Chapter 14
Sugarcane Biofuel Production in the USA

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Abbreviations

CHP	Combined heat and power
DOE	Department of Energy
DNR	Department of Natural Resources
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERS	Economic Research Service
RFS	Renewable Fuel Standard
RIN	Renewable identification number
UN	United Nations
US	United States
USA	United States of America
USDA	United States Department of Agriculture

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14.1 Overview of the Sugarcane Industry in the USA

14.1.1 Status of Sugarcane Production

Sugarcane has been extensively cultivated and processed in the USA since Etienne DeBoré first granulated sugar for commercial production in the state of Louisiana in 1795 (Heitmann 1987). In addition to Louisiana, sugarcane is grown in the mainland states of Florida and Texas. With the closure of the last sugar factory in 2017, the Pacific Ocean island state of Hawaii no longer cultivates the crop. In 2017–2018, sugarcane was harvested from ~345,000 hectares and processed in 16 raw sugar factories. Raw sugar was processed into white sugar in eight refineries.

Table 14.1 contains a comparison of production statistics among the states which cultivated sugarcane in the 2017–2018 production period. Biomass productivity varies considerably among the three mainland states. Averaged over the three most recent production years, sugarcane biomass yield in Mg ha^{-1} $year^{-1}$ is 92.4 for Florida, 78.5 for Texas, and 67.0 for Louisiana (USDA 2017). Lower comparative biomass yields for Louisiana and Texas reflect a short growing season in a temperate environment and semiarid conditions, respectively. Sugar recovery rate also varies, with Florida, Louisiana, and Texas averaging 12.13, 11.61, and 9.99%, respectively, as an average of production years from 1980 to 2017 (ERS USDA 2018a). Sugarcane accounts for approximately 45 percent of the total domestic sugar production, with sugar beets accounting for the rest (ERS USDA 2018b).

To ensure and protect the domestic supply of sugar and provide price stability, the USA uses price supports, domestic marketing allotments, and import quotas to control the supply of sugar marketed in the country (ERS USDA 2018c). The federal commodity support program features nonrecourse loans to processors and is designed to avoid the forfeiture of sugar put under loan in compliance with a no-cost provision for the federal government. Also designed to help avoid loan forfeitures is a provision that diverts excess sugar to conventional ethanol production.

14.1.2 Status of Energy Cane Production

Energy canes are complex hybrids between *Saccharum officinarum* L. and *S. spontaneum* L., *S. barberi* Jeswiet, and/or *S. sinense* Roxs. (Bischoff et al. 2008). Energy cane was developed as a biomass feedstock in response to higher fossil fuel prices

Table 14.1 US factory production statistics for the 2017–2018 production year

State	Metric tons of cane processed	Metric tons of 96° sugar produced	Cubic meters of molasses 79.5/80° Brix
Florida	15,688,470	1,760,447	367,400
Louisiana	13,639,452	1,649,335	294,643
Texas	1,493,041	149,794	41,325

Sugar J (2018a, b)

in the 1970s and the prediction by some that oil production had reached its peak. To determine geographic adaptation, energy cane performance trials were established to determine the biomass yield potential at multiple locations as far north as 33° North latitude (Owens et al. 2016). Dry matter yields ranged from 22 to 24 Mg ha^{-1} year^{-1} at the most northerly site, where hybrids were challenged by cold temperatures, to over 45 Mg ha^{-1} year^{-1} at the southern sites. Energy cane produces abundant biomass with relatively modest inputs, which makes a suitable feedstock for lignocellulosic conversion.

14.2 Bioenergy Production

14.2.1 Introduction

Fossil fuels have boosted industrialization and economic growth over the years. However, the adverse effects (greenhouse gas emission, air pollution, and global climate change) associated with fossil fuels have raised concerns regarding their economic and environmental sustainability and have shifted the attention to renewable energy sources such as wind, solar, nuclear, and bioenergy (Maradin et al. 2017). Bioenergy can be divided into first-generation crops such as sugars from sugarcane or sugar beets and starch from corn, rice, and wheat and second-generation energy sources such as various lignocellulosic biomass materials (Aita and Kim 2011). First-generation ethanol produced from crops has been the driving force in renewable energies. However, over the last decade, research on second-generation ethanol from lignocellulosic biomass has been searching for a significant breakthrough that will lead to it being cost competitive with first-generation ethanol. Unfortunately, the development of a lignocellulosic ethanol market has been slower than expected due to the perception of high technological risk, intensive capital costs, and the low oil prices that result in poor economics for the biorefineries (Kim and Kim 2014; Stephen et al. 2012).

14.2.2 First-Generation Biofuel Production

Sucrose, in the form of either raw sugar or molasses, is quite energy-rich with a combustion enthalpy of 16 MJ kg^{-1}; however, as carbohydrate it is non-suitable for direct energy conversion, especially through combustion. The most commonly proposed transformation is the microbial conversion to alcohols. Chemical conversion is possible but requires high-purity materials, typically at the level of refined sugar or above. For both microbial and chemical methods, the main challenge is the effective conversion and retention of the carbon.

From 1985 to 1987 several raw sugar/syrup/molasses-to-ethanol facilities have operated (up to 121,000 m^3 $year^{-1}$) and/or were planned (up to 586,000 m^3 $year^{-1}$) in Louisiana due to generous subsidies from the state of Louisiana. These subsidies ceased in 1989 and forced the existing facilities into bankruptcy or relocation to other states with subsidized corn-based ethanol (DNR Louisiana 2018; Troy 1993, 1994). The favorable regulatory environment created by the Energy Independence and Security Act of 2007 led to renewed efforts to produce sugarcane-based ethanol in the USA in Louisiana, California, and Hawaii (Jensen 2011; Voegele 2009). These projects were projected to generate an aggregate total of 375,000 m^3 $year^{-1}$ of ethanol, but none has achieved online status in the face of low fossil fuel prices. As of 2018, no large-scale fermentation-based fuel production from sugarcane or energy cane or molasses exists in Louisiana, Florida, Texas, or Hawaii (EIA 2018a). The economics are fundamentally challenged by the stoichiometry of the conversion. Five conversions of glucose/fructose are considered in Table 14.2.

The pyrolytic conversion of glucose to carbon, the conversion into syngas, and reforming the syngas to methane allow access to practically all chemicals derived from natural gas or coal. Also shown are the microbial conversion into ethanol and butanol, respectively. By assuming a stoichiometric yield (which cannot be achieved in an industrial facility), Table 14.2 shows the potential yield of the respective chemical and its market value. In the last column, the equivalent sugar price is given, i.e., if sugar would be below this value, cost parity between raw material and final product would be given (omitting any process cost, overhead, etc.).

Currently, the raw sugar price centers on 0.55 \$ kg^{-1}, i.e., none of the described fuels can be made economically from cane sugar (even less from energy cane due to its lower sugar content). Blackstrap molasses are fairly expensive in the US at 132 \$ t^{-1} due to their use as animal feed (Feedstuff 2018; USDA 2018b). Considering the average composition of Louisiana blackstrap molasses, the sugars (sucrose and invert) would cost \$0.304 kg^{-1}, a feedstock cost that would prohibit its use for fuel production except for butanol. However, butanol's value exceeds gasoline prices in the USA, and it is therefore predominantly used as a solvent and a chemical intermediate. While there have been many studies detailing the

Table 14.2 Basic sugar conversion processes

Fuel		Stochiometric yield [kg fuel kg^{-1} sucrose]+	Fuel market value [\$ kg^{-1} fuel]	Sugar cost [\$ kg^{-1}]
Carbon	$C_6H_{12}O_6 \rightarrow 6\ C + 6\ H_2O$	0.421	0.014[a]	0.0059
Syngas/ methane	$C_6H_{12}O_6 \rightarrow 6\ CO + 6\ H_2$ $C_6H_{12}O_6 \rightarrow 3\ CH_4 + 3\ CO_2$	0.281	0.127	0.0356
Ethanol	$C_6H_{12}O_6 \rightarrow 2\ C_2H_6O + 2\ CO_2$	0.538	0.372[b]	0.200
Butanol	$C_6H_{12}O_6 \rightarrow C_4H_{10}O + 2\ CO_2 + H_2O$	0.2598++	1.325[c]	0.344

+Sucrose being converted to invert sugar (fructose/glucose)
++Due to by-products, butanol is produced typically at maximum 60% of the total solvent yield
[a]EIA (2018b)
[b]USDA (2018a)
[c]Zullo (2016)

technical and economic feasibility of converting molasses into ethanol, they all (directly or indirectly) acknowledge the lack of cost competitiveness with corn-derived sugars (Lipinsky 1976; Polack et al. 1981; Rein 2004; USDA 2006). Even the existing corn ethanol plants cannot sustain themselves by producing ethanol alone; they survive by selling the product mix of ethanol, carbon dioxide, and dried distiller's grain (produced at a 1:1 ratio with ethanol).

Bagasse, a coproduct of sugarcane processing, is often falsely declared a waste. It is used as a fuel for the raw sugar factory, and two integrated factories in Florida are also employing it as the fuel for their refineries. As such, its value is based on its energy content. Its composition is typically assumed to be $CH_{1.5}O_{0.7}$ and yields on average a gross calorific value of 19,410 kJ kg^{-1} (Chen and Chou 1993). Normally the heating value is depressed due to moisture and ash content. In Louisiana, the average bagasse composition (50.7% moisture, 3.3% ash) would mean a heating enthalpy of 9362 kJ kg^{-1}, which equates to 0.189 kg of natural gas and a value of \$0.024 kg^{-1} (Ehrenhauser et al. 2018). This value seems quite favorable for advanced fuel production; however, chemical conversion of biomass through pyrolysis, gasification, or catalytic upgrading is challenging due to the high variability of the material and/or the lack of cost competitiveness with fossil fuels in the US. Nonetheless, there are currently two pilot facilities operating in Louisiana converting bagasse.

American Biocarbon (Whitecastle, LA, USA) produces biocarbon from bagasse (American Biocarbon 2018). Based on the sum formula, the maximum yield would be 49% carbon from pure bagasse. Unfortunately, the presence of ash challenges the product, as the removal of water (and loss of carbon) from the bagasse raises the ash level accordingly, reducing the quality of the produced fuel. High-quality bagasse (low ash and low moisture) is therefore desirable for this process. In Raceland, Louisiana, Stora Enso operates an acid digestion-based pilot plant, which produces xylose and glucose (Stora 2018). However, their main product is xylose intended as a feedstock for xylitol and chemicals. Both facilities utilize excess bagasse, i.e., bagasse exceeding the energy need of the neighboring raw sugar factory, and function therefore as an offset to bagasse handling/disposal cost to the raw sugar factory.

Based on the fact that bagasse is already a fuel, it seems obvious to point out that any conversion will come with a loss of material and energy content, i.e., value. As such, direct thermal utilization through combustion for heating purposes and electric power generation seems to be the most viable path for bagasse to energy conversion in the USA.

14.2.3 Second-Generation Biofuel Production

Bioenergy from lignocellulosic biomass is one of the most promising options having minimal impact on food and water resources, land use, and the ecosystem (Manochio et al. 2017). According to a study supported by the United States (US) Department of Energy (DOE) and the US Department of Agriculture (USDA), the United States has the capacity to support the production of 1.3 billion dry tons of biomass annually if dedicated energy crops could be developed, grown, and harvested sustainably (Perlack et al. 2005). The United States has put in place initiatives to promote the commercial production of second-generation ethanol. These initiatives were developed under the Energy Policy Act of 2005 and were published as the Renewable Fuel Standard (RFS), which was later updated by the Energy Independence and Security Act (EISA) of 2007 (EPA 2018a). These policies mandate increasing the volume of biofuels to be blended into gasoline and diesel, while providing a premium price for biofuels based on a credit system known as renewable identification number (RIN) (EPA 2018b). A RIN is a 38-digit numeric code that singly identifies each gallon of renewable fuel that is produced in or imported into the US throughout the supply chain and separated from the renewable fuel upon blending with either gasoline or diesel (Klein-Marcuschamer and Blanch 2015). RINs can be used to comply with the RFS mandates or traded into economic incentives. This has created tensions between the renewable fuel and the fossil fuel producers and importers arguing that consumers should use the fuel of their choice without government interference and that the mandates create a blend wall where the current infrastructure cannot support blends higher than 10% (Oller 2014). In the USA, ethanol can be blended with gasoline up to 10%, this gasoline blend is referred to as E10, and it requires no major technological adjustments to the existing infrastructure or motor vehicles. However, for a biofuel producer to be profitable after the blend wall is reached, higher biofuel blends and more fuel-flexible cars must be available as well as consumer demand (Klein-Marcuschamer and Blanch 2015). Although a 15% gasoline blend (E15) has been approved by the US Environmental Protection Agency (EPA) for use in light-duty conventional vehicles model year 2001, no agreements have been reached between the oil refiners, vehicle producers, and the biofuel industry (Valdivia et al. 2016). This has become a key argument in support of drop-in fuels or advanced hydrocarbon biofuels (i.e., gasoline, diesel, and jet fuel) from lignocellulosic biomass, that is, fuels that would not require a change in the distribution and consumption infrastructure.

An ethanol production target was set for 136 billion liters of renewable fuels by 2022 with a cellulosic mandate of 60 billion liters (EPA 2018a). In 2007, DOE announced a loan guarantee scheme for the construction of six commercial-scale biorefineries with various processing technologies to meet these targets (Table 14.3). The major goals were to make ethanol from nonfood biomass (including agricultural residues such as sugarcane and energy cane bagasse) at a price competitive to gasoline and to increase the use of renewable and alternative fuels. The support of the US government toward the commercialization of second-generation fuels has been significant but has not been sufficient. A commercial scale has an output of at least 25 million liters of biofuel per year (Sims et al. 2010). As of February 2018, there were no commercial-scale second-generation ethanol facilities fully operational (Table 14.3). Only Poet-DSM remains committed to converting agricultural residues (mainly corn stover) into renewable fuel. The US second-generation ethanol projected capacity at the end of 2017 was estimated at 220 million liters with only six million liters registered (Ramos et al. 2016; USDA 2018c), an outcome that can be attributed to the biorefineries still facing processing challenges as well as not

Table 14.3 US second-generation commercial-scale biorefineries and current status

Company	Location	Biomass	Process	Projected output	Invested (loan)[a]	Status
				Million liters per year	Million USD	
Abengoa	Hugoton, Kansas	Corn plant and agricultural residues	Enzymatic hydrolysis	95	400 (132)	Filed for bankruptcy (2016)
Alico	Vero Beach, Florida	Yard, wood and vegetative waste	Syngas fermentation	30	300 (33)	Sold technology to INEOS Bio (2008); INEOS Bio plant sold to Alliance (2017)
BlueFire renewable	Fulton, Mississippi	Municipal cellulosic waste	Concentrated acid hydrolysis	72	300 (49)	Not known construction activity (2011)
DuPont	Nevada, Iowa	Corn stover	Enzymatic hydrolysis	114	200	Closed down (2017)
Iogen	Idaho Falls, Idaho	Agricultural residues	Enzymatic hydrolysis	68	200 (80)	Canceled construction (2008)
POET-DSME[b]	Emmetsburg, Iowa	Corn stover	Enzymatic hydrolysis	91	250	Operational/ adjacent to corn ethanol facility
Range fuels	Soperton, Georgia	Wood chips	Gasification	150	320 (76)	Closed down (2011); sold to LanzaTech

[a]Loan received from U.S. DOE

[b]POET was awarded a $105 million loan from U.S. DOE but declined it when it partnered with DSM

Janssen et al. (2013), Hayes (2016), Lane (2016, 2017), Hirtzer and Renshaw (2017), USDA (2018c)

being cost competitive with first-generation ethanol and fossil fuels, despite the financial incentives put in place. Second-generation ethanol production has also been affected by shale gas, a source of natural gas that has affected US natural gas prices, increasing demand and driving down prices (Janssen et al. 2013). Second-generation ethanol production can allow for the high-value utilization of hemicellulose, lignin, and process by-products to offset the costs associated with ethanol production (Fang et al. 2018). Some companies originally designated for the ethanol market (i.e., Blue Fire Renewables, Virdia (acquired by Stora Enso) Gevo, Amyris, Codexis, LS9 (acquired by REG Life Sciences, LLC), Virent) have shifted their research focus and plan to target the specialty chemicals market instead. A strategy is required that would allow these companies and the like to take advantage of the revenues from the specialty chemicals market until second-generation ethanol technologies become cost competitive to those of fossil fuels and are ready for commercialization.

14.2.4 Cogeneration of Electricity

14.2.4.1 Cogeneration from Sugarcane

Cogeneration in the cane sugar industry in the United States has been done primarily to satisfy the industry's internal power needs while only few factories have entered into agreements to sell electricity to utility companies. The installation of cogeneration facilities to sell electricity to the grid in Louisiana has been hampered by the poor CHP (combined heat and power) policy climate, allowing utility companies to charge high standby power rates and make the interconnection process more difficult (Chittum and Kaufman 2011). Six out of eleven sugar factories in Louisiana operate turbogenerators with capacities between 0.8 and 4.5 MW, for a total capacity of 14.3 MW (Spieker 2017). The largest producer, Lafourche Sugars, is the only one configured to sell electricity to the utility. It generates about 4.5 MW, of which most is used by the factory and typically less than 0.5 MW is sold. Lafourche Sugar's cogeneration project was initiated due to the existence of a pilot program from the Louisiana Public Service Commission to restudy the feasibility of implementing a renewable portfolio standard. After obtaining input from the utility companies participating in the program during 3 years, a mandatory renewable portfolio standard was not recommended in 2013 (Louisiana Public Service Commission 2013).

In Florida, all four sugar factories cogenerate, with the installed or permitted capacities ranging from 9.4 to 128.9 MW, for a total of 221.4 MW. The United States Sugar Corporation (US Sugar) facility has installed a capacity of 70 MW (US DOE 2018). Typically, less than 10% of the power production is sold to the utility. Okeelanta Power LP has a capacity of 128.9 MW (US DOE 2018). It is the only sugar mill configured to sell most of its electricity to the utilities. During the crushing season, the bagasse provides about two-thirds of the factory's power needs. Bagasse is complemented with wood chips, with a higher percentage during off-season (Monroe and McConnell 2014) to meet the electricity demand for the utilities. The only sugar mill in Texas, Rio Grande Valley Sugar Growers Inc. factory, has three 2.5 MW and a 16 MW backpressure unit. In normal operation, only the 16 MW unit is used, and it produces 9–10 MW, of which about 8 MW are consumed internally with 1–2 MW being supplied to the utilities. The utility payments to the factories for the power they receive are very low—usually only about $0.02/kWh. The Hawaiian sugar industry has ceased to exist. However, in the early 1970s, when there were over a dozen factories in operation, the Hawaiian sugar industry embarked on a major cogeneration effort. The factories installed high-pressure boilers (3.1–8.3 MPa), condensing/extraction turbogenerators, and utilized quintuple effect evaporator schemes with triple vapor bleeding to maximize their cogeneration potential. Many of the Hawaiian factories were able to sell about 5–15 MW to the utilities at good prices.

14.2.4.2 Cogeneration from Energy Cane

Energy cane varieties in Louisiana have the potential to produce between 206.9 and 277.1 kWh/t by burning the bagasse, containing 50% moisture, after processing in a conventional sugar mill. The released variety Ho 02-113 can produce 110 MW when it is processed at a rate of 10,000 t/day during 120 days (Aragon et al. 2015). Energy cane has not yet been widely adopted as a bioenergy source in the US, although its use has been encouraged by the US Department of Energy. The availability of data across the supply chain and the lack of distribution infrastructure for biofuels are among the barriers to its adoption.

14.3 Economics of Bioenergy Production

This section presents some economic estimates of the potential costs of utilizing sugarcane as a biofuel feedstock in both first- and second-generation ethanol production in the United States, as well as some factors which may limit the use or expansion of the use of sugarcane and energy cane as a biofuel feedstock. The specific region of focus presented here is for sugarcane production in Louisiana, a major sugarcane-producing state in the United States.

14.3.1 Biofuel Costs

The USDA conducted a major study in 2006 to evaluate the economic feasibility of producing ethanol from sugar in the US (Shapouri and Salassi 2006). Ethanol production cost values were estimated utilizing a variety of sugar source feedstocks including sugarcane, sugar beets, molasses, raw sugar, and refined sugar. Total ethanol production costs utilizing various sugar feedstocks were compared to corn ethanol production costs utilizing both wet milling and dry milling processes. Given the relative relationship between commodity market prices of raw sugar and corn, estimated ethanol production costs per liter of ethanol were higher utilizing various sugar sources as feedstocks compared with the use of corn as the major feedstock. Ethanol production costs utilizing sugar feedstocks were estimated to be \$0.63 l^{-1} utilizing sugarcane juice as the major feedstock, while production costs utilizing molasses or raw sugar as the major feedstock were estimated to be \$0.34 l^{-1} and \$0.92 l^{-1}, respectively. Estimated ethanol production costs utilizing corn in wet milling and dry milling processes were \$0.27 and \$0.28 l^{-1}, respectively.

Current estimates of ethanol production costs utilizing sugarcane juice as a feedstock were developed for the Louisiana sugarcane-producing region of the USA. These estimates are presented in Table 14.4 and are based on a typical sugarcane yield of 89.6 mt ha^{-1} (harvested) and a raw sugar recovery rate of 115 kg of raw sugar mt^{-1} of sugarcane. Molasses volume is based on a rate of 0.25 l kg^{-1} of

Table 14.4 Estimated costs of producing ethanol from sugarcane in Louisiana, USA

Production/cost factor	Unit	Value
Sugarcane yield per harvested area	mt ha^{-1}%	89.6
Percent of total farm area harvested[a]	%	76%
Sugarcane yield per total farm area	mt ha^{-1}	68.1
Raw sugar recovery from sugarcane	kg mt^{-1}	115.0
Raw sugar yield per total farm area	kg ha^{-1}	7834
Sucrose from raw sugar	%	96.0%
Sucrose from sugarcane per total farm area	kg ha^{-1}	7521
Molasses yield per total farm area	kg ha^{-1}	2760.5
Sucrose from molasses	%	49.2%
Sucrose from molasses per total farm area	kg ha^{-1}	1358
Total sucrose from sugarcane and molasses	kg ha^{-1}	8879
Total sucrose recovery rate	%	13.0%
Ethanol yield from sucrose[b]	l mt^{-1}	588.1
Ethanol yield per total farm area	l ha^{-1}	5222
Sugarcane production costs[c]	\$ ha^{-1}	\$1357
Land rent[d]	\$ ha^{-1}	\$395
Processing costs	\$ ha^{-1}	\$1569
Total production and processing costs	\$ ha^{-1}	\$3321
Ethanol cost per liter	\$ l^{-1}	\$0.64

[a]Sugarcane harvested through third stubble with 24% of total farm area in fallow/plant
[b]Assumed practical ethanol plant conversion rate
[c]Variable and fixed sugarcane production costs for Louisiana for the crop year 2017
[d]Land rent charged at a one-sixth crop share rate after deduction of processing crop proceeds

raw sugar. For sugarcane production cycle through harvest of a third stubble crop, 76 percent of total farm area would be harvested in a given year. Farm operations on the remaining farm area would include fallow and planting activities. Sugarcane production costs utilized in the evaluation were for the 2017 crop year (Deliberto et al. 2017).

With this level of sugarcane production per hectare and assuming typical sucrose extraction rates for raw sugar and molasses, the total sucrose production would be 11,681 kg ha^{-1} (harvested) and 8879 kg ha^{-1} of the total farm area, and the total ethanol production potential for this case scenario would equal 5222 l ha^{-1} of the farm area. At current crop production costs for sugarcane in Louisiana, costs of producing ethanol from sugarcane juice were estimated to be \$0.64 l^{-1} of ethanol, similar to cost estimates from the earlier USDA study. The use of sugarcane juice as a feedstock in traditional ethanol production in the USA has not been economically viable relative to corn grain. As a result, much of the focus of research and development has recently focused on the potential for feedstock such as high-fiber energy cane to serve as a biomass feedstock in cellulosic biofuel production.

14.3.2 Biofuel Feedstock Costs

Several research studies over the past few years have been conducted to evaluate the relative economic feasibility of utilizing high-fiber energy cane varieties of sugarcane as a potential biomass feedstock in the production of cellulosic ethanol or other advanced biofuels. These studies have focused on the estimation of the cost of the energy cane biomass as a feedstock input into cellulosic biofuel production.

Salassi et al. (2014) explored the crop establishment and whole farm production costs of growing energy cane as a biofuel feedstock in the southeastern USA. Variable production costs for energy cane production were estimated to be in the \$63–\$76 mt^{-1} range, and total production costs were estimated to range between \$105 and \$127 mt^{-1} of feedstock biomass dry matter material. Mark et al. (2014) compared the estimated feedstock costs of energy cane as a cellulosic biofuel feedstock input and made comparisons to costs of producing ethanol from corn grain. The study concluded that varietal improvements that would provide higher biomass yields and longer crop stubbling ability in energy cane were the most likely means of improving the economic feasibility of biofuel production from energy cane relative to corn.

Another study evaluated the potential for the expansion of energy cane production as a biofuel feedstock over a six-state region in the southeastern USA (Salassi et al. 2015b). Within the southeastern region of the USA, approximately 10.9 million ha of agricultural land exist in the current crop production. Another 1.15 million ha of croplands were estimated to be available for the potential expansion of energy cane production. The study reported that the estimated biofuel feedstock costs for energy cane could decline substantially if higher yielding energy cane varieties could be developed.

Concentration of the biofuel feedstock crop production in specific regions of the USA is dependent on the relative comparative advantage of production in a specific region based on several agronomic and economic factors (Salassi et al. 2017). For the southeastern region of the USA, energy cane, among a few other crops, has been identified as a feedstock crop with the greatest potential for further development of production. Field trials evaluating alternative varieties of high-fiber energy cane through several years of stubble crop production have recently been completed to allow for a more accurate estimation of biofuel feedstock costs utilizing energy cane.

Estimates of energy cane crop yields utilized in this study were taken from energy cane variety field trials conducted at the Louisiana State University AgCenter Sugar Research Station in St. Gabriel, Louisiana (Gravois et al. 2014). Five alternative varieties of energy cane were planted in 2008 in research plots on the station. These plots were harvested over the next 6 years to estimate the yield for the plant

Table 14.5 Feedstock production acreage requirements to supply fixed daily biomass quantity

Crop production phase	Feedstock crop harvest yield (mt ha^{-1})	Feedstock production acreage requirement[a] (ha)
(1) Energy cane through third stubble	90.56	12,982
(2) Energy cane through fourth stubble	88.66	13,261
(3) Energy cane through fifth stubble	87.74	13,400

[a]Production area required to meet a daily feedstock requirement for processing facility specified to be 13,063 harvest weight (mt day^{-1}), based on a processing rate of 544 mt h^{-1} at 24 h per day. Example for a Louisiana harvest season of 90 days, October 1 through December 31

Table 14.6 Estimated feedstock production costs for alternative cropping sequences

	Feedstock production scenarios[a]		
Estimated feedstock costs	1	2	3
	($ h^{-1})		
Variable cost	1028	1049	1064
Fixed cost	330	332	333
Total production cost	1358	1381	1397
Land rent at break-even revenue[b]	272	276	279
	($ mt^{-1} harvest weight)		
Variable cost	11.35	11.83	12.13
Fixed cost	3.64	3.74	3.80
Total cost	14.99	15.57	15.92
Land rent	3.00	3.11	3.18
Total cost plus rent	17.99	18.69	19.11
	($ mt^{-1} harvest weight)		
Variable cost	61.54	60.69	$58.88
Fixed cost	19.76	19.21	$18.45
Total cost	81.31	79.89	$77.33
Land rent	16.26	15.98	$15.47
Total cost plus rent	97.57	95.87	$92.80

[a]Scenario 1 = 90-day processing season, energy cane harvested through third stubble; Scenario 2 = 90-day processing season, energy cane harvested through fourth stubble; Scenario 3 = 90-day processing season, energy cane harvested through fifth stubble
[b]Land rent charged at a rate of one-sixth crop share at break-even revenue

cane crop (harvested in 2009) and the first stubble through fifth stubble crops (harvested in 2010 through 2014).

For three alternative energy cane feedstock production sequences, the production area required to supply a processing facility with a fixed daily supply of feedstock biomass over a specified harvest season is shown in Table 14.5. The processing capacity utilized here is similar to what currently exists for sugarcane processing in Louisiana, USA. With a processing capacity of 544 mt h^{-1} and a daily processing period of 24 h, the daily feedstock requirement for a processing facility at this specified capacity would be 13,063 mt day^{-1}. It would require approximately 13,000 ha of energy cane to supply a processing facility for a 90-d processing season. Estimates of variable and fixed production costs taken from values for the 2015 crop year for sugarcane in Louisiana were used to develop these energy cost estimates (Salassi et al. 2015a).

Current estimates of energy cane feedstock production costs per area and per output unit are shown in Table 14.6 for three cropping sequences (harvest through third stubble, fourth stubble, and fifth stubble). Total production costs for energy cane feedstock production were estimated to range from \$1358 to \$1397 ha^{-1}. On a unit of biomass output basis, production costs per meter of harvest weight were estimated to be in the range of \$17.99 to \$19.11 mt^{-1}. Whereas, on a dry weight basis, estimated feedstock costs of energy cane as a biofuel feedstock input were estimated to range between \$92.80 and \$97.57 dry mt^{-1}.

14.4 Challenges and Opportunities for the Use of Sugarcane and Energy Cane for Bioenergy in the USA

While it is estimated that around 30% of world ethanol production comes from sugarcane (REN21 2016), there are no commercial enterprises producing ethanol from sugarcane or energy cane in the USA (USDA 2018c). The value of sugar as a sweetener is the primary reason it is not used commercially for conversion to liquid fuel. The relative economic disadvantage of sugar feedstock sources compared with corn grain in traditional ethanol production has been, and continues to be, a major limiting factor for the use of a feedstock such as sugarcane juice to produce biofuel in the USA (Shapouri and Salassi 2006).

Predictions of world food shortages make land use changes to accommodate the expansion of bioenergy crop production problematic. World population is predicted to exceed 11 billion inhabitants by 2100, an increase of almost 50% (UN 2017). Reductions in the food supply would likely be concomitant with farmland diversion for the production of dedicated biomass crops. However, the use of idle cropland that is not occupied by commercial crop production presents an opportunity for the production of sugarcane and energy cane biomass feedstocks in the subtropical environment of the lower southern states (Salassi 2015).

Expansion to more northerly latitudes beyond the confines of the sugar-growing region would require enhanced cold tolerance. Experimental sugarcane and energy cane clones with improved cold tolerance have been identified, and progress is being made to develop genetic markers to breed varieties for cultivation outside of the traditional geographic zone of production (Hale et al. 2017; Khan et al. 2013). Other major issues associated with the expansion of the cultivation of sugarcane or energy cane as biomass crops for biofuel production include impacts on air, soil, and water quality, allocation of water resources, and deforestation. These and other issues are addressed in a comprehensive overview of cultivating sugarcane for use in bioenergy applications (Sandhu 2018) and its use as a renewable energy resource from a sustainable production perspective (Johnson et al. 2018).

A sugar factory stream currently in excess of the internal needs for fuel is bagasse. Based on the known bagasse production and consumption as a factory fuel, it is estimated that approximately a million metric tons of bagasse are available for use for the development of other energy sources like second-generation ethanol, pelletized fuel, biochar, or other forms of energy or bio products. Sugarcane crop residue captured in the field or at the processing facility represents another potential biomass source for the production of energy. Harvest residue dry matter ranged as high as 19.6 Mg ha^{-1} in a long-term harvest residue study conducted by Viator and Wang (2011). Failure to return crop residue to the field, however, could undermine the sustainability of sugarcane production. Cherubin et al. (2018) recently reviewed the implications of harvest residue removal and discussed opportunities to mitigate its negative effects.

The Brazilian model of broadening out to use sugarcane as a renewable energy crop may not be repeatable in the USA primarily because of the relatively high cost of using sugar feedstocks for ethanol, but energy cane and other sources of lignocellulosic biomass are promising feedstocks for the production of ethanol. There are, however, still several challenges at each processing step of ethanol conversion which has prevented second-generation biorefineries to be commercially available to date. Biorefineries will require a consolidated bioprocessing approach using pretreatment, enzymatic degradation, and fermentation which can efficiently and completely utilize the biomass. In addition to ethanol, the production of other by-products from lignocellulosic biomass holds great potential for increasing the value and usefulness of biofuels. The future success of second-generation ethanol will require dependable financial incentives and supportive regulations, which are instrumental in driving the commercial production and adoption of second-generation ethanol.

14.5 Conclusion

Bioethanol in the USA is made from corn and not from sugarcane or energy cane feedstocks. The higher value of raw and refined sugar relative to corn makes sugarcane ethanol not economically feasible. Molasses is the possible exception, as its cost at times is competitive with the cost of corn. Molasses supply, however, is limited due to long-standing contractual commitments primarily with the animal feed industry and a challenge due to the lack of proximity of raw sugar factories to corn ethanol biorefineries. Continuation of the US sugar program, which serves to support and stabilize prices, diminishes the likelihood of sugarcane being used for conventional fermentation to ethanol. More promising is the production of second-generation ethanol from energy cane. Federal government initiatives have encouraged the commercialization of second-generation ethanol through mandated biofuel volume targets. But challenged by low fossil fuel prices, processing issues, and relatively high costs, second-generation biofuels have yet to achieve commercial status. A sustained commitment to sugarcane and energy cane biofuel research and development is needed to overcome the challenges being faced by this industry which would help yield a profitable market in advanced biofuels.

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