Chapter 2
Moving Toward Energy Security and Sustainability in 2050 by Reconfiguring Biofuel Production

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2.1 Introduction

For secure and sustainable bioenergy and biofuel production to become a reality by the middle of the twenty-first century, building on the current infrastructure and existing technology is essential. However, at the same time, we must make substantial improvements and/or changes in the feedstocks used, the process technologies applied, and the fuels produced, to achieve true sustainability (see Buchanan and Orbach, Chap. 1). A critical question is: What role will advanced biofuels play in the energy portfolio of the world 20–50 years from now? There is increasing evidence that commercial biofuel production can be reconciled with feeding humanity and preserving the environment, provided that we invest the time and effort needed to make the improvements necessary to achieve this goal (Lynd and de Brito Cruz 2010).

The biofuel production concept described in this chapter has the potential to meet the challenges of sustainability, sufficient supplies, and economic feasibility by combining proven technologies with promising innovations that are currently under development. We envision a decentralized, community-based system with integrated crossover bioprocessing units to convert biomass into third generation drop-in biofuels (long-chain alkenes, alkanes, and alcohols) and bio-derived chemicals. These systems could be developed on green-field sites or built onto first or second generation biofuel (biodiesel, ethanol) facilities.

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Such systems will require advancements in feedstocks used to produce biofuels and chemicals (Perlack and Stokes 2011). Plants (trees, row crops, grasses) bred for rapid growth, high yield, and desirable composition will be needed to support multiuse production of food, feed, fuels, and chemicals. Perennial plants able to grow with minimal inputs (fertilizer, pesticides, irrigation water) on lower quality (fallow) land would be most desirable in terms of sustainability. However crop residues or cover crops could provide dual use of land, as well as increased sustainability (Perlack and Stokes 2011; see Sripada et al., Chap. 8). Single-celled phototrophs (e.g., algae or cyanobacteria) that can fix CO_2 into oil are also emerging as potential feedstocks. Compared to the current biofuel production system, cyanobacteria, as autotrophic prokaryotes, do not require arable land and can grow to high densities by efficiently using solar energy, CO(2), water, and inorganic nutrients. Moreover, genetic techniques for cyanobacteria have been developed, and recently several chemicals including ethanol, isobutanol, and isoprene have been produced directly by engineered cyanobacteria (Zhou and Li 2010).

Advanced conversion systems are also needed to transform biomass feedstocks into biofuels and chemicals. Efforts to improve the biochemical platform are focused on pretreatment strategies and engineering microbes and their enzymes to deconstruct carbohydrate polymers and produce long-chain hydrocarbons or alcohols. Thermochemical efforts are being directed toward integrated thermo-catalytic processes that can readily switch among a multitude of feedstocks. Conversion systems of the future must optimize the value of products produced, minimize energy and water use, be scalable to distributed processing networks (to minimize feedstock logistics challenges), and produce minimal waste products.

While the United States has produced corn-based fuel ethanol for over 30 years, a comprehensive energy security plan was lacking prior to the Energy Policy Act (EPAct) of 2005. To meet the requirements of the EPAct, EPA adopted a limited program that applied to the year 2006. This was followed by a more comprehensive program in May 2007 referred to as the Renewable Fuels Standard 1 (RFS1). Under RFS1, the required renewable fuel mandate for 2006 was set at 4.0 billion gallons, and this was to ramp up to 7.5 billion gallons by 2012. The Energy Independence and Security Act of 2007 (EISA) made significant changes in the structure and magnitude of the renewable fuel program. The revised statutory requirements of EISA specify the volumes of cellulosic biofuel, biomass-based diesel, advanced biofuels, and total renewable fuel that must be used in transportation fuel yearly from 2010 to 2022. The EISA fuel program, designated RFS2, mandates the use of 15.2 billion gallons/year of renewable fuel by 2012 and 36 billion gallons/year by 2022 (Federal Register 2010).

In 2010, US corn ethanol plants produced over 12 billion gallons of ethanol from 4.568 billion bushels of corn (Wilson 2011). The majority of the increased biofuel production called for in RFS2 is mandated to come from cellulosic feedstocks and is targeted at 16 billion gallons by 2022. Second generation biofuels include cellulosic ethanol and cellulosic diesel. Along with a projected 15 billion gallons/year of corn ethanol and 5 billion gallons/year of other renewable biofuels, such as biomass-based diesel, renewable hydrocarbons, and higher alcohols, the goal is to replace 20 % of current crude oil use in the United States by 2022 (Regalbuto 2009).

Replacing traditional gasoline, diesel, and jet fuels with renewable fuels will have a wide range of environmental, societal, and economic impacts. The significance and timing of these impacts will be affected by how rapidly biofuels replace petroleum-derived fuels, which in turn is affected by market forces (crude oil price and availability, feedstock prices), technology development, political conditions, and regulatory factors. The impacts of biofuel production on environmental, societal, and economic factors will be affected by the: (1) type of fuel produced and its use, (2) types and locations of the feedstocks, (3) locations, methods, and scale of conversion systems, (4) yields of products and coproducts from a given feedstock, and (5) challenges associated with use of these feedstocks (Federal Register 2010).

2.2 Present-Day Biofuel Production

2.2.1 Ethanol

The United States is currently the largest ethanol producer in the world (Renewable Fuels Association 2014c). The US ethanol industry expanded rapidly from the late 1990s to the present (Table 2.1), spurred by the phaseout of the gasoline additive methyl tertiary butyl ether (MTBE) and by state and federal mandates and tax incentives. The majority of present-day domestic ethanol biofuel production comes from approximately 190 operating facilities, processing mostly corn and similar grains, such as milo and barley. Most of these facilities are located in the Midwest near the site of feedstock production (Fig. 2.1); however, some are colocated with dairies or beef cattle feeding operations outside the Corn Belt. Seven small facilities convert simple sugars from food or beverage waste into ethanol, and in 2010, 3 million gallons were produced from two facilities using woody biomass as the feedstock (Renewable Fuels Association 2014a).

Over 90 % of corn ethanol plants use dry-grind technology, while the remaining facilities use wet-milling processes. Dry-grind facilities grind the entire corn kernel and generally produce one primary coproduct, dried distillers' grains with solubles (DDGS), which is a valuable livestock feed. Some distillers' grains are sold in a wet or modified wet condition for local use; however, storage and transportation are limiting factors. Two companies operate dry-mill ethanol plants that fractionate the corn upstream of ethanol production. They produce additional coproducts such as food- or fuel-grade corn oil and corn bran. Wet mill facilities separate the corn kernel into its components, germ, fiber, protein, and starch, prior to processing, and from these produce other coproducts, including gluten feed, gluten meal, and food-grade corn oil, in addition to DDGS (Federal Register 2010).

Ethanol production requires the use of water, electricity, and steam; the steam needed to heat the production process is usually generated on-site by burning natural gas. At least 27 plants use combined heat and power technology, producing their own electricity and using waste heat from power production for the process

Table 2.1 United States ethanol production capacity

Year	Total ethanol plants	Ethanol production capacity (BGY)	Plants under construction or expanding	Capacity under construction or expanding (MGY)	States with ethanol plants
1999	50	1.70	5	77	17
2000	54	1.75	6	92	17
2001	56	1.92	5	84	18
2002	61	2.35	13	391	19
2003	68	2.71	11	483	20
2004	72	3.10	15	598	19
2005	81	3.64	16	754	18
2006	95	4.34	31	1,981	20
2007	110	5.49	76	6,130	21
2008	139	7.89	61	5,536	21
2009	170	12.48	24	2,066	26
2010	187	13.03	15	1,432	26
2011	204	14.07	10	560	29
2012	209	14.91	2	140	29
2013	211	14.84	2	50	28

BGY Billion gallons per year; *MGY* Million gallons per year
Source: Renewable Fuels (2014b)

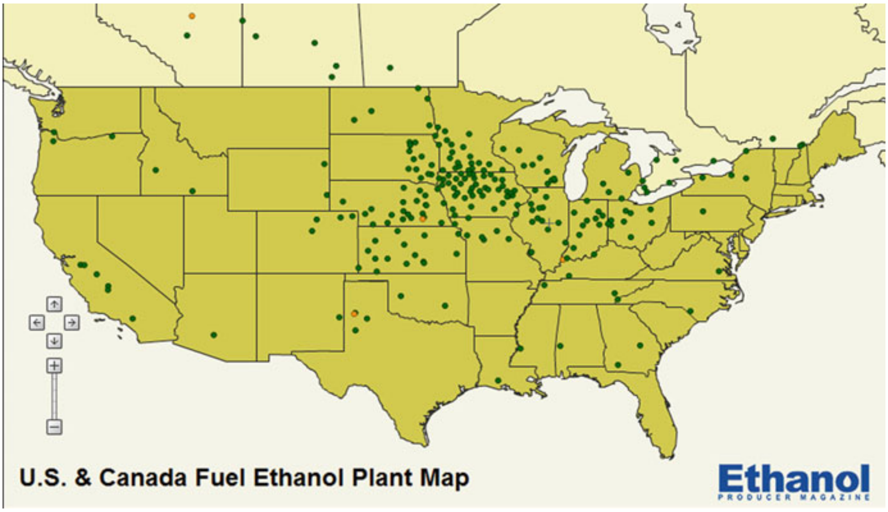

Fig. 2.1 United States and Canada fuel ethanol plant map (Source: Ethanol Producer Magazine)

steam. The large amounts of carbon dioxide gas produced during fermentation are vented in most plants. However, at sites where local markets exist, carbon dioxide gas is captured, purified, and sold to the food processing industry for use in carbonated beverages and flash-freezing applications (Federal Register 2010).

Because of poor ethanol margins in 2008 and 2009, a number of ethanol producers idled production, halted construction projects, sold off plants (frequently to oil refining companies), or filed for bankruptcy. However, as market conditions improved in 2010, many of these idled facilities came back on line. Although RFS2 does not have a specified volume requirement for corn ethanol, EISA allows up to 15 billion gallons of the 36 billion gallon requirement for total renewable fuel in 2022 to be met by conventional biofuels, such as corn ethanol. Future growth in the corn ethanol industry will depend upon the relationship between crude oil and corn prices. Crude oil prices fluctuate in response to political turmoil (primarily in the Middle East), new supplies (e.g., Canadian tar sands, US fracking), and the world economic activity. Corn prices depend on worldwide food and feed demands, yields as affected by weather conditions, development of improved hybrids, and competing uses (Federal Register 2010).

2.2.2 Biodiesel

The United States was the world's largest producer of biodiesel (long-chain fatty acid monoalkyl esters prepared from lipid-bearing feedstocks) in 2008, with Germany, France, Brazil, and Argentina rounding out the top five. However in 2010, as US production remained at nearly the same level, Brazil became the largest producer and the United States moved to fifth in the top group (US Energy Information Administration). Domestic production of biodiesel is considerably lower than for ethanol. Biodiesel production in the United States was just under 1.1 billion gallons in 2012 (National Biodiesel Board). First generation commodity vegetable oils such as soybean (see Redick, Chap. 3 and Stojsin et al., Chap. 9), along with waste lipids such as animal fats, are currently the most commonly used feedstocks for biodiesel production in the United States. However, the limited supply of these lipids is insufficient to displace a significant percentage of middle distillate fuel (diesel) consumption in the United States. For example, it has been estimated that if all US soybean production were dedicated to biodiesel, only 6 % of diesel demand would be satisfied (Hill et al. 2006). Therefore, exploration of high lipid-yielding alternatives suitable for fallow lands that require minimal agricultural inputs and do not compete with the food chain has emerged as a priority (Tilman et al. 2009). Crops such as camilina and carinata are leading options for use in rotation with wheat in arid regions.

Lipids can also serve as feedstocks for the production of renewable hydrocarbons via traditional catalytic hydrotreatment. The chemical composition and fuel properties of renewable diesel derived from lipids are different from biodiesel and in many cases more approximate than that of petrodiesel. While the renewability aspect of renewable diesel is retained versus biodiesel, advantages of biodiesel such as biodegradability, positive energy balance, excellent lubricity, and high flash point are sacrificed. However, disadvantages such as poor oxidative stability, cold flow properties, and energy density as well as elevated NO_x exhaust emissions versus petrodiesel are eliminated if renewable diesel is prepared instead of biodiesel

(Knothe 2010). The process for producing renewable jet fuels from lipids is similar to that for renewable diesel. To date, commercial production of renewable diesel and jet fuels from lipids is essentially limited to pilot scale for demonstration purposes.

2.3 Achieving the Biofuel Production Mandate of 2022

2.3.1 RFS2

As a result of the statutory requirements of RFS2, the most important step for the next decade in the biofuels industry will be commercial production of ethanol from cellulosic feedstocks. Biomass is the most promising sustainable source of liquid fuels, and the DOE has estimated that 1.3 billion tons of un- or underutilized biomass is available annually (Perlack et al. 2005; Perlack and Stokes 2011). Cellulosic ethanol would contribute significantly to the larger goals of creating a sustainable energy supply, reducing greenhouse gas emissions, assuring energy security, and promoting rural economic development. Ethanol will very likely be the world's first cellulosic biofuel because several large-scale demonstration and commercial-scale production facilities will begin operation in 2014. Moreover, the infrastructure for distributing and using ethanol is already available. Future research will develop technologies to convert lignocellulosic sugars into drop-in biofuels (long-chain hydrocarbons and alcohols). However, it is likely that these processes will follow commercialization of lignocellulosic ethanol, where issues such as feedstock supply and logistics will be resolved (Lynd and de Brito Cruz 2010).

Electric and hydrogen powered vehicles are also being developed as alternatives to petroleum-driven spark-(gasoline) and compression-(diesel) ignition engines. While biomass could also be used to generate either electricity or hydrogen, storage of these energy sources is problematic. Batteries are impractical for aviation and on-highway heavy-duty long-haul trucks. Due to the significant weight of the battery pack, electric drivetrains are less likely to be used for long-haul applications, unless applied in combination with on-the-road charging technologies such as inductive charging or overhead catenary wires (den Boer et al. 2013). In the most aggressive scenarios for electrification of light-duty vehicles, liquid fuels still provide more than 50 % of US transportation energy. Hydrogen-based fuels may be a possibility for fleet vehicles, but wider use would be limited by the lack of a hydrogen distribution infrastructure. Therefore achieving a sustainable transportation sector is more likely with liquid biofuels than without them (Regalbuto 2009).

Ethanol has been used in automotive fuels in the United States since the late 1970s. As a high-octane oxygenated additive, ethanol improves combustion, which allows clean air standards to be met. The drawbacks to using ethanol as a complete replacement for gasoline are its hygroscopicity and lower energy density. Ethanol has only two-thirds the energy density of gasoline, and cars running on E85 (85 % ethanol and 15 % gasoline) get about 30 % lower gas mileage (Regalbuto 2009).

Un- or underutilized cellulosic feedstocks have the potential to greatly expand biofuel production, both volumetrically and geographically (Federal Register 2010). Efforts to scale-up and deploy cellulosic biofuel technologies have increased dramatically in the United States in the last few years as a result of the $1.01/gallon tax credit for cellulosic biofuel introduced in the 2008 U.S. Farm Bill and the aggressive targets for cellulosic biofuel volume mandated by the RFS2 program. A wide range of feedstocks, conversion technologies, and fuels are under investigation for biofuel production. Cellulosic ethanol and other alcohols are considered promising for long-term use in gasoline blending. There is also growing interest in synthetic hydrocarbons from cellulosic feedstocks (Federal Register 2010).

Feedstocks from a wide variety of sources are being investigated for cellulosic biofuel production. Urban waste is cheap, abundant, and available where the fuel would be used. Agricultural residues, such as corn stover and cereal straws, are being evaluated widely in the Midwest for potential coprocessing at corn ethanol plants. Woody biomass, including forest thinnings, pulp and paper mill waste, and yard waste are significant resources in the eastern and southern parts of the United States. Dedicated energy crops such as switchgrass, cane, sorghum, poplar, and miscanthus are also being considered for cellulosic biofuel production. These crops have the potential for high yields and sustainable growth. While urban waste, agricultural residues and forest residues will likely be the first feedstocks used in the production of cellulosic biofuel, land availability and sustainable removal rates may be limitations. The US billion-ton update (Perlack and Stokes 2011) modeled energy crop potential using an agricultural policy simulation model taking into account additional energy crop sustainability requirements. As a result of the spatially explicit land-use change modeling that was used, energy crop potential was estimated to be much greater than in the 2005 US billion-ton study (Perlack and Stokes 2011 Table ES.1). In the Final Rule for RFS2, the EPA estimated that a majority of the feedstocks for the production of the 16 million gallons of cellulosic biofuel mandated by RFS2 for 2022 are expected to come from dedicated energy crops (Federal Register 2010, p. 14754). Viable harvesting, transportation, and storage solutions still need to be developed for these feedstocks.

2.3.2 Cellulosic Ethanol

Two general approaches are being developed to convert cellulosic biomass into ethanol: the biochemical platform and the thermochemical platform. The biochemical platform uses various pretreatment strategies to open the structure of biomass, followed by use of acids or microbial enzymes to deconstruct cellulose and hemicellulose into monomers. Yeast are then used to ferment the sugars to ethanol. The non-fermentable solids, including lignin, are typically used to generate heat and electricity to power the biomass-to-ethanol conversion process. Lignin can constitute up to 40 % of the stored energy in biomass. Despite recent developments, such as more efficient enzymes, breeding more readily deconstructed plants, and consolidation of processing steps, production costs remain higher than that of fermenting corn starch (Federal Register 2010). The thermochemical platform for ethanol production from cellulosic substrates uses gasification to convert biomass into syngas, which is then converted into ethanol by metal or microbial catalysts. The main limitations of this approach are metal catalyst poisoning by impurities in the syngas or low ethanol tolerance of microbes that convert syngas into ethanol.

Lignocellulose, as well as plant lipids, can also be converted to hydrocarbon biofuels like gasoline, diesel, and jet fuel as "drop-in" petroleum replacements. Conversion routes may combine a variety of biochemical, thermal, and catalytic processes. For example, sugars produced through the biochemical process can be fermented into hydrocarbons instead of alcohols by genetically altered microorganisms (Lee et al. 2008). Genes have been isolated that, when expressed in *Escherichia coli*, produce alkanes, the primary hydrocarbon components of gasoline, diesel, and jet fuel. If commercialized, this single step conversion of sugar to fuel-grade alkanes by a recombinant microorganism would lower the cost of producing "drop-in" hydrocarbon fuels that are low-carbon, sustainable, and compatible with the existing fuel distribution infrastructure. The process does not require elevated temperatures, high pressure, toxic catalysts, or complex operations. The recombinant *E. coli* secretes the hydrocarbons from the cell, so it is not necessary to rupture the cell. In addition, because the hydrocarbons are insoluble in water, they will form a separate organic phase that can be recovered without distillation. Moreover, this phase separation will minimize inhibition of the microbes by the accumulating fermentation product as that occurs with alcohol (Schirmer et al. 2010).

Dissolved sugars can also be converted into hydrocarbons through routes that resemble petroleum processing more than fermentation. Dumesic and coworkers have developed several routes in which dissolved sugars react in the presence of solid-phase catalysts under carefully controlled conditions that avoid unwanted by-products. They can convert carbohydrates into targeted ranges of hydrocarbons for use as fuels or chemical feedstocks (Kunkes et al. 2008; Chheda et al. 2007).

Themochemical conversion processes that transform biomass into synthesis gas or pyrolysis oil can also be adapted to produce third generation biofuels. An updated pyrolysis approach developed by Huber and coworkers uses catalysts to convert biomass into high-octane gasoline-range aromatics in a single, simple, inexpensive step (Carlson et al. 2008; Huber and Dale 2009). These chemical methods produce heat and water, which preserves resources and helps lower cost. Like pyrolysis, gasification also uses whole biomass but converts it spontaneously at very high temperatures into a mixture of carbon monoxide and hydrogen, or syngas, so named because it is a starting material for processes such as Fischer-Tropsch synthesis (FTS). Schmidt and coworkers (Dauenhauer et al. 2007) have combined the three reactions of older thermal gasification processes into a single, small reactor in which gasification takes place over a catalyst to directly produce third generation biofuels.

2.3.3 *Algae, Photosynthetic Bacteria, and Cellulosic Ethanol*

The need to develop other biomass feedstocks has helped to reinvigorate interest in algae as one of the most promising feedstocks for biofuels. The productivity of algae and photosynthetic bacteria is roughly 100 times than that of agricultural crops, without competing for arable land (Schirmer et al. 2010). Algae store chemical energy in the form of biological oils, such as neutral lipids or triglycerides, when subjected to stresses such as nutrient deprivation (Wijffels and Barbosa 2010). The oil can be extracted from the organisms and converted into biodiesel by transesterification with short-chain alcohols such as methanol or ethanol (Chisti 2007). Research and demonstration programs are being conducted worldwide to develop the technology needed to commercialize algal lipid production. For example, Arizona State University has an ongoing project working to generate biodiesel from lipids produced by a photosynthetic cyanobacterium (Arizona State University 2014). Algal oil can also be converted into linear hydrocarbons by catalytic deoxygenation/hydrogenation (Lestari et al. 2009). Algae also synthesize other fuel products such as hydrogen, ethanol, and long-chain hydrocarbons that resemble crude oil, or the algal biomass can be converted to biogas through anaerobic fermentation (Wijffels and Barbosa 2010).

In a similar fashion, photosynthetic cyanobacteria are also being targeted for their potential to produce biofuels directly from CO_2 and sunlight. Because they are more amenable to metabolic engineering compared to eukaryotic algae, cyanobacteria are being engineered to optimize yields of lipids containing C16 and C18 fatty acids for biodiesel production. Furthermore, companies such as Joule Biotechnologies and several universities are engineering cyanobacteria to directly produce hydrocarbon fuels (Halfmann et al. 2014). Cyanobacteria can be cultivated over a wide range of salt and fixed-nitrogen concentrations and at CO_2 levels up to 5 %. Some cyanobacteria are able to fix atmospheric nitrogen. These traits make the microorganism well suited for growth using flue gas effluent from power plants or CO_2 from ethanol plants as a carbon source before release into the atmosphere. Cyanobacteria and algae can also use agricultural runoff water contaminated with fertilizers as a fixed-nitrogen source when it is available. This renewable solar energy-to-biofuels approach is well suited to arid regions with high levels of sunlight. Biofuel production from cyanobacterial photobioreactors should be scalable to a point where it represents a major source of carbon-neutral fuel within the next 10–15 years (Arizona State University 2014).

Most cellulosic ethanol companies are in various stages of proving their technologies. Many have fallen behind in their commercialization schedules, primarily due to lack of funding. Obtaining capital is challenging given the state of the economy. At the present rate of development, maximum cellulosic ethanol capacity is estimated to be 337 million gallons in 2013, which is less than currently mandated by RFS2 (Federal Register 2010). Renewable hydrocarbons derived from biomass may win out over cellulosic ethanol because of their high energy density and compatibility with existing energy infrastructure. If recent technological innovations result in competitive production costs, hydrocarbons rather than ethanol may be the dominant biofuel.

2.4 Prospects for Biofuel Production by 2050

Based on current energy policy in the United States, it would appear that ethanol, derived from corn and lignocellulose, will be the main liquid transportation biofuel through 2020. EISA allows 15 billion gallons of the 36 billion gallons of renewable fuel mandated for 2022 to be met by conventional biofuels. It is expected this will be filled by corn ethanol (Federal Register 2010). EISA increased the cellulosic biofuel mandate to 16 billion gallons by 2022, representing the bulk of the renewable fuels mandate. To become cost competitive with corn ethanol, lignocellulosic ethanol will require further improvement in pretreatments, enzymatic conversion to simple sugars, and mixed sugar fermenting microbes (Hughes et al. 2008, 2011; Kumar and Murthy 2011; Laluce et al. 2012). Current investments in demonstration and small commercial-sized lignocellulosic ethanol facilities should speed up technology improvement. If total ethanol production (15 billion gallons from corn and 16 billion gallons from cellulosic feedstocks) reaches 31 billion gallons by 2022, that would meet approximately 20 % of the US liquid fuel transportation needs and would come close to achieving the EISA goal of 36 billion tons of biofuels. This degree of market penetration by ethanol will require a further increase in the allowable level of ethanol blended into gasoline (United States Environmental Protection Agency) and/or substantially more flex-fuel vehicles in the US transportation fleet.

Expansion of the biofuel market share above 20 % will likely involve production of third generation, drop-in biofuels (i.e., liquid hydrocarbons) in order to overcome infrastructure limitations of ethanol (United States Department of Energy 2012). Hydrocarbons can be made from lignocellulosic sugars through microbial fermentation or liquid-phase catalysis or directly from biomass via catalytic pyrolysis or gasification and Fisher Tropsch reactions. Lipids from nonfood crops, as well as algae, can also be converted to renewable hydrocarbon fuels (National Science Foundation 2008). The direct conversion of CO_2 with solar energy to biofuel by photosynthetic microorganisms such as microalgae and cyanobacteria has several advantages compared to traditional biofuel production from plant biomass, such as (1) oxygenic photosynthesis, (2) high per-acre productivity, (3) nonfood-based feedstock, (4) growth on nonproductive and nonarable land, (5) utilization of a wide variety of water sources (fresh, brackish, seawater, and wastewater), and (6) production of valuable coproducts along with biofuels (Radakovits et al. 2010; Parmara et al. 2011; Machado and Atsumi 2012).

Logistical challenges of transporting, storing, and maintaining acceptable quality biomass will restrict the size of future biorefineries. As pretreatment, conversion, and separation technologies continue to improve, it is likely that these platforms will be scalable to the community level, which will enhance

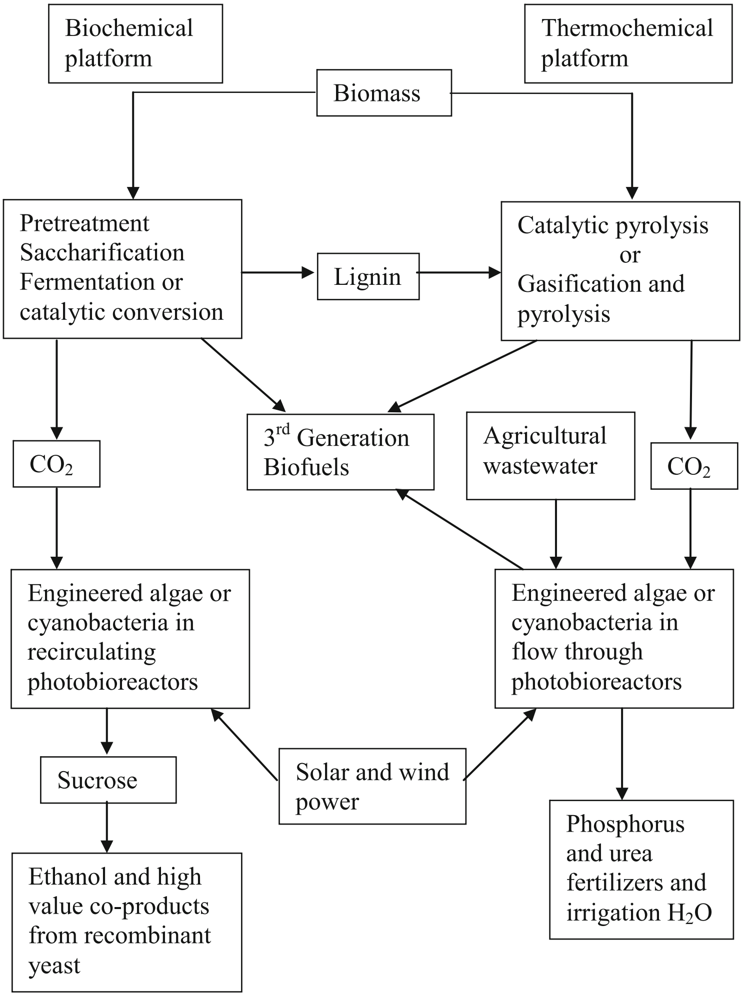

Fig. 2.2 Integrated, community-scale biorefinery

environmental, economic, and social sustainability. These biorefineries are also likely to be most economical and energy efficient if they are able to transform coproducts of one process into higher-value products through an integrated design. Both biochemical and thermochemical processes will be needed to convert biomass into third generation biofuels and bioproducts. Underutilized resources of these processes will be CO_2 and heat which can be used to culture engineered algae or cyanobacteria in photobioreactors to produce a range of products via photosynthesis.

A proposed integrated biorefinery concept outlining the biochemical and thermochemical platforms is shown in Fig. 2.2.

This multiproduct, community-based system will produce third generation biofuels, valuable coproducts, and fertilizer. The system can be used in any location due to its self-contained and autonomous design. The primary inputs are biomass, CO_2, and sunlight for photosynthesis, as well as solar or wind power to provide electricity (see Buchanan and Orbach, Chap. 1).

Algae and cyanobacteria possess the characteristics to produce third generation, energy-dense biofuels compatible within this proposed community scale system. They can grow in fresh or salt water, using sunlight to drive CO_2 photosynthesis and fix N_2, and have a photosynthetic efficiency fivefold greater than terrestrial plants. Another option in this community-based system would be to culture the algae/cyanobacteria on domestic or animal wastewater effluent, taking advantage of mixotrophic metabolism to use both CO_2 and dissolved nutrients. Cyanobacteria are particularly attractive, as they grow even more rapidly than algae and are easier to genetically engineer. Some strains are already grown at industrial scale for production of food and nutritional supplements. Because these organisms are generally regarded as safe (GRAS), coproducts from cyanobacterial biofuel production should be acceptable for feed and food applications.

Research is currently underway to engineer cyanobacteria to produce and excrete specific energy-dense liquid fuels (Halfmann et al. 2014). This would allow cells to remain circulating within the photobioreactor, while the product could be recovered via gas stripping or phase separation. Solar or wind power could generate electricity for pumps and control systems. CO_2 for photosynthesis would come from the biomass conversion units or could also be obtained from the air via enrichment membranes. The cellular biomass byproduct can be used for animal feed. Additional coproducts are urea and phosphorus fertilizers. Urea could reduce the use of anhydrous ammonia. Also, there will be a need for urea for the new tier 4 truck diesel emissions standards that must be met worldwide.

In addition, the cyanobacteria could be engineered to produce sucrose, which could feed a recombinant yeast that produce a high value protein-based coproduct. This algal or cyanobacterial photobioreactor system can be assembled from UV resistant polymers, with fluid circulation powered by solar- or wind-generated electricity. Pumps powered by solar/wind energy are already being used for remote water pumping applications at the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX. The wind turbine will generate 3-phase variable voltage, variable frequency AC electricity.

In the near- to mid-term future, revenue streams aside from fuels will be needed to render production of biofuels from algae profitable. Other factors improving the economics of biofuel production from algae include high petroleum oil prices, high yield of lipids from algae, and continued biofuels subsidies and/or tax credits (Gallagher 2011). Technical hurdles to be solved include: (1) the ability to cultivate stable algal cultures under industrial conditions while achieving both high productivities and lipid content, (2) the capacity to increase the volume of algal oil produced per unit of surface area per year, (3) the development of low-cost harvesting and oil extraction methods, and (4) strategies to utilize the biomass remaining after oil extraction.

2.5 Conclusion

A secure and sustainable system for bioenergy and biofuel production must build on the current infrastructure and existing technology, but must also develop and implement new technologies and innovative concepts. This chapter described a biofuel production system that could combine existing and future technologies and has the potential to provide energy security by 2050. This system could not only produce third generation, drop-in biofuels from both biomass and CO_2, but could also produce a high-value coproducts, urea and agricultural fertilizers, and transform wastewater effluent into acceptable irrigation water. The integrated, community-based design could economically produce energy in an environmentally and socially sustainable manner. This system could also foster cap and trade reduction in carbon dioxide because cyanobacteria will fix carbon dioxide into fuels, foods, and fertilizer. It is clear that no single energy source can sustainably meet all future energy needs; however, biofuels provide an option that can address the energy demands of the transportation sector. It is expected that advanced biofuels and bioproducts will be obtained from lignocellulosic and algal biomass. The biofuels industry must continue to develop technologies for converting biomass to biofuels that are economically and environmentally sustainable on a large scale.

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