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Article

An energy and economic analysis of energy crops processing into bioethanol as a gasoline substitute

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Abstract: two crops, energy cane and sweet sorghum which could be cultivated at marginal lands in subtropical climate (southeast U.S.) were analyzed to determine their potential to be processed into bioethanol as a gasoline substitute. A solution of sucrose and reducing sugars (shortly sugars) separated in the form of “juice” by squeezing those crops is a well known semi-product to be converted into bioethanol by a greatly established in Brazil technology (1G-technology). The residue is called bagasse and consisted of fiber and moisture. Fiber (mainly composed of cellulose, hemicellulose, and lignin) could be employed in the process of its lignocellulosic conversion to make a solution of sugars as an intermediate step in their fermentation into bioethanol. This technology (2G-technology) is yet at a development stage. Bagasse, on the other hand, is an energy carrier required to generate electricity and steam essential for both technologies. The analysis was done for the case when all the necessary energy demand is satisfied by the internally generated bagasse what makes the process of bioethanol production fully renewal and self-sufficient (sustainable). Due to a seasonal character of harvesting and continuous bioethanol manufacturing, the calculated energy balance accounts for sugars storage in the form of their concentrated solution (syrup). The economic efficiency for bioethanol production as a gasoline substitute was determined in comparison with the power generation option in dependence on gasoline and electricity prices meaning that both crops could be combusted to generate renewable electricity. As was shown by the analysis, manufacturing of bioethanol from sugars in “juice” compared to the sugars obtained through lignocellulosic conversion of fiber is associated with 2.5-4 times higher economic efficiency. In order to stay competitive with renewable electricity, bioethanol from fiber should include both

cellulose and hemicellulose conversion into fermentable to bioethanol sugars. In spite of a higher sugars percentage in the sweet sorghum “juice”, the relative selling cost of one tonne of energy cane supposed to be higher due to greater (more than three times) fiber content. The analysis showed that sugars in crops have value about three times higher than fiber; therefore, taking into account this proportion, increasing sugars content at the expense of fiber could be the way to improve quality of energy cane varieties. A greater yield of energy cane also favors a better economic land-use efficiency to produce bioethanol as a gasoline substitute.

Keywords: energy; biofuel; economics; sustainability.

1. Introduction

A bio-chemical conversion of biomass into biofuels and bioproducts usually involves production of reducing sugars (glucose, fructose, and etc.) at an intermediate stage. The already established in Brazil 1G-technology of bioethanol manufacturing from sugar cane imply a direct separation of sucrose and reducing sugars (shortly sugars) from fiber in the form of diluted juice (technical term) by squeezing the crops. That juice is converted into bioethanol by fermentation of its constituent sugars [1]. The fibrous solid material left after squeezing is called bagasse and contains almost equal weights of fiber and moisture.

The second bioethanol generation 2G-technologies imply bio-chemical lignocellulosic conversion of fiber constituents cellulose and hemicelluloses into sugars. Both technologies require substantial amount of electricity and steam and in order to be sustainable their energy demands have to be met by renewable energy sources. Bagasse is a renewable heat carrier that regularly used in the sugar industry to supply electricity and heat for an internal consumption and export [2].

Taking into account that harvesting period of cane-like crops in subtropical climate (southeast U.S.) lasts about three months, sugars have to be extracted and kept for an extended period provided continuous operation of bioethanol production in biorefineries during the year. Concentrated syrup of reducing sugars (65-85%) permits their storage without deterioration in off-season period [3] and, thus, represents a good semi-product for the following processing.

In order to be fully renewable a combination of 1G and 2G-technologies for biofuel production should have a balanced bagasse consumption rate meaning that feedstock-bagasse in lignocellulosic conversion and fuel-bagasse combusted in power and steam generation units should not exceed a total amount of internally generated bagasse. Moreover, economic feasibility of utilizing bagasse in lignocellulosic conversion becomes clear in comparison with power generation option implying burning bagasse in boilers to produce renewable electricity for external consumers.

Authors of several publications investigated the influence of different pretreatment methods, capital and variable cost reductions as well as different options for 1G and 2G-technology integration on techno-economical indicators of biofuel-bioethanol manufacturing [4-7]. However, the influence of crops composition in respect to their sugars and fiber content on energy balance and economics of such integration is not clearly presented. This dependence is of great importance and should be aligned with many other agrochemical characteristics (yield, diseases, soil quality, climate, and etc) to target the best variety suitable for biofuel production.

Two cane-like crops, energy cane and sweet sorghum which could be cultivated at marginal lands unsuitable for sugar cane in southeast U.S. are considered the ideal candidates for conversion into biofuels and bioproducts. Their composition and yields based on the data adapted from [8] are presented in Table 1.

In order to compare different technological options for crops processing a conceptual model for biofuel and electricity production is introduced (Fig.1). It has the following main features: i) 1G and 2G-technologies are combined on the base of their self-sufficiency on internal energy carrier (bagasse); ii) feedstock handling includes a syrup production stage. Based on calculated balances, 1G and 2G technologies are compared and the economic efficiency of bagasse utilization in lignocellulosic conversion vs. renewable electricity generation is estimated in dependence on gasoline and electricity prices. From the data obtained, the acceptable cost of one tonne (metric) of crops and separate costs of sugars and fiber are calculated under an assumption of their utilization in a bioethanol production plant.

Table 1. Sweet sorghum and energy cane composition and yield [8]

Component	Sweet Sorghum (Dale, M81-E, Theis, and Topper)	Energy Cane (L79-1001(L))
Sucrose,%	6.9	7.2
Glucose and fructose, %	4.3	1.1
Total sugars, %	11.2	8.3
Ash	0.96	1.3
Fiber,%	10.6	23.9
Cellulose,%	44.6	43.3
Hemicellulose,%	27.1	23.8
Lignin,%	20.7	21.7
Ash,%	0.4	0.8
Moisture,%	77.2	66.5
Yield, tonne/acre-year	22.1	36.8

2. A conceptual technological model for biofuel and electricity production

2.1. Front end plant

A conceptual model embraces a combined unit with four main technological blocks: front end plant, lignocellulosic pretreatment and hydrolysis, biorefinery, and power generation stations (Fig.1). The front end plant works only during harvesting season. The harvested crops are delivered to the front-end plant that takes sweet sorghum or energy cane stems and squeezed them in the milling section with production of bagasse and crude juice. A crude juice represents a solution in water of soluble sugars, ash and insoluble solid particles (dirt, fiber, etc.) An extra imbibition water (25%wt. of the input feed) is added to allow for a better sugars extractions from the crops. In clarification section, solid particles are removed from the juice by filtration and along this way sucrose was hydrolyzed into glucose. Then, clarified juice is concentrated in 5-effect evaporation unit to the syrup with water content about 30%wt. As it was mentioned above, the need of making syrup is dictated by the seasonal character of

harvesting and necessity to storage sugars without deterioration providing continuous work of a biorefinery.

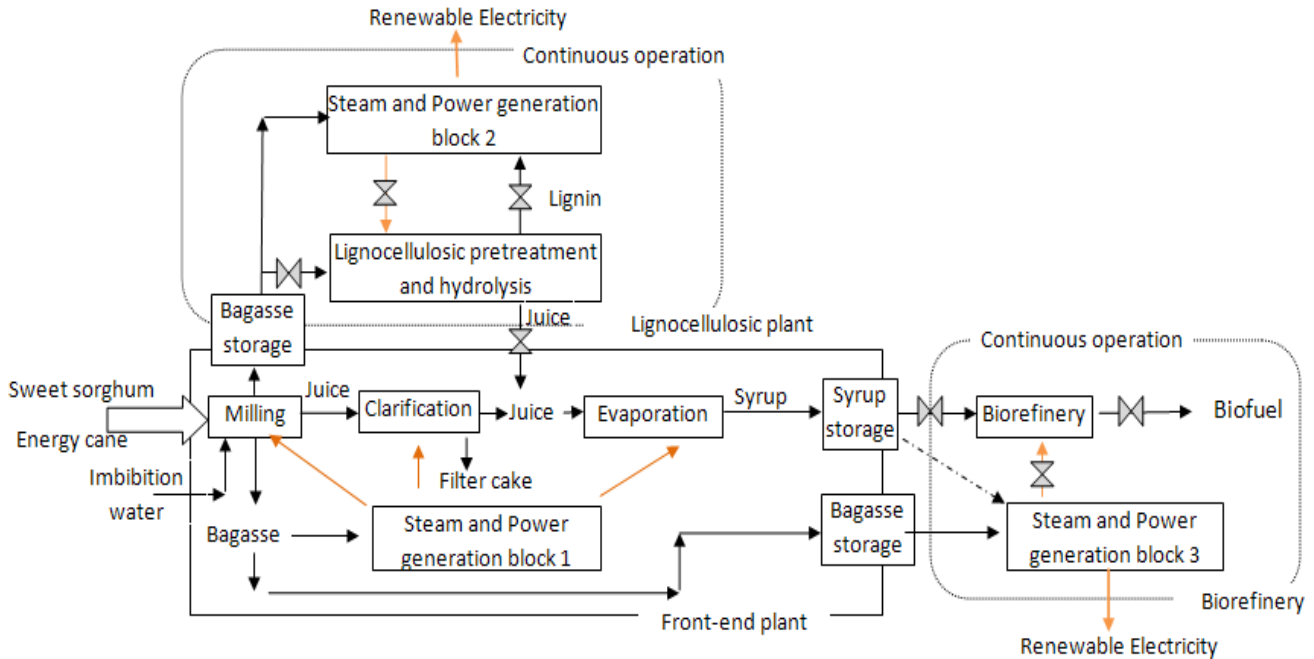


Figure 1. A conceptual model for renewable electricity and biofuel production from cane-like crops. Black arrows denote material streams and orange arrows denote energy streams (power and steam).

The input parameters for modeling are taken from [2] and presented in Table 2. The electricity consumption in milling section (knives, shredders, and mills) is taken equal to 90 kWh/tonne-fiber [2]. It comprises more than 90% electricity consumption in the front-end plant.

Table 2. Input data for the front-end plant, power and steam generation modeling

Milling	
Imbibition water	25% of the input flow
Sugar lost in bagasse	4% of the total sugars input
Fiber lost in juice	1% of the fiber input
Bagasse moisture	50%
Clarification	
Sugars lost in the filter cake	1% of the total sugars input
Evaporation	
Live steam pressure (P) and temperature (T)	P=2.6 atm.; T=130 ⁰ C
Number of effects	5
Driving temperature difference in evaporators	10-15 ⁰ C
Power and steam generation	
Heating value of bagasse (\approx 50% of fiber)	9000 kJ/kg (HHV)
Boiler efficiency (heating value of bagasse transferred to steam)	65%
Isentropic steam turbines efficiency	80%
Thermal efficiency of electricity production from bagasse	17%

Steam and power generation block 1 consists of pump and boiler connected to a steam turbine with a power generator. Parameters of this block (maximum pressure of steam and its temperature) were selected to meet exactly power and exhaust steam requirements to produce syrup and bagasse in the front-end plant. The exhaust steam after turbine becomes live steam for a 5-effect evaporation unit where water is removed and juice is concentrated to syrup. The heat needed for boiler operation is provided by bagasse that was burnt in its furnace. The simulation was performed by the program “Sugars” [9]. The results of mass and heat balances modeling are presented in Table 3. The content of sugars accounts for sucrose hydrolysis into glucose.

Table 3. Sugars production and bagasse consumption in the front-end plant per 1 tonne of throughput crops

Crops	Sugars in Syrup, kg	Electricity, kW-h	Steam, kg	Bagasse consumed, kg	Bagasse left, kg
Sweet sorghum	110	10.9	0.268	107	112
Energy cane	82.4	23.7	0.199	90.7	481

2.2 1G- sugars biorefinery

As an example of sugars conversion into biofuels, the bioethanol production is selected due to advanced process development and availability of data regarding its energy efficiency and economics [10, 11]. The exothermic effect of sugars fermentation into bioethanol is negligible, at the same time the average energy demand for ethanol distillation and dehydration is significant and estimated as 6500 MJ/ton-ethanol [11]. Assuming 90% sugars conversion to ethanol, as it was accepted in [10], and knowing theoretical yield of ethanol (0.51 kg-ethanol/kg-sugars) as well as heating value of bagasse (see Table 1) the approximate energy requirement to recover ethanol through distillation and molecular sieve dehydrating in terms of bagasse is 365 kg-bagasse/tonne-sugars. This means that steam and power generation block 3 consumes 365 kg of bagasse to generate steam to perform recovering of ethanol produced from 1 tonne of sugars. The results of mass and energy balance of 1G-sugars biorefinery are presented in Table 4. The bagasse left after 1G-sugars biorefinery is calculated as a difference between leftover bagasse in front-end plant (see Table 3) and bagasse consumed in biorefinery.

Table 4. Bagasse consumption and bioethanol production from 1G-sugars in biorefinery per 1 tonne of crops throughput

Crops	Bioethanol production, gal	Bagasse consumed, kg	Bagasse left, kg
Sweet sorghum	16.9	40.2	71.9
Energy cane	12.7	30.1	451

2.3 Lignocellulosic conversion and 2G-sugars biorefinery

The following assumptions for lignocellulosic conversion have been taken: conversion of cellulose and hemicellulose into sugars is 85%; concentration of diluted sugars in juice is 12% [10], lignin with

50%wt. moisture is separated from the liquid flow and used for power generation; the heating value of bagasse-like lignin is 10000 kJ/kg [5].

As seen in Table 4, some bagasse left unused at 1G-bioethanol production stage. That rest of bagasse could be used in lignocellulosic plant (Fig. 1) to generate extra amount of sugars (2G-sugars) for 2G-bioethanol. In this case, the role of bagasse is twofold. It supplies fiber components cellulose and hemicelluloses to be converted into sugars and it represents, as in previous sections, an energy carrier to run the process. In [11], authors estimated the data regarding energy demand for biomass pretreatment as well as energy to produce required chemicals and enzymes. According to their estimations for corn stovers, the ratio between biomass-fuel needed for pretreatment to biomass-fuel for ethanol recovery is about 1.8-2.0. The value 660 kg-bagasse/tonne-sugars was assigned for pretreatment stage for the following calculations. The calculated by simulation program “Sugars” bagasse-fuel consumption to evaporate water to concentrate sugars and other soluble organics from 12% to 70% is about 1 tonne-bagasse/tonne-sugars. Taking into account 85% conversion rate of fiber constituents (cellulose and hemicelluloses) into sugars 3430 kg-bagasse and 3560 kg-bagasse (as feedstock) are needed to produce 1 tonne of sugars from sweet sorghum and energy cane, respectively. The results are summarized in Fig. 2 a, b.

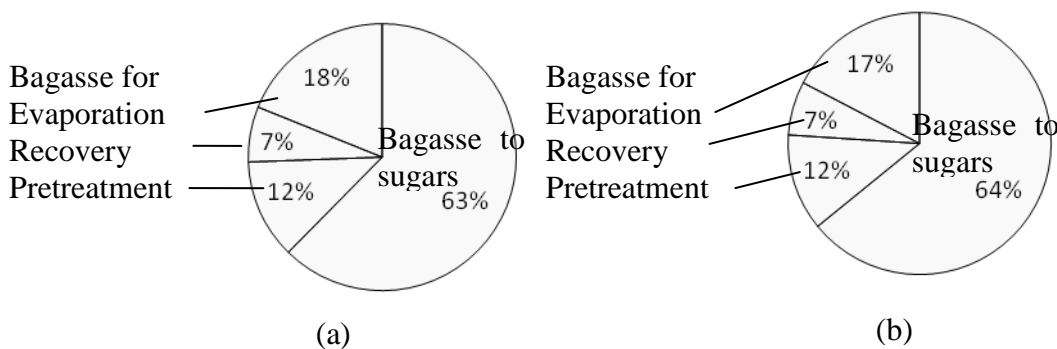


Fig 2. Distribution of bagasse consumption to produce 1 tonne of sugars: (a) sweet sorghum with total bagasse consumption 5.50 tonnes; (b) energy cane with total bagasse consumption 5.56 tonnes.

The lignocellulosic conversion provides an extra amount of sugars (2G-sugars) which are converted in bioethanol in biorefinery. Both processes consume bagasse left after 1G-bioethanol manufacturing. The numerical estimations regarding lignocellulosic bioethanol (2G-bioethanol) production from bagasse are presented in Table 5.

Table 5. Ethanol production from 2-G sugars and bagasse consumption in biorefinery per 1 tonne of crops throughput

Crops	Sugars in syrup, kg	2G-bioethanol production, gal	Increase compared to 1G-bioethanol, %	Bagasse consumed, kg
Sweet sorghum	13.1	2.02	12.0%	71.9
Energy cane	81.1	12.5	98%	451

2.4 Economics of bioethanol and renewable electricity production

The economic analysis for lignocellulosic conversion of corn stover with dilute acid pretreatment with enzymatic hydrolysis and co-fermentation reported in [10] is adapted in this paper. The financial conditions for building a bioethanol plant are presented in Table 6.

Table 6. The financial conditions for building a lignocellulosic plant coupled with biorefinery to produce bioethanol [10]

Ethanol production	61.0 MMgal/yr
Life time	30 years
Total capital investment	422,000,000 \$
Equity percent of total investments	40%
Internal rate of return (after tax)	10%
Loan rate	8.0%
Term of loan	10 years

The itemized minimum bioethanol manufacturing price is presented in Table 7. For the purpose of following comparison between bioethanol and renewable electricity production the credit related to the extra electricity generated from the lignin is excluded from this price. Compared to 2G-bioethanol manufacturing, 1G-bioethanol allows for eliminating capital and fixed operating costs corresponded to pretreatment, neutralization and conditioning, saccharification, and enzyme production. As a result, the expenditures related to capital investment are declined by at least 40%. This number (40% reduction) was taken to estimate 1G-bioethanol minimum manufacturing price. The heating value of ethanol per gallon is lower than the same of gasoline in about 1.52 times, therefore to be equal in heating values its volume supposed to be correspondingly higher (see last line in Table 7). At the same financial and operational condition the minimum manufacturing price of electricity is 0.06 \$/kWh [10].

Table 7. Minimum manufacturing cost for 2G-bioethanol and 1G-bioethanol in 2007 US dollars

Item	Lignocellulosic biomass to bioethanol (2G), \$/gal	Sugars to bioethanol (1G), \$/gal
Enzymes and chemicals for pretreatment	0.340	0
Other chemicals	0.071	0.071
Waste disposal	0.025	0.025
Fixed costs	0.175	0.080
Capital depreciation	0.22	0.13
Average income tax	0.12	0.070
Average return of investment	0.566	0.323
Minimum manufacturing price	1.52	0.71
Minimum	2.31	1.08

manufacturing price of gasoline equivalent		
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3. Results and discussion

In order to determine economic efficiency of 1G and 2G-bioethanol technologies, they are compared with the renewable electricity production. As seen in Fig. 1, if all valves surrounding lignocellulosic plant are closed, instead of production 2G-bioethanol, bagasse is utilized for renewable electricity generation in the steam and power generation block 3. Accounting for the fact that power is also generated from unconverted lignin in lignocellulosic plant, this amount is subtracted from the power obtained from bagasse. If all valves surrounding biorefinery are closed, instead of production 1G-bioethanol, the heating values of sugars in syrup (dashed line) and bagasse, previously assigned to run the process of 1G-sugars conversion into bioethanol, are utilized to generate renewable electricity in power generation block 2.

The breakeven prices of electricity for 1G and 2G-bioethanol production are calculated by the following formula:

$$GS(PR_{gs} - MPR_{gs}) = EL(PR_{el} - MPR_{el}) \quad (1)$$

where GS is gasoline equivalent production by 1G or 2G-technology per 1 tonne of crops and EL is a net-electricity that could be generated instead of bioethanol on 1G or 2G-technology per 1 tonne of crops; PR_{gs} is price of gasoline and MPR_{gs} is the minimum manufacturing price of gasoline equivalent for 1G or 2G-bioethanol; PR_{el} is calculated breakeven price of electricity and MPR_{el} is the minimum manufacturing price of electricity (0.06\$/kW-h). The difference between two prices implies expenditures for feedstock growing, harvesting, transportation, and handling in the front end plant as well as a profit from the entire process. The higher is the difference the more economically sound is the technology. The comparison is made under an assumption that the difference in minimum manufacturing prices for bioethanol and electricity do not change with increasing production rates.

The breakeven prices of renewable electricity for 1G gasoline-equivalent produced from cane-like crops (sweet sorghum and energy cane) are presented in Fig. 3. They are the same for both crops because both gasoline-equivalent and electricity production (GS and EL in formula (1)) are linearly proportional to the content of sugars in syrup. The thermal efficiency of electricity production from syrup (electricity production per unit of heating value) was taken equal to that of bagasse (see Table 2). As seen in Fig.3, at the price of gasoline 3.5\$ per gallon the breakeven cost of electricity is about 35cents per kW-h. This result can be interpreted in the following way. If at 3.5\$/gal of gasoline the corresponded electricity cost is lower than 35 cents/KW-h, production of biogasoline is economically superior to renewable electricity. The higher is that difference (between breakeven and real cost of electricity) the better is economical environment for bioethanol production.

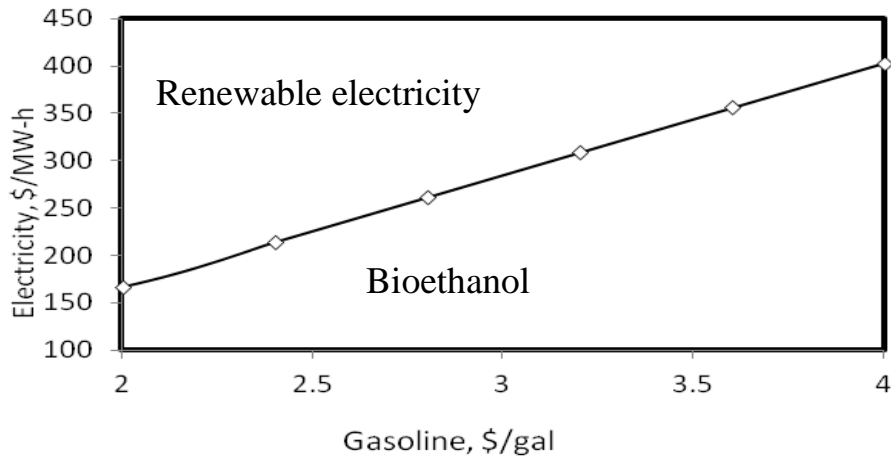


Fig.3. Breakeven prices of electricity for 1G-biogasoline (1G-bioethanol replaces gasoline) production from sweet sorghum and energy cane.

For comparison, in 2009-2011 the average electricity price in US stayed around 9.8-9.9 cents/kW-h and gasoline price was increased from 2.4 to 3.4 \$/gallon [12].

The breakeven prices of renewable electricity for 2G-gasoline equivalent produced from cane-like crops (sweet sorghum and energy cane) are presented in Fig. 4.

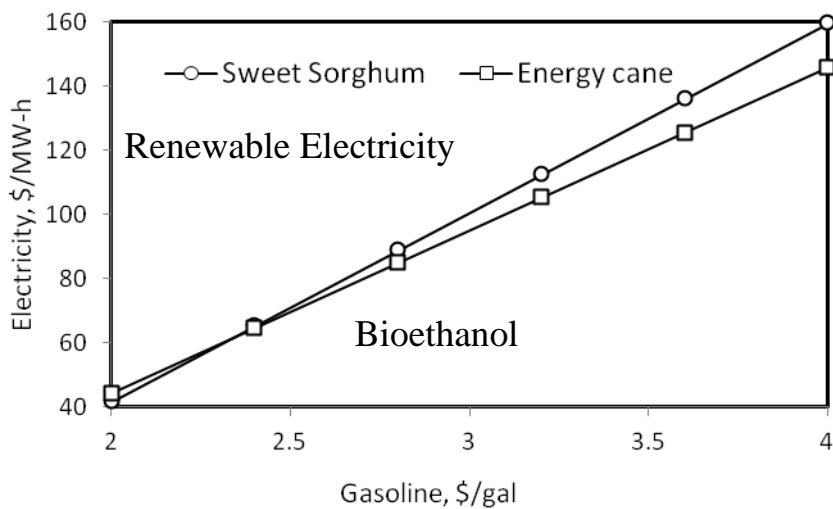


Fig. 4. Breakeven prices of electricity for 2G-biogasoline (2G-bioethanol replaces gasoline) production from sweet sorghum and energy cane.

As seen in Fig. 3 and 4, breakeven electricity prices are higher for 1G-biogasoline, therefore, in the range of the gasoline prices considered, the economical profitability of 2G-technology is 2.5 – 4 times lower than that of 1G. An insignificant difference between sweet sorghum and energy cane in Fig.4 is due to slightly different composition of their fibers (only cellulose and hemicellulose are converted into sugars). The breakeven prices of electricity at 2.8-3.0 \$/gallon of gasoline give the values that are very close to the current ones (≈ 10 cents/kW-h). A specific attention is supposed to be given to the efficiency of pretreatment stage and utilization of the hemicellulose derivative – xylose (C5 sugars). For instance, if only the cellulose derivative – glucose is extracted with 90% efficiency for the

following conversion into biofuel (bioethanol) the breakeven prices of electricity 9-10 cents/kW-h are shifted to 3.2-3.4 \$/gallon.

Assume that bioethanol production is superior to electricity for both 1G and 2G-technologies. A minimum manufacturing price of bioethanol includes a minimum manufacturing price of electricity and steam generated for internal needs. In order to get benefit of an excess of electricity produced from lignin, that electricity is accounted as sold at a minimum manufacturing price. In this case, at a given gasoline price PR_{gs} the price of 1 tonne of crops PR_{cr} that includes growing, harvesting, transportation, and handling at the front end plant can be calculated as follows

$$PR_{cr} = GS_{1G}(PR_{gs} - MPR_{gs-1G}) + GS_{2G}(PR_{gs} - MPR_{gs-2G}) + EL_{2G}MPR_{el} \quad (2)$$

where GS_{1G} , GS_{2G} are gasoline equivalents production by 1G and 2G technologies per 1 tonne of crops; MPR_{gs-1G} , MPR_{gs-2G} are minimum manufacturing prices of gasoline equivalent for 1G and 2G bioethanol technologies, respectively (Table 7); EL_{2G} is electricity generated from lignin from 1 tonne of crops; MPR_{el} – minimum manufacturing price of electricity (6 cents/kW-h [10]).

Neglecting a slight difference between fiber composition in sweet sorghum and energy cane, the prices of fiber PR_{fb} , sucrose and reducing sugars PR_s can be calculated by solving the system of algebraic equation as follows

$$C_{fb}^{ss} PR_{fb} + C_s^{ss} PR_s = PR_{ss} \quad (3)$$

$$C_{fb}^{ec} PR_{fb} + C_s^{ec} PR_s = PR_{ec} \quad (4)$$

where C_{fb}^{ss} , C_s^{ss} , C_{fb}^{ec} , C_s^{ec} are fractions of fiber and sugars in sweet sorghum and energy cane, respectively; PR_{ss} , PR_{ec} are prices of sweet sorghum and energy cane, respectively. The results of calculations on formulas (2), (3) and (4) for gasoline price 3.6 \$/gal (average regular pump price in 2012 [12]) are presented in Table 8. All calculated prices for crops, their fibers and sugars include a profit as well as expenses for growing, harvesting transportation and preliminary handling in the front-end plant.

Table 8. Sweet sorghum, energy cane, fiber, and reducing sugars prices in biofuel (bioethanol) production technology at the price of gasoline 3.6 \$/gal. Those prices include a profit as well as expenses for growing, harvesting transportation and preliminary handling in the front-end plant.

Crops	Crops, \$/tonne	Fiber, \$/tonne	Sugars, \$/tonne
Sweet sorghum	30.0	68	204
Energy cane	33.1		

It is noteworthy to mention that the price of sugarcane to produce sugar in Louisiana was higher; it was about 56 \$/tonne(metric) in 2011/2012 even with excluded expenses in the processing plant [13]. A substantially higher price of sugarcane confirms a generally accepted statement that growing biomass for energy sectors is not supposed to be in competition with the food industry.

Two considered crops are different in both their composition and yield (see Table 1). These parameters have to be accounted for calculating of the land-use economics. The results of calculation are presented in Table 9 for the area of 50000 acres.

Table 9. The land-use efficiency indicators for two crops and two different scenarios. The calculations are made for the area of 50000 acres and the land-use efficiency is calculated at the price of gasoline 3.6 \$/gal.

Crops	Technology	Sugars, MMtonne/year	Gasoline equivalent, MMgal/year	Electricity, MW	Land-use efficiency **, \$/acre
Sweet sorghum	1G+ electricity	0.122	12.3	3.82	N/A
	1G + 2G	0.137	13.8	0.97*	663
Energy cane	1G+ electricity	0.152	15.3	39.7	N/A
	1G + 2G	0.301	30.3	5.78*	1218

*Generated from lignin separated from reducing sugars

** Land-use efficiency indicator includes a profit as well as expenses for growing, transportation and preliminary handling in the front-end plant.

The better cost of energy cane compared to sweet sorghum in line with its higher yield makes energy cane almost twice economically superior in respect to land-use efficiency (Table 9). The data from Table 8 could be used by agrochemicals to breed crops with even better characteristics for the purpose of bioethanol production. For instance, as seen in Table 8, replacing some portion of fiber with sugars with the ratio lower than 3:1 would lead to a better fit for processing into bioethanol and, therefore, to an increase in their price.

4. Conclusions

As it was shown, edible sugar manufacturing from sugar cane stays superior to bioethanol production from can-like crops (sweet sorghum, energy cane). Based on conducted analysis, a cultivation of sweet sorghum and energy cane to produce bioethanol as a gasoline replacement at marginal lands, unsuitable for sugar cane, sounds economically feasible at the present price range for fuels and electricity in the U.S. However, bioethanol from sugars extracted directly from crops (1G technology) compared to the sugars obtained through the lignocellulosic conversion (2G-technology) is associated with 2.5-4 times higher breakeven prices of electricity what points out on its substantially higher economic efficiency. In order to stay competitive with renewable electricity production the lignocellulosic conversion should include both cellulose and hemicellulose conversion into bioethanol in a biorefinery. The relative selling price of one tonne of energy cane is higher than the same of sweet sorghum mostly because of a greater fiber and lower moisture content. The analysis showed that sugars have value about three times higher than fiber; therefore, taking into account this proportion, an increase in sugars content at the expense of fiber could be the way to improve quality of energy cane varieties for bioethanol production. A greater yield of energy cane allows for increasing land-use efficiency for bioethanol production in about two times.

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Conflict of Interest

The author declares no conflict of interest.

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