processes will produce sulphur-free lignin, which offers several advantages in chemical and material production. Still, despite these advantages, lignin sulphonates and lignin sulphates from "old" pulping processes exhibit performance properties because of the sulphonate and sulphate groups.

Lignin applications are becoming increasingly visible: the amounts of lignin produced annually are huge. The variety of valuable compounds that could be produced from the aromatic lignin could answer doubts over the ability of bio-production to produce aromatics.

Several other future options include: extraction of cellulose fibre and valuable products from bark (e.g. fine chemicals and pharmaceuticals), wood extractives (fatty acids used in products like water-based resins), pulping liquor (carbohydrates used as hydrocolloids, emulsifiers and food ingredients). There are several comprehensive sources of information on the chemistry of wood (e.g. Sjostrom, 1993).

Bioökonomierat (2016) has suggested two major lines of development for innovative wood biorefinery processes that concur with the above analysis:

- digestion of wood with subsequent enzymatic hydrolysis to obtain fermentation feedstocks and lignin
- thermochemical processes that provide fuel or basic chemicals as a result of pyrolysis or gasification.

Box 5.2. **The Agro-industrie recherches et développements biorefinery hub and Bioraffinerie recherches et innovation at Bazancourt-Pomacle, northern France**

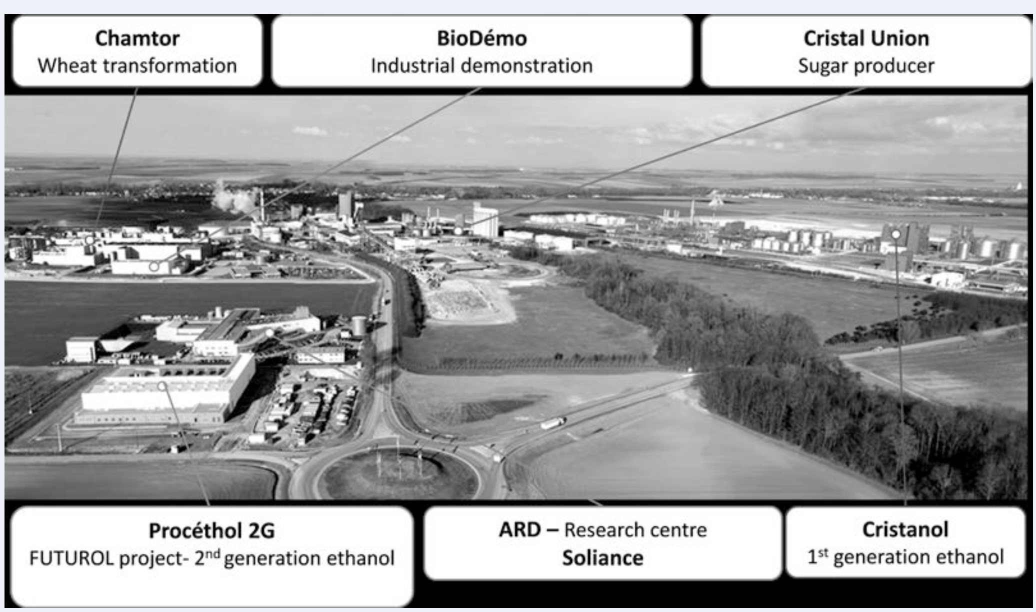
Agro-industrie recherches et développements (ARD) is a mutualised private research structure, owned by major players in the French agri-business as well as regional farming co-operatives, the latter being a particular strength. It was created in 1989 by exploiting the notion of value creation through non-food applications to find new opportunities from the produce of its shareholders (e.g. cereals, sugar beet, alfalfa, oilseeds). Subsequently, ARD started two subsidiaries – Soliance (molecules for cosmetic products) and BIODEMO, the largest capacity demonstration platform in France, which has hosted Amyris, BioAmber and Global Bioenergies.

The innovation hub Bioraffinerie recherches et innovation (BRI) is an open hub in the field of biorefining. BRI brings together various biorefineries at Bazancourt-Pomacle, the R&D centre ARD, as well as the French engineering schools École centrale Paris, Agro Paris Tech and NEOMA Business School. Therefore, it covers the value chain from fundamental research to the pre-industrial prototype.

It has had public financial support from the Ministry of Industry of France, the General Council of the Marne Département, the Region Champagne-Ardenne and the city of Reims. The combination of farming co-operatives, private industry and backing through regional and national public policy and funding is perhaps the optimal model that can be reproduced in many locations.

Further added value has been created through an industrial ecology network. The end-of-pipe philosophy is clearly insufficient to prevent pollution. Equally, cleaner production has its limits. The industrial ecology approach considers, in the absence of a viable cleaner production alternative, using waste as a marketable by-product. Using waste from one process as an input to another process at the same site removes transportation and waste disposal or treatment costs.

Figure 5.7. **Business units at Bazancourt-Pomacle**



Source: Schieb and Philp (2014), “Biorefinery policy needs to come of age”.

The most advanced wood biorefineries are found in Scandinavian countries. Borregaard (Norway), for example, boasts the most advanced biorefinery in the world. It has been making vanillin – one of the most valuable products made from wood – for more than 50 years (Borregaard, n.d.). Each year, it produces 1 500 tonnes from spruce wood.

In 2009, Chempolis, a Finland-based biorefining technology corporation, commissioned a biorefinery in Finland. Operating as a technology centre for testing customer raw materials for bioethanol, biochemicals and paper-making fibres, it has been also called the world's first demonstrator "third generation" wood-to-ethanol biorefinery.

In the northern portion of the Russian Federation, the Komi Republic could host a plant that would produce 100 000 tonnes of bioethanol per year from wood waste (Il Bioeconomista, 2016). The total investment required is estimated at EUR 136 million. A process to create a pool of investors is underway with different options under consideration, including a public-private partnership. Under the plans, the facility would process up to 400 000 tonnes per year of feedstock such as unusable timber and sawmill residues. The Komi Republic has rich forest resources, and local authorities have proposed a site of 15.6 acres for the plant.

Wastewater biorefineries

Probably the most widespread application of biotechnology worldwide is biological wastewater treatment technology. The core technologies have an unparalleled role in pollution prevention. Yet, in developing countries, 90% of sewage and 70% of industrial wastes are discharged without treatment into surface water. Wastewater management would play a central role in achieving future water security in a world with increased water stress (UN-Water, 2015).

With over a century of experience in biological wastewater treatment, advances beyond basic biochemical oxygen demand (BOD) and chemical oxygen demand (COD) removal are available. Small, modular systems requiring minimal civil engineering and maintenance are ideal for small, remote communities, while highly intensive plants can cater to city-sized populations. It would appear that large problems could be solved simply with greater implementation of biological wastewater treatment technologies (El-Chichakli et al., 2016). However, two points are worth bearing in mind.

1. Converting biodegradable materials in wastewater into non-toxic biomass, water and CO_2 has no added value.
2. Treatment of municipal wastewater accounts for approximately 3% of global electricity consumption and 5% of non-CO_2 GHG emissions, principally methane from anaerobic digestion (Li et al., 2015). In many cases, large wastewater treatment plants are the largest energy-consuming facilities in a city.

Future wastewater biorefinery models could well be derived from promising R&D. Considering the energy content embedded in wastewater is two to four times the energy used for treatment, future utilities could become energy-positive with the development of energy recovery technologies (McCarty et al., 2011). Moreover, these facilities could also recover other value-added resources such as nutrients, metals, chemicals and clean water. In this way, they could become closed loop waste biorefineries of very high productivity and efficiency (Lu and Ren, 2016), and potentially carbon-negative. Although global stocks of phosphate for fertilisers are being depleted, nutrients such as the phosphates and nitrogenous pollutants in wastewater contribute to disastrous instances of eutrophication.

Plastics from wastewater

Research is demonstrating how the organic carbon present in domestic wastewater can be converted by mixed microbial cultures into polyhydroxyalkanoate (PHA) bio-based plastics. These plastics are biodegradable with a range of functions that can replace traditional fossil-based plastics. Over 22 months, the Brussels North Wastewater Treatment Plant operated a pilot-scale biorefinery process to evaluate PHA production integration with services of municipal wastewater and sludge management (Morgan-Sagastume et al., 2015). Full-scale demonstration of the complete value chain alongside continuous polymer production remains to be validated (Paillard, 2016). Currently, this technology is at TRL 6.

Microbial electrolysis cells: Electricity from wastewater

Microbial electrolysis cells (MECs) can theoretically convert any biodegradable waste into H_2, biofuels and other value-added products. Since their invention in 2005 (Kadier et al., 2016), research has increased the H_2 production rate and yield by several orders of magnitude. However, many challenges must be overcome for MECs to be applied in large-scale systems (Randolph and Studer, 2013).

MEC technology can, in theory, be integrated into lignocellulosic biorefining. These biorefineries produce large amounts of wastewater that contain biodegradable organics. These can be used in MECs for additional energy production (Zeng et al., 2015).

Hungarian researchers (Szollosi et al., 2016) have developed a microbial fuel cell technology. It can produce a low-alcohol beer while it generates small amounts of electricity. Perhaps one day it will be possible to brew beer from wastewater in an energy-positive and carbon-negative process.

In Canada, Metro Vancouver (23 local authorities in the province of British Columbia) is working with Genifuel to build a demonstration plant that can convert raw sewage into biocrude oil. The technology is being licensed from the Department of Energy's Pacific Northwest National Laboratory (Ramirez, 2016).

Biogas biorefining

Anaerobic digestion of sewage sludge to produce biogas – a mixture of hydrogen, methane and carbon dioxide – has been used for over a century in the biological treatment of wastewater. Typically, it stabilises sewage sludge by removing pathogens. However, methane is typically used to generate electricity. This can often be enough to power an entire wastewater treatment plant, adding to the environmental and economic sustainability of such plants.

Anaerobic digestion is highly scalable. It has been perfected down to individual farm level, where a variety of waste materials can be converted to biogas (e.g. sludge, grass, solid manure, chicken manure and straw). Moreover, the effluents after anaerobic digestion are better balanced to meet crop needs than raw manure slurries. This reduces the need for supplementary chemical nitrogen and phosphorus fertilisers (Massé et al., 2011), while reducing GHG emissions (Siegmeier et al., 2015).

Biogas production is seen as part of the biorefinery concept (Kaparaju et al., 2009). Multiple biofuels production from, say, wheat straw (bioethanol, biohydrogen and biogas) can increase the efficiency of biomass use enshrined within the cascading use of the biomass concept. Volatile fatty acids (VFAs) produced from anaerobic microbial activity are often considered a nuisance or environmentally damaging. Yet they have potential as precursors for the biotechnological production of PHAs as bio-based plastics (Martinez et al., 2016).

The Centre for Advanced Sustainable Energy in Northern Ireland funds the BioGas to BioRefinery research project (QUB, n.d.). It aims to produce an evidence-based roadmap to develop a bioeconomy there. On the one hand, the research reviews the potential of feedstocks for biogas production in the country. On the other, it demonstrates the environmental and economic benefits of advanced use options for biogas from wastes.

Food waste biorefining

Roughly one-third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tonnes per year (FAO, 2011). Further, the energy used in producing the food is also wasted. This means the GHG emissions associated with the production have been released with no benefit at all. Food that is produced but not eaten adds 3.3 billion tonnes of GHGs to the planet's atmosphere This makes food wastage the third top emitter after the total emissions of the United States and China (FAO, 2013).

TerraServ, a South African start-up formed in 2014, is developing a process to biologically convert food wastes into products such as hand sanitisers, whiteboard cleaners and glass cleaners under the brand name EcoEth (TerraServe, n.d.). The feedstocks are generally off-specification foods from manufacturers, goods damaged in transit or past their sell-by date. In the current phase of development (mid-2016), the company processes around 200 kg of food waste per month. Within the next year, it intends to increase this to 1-12 tonnes per month. The process is based on fermentation to ethanol. Ultimately, it aims to recycle wastewater and employ biological wastewater treatment, and to use as much solar heating as possible to minimise the carbon footprint (Coetzee, 2016).

Enterra of British Columbia, Canada, takes food waste from farmers, grocery stores and food producers in Metro Vancouver and the Fraser Valley, and feeds it to voracious black soldier fly larvae (Enterra, n.d.). In turn, the larvae can be processed into fertiliser and animal feed ingredients. Canada has recently approved this approach for chicken feed.

Note

1. Organic chemistry can be defined as a chemistry sub-discipline involving the scientific study of the structure, properties and reactions of organic compounds and organic materials, i.e. matter in its various forms that contain carbon atoms. However, biorefining most normally refers to "renewable" carbon.

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