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The Biomass Based Electricity Generation Potential of the Province of Cienfuegos, Cuba

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Abstract By 2013, the province of Cienfuegos in Cuba consumed about 5165 GWh of primary energy, of which an estimated 60 % was used to produce 767 GWh of electricity. 29 % of the primary energy was obtained from renewable fuel, and only less than 5 % of the biomass energy, was used to produce about 27 GWh of biomass based electricity. This study proposes and assesses opportunities to produce electricity from biomass in the sugar industry of the province. The scenarios considered include: upgrading the agricultural yield of sugarcane, producing energy cane and combusting it after the sugarcane milling season, combusting the filter cake, combusting marabu (*Dichrostachys cinerea*, a bush tree considered a plague in Cuba) after the sugarcane milling season, and updating the electricity generation technology. Results are given for the different scenarios and it is shown that a combined scenario, including upgrading agricultural yield of sugarcane, upgrading electricity generation technology, combusting filter cake, and producing energy cane to generate electricity after the sugarcane milling season, thus allowing to use the generation units in sugar factories during 8000 h per year affords a potential production of 1150 GWh of electricity, 50 % more than consumed in Cienfuegos province in 2013.

Keywords Bioelectricity · Biomass · Bioenergy · Sugar industry

Abbreviations

HHV	High heating value (MJ/kg)
LHV	Low heating value (MJ/kg)
MC	Moisture content
tc	Ton of sugar cane milled

Subscripts

d.b.	Dry basis
w.b.	Wet basis

Introduction

During recent decades, energy issues turned worldwide into a fundamental component of the strategic discussions on sustainable development [1, 2]. The world energy demand increases faster than the global population [3]. With about 80 % of the energy obtained from fossil fuels [4], the effects on climate change threaten human security, e.g. by affecting the weather patterns and the economy [5–7]. Moreover, as fossil fuel reserves are limited, a transition towards a sustainable energy supply is mandatory. A core element of this transition is the use of biomass to generate renewable energy [8]. It is foreseen that renewable energy will play a major role in the rest of the twenty-first century [9] and will be very important to increase energy security [10]. Moreover, biomass based energy is environmentally viable and economically feasible [11] and biomass is the only renewable resource capable of

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substituting oil, both as fuel and in chemical applications [12, 13].

Currently, biomass covers about 9 % of the world's primary energy demand [4], and there is potential to further increase the energy production from biomass [14]. However, some biofuels are produced from food crops, which may increase food prices and affect food security [15, 16]. Moreover, the increase of bioenergy crops demands more agricultural land, which is a further threat to the environment [17]. Life cycle analysis studies demonstrate that greenhouse gas emissions reduction realized by using biofuels are currently limited as a result of the high carbon intensity of growing crops and producing the fuel [18]. Although the use of biofuel can potentially reduce the emissions of greenhouse gases compared with fossil fuels [19], other studies point out that several biofuels even show higher environmental impacts than fossil fuels. To address the ''food, energy and environment trilemma'' [20], alternative biomass sources including crop residues, wood and forest residues, as well as municipal and industrial waste were suggested. These might meet a substantial share of the future energy demand [21].

The current energy consumption in Cuba shows an increasing trend and is expected to rise further in the future [22]. Moreover, the transition to a market economy will likely accelerate and intensify this trend. Historically, the Cuban energy supply strongly depended on imports from abroad [22]. More recently the "energetic revolution" made the country more efficient after implementation of energy management strategies and technological update of devices with small electricity consumption (light bulbs, domestic water pumps, etc.), mainly in residential areas, which account for 56 % of the electricity consumption of the country [22, 23]. Moreover, since it mainly focused on the residential sector, the energetic revolution resulted in a limited impact on the energy efficiency of industry, transport and agriculture [24].

As shown in Table 1, the Cuban electricity mix shows an almost complete dependence on non-renewable sources [25, 26]. Only in remote locations, inaccessible to the national electric grid, renewable technologies such as solar panels and wind turbines were implemented with government support [26]. However, during recent years, government increased its efforts to use renewable energy, aiming at increasing the share of electricity from biomass to 24 % by 2030 [27]. Still, the potential of biomass remains currently underused [25].

The province of Cienfuegos, is located in the south central area of Cuba and occupies 4178 km^2 (417,800 ha). It has a varied economy based on agriculture, industry and tourism. Cienfuegos is also the location with the largest oil refinery and the second sea port of the country. In 2013, the province consumed about 5165 GWh of primary energy [23]. An estimated 60 % of this energy was used to produce around 768 GWh of electricity [23]. Renewable resources accounted for 29 % of the primary energy production, and only less than 5 % of the primary energy was used to produce about 27 GWh of biomass based electricity. Bagasse, an important byproduct of the sugar industry [28], was the main source.

Sugar industry is the main source of electricity from biomass in Cienfuegos (and in Cuba), and could potentially produce an important share of the electricity mix of the province. Unfortunately, inadequate policies and decisions in 2001 reduced the number of sugar factories in Cuba from 156 to about 70, of which some are used during the milling season depending in the availability of sugarcane [29]. The Cuban sugar industry is characterized by the use of outdated technologies and by low agricultural yields in the production of sugarcane. Nevertheless, the sugar factories have the infrastructure to generate electricity from biomass, but are in use only for 3600 h per year. Opportunities exist however to increase the production of electricity from biomass during and after the sugarcane milling season. These include increasing the agricultural yield of sugarcane and using additional new fuels to generate electricity, such as the filter cake produced in the sugar industry, biomass from a bush tree known as marabu, and energy cane. Updating the energy generation technology is another opportunity [30]. Part of these suggestions are rather obvious; others e.g. using filter cake as a fuel or the combustion of energy cane or marabu after the sugarcane milling season to extend the use of the electricity generation infrastructure to far above 3600 h per year, are more innovative and new in Cuba.

Table 1 Cuban electricity mix (after: http://www.iea.org/statistics/statisticssearch/report/?year=2012&country=Cuba&product=ElectricityandHeat)

Energy source	Electricity generation (GWh)	Share in energy mix (%)
Fuel oil	15,652	84.92
Gas	2092	11.35
Biofuels	555	3.01
Hydro	111	0.60
Wind	17	0.09
Solar photovoltaic	5	0.03

Moreover, it should be considered that the actual state of development of Cuba, only offers limited funding for investments. Possibly the recent political events will change this situation.

This paper presents and analyses measures to increase the electricity production from biomass in the province of Cienfuegos, with an increasing degree of technological complexity, the most complex ones requiring the highest investments. The analysis is mainly conducted from the technological point of view, but attention is also given to the economic analysis and the environmental impact.

Biomass Sources

The sources of biomass in Cienfuegos include:

- Agricultural waste: rice husk, sugarcane straw.
- By-products of the sugar industry: bagasse, filter cake [31].
- *Dichrostachys cinerea* (marabu, a woody bush).
- Pig manure.
- Municipal solid waste (MSW).

Table 2 shows the quantities of biomass available in the province.

Other biomass sources, mainly from agricultural waste are available, but in too limited quantities or too disperse to be considered. In general, marabu accounts for the main potential biomass source followed by bagasse.

Technical–Economic Assessment of Electricity from Biomass in Cienfuegos

The production of electricity from biomass is related to the properties of the biomass, the available technology and the potential economic revenue. Table 3 shows the chemical composition, ash content and heating values of Cuban biomass.

Table 2 Biomass sources of the province of Cienfuegos [23]

Biomass source	Quantity (kt/y)
Rice husk	1
Sugarcane straw	57
Bagasse	459
Filter cake	63
Dichrostachys cinerea (Marabu)[a]	2553
Pig manure	166
Municipal solid waste (MSW)[b]	113

[a] Total mass available in the province. Marabu has a renewability of 3 years

[b] 752,000 m^3 with a density of 150 kg/m^3; of course MSW is not completely biomass

The heating value of biomass on wet basis is calculated using the equation [32]:

$$LHV_{w.b.} = HHV_{d.b.} - 2.44 \cdot (9 \cdot H + MC) \qquad (1)$$

where $LHV_{w.b.}$, low heating value on wet basis (MJ/kg); $HHV_{d.b.}$, high heating value on dry basis (MJ/kg); H, fraction of hydrogen in the biomass; MC, moisture content.

Sugarcane has the highest potential of sunlight conversion of all crops, up to 6.7 % [33]. Byproducts and wastes from the sugar industry and agricultural wastes from sugarcane growing are the main biomass sources in the province of Cienfuegos. Electricity production in sugar factories relies on bagasse and sugarcane straw combustion in biomass kilns to produce steam, which in turn is used to produce electricity and heat. The cogenerated heat is required for the sugar production process. Sugarcane straw is an agricultural waste from sugarcane harvesting, while bagasse is a by-product of the sugar industry. The surplus electricity produced is sold to the national electric grid. In view of their availability and characteristics, filter cake [31] and marabu are also suitable for combustion in the kilns.

The sugar industry in Cuba operates only for about 3600 h per year, i.e. only during the sugarcane milling season, and the factories are inactive during the remaining part of the year. The 4 operational sugar factories in the province of Cienfuegos, have an installed electricity generation capacity of 29 MW in total, and can thus produce 104.4 GWh of electricity during the sugarcane milling season. A fifth operational sugar factory exists, but as a result of the shortage of sugarcane is not operational during the milling season. In 2013, using 1911 kt of milled sugarcane the sugar factories in Cienfuegos generated 26.7 GWh of electricity and 819 GWh of thermal energy [23]. Sugar factories in Cienfuegos operate with outdated technology causing a low electricity generation efficiency: the steam boilers work at 18–23 bar generation pressure combined with counterpressure turbogenerators of up to 8 MW. This technology allows to produce up to 41 kWh per ton of milled sugarcane (tc) [34]. Currently the electricity production in the 4 factories averages 27 kWh/tc, while sugar production consumes 13 kWh/tc, so that surplus electricity production is only 14 kWh/tc.

There are different technologies to generate electricity in the sugar industry, covering a wide range of steam parameters varying from 21 to 110 bar of pressure and 300–540 °C of temperature [35]. State of the art electricity generation technology for sugar factories uses high pressure and temperature steam parameters (>60 bar and >450 °C) resulting in higher surplus electricity production [35]. Modern plants in Brazil (first world sugar producer)

Table 3 Chemical composition and heating values of Cuban biomass (on dry basis) (after: [31, 32])

Biomass	MC (%)	C (%)	H (%)	O (%)	Ash (%)	LHV (MJ/kg)	HHV (MJ/kg)
Bagasse	50	47.2	7.0	43.1	2.7	15.8	17.3
Sugarcane straw	45	43.5	6.1	41.1	9.3	15.7	17.2
Filter cake$_{d.b.}$	70–80	32.5	2.2	2.2	14.5	8.8	14.5
Marabu	19	48.6	6.3	43.6	1.5	19.3	20.7
Rice husk	8–10	38.2	5.6	33.7	22.5	15.2	16.5

generate up to 72 kWh/tc of surplus electricity [36]. When part of the harvested cane straw is used and the industrial process is optimized, the surplus electricity production reaches 140–150 kWh/tc [36, 37]. Consequently, sugar factories in Cienfuegos can in principle increase their surplus electricity production by 50–125 kWh/tc.

Moreover, the sugarcane production in Cienfuegos averages 48 t/ha [23]. With the soil characteristics in the sugarcane farms of Cienfuegos and an improved selection of sugarcane varieties, it is possible to reach an agricultural yield of 90 t/ha [38].

Three potential scenarios allow thus to increase the electricity production from biomass in sugar factories:

1. Using the electricity generation technology as installed today but with increased biomass production.
2. Using the electricity generation technology as installed today, but with minor investments e.g. in the clarification of the sugarcane juice, producing filter cake and/or in the harvesting technology of the marabu.
3. Installing state of the art technology.

The first scenario relies on upgrading the sugarcane yield and thus increasing the biomass production. This might result in operating the 5th sugar factory during the milling season. To produce electricity after the end of the milling season, it is possible to harvest energy cane on the lands where now marabu grows, [39].

The second scenario allows using filter cake, a waste from the sugarcane juice clarification process, as fuel to increase the electricity output [31]. For this scenario investing in belt filters to dewater filter cake is necessary. Another possibility consists in combusting marabu after conclusion of the milling season, and implies investing in marabu harvesting machines.

The third scenario consists of installing state of the art electricity generation technology in the sugar factories. The potential of the first two scenarios can be combined with the third scenario to increase the electricity production.

The economic feasibility of the three scenarios can be assessed by considering the payback period as an evaluation criterion. The payback period is defined as the time which allows recovering the investment after the initial expenditure.

Scenario 1

Agricultural Optimization

The five sugar factories of Cienfuegos are supplied by 39,812 ha of sugarcane fields. The sugarcane production in the province faces low agricultural yields, which resulted in a reduction of the sugar industry in Cienfuegos from 12 sugar factories to 5 in 2001. Currently only 4 sugar factories operate during the milling season as a result of the lack of sugarcane.

The low yields are a result of malpractices including [40]:

- Incorrect preparation of the soil prior to sowing, and use of seeds of substandard quality resulting in low germination incidence. This gives a low density of the plants (53 % of the lands with low density, 31 % with medium and only 16 % with high density of sugarcane).
- With only 67 % of the sugarcane lands provided with fertilizer, there is certainly room for optimization of the fertilization. Moreover, the dosage of fertilizer is suboptimal during the growing phases of sugarcane, as applying fertilizer usually only starts months after the seeding. Out of phase fertilization, combined with limited pesticide use (only 61 % of the required amount) results in weed overgrowth, which absorbs up to 45 % of the applied fertilizer. Weed competition reduces sugarcane yields to 65 % of its potential [40].

Increasing the sugarcane productivity to 90 t/ha requires to plant high yield sugarcane varieties to replace current plantations. It also necessitates adapting current agricultural practices, and avoiding existing sowing and tillage malpractices. The current fertilizing practices result in 50 % loss of nitrogen, 80 % of phosphorus and 60 % of potassium. Fertilizer accounts for the major cost of tillage. Increasing the total amount of fertilizer per ha is unnecessary, but the dosage during the growth of the sugarcane should be optimized. Since only 67 % of sugarcane lands are fertilized, more fertilizer is needed to ensure the fertilization of all sugarcane lands, even if the fertilizing practices are improved. Weed competition should be limited, which requires increasing use of pesticides, or application of physical methods to reduce weed, or an integrated pest management approach.

Upgrading the agricultural yield will of course increase fuel consumption during the mechanical harvest of the sugarcane, which is related to the sugarcane yield as shown in Table 4 [32].

The interpolated data show that the mechanical harvest of 1 ha of sugarcane with a yield of 90 t/ha requires about 89 l of diesel. In Cienfuegos, around 55 l/ha are consumed during harvesting.

One ton of sugar cane processed in a sugar factory in Cienfuegos yields on average around 240 kg of bagasse (50 % moisture), 91 kg of sugar, 33 kg of filter cake (70–80 % moisture) and 26 kg of molasses [31]. Table 5 shows the potential increase of production with the upgraded yield for the 39,812 ha currently planted with sugarcane.

The reduction of surplus electricity production for an upgraded yield might look unexpected. In the sugar factories of Cienfuegos, 29 MW of electricity generation capacity is currently installed. Consequently, during the sugarcane milling season (3600 h) a maximum of 104 GWh can be generated. Yet for different reasons (failures, in the generation unit or in other sections of the factory) the generators are operative only about 59 % of the sugar milling season time. For an agricultural yield of 90 t/h, around 860 kt of bagasse is produced, of which 548 kt is sufficient to satisfy the bagasse demand for the electricity generation capacity currently installed. Moreover, the electricity demand in sugar factories rises from around 25 to 47 GWh because of the higher mass of sugarcane to be processed, which explains the reduction of surplus electricity production for the upgraded yield. Summarizing: more sugarcane produced gives more electricity. However, electricity needed for the production of the increased amount of sugar, reduces the surplus electricity.

Upgrading the agricultural yield implies operating the 5 sugar factories of the province. This will result in increasing the productivity of sugar factories with lower production costs. Producing surplus electricity in sugar factories cost 30 $/kWh and is sold to the national grid at 127 $/MWh. In general, the main cost of the sugar production is the cost of sugarcane. Currently producing 1 t of sugar costs around 354 $. The increased sugarcane yield will increase the costs of fertilizers, weed abatement and electricity, although the production cost per ton of sugarcane will be reduced, which contributes to lowering the production cost of sugar to 274 $ per ton. To upgrade the sugarcane yield, an initial investment of 19,030 k$ is required to plant high yield varieties. The economic impact of improving the sugarcane yield is shown in Table 6.

Molasses and bagasse are byproducts of the sugar production, which are somehow valorized in different ways. Molasses are valorized as raw material to produce alcohol and/or animal feed. Moreover, bagasse is valorized as a fuel to produce electricity or as raw material in the production of bagasse boards or paper and more recently for methanol production. Although the upgraded agricultural yield allows operating the fifth sugar factory of the province, surplus electricity production is reduced because of the limited and outdated electricity generation capacity exploited in the sugar factories of the province. Nonetheless, resulting from an upgraded yield, the revenues from the commercialization of sugar, molasses and the surplus bagasse will increase. Considering an investment of 19,030 k$ the payback period is 0.3 years. So, although

Table 4 Fuel consumption for different sugarcane yields [40]

Sugarcane yield [t/(ha year)]	Fuel consumption (l/t)
15–20	3–2
30–40	1.6–1.2
100	0.94

Table 5 Estimated production with the current and enhanced agriculture yield in Cienfuegos (for 39,812 ha of sugarcane)

Product	Production	
Sugarcane yield (t/ha)	48	90
Sugarcane (kt)	1911	3583
Sugar (kt)	174	326
Bagasse (kt)	459	860
Surplus bagasse (kt)	0	312
Molasses (kt)	50	93
Surplus electricity (GWh)	27	15

Table 6 Estimated economic balance of improving the sugarcane yield in the province of Cienfuegos

Product	Costs (k$)		Revenue (k$)	
Yield (t/ha)	48	90	48	90
Sugar	61,560	89,308	62,604	117,382
Bagasse	–	–	0	24,513
Molasses	–	–	7950	14,906
Surplus electricity	801	469	3391	1984
Total	62,361	89,776	73,944	158,785

this scenario is economically benign it does not allow to generate more surplus electricity.

Energy Cane

Energy cane is a variety of sugarcane with a higher biomass yield giving only a low quality juice, resulting in a low sugar production. Energy cane can grow on the lands where now marabu grows. Growing sugarcane on this lands to produce sugar, alcohol and other byproducts is of course preferable to growing energy cane, but, with only 5 sugar factories available in the province, no capacity remains to process the extra sugarcane.

A sugar factory, operating about 150 days per year, provides an opportunity to combust bagasse from energy cane after the sugarcane milling season. This allows factories to continue operating 4000 h after the sugarcane milling season to generate up to 63 GWh of surplus electricity (considering operation of the 5 sugar factories available in the province for 4000 h), giving together with the surplus electricity produced during the milling season 90 GWh per year. An estimated 1160 h is needed for maintenance of the sugar factories.

The selection of energy cane is based, on the one hand, on its higher biomass production as compared to other high-yield bioenergy crops [41]; on the other hand, this crop will be harvested and milled after the sugarcane milling season, thus extending the operation period of sugar factories.

Energy cane shares many characteristics with sugarcane; yet, the higher biomass content (about twice that of sugarcane) and the lower percent of sugar, make it ideal for bagasse production [42]. Yields of 100–150 t/ha of energy cane can be achieved with the existing varieties in Cuba [43], which in general averages around 100 t/ha (producing twice the mass of bagasse and half of the juice of sugarcane varieties) [44]. One t of milled energy cane yields 540 kg of juice and 460 kg of bagasse ($LHV_{w.b.} = 14.56$ MJ/kg for 50 % moisture). Since the energy cane juice is of low quality is mainly used to produce alcohol or as cattle feed.

Since producing energy cane is based on the same agricultural technology as that of sugarcane, it is produced at similar costs per ha, resulting in lower costs per t because of the higher biomass (around 11.4 $/t). Considering that its production entails a cost, no more energy cane will be produced than needed to support the electricity generation.

Table 7 shows the economic assessment, under the assumption that the 5 sugar factories of the province are operating. An average distance of 25 km to transport the energy cane to the sugar factory is considered, and a market price of 15 $/t for the juice. The juice can be used to produce ethanol (about 50 kg/t) [45] or can be used as animal feed.

Table 7 Cost/benefit assessment of electricity production from energy cane in sugar factories

Product	Production	Costs (k$)	Revenue (k$)
Energy cane (kt)	1281	14,639	0
Surplus electricity (GWh)	63	2074	7964
Juice (kt)	718	–	10,763
Total	–	16,713	18,727

To plant and grow energy cane, the marabu should be cleared, which implies a cost of around 98 $/ha.

To provide sufficient biomass to allow the 5 sugar factories to produce 63 GWh of electricity, an estimated 12,813 ha of marabu needs to be cleared and planted with energy cane. Processing the energy cane to obtain bagasse demands 5 kWh/tc.

The investment to clean the lands grown with marabu and to plant the energy cane is estimated at of 7380 k$ and can be paid back in 3.7 years.

Scenario 2

Filter Cake

Filter cake is a waste of the sugar production, and contains 70–80 % of moisture. In Cienfuegos, filter cake is used as fertilizer on the sugarcane fields. To limit transportation cost, most of the filter cake is deposited in the fields near the sugar factories resulting in over-fertilization of the cane fields, with serious implications on the soil [31]. Filter cake can be used as fuel in the furnaces of the factory boilers [31], but its water content should then be reduced. Stephen [46] proposes dewatering the filter cake to 35–40 % of moisture using a belt filter press. The sugar factories in Cienfuegos produce each up to 3.5 t/h of filter cake. With the upgraded yield filter cake production would increase up to 6.6 t/h. A belt filter press to dewater 4.5 t/h of filter cake produces 2.4 t/h of waste water and 2.1 t/h of filter cake (40 % moisture). Such a belt filter press costs around 30,000 $ and a belt filter press with a capacity of 7 t/h costs around 45,000 $. To dewater the filter cake produced in sugar factories 5 belt filters of different production capacities are required for current and upgraded yield respectively. Today the electricity generation units in the sugar factories operate below their nominal capacity. The use of filter cake helps bringing the production closer to its nominal capacity. Table 8 shows the cost-benefit assessment of using filter cake to produce electricity in the sugar

Table 8 Estimated annual costs and revenues of using filter cake to produce electricity

Product	Production		Costs (k$)		Revenues (k$)	
Yield (t/ha)	48	90	48	90	48	90
Filter cake (kt)	63	118	–	–	0	0
Electricity (GWh)	5.1	9.5	153	286	646	1211
Total	–	–	153	286	646	1211

factories considering both the current and the upgraded sugarcane yields.

Acquiring the belt filters necessitates a 150,000 $ investment to cover the current yield and 225,000 $ for the upgraded yield. The payback period for both current and upgraded agricultural yields is between 0.9 and 0.7 years. The attractiveness of this option is double: (1) it increases the surplus electricity production, and (2) it avoids the transportation cost of filter cake and its disposal as fertilizer on the sugarcane fields affecting the soils.

Dichrostachys cinerea (Marabu)

Dichrostachys cinerea, also known as marabu in Cuba, is a 5 m tall bush tree which is considered a plague. It behaves as an invasive plant, spreading very fast. During the last 150 years this plague gradually covered over 1.7 million ha in Cuba [23]. Primary production figures are about 37 t/ha [47] with a re-growing period of 3 years without fertilizer or tillage [48]. The eradication of marabu is a primary goal of Cuban agriculture and proved not easy.

In the province of Cienfuegos, about 69,000 ha are covered by marabu, which can be combusted in sugar factories after the sugarcane milling season in the same way as energy cane. This biomass is indeed already there and can be used to produce electricity. Harvesting marabu is not an easy task and two ways are indicated: manual and mechanical. Manual harvesting requires a great deal of manpower and is less efficient and more expensive than mechanical harvesting. The Leyca 1150 is a harvesting machine specifically designed to mechanically harvest marabu. In addition to the harvesting machine, two tractors with a 5 t trailer each (to collect the harvested marabu) and a truck of 30 t (to transport the biomass to the sugar factory) are needed. The Leyca 1150 harvests 15 t/h and consumes 30 l/h of diesel and costs 280,000 € (308,000 $, at a currency exchange of 1 € = 1.10 $). With this technology, it is possible to harvest 35.6 t/ha of marabu. The rest of the required equipment is already available in sugar factories, where it is used to collect and transport sugarcane to the factory during the sugar production season. Marabu can supply enough biomass to support the generation of electricity during 4000 h after the milling season.

Since marabu contains 19 % of moisture [48] resulting in a $LHV_{w.b.}$ of 18.87 MJ/kg, supplying the biomass demand of the sugar factories requires 571,229 t/year (3 427 t/d). To sustain this supply 16,046 ha should be yearly harvested. To guarantee the harvest of marabu on the long term, considering its 3 years re-growth period, 48,137 ha are required in total, an area readily available in the province.

Collecting this amount of wood biomass requires 23 Leyca 1150 machines. The other equipment is available in the sugar factories for the sugarcane milling season. Considering the electric efficiency of the sugar plants and the biomass properties of marabu, 121 kWh/t can be generated, of which 5 kWh/t are consumed by the factory during the electricity generation process. Considering the characteristics of the province and the location of the sugar factories, we assumed an average distance of 25 km to transport the marabu to the sugar factory, although in practice the average distance could be lower. Table 9 shows the cost/benefit assessment of this scenario.

To harvest the marabu needed implies an investment of 7038 k$. The attractiveness of this investment lies in the fact that more marabu than required is already available in the province. The investment has a payback period of 3.9 years. Although this option allows to extend electricity generation from biomass in sugar factories beyond the sugarcane milling season, the production of energy cane is more attractive, as it needs a similar investment and has a shorter payback period.

It should not be forgotten that the biomass obtained from cleaning the lands where marabu grows to plant energy cane, can also be combusted.

Scenario 3

Technological Update

Technological innovation allows to improve the efficiency of the production of sugar and its by-products. More in particular installing cogeneration units with a production capacity of 140 kWh/tc of electricity, will increase the

Table 9 Estimated annual costs and revenues of producing electricity from marabu in sugar factories

Product	Production	Costs ($)	Revenues ($)
Cropping marabu (kt)	531	4194	0
Surplus electricity (GWh)	62	1927	7822
Total	–	6121	7822

energetic efficiency of sugar factories. Considering the current production of sugarcane (1911 kt) harvested during 3600 h, it is possible to support the installation of 75 MW of electricity generation capacity. An upgraded sugarcane yield producing 3583 kt of sugarcane, corresponding to an electricity generation capacity of 150 MW can be supported. Cogeneration units are available for capacities of 20 and 35 MW [49]. Two scenarios are realistic:

1. Installing 4 units of 20 MW, one for each of the currently operating sugar factories (for a sugarcane yield of 48 t/ha).
2. Installing 3 units of 35 MW and 2 units of 20 MW, one in each of the 5 sugar factories existing in the province (for a sugarcane yield of 90 t/ha). The units will be located according to the milling capacity of the different sugar factories.

Cogeneration units between 20 and 35 MW cost 2500 and 2000 €/kW respectively, representing a total cost of 50 and 70 € million (58–81.2 $ million at a currency exchange of 1 € = 1.10 $). These units have an electricity generation efficiency of 27–28 % and a thermal efficiency of 58–56 % [45]. In total 220 and 341 million $ needs to be invested for scenarios 1 and 2, respectively. An updated electricity generation technology will allow to increase surplus electricity up to 268 GWh for the current agricultural yield or up to 502 GWh for the upgraded yield. The cost/benefit assessment for a cogeneration unit estimating the yearly operational costs and revenues is shown in Table 10.

The investments can be estimated at 220 $ million for current agricultural sugarcane yield and at 341 $ million for the upgraded yield. From the cost/benefit analysis this would give payback periods of 8.5 and 7.0 years for both the current and the upgraded yields, respectively. This scenario requires large investments and the rather long payback periods do not favor its feasibility. However, it offers an opportunity to decrease the use of fossil fuels and to replace it by available biomass. Most feasible is combining this scenario with some of the previous scenarios.

Combining the Scenarios with the Highest Electricity from Biomass Potential

Some of the scenarios considered before can be combined to maximize both the electricity production and the economic performance of the sugar industry. Combining the agricultural enhancement i.e. increase the sugarcane yield up to 90 t/h, with the combustion of filter cake, with the production of energy cane on marabu areas to produce electricity after the sugarcane milling season, with the implementation of a technological update appears an attractive option. This combination allows to operate the electricity generation unit for 8000 h per year instead of the usual 3600 h. Table 11 provides the production data of the combined scenario.

This scenario will allow increasing the electricity production from biomass along with the production of sugar, molasses and energy cane juice. For the combined scenario a total investment of 372 million $ is required. Table 12 shows the cost/benefit core data of this scenario.

Considering an investment of 372 $ million the cost/benefit analysis shows a payback period of 2 years. Although a more detailed economic assessment is indicated, this combination is most attractive. Considering the electricity efficiency of the new generation units the production of energy cane becomes a realistic economic opportunity. In this case a surplus of electricity of 1150 GWh can be potentially produced, or 50 % more electricity than consumed in 2013 in the province of Cienfuegos (767.6 GWh).

Realizing these scenarios could contribute to expand the sugar industry by installing new sugar plants, creating new employments and increasing the electricity generation capacity and the national energy security.

Table 10 Estimated annual costs and revenues of upgrading the generation technology in sugar factories of Cienfuegos

Product	Costs (k$)		Revenues (k$)	
Yield (t/ha)	48	90	48	90
Surplus electricity	8026	15,049	33,977	63,707

Table 11 Estimated production of combined options

Product	Production
Sugar (kt)	326
Molasses (kt)	93
Energy cane juice (kt)	1155
Surplus electricity (GWh)	1150

Table 12 Estimated annual costs and revenues of the combination of different scenarios

Product	Costs (k$)	Revenues (k$)
Sugar	89,308	117,382
Molasses	0	14,906
Energy cane Juice	0	17,323
Surplus electricity	23,597	146,010
Total	112,905	295,621

Table 13 Electricity generated and neutral CO_2 emissions for the different scenarios

Scenario	Yield (t/ha)	Total electricity (GWh)	Surplus electricity (GWh)	Carbon neutral emissions (kt—CO_2)
Agricultural yield	48	52	27	58
	90	62	15	69
Energy cane	100	68	62	77
Filter cake	48	2	2	2
	90	3	3	4
Marabu	37	68	66	77
Technology update	48	268	243	302
	90	502	455	565
Combination of scenarios	–	1160	1150	1307

Environmental Benefits

Electricity generation accounts for 25 % of the global GHG emissions [50] and other environmental impacts. Since biomass is considered carbon neutral [51], biomass based electricity reduces GHG emissions compared to fossil fuel based electricity. However, producing biomass causes several environmental impacts associated with the consumption of energy, fertilizers, pesticides and other inputs/emissions related with planting and growing of sugarcane. Since bagasse is a byproduct of sugar production, it may be considered that all the impacts of sugarcane production are allocated to sugar. Although a deeper environmental assessment is needed to establish the environmental benefits of the different scenarios discussed when compared with the fossil fuel based electricity currently generated in Cienfuegos, only the impact on GHG emissions, will be considered in this case.

Electricity generation in Cuba emits 1.127 kg of CO_2 per kWh [52]. Since biomass CO_2 emissions are considered carbon neutral (emissions of combusting biomass equals the mass of CO_2 absorbed during its cultivation), generating biomass based electricity reduces the national net GHG emissions. Table 13 shows the carbon neutral emissions for each scenario.

The net $CO_{2\text{-eq}}$ emissions in Cuba account for 25,056 kt. The scenarios included in Table 13 account for 0–2 % of the national $CO_{2\text{-eq}}$ emissions. Moreover, the combined scenario add up to 5.2 % of the national $CO_{2\text{-eq}}$ emissions. These carbon neutral emissions accounts for an important reduction of the national net GHG emissions.

Conclusions

The sugar industry in Cienfuegos offers a realistic opportunity to increase the electricity production from biomass. To this end different options exist: to enhance the agricultural yield of sugarcane which increases the biomass production, to combust filter cake during the sugarcane milling season, to either combust marabu or produce energy cane to generate electricity after the milling season and to update the electricity generation technology in the sugar factories. Each scenario shows economic benefits. Moreover, an assessment of the combination of some of selected scenarios to produce electricity for 8000 h per year, is economically attractive. This combination of scenarios can potentially produce 1150 GWh of electricity, over 33 % more electricity than the 767 GWh consumed by the province of Cienfuegos in 2013. Therefore, there is a potential to export electricity to other provinces using the national grid, and to consider the province CO_2—neutral.

The implementation of the different scenarios strongly depends on the availability of financial resources. If the most indicated combined scenario cannot be implemented at once, selected individual scenarios including upgrading the agricultural yield of sugarcane, combusting the filter cake and the marabu could be implemented improving both the electricity production from biomass and the economic performance of the sugar industry.

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