The current potential of low-carbon economy and biomass-based electricity in Cuba

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Abstract

The emissions of greenhouse gases stand as a major threat of today. Moving towards CO_2 neutral or low-carbon economies is a need to achieve sustainable development. This study assesses the potentialities to move Cuba towards a low-carbon economy by replacing the current electricity mix, dominated by fossil fuel based electricity generation, with biomass-based electricity generation. Results show that biomass can support over 97% of the electricity generation planned by the Cuban government for 2030. Replacing fossil fuel based electricity with biomass-based electricity today potentially reduces up to 81% of the greenhouse gas emissions as compared to the emission levels of 2012. Implementing biomass-based electricity generation in Cuba can also reduce the costs of electricity generation by 1 to 30% (depending on the market price of fossil fuels).

Keywords: Low-carbon, carbon- neutral, biomass, sugar industry

1. Introduction

Climate change, a major environmental threat of today, is mainly caused by anthropogenic greenhouse gas emissions (GHG). The contribution of the different sources worldwide is shown in Fig. 1.

Fig. 1. Global warming by source (IPCC, 2014). AFOLU = agriculture, forestry and other land use

The contributions of electricity and heat production, agriculture, forestry and other land use (AFOLU), industry, and transport account together for over 80% of the greenhouse gas emissions. The effects of climate change unevenly affect the different geographical regions of the planet: some developing countries are impacted most, but industrialized nations are far from immune (Stern, 2007). In addition to the environmental effects, several economic and health consequences are associated with climate change (Stern, 2007).

The Kyoto protocol defined GHG emission quota for industrialized nations, and stands as the most successful global effort to mitigate climate change and global warming. Several countries designed and implemented both adaptation to climate change and mitigation strategies of GHG emissions (Burch, 2010). More recently, at the 21st conference of the parties of the UNFCCC (2016) in Paris, the Paris Agreement was adopted, and so far, 147 parties have ratified the agreement (although the United States withdrew from it). The agreement entered into force on November 4th, 2016 (http://unfccc.int/2860.php).

Different approaches have been proposed to achieve carbon neutrality (Osmani and O'Really, 2009; Premalatha et al., 2013), many of which prove difficult to realize, even using state of the art technology. Moreover, efforts towards a low-carbon economy can be found in different countries (Shimada et al., 2007; Ekins et al., 2011; Zhang, 2011), to counteract the high GHG emissions. In general, most efforts focusses on technological solutions (Fuller et al., 2009). Although fragmented measures towards a low-carbon economy were implemented in different countries, by the end of 2010 most regions in the world did not show much progress in reducing CO_2 (Mundaca et al., 2013). This illustrates the limited effectiveness of the environmental policy portfolios to promote a low-carbon economy, and points to the need of reducing fossil fuel based energy consumption (Mundaca et al., 2013). Realizing low-carbon economies requires the implementation of adequate policies for economic and technological development, energy efficiency, innovation and development of renewable energy sources (Hu et al., 2011).

Considered a main pathway to a low-carbon economy, renewable energy technologies are likely to become the main stream of energy technologies for the decades to come (Dagoumas and Barker, 2010). Thus, there is a need to discuss policies promoting renewable energy (Foxon, 2011). In general, some results show that renewable energy development influences the economic growth more than non-renewable energy (Al-mulali et al., 2014). This applies in particular to Latin-American countries as Cuba, where biomass-based electricity promotes economic growth (Bildirici, 2013; Shahbaz et al., 2016).

Cuba has a large potential of renewable energy (mainly biomass-based), although the current economic situation makes it difficult to realize this option (Vazquez et al., 2015). This is the main reason for the low official renewable energy target, aiming at a 24% of the electricity generation by 2030 to be based on renewable energy sources (http://www.granma.cu/cuba/2014-11-06/abre-camino-de-la-actualizacion). Implementing appropriate measures, allows generating 25% of the electricity with renewable sources in 2020, (Käkönen et al., 2014). Furthermore, energy in

Cuba historically depends on fossil fuel imports. Therefore, promoting renewable energy will contribute to the energy security of the country and reduce its fossil fuels dependency.

Economic sectors in Cuba use most often outdated technology. In combination with an inefficient agriculture (Font and Jancsics, 2015). This causes energy overconsumption and increases GHG emissions. In addition, existing malpractices and inadequate operation of projects and processes in Cuban companies (Ochoa et al., 2010a; Sagastume and Vandecasteele, 2011; Sagastume et al., 2012; Cabello et al., 2013; Sagastume et al., 2016a). The general picture shows a potential to reduce GHG emissions, while moving the country towards a low-carbon economy, and a need to reduce inefficiencies. In general, renewable energy promotes economic growth, while increasing the energy security, and reduces GHG emissions. Therefore, this study identifies and quantifies, on the one hand, the opportunities to reduce the GHG emissions and achieve a low-carbon economy and, on the other hand, the potentialities to increase the generation of biomass-based electricity in Cuba.

In general, this paper deals with:

1) GHG emissions in Cuba:
    - Identify the different sectors emitting GHG and quantify their emissions.
    - Characterize the sectors accounting for most of the GHG emissions.
    - Identify opportunities to reduce GHG emissions.
2) Characterization of the use of biomass:
    - Characterize the exploitation of biomass sources and the production of biomass-based electricity.
    - Identify biomass sources with a high potential to be used for electricity generation.
3) Potential scenarios:
    - Identify scenarios to increase the generation of biomass-based electricity.
    - Assess the performance of each scenario:
        - ✓ GHG emissions balance of each biomass source considered in each scenario.
        - ✓ Electricity and surplus electricity production.
        - ✓ Investment costs.
4) Compare the GHG emissions and the surplus electricity generation from the different scenarios with the current situation.

2. Materials and methods

The information regarding the agriculture and sugarcane land, electricity generation, biomass production, GHG emissions, etc., was taken from the Cuban National Office of Statistics (ONE, 2016a). When needed the information was complemented with literature data.

To define the net carbon emissions and the bioelectricity potential of the different biomass sources in this study, a carbon and electricity balance was developed for each of them. The balance address the main inputs (i.e. diesel, fertilizers, etc.) resulting in GHG emissions, as well as the GHG emissions from the incineration of the biomass and the carbon absorbed during biomass production.

3. Results.

The island of Cuba covers 110,000 km^2 and the population is slightly over 11 million inhabitants (ONE, 2014). Net emissions in Cuba account for 30.3 $MtCO_2$eq., which coincides with about 0.06% of the global 49,000 $MtCO_2$eq. emitted in 2010 (IPCC, 2014). Although reducing GHG emissions in Cuba is a limited contribution to the global GHG emissions, the national policy will act as an example on how to approach climate change in developing countries. Less industrialized nations contribute some 15% of the global CO_2eq. emissions (Oliver et al., 2015), and their emissions need to be addressed if we want to help to achieve the world targets. Moreover, from a sustainable development perspective, moving towards a low-carbon economy implies installation of more renewable energy sources, which promotes economic growth, energy self-sufficiency and energy security of the country. Furthermore, implementing carbon neutral strategies in small developing nations highlights challenges and opportunities on the transition towards a low-carbon economy.

3.1. GHG emissions

3.1.1 GHG by sector

The primary energy consumption in Cuba is spread over different economic, public and residential sectors as shown in Table 1, which were last updated in 2012 (ONE, 2016a). The net GHG emissions (in $CO_{2eq.}$) were calculated considering the CML 2001 GWP (updated in January 2016: http://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors): CO_2 (1 kg_{CO2}), CO (3 kg_{CO2}), CH_4 (28 kg_{CO2}) and N_2O(265 kg_{CO2}).

Table 1. GHG emissions in Cuba in 2012 (million t CO_2eq.) (ONE, 2016a)

In 2012, energy related emissions accounted for 72% of the total GHG emissions, while agriculture, forestry and other land use was the main CO_2 sink, absorbing 31% of the equivalent CO_2 emissions. Results show that CO_2 emissions accounts for over 96% of the net GHG emissions.

3.1.2. Opportunities to reduce GHG emissions

Most of the GHG emissions in Cuba are located in a limited number of sectors. Fig. 2 shows the contribution of the different sectors to the primary energy consumption, highlighting the main consumers.

Fig. 2. Primary energy consumption by sectors (ONE, 2016a).

Electricity generation (E.G), mining (Mi) and the manufacturing industry (M.I) account for 80% of the primary energy consumption. Electricity generation, which uses 59% of the primary energy consumption, accounts for most of the country's GHG emissions.

Over the last twenty years, electricity generation steadily increased (ONE, 2016a), and also GHG emissions showed a general upward trend, as shown in Fig. 3. Important fluctuations were documented, which reflected the economic instability of the country, which affected fuel availability and energy consumption of different sectors.

Fig. 3. Evolution of the electricity generation and the GHG emissions in Cuba (1992-2012) (ONE, 2015a; ONE, 2016a)

Given the importance of energy related emissions in the Cuban GHG emissions, and the high consumption of primary energy (59% of the overall consumption), a relation between the electricity generation and the net GHG emissions is expected. The influence of electricity generation on the overall GHG emissions in Cuba is presented in Fig. 4.

Fig. 4. Fraction of Cuba's GHG emissions resulting from power generation in the overall GHG emissions.

Figure 4 shows that, on average, between 1992 and 2012, power generation accounted for 49% of the overall Cuban GHG emissions. Between 2002 and 2012, this average increased to 52%. This opened opportunities for replacing fossil fuel based electricity by low-carbon alternatives and making progress toward a low-carbon economy. Other sectors (i.e. mining, the manufacturing industry, transport and telecommunication, residential, construction, sugar industry, agriculture, commerce, company services and public administration) accounting for around half of the GHG emissions, provide either limited information for some sectors (e.g. the mining sector), or hardly communicate on their contribution to the primary energy consumption and thus in the GHG emissions (e.g. the manufacturing industry). These sectors do not offer significant opportunities, at least in the middle term, for a low-carbon economy transition. Therefore, they are not systematically addressed in this study, which focusses on alternatives to fossil-fuel based electricity.

Moreover, agriculture and the sugar industry account for limited direct GHG emissions in Cuba. On the other hand, this sectors produce biomass that can replace the fossil fuels, while reducing the net GHG emissions. In total, agriculture is planned using 57% of the national territory, but only less than half of these lands are currently in production (ONE, 2016c). Sugarcane fields cover 6.5% of the national territory and account for 11% of the agricultural land and 26% of the land currently in production. In 2001, the sugar industry was reduced from 156 sugar mills to around 70 active mills, although their operation during the sugarcane-milling season depends on the sugarcane availability (Alonso-Alonso-Pippo, et al., 2008). Given the small contribution of agriculture and the sugar industry to Cuba's GHG emissions and their biomass production, these sectors provide an opportunity to replace fossil fuels based electricity toward a low-carbon economy.

3.1.3. Characterize sector(s) with significant opportunities to reduce GHG emissions.

The national electricity generation system uses different generation technologies as show in Table 2.

Table 2. Electricity generation systems in Cuba (ONE, 2009; ONE, 2016b).

Thermoelectric power plants, internal combustion engine units and combined cycles account for 94% of the national electricity generation. Thermoelectric power plants use mainly technology older than 30 years, mostly stemming from the former socialist network. Renewable energy production (solar panels, eolic parks, hydroelectric power plants, biomass generation units, etc.) represent a small share, 0.7 % in 2014 of the electricity mix. In Cuba, the electricity mix is dominated by the use of fossil fuels (Fuel oil + Gas), as show in Fig. 5.

Fig. 5. Evolution of the electricity mix in Cuba (ONE, 2009; ONE, 2015a; ONE, 2016a)

Currently, according to Fig. 5, fossil-fuels (fuel oil + gas) support around 96% of the electricity generation, on average emitting 0.879 t_{CO2}eq./MWh (Cabello et al., 2012). In the 1970s, biomass (mainly bagasse) supported slightly over 20% of the electricity generation in Cuba. But currently, only 3% of the electricity generation results from bagasse or other biomass sources. Other renewable sources (i.e. hydro and eolic + solar photovoltaic) have accounted for 0.3 to 4.2% of the electricity mix. Currently, they account for 0.7% in total.

Moreover, Suarez et al. (2016), point to a potential of at least 2,075 MW that could be fueled with biomass, solar energy, wind and hydraulic energy. Thereby, replacing fossil fuels electricity production.

3.2. Characterize the use of biomass

3.2.1. Biomass sources with high potential for electricity generation

Different renewable electricity sources exist in Cuba, including biomass, hydraulic, wind and solar energy. Cuba, as a tropical country has a large potential to use solar energy, which currently is hardly used. Solar photovoltaic and eolic currently produce less than 1% of the electricity in Cuba, their use increased from 0 GWh in 2001 to 37.2 GWh in 2014 (ONE, 2016a). The eolic potential shows some areas with moderate to exceptional wind power densities (i.e. wind power densities from 500 to 1,000 W/m^2). In total, a potential of 1,200 to 3,500 MW has been identified (Maegaard, 2013).

Biomass sources account for most of the renewable energy in Cuba (ONE, 2016a). Different opportunities to increase the biomass-based electricity in the sugar industry exist. The production of sugar results in filter cake (an organic waste from sugarcane juice filtration), of which the management poses a challenge (Ochoa et al, 2010b). Given its high organic content, the use of a filter cake/bagasse mixture in the biomass furnace of sugar plants has been suggested (Ochoa et al., 2010b). In Cuba, waste and byproducts from the sugarcane agriculture and from the sugar industry account for most of the available biomass, which is used in sugar plants to produce most of the biomass-based electricity. Thus, increasing the electricity output of sugar plants seems like a reasonable opportunity to replace some of the fossil fuel based electricity.

All over the country, sugarcane is harvested from 713,400 ha (ONE, 2016c), making it the most important crop. Moreover, in sugar plants in Cuba over the last 35 years the sugarcane-milling season ranged from 60 to 126 days (Gonzales-Corzo, 2015). Therefore, the opportunity to use the electricity generation units of sugar plants after the sugarcane-milling season should be considered. The idea to use more of the capacity of the sugar factories has repeatedly been discussed (Montiel, 2003; Travieso and Cala, 2007; Sagastume et al, 2016b), but very little has actually been implemented in the sugar plants.

Other biomass sources resulting from agriculture and livestock breeding (i.e. rice husk, pig manure, etc.) are equally available in Cuba. In general, agricultural waste is produced in limited quantities or is too disperse to be considered (Sagastume et al., 2016b). On the other hand, 794.7 kg of manure are produced during the life cycle of a swine head (Sagastume et al., 2016a), with 3.5 million swine heads slaughtered in 2015 (ONE, 2016a). Additionally, 3.3 million tons of MSW (with over 60% of organic content (Körner et al., 2008)) are yearly generated (ONE, 2010). However, pig farms and landfills are rather dispersed and it proved difficult to use them economically sound. A more detailed study is required to assess the potential of these alternatives at limited scales. Another widely available biomass source is marabu (Dichrostachys cinerea), a bush tree considered a fast spreading plague. The possibility of either using it as a biomass source in sugar factories or to replant the areas covered by marabu with energy cane for biomass production has been suggested (Sagastume et al., 2016b). In Cuba, over half of the agricultural land is either unused or infested with marabu. In total, marabu covers over 1.7 million ha (15% of the Cuban territory) (Sagastume et al., 2016b). It accounts for the largest unused biomass source in Cuba, which can be combusted in sugar factories after the sugarcane milling season finished. Marabu expands fast and the use of the areas of marabu in other application is feasible. Energy cane is a sugarcane variety with a higher bagasse yield, that produces a lower quality juice, which is less adequate for sugar production. Both bio-energy sources are characterized below.

3.2.2. Carbon balance of biomass sources

In the recent past, biomass fuels were often considered carbon neutral, but different studies proved this assumption erroneous (Rabl et al., 2007; Johnson, 2009; Shirvani et al., 2011). Indeed, the use of fossil energy, fertilizers and other inputs to grow the biomass results in net GHG emissions. Therefore, a GHG balance of the different alternatives of biomass-based electricity is indicated. The combustion properties of these biomass sources are given in Table 3.

Table 3. Chemical composition and heating values of Cuban biomass (on dry basis) (after: Suarez et al., 2000; Ochoa et al., 2010a)

The Lower Heating Value of the bagasse on wet basis ($LHV_{w.b}$) was determined using equation (1) (Shariff et al., 2014):

$$\mathrm{LHV_{w.b}} = \mathrm{HHV_{d.b}} \cdot (1 - \mathrm{MC}) - 2.447 \cdot \mathrm{MC} \qquad (1)$$

where MC is the moisture fraction.

Using the biomass properties shown in Table 3, the LHV on wet basis was calculated with equation 1 for the different biomass sources in this study. Moreover, with the annual yield of each biomass and the electricity efficiency (% of the $LHV_{W.B.}$ transformed into electricity), the electricity potential of each biomass source was estimated. Table 4 shows the electricity potential, for a 28% electricity efficiency technology (which is a basic assumption in this study), of the biomass sources.

Table 4. Electricity potential of biomass

As compared to energy cane, marabu requires more land (because of its growing period), although it is not farmed. The higher electricity generation potential per ha per year of marabu as compared to sugarcane is explained by its lower moisture content (Table 3). Nevertheless, sugarcane is a more desirable option than marabu as products and byproducts other than electricity are produced in sugar plants (i.e. sugar, molasses, etc.).

3.2.2.1. Sugarcane and energy cane based biomass

In 2015, the sugarcane yield in Cuba averaged 43.3 t/ha, which resulted in about 31 million t of sugarcane. Good agricultural practices, may lead to higher yields varying between 100 to 120 t/ha (Alonso-Pippo et al., 2008; Contreras et al., 2009). Biomass sources from sugarcane include bagasse (remnant of the pressed cane after extracting the juice, which is a byproduct of the sugar industry) and filter cake (organic waste resulting from the clarification and filtration of the sugarcane juice during sugar production). Filter cake is usually used as fertilizer, but often results in overfertilization of fields nearby the sugar plants, which affects the soil and the groundwater (Ochoa et al., 2010b). A more efficient scenario for bagasse and filter cake based electricity implies a higher sugarcane yield. An average yield of 90 t/ha was proposed as a realistic target (Sagastume et al., 2016b), which would increase biomass production (see Table 5). In Cuba, on average one ton of sugarcane results in about 240 kg of bagasse, 91 kg of sugar, 33 kg of filter cake and 26 kg of molasses (byproduct of the centrifugation process, during which sugar is extracted, from the dense viscous syrup resulting from boiling the clarified and filtered sugarcane juice) (Ochoa et al., 2010b). Using the average yield of product, byproducts and waste streams of sugarcane in the Cuban sugar industry, the production for both the current and the more optimal yields was estimated (see Table 5).

Table 5. Estimated production of sugarcane based products at current and improved yields

Moreover, planting energy cane after the sugarcane-milling season is a viable alternative to generate electricity after the sugarcane-milling season, although in Cuba this is not standard practice. Existing varieties of energy cane in Cuba potentially yield between 100 and 150 t/ha (Ortiz, 2010). One ton of energy cane produces 540 kg of juice and 460 kg of bagasse. The bagasse can be used to generate electricity, while the juice is used to produce alcohol or as animal feed.

The use of fossil energy, fertilizers and other inputs to grow the biomass result in net GHG emissions. Therefore, a GHG balance of the different alternatives of biomass-based electricity is needed to assess the potential emission reduction in particular of CO_2. As different products and byproducts including electricity, are obtained in the sugar industry, a GHG allocation approach was used. In this study, GHG emissions were allocated as a function of the carbon fraction of each product/byproduct. Sugarcane consists of roots, stalk (millable part of sugarcane, which has the highest sugar concentration) and trash (agricultural waste from harvesting sugarcane consisting of straw and cane tops, which comprise green leafs, leaf bundle sheath and green tops with low sugar concentration and high moisture). The carbon balances of sugarcane and energy cane are described in Fig. 6. The carbon fractions of the different parts of the sugarcane (stalks, roots and trash) and of the products, byproducts and waste streams of the sugar industry, considered in the balance, are shown in Annex 1.

Fig. 6. Carbon balance of the wastes and products resulting from sugarcane and energy cane (per t of stalks (tc))

Sugarcane has the highest sunlight conversion rate of all crops (Alonso-Pippo et al., 2011). By-products and waste from the sugar industry are the main biomass sources in Cuba. During the growing of both sugarcane and energy cane the carbon uptake (i.e. inorganic CO_2 from the atmosphere is fixed in organic compounds in plants through photosynthesis). Based on the carbon fractions of the different parts of the sugarcane (see Annex 1), the carbon uptake was calculated. In total, 799 kg of CO_2 is absorbed per t of sugarcane stalks harvested, resulting in 218 kg of carbon, from which more than half remains on the fields (roots + trash). During the harvesting of sugarcane, trash is left on the fields, mainly because of its low sucrose content. Although milling the trash and the stalks together increases the available biomass at the sugar plant, during the milling process the biomass absorbs some juice, which represents a loss of sucrose. In addition, milling trash results in juice with a low sucrose content requiring more energy to be processed. The sugarcane consumed at the milling plant (stalks) accounts for the remaining carbon: bagasse for about 27% of the carbon absorbed by the sugarcane, the filter cake for 1%. Therefore, 27% of the GHG absorbed during sugarcane growing are allocated to the bagasse based electricity, and 1% to the filter cake based electricity. The remaining GHG absorbed are related to the production of sugar and molasses.

Moreover, energy cane absorbs 925 kg of CO_2 per t of stalks harvested. However, as energy cane is grown to produce biomass rather than sugar, the trash is harvested with the stalks, rather than disposed on the fields, and is milled with the stalks in the sugar plant.

To define the carbon cycle of sugarcane and energy cane, a carbon balance of the electricity generation process, considering all the GHG emissions on a life cycle approach (from growing cane to power generation), is necessary. In this way, the net GHG emissions can be calculates for this process. The contribution of the fertilizers, pesticides and fossil fuels consumed to grow sugarcane were considered. For diesel, an emission factor of 3.18 $kgCO_2eq./kg_{diesel}$, including its production from oil extraction, refining and distribution and combustion emissions, was used (Lopez et al., 2009). Based on the specific diesel consumption (per ha), fertilizers and pesticides and their specific GHG emissions, the emissions of the different biomass sources in this study were estimated. The GHG emissions resulting from the use of diesel, fertilizers and pesticides are shown in Annex 2.

The GHG balances of sugarcane and energy cane are shown in Fig. 7 and Fig. 8.

Fig. 7. GHG balance of sugarcane based electricity production in sugar plants (90 t/ha yield) in Cuba.

The GHG cycle of sugarcane based electricity takes off with the emissions by diesel, fertilizers, etc. in agriculture. The CO_2 uptake by agriculture was calculated as shown in Fig. 6. Afterwards sugarcane is transported to the sugar mill, where sugar is produced, with bagasse, molasses and filter cake as side products. Sugar production requires both heat and electricity, which are produced in cogeneration units within the sugar factories. The surplus of the electricity production (excess of electricity) is sold to the electricity network. In total, considering the overall GHG emissions for the sugarcane/energy cane based electricity generation and the carbon uptake during the growth of cane, net emissions per t of biomass of 29.9 for a yield of 43.3 t/ha and 29.3 kg_{CO2}eq. for a yield of 90 t/ha are obtained (i.e. 0.22 and 0.21 kg_{CO2}eq./kWh respectively).

Energy cane production has similar requirements as sugarcane, consuming similar amounts of inputs (fertilizer, pesticides, tillage, etc.) (Sagastume et al., 2016b). Therefore, the same inputs considered for sugarcane were considered for energy cane.

Fig. 8. GHG emission balance of energy cane in Cuba.

Overall, producing and processing 1 ton of energy cane results in the emission of 29.3 kg_{CO2}eq., and allows to generate about 412 kWh of surplus electricity (0.07 kg_{CO2}eq./kWh). The juice obtained can be used as animal feed or to produce approximately 27 kg of ethanol in an alcohol distillery.

3.2.2.2. Marabu

Marabu yields about 37 t/ha of biomass (Abreu, 2012). The plants re-grow every three years (12.3 $\frac{\mathrm{t}}{\mathrm{ha \cdot year}}$), without added fertilizers or tillage (Abreu et al., 2012). The current stock of marabu offers an opportunity to produce biomass-based electricity. Moreover, eradicating marabu is a primary goal of Cuban agriculture, which proved difficult thus far. The lack of an adequate approach to eradicate marabu promotes its growth rather than reducing the area it occupies. The use of marabu as a biomass source has already been suggested (Pedroso and Kaltschmitt, 2012; Sagastume et al., 2016b). Currently, about 69,000 kt of marabu are available all over the country. The GHG balance of marabu is shown in Fig. 9.

Fig. 9. GHG and electricity balance of marabu for electricity production in Cuba.

From equation 1, marabu has a $LHV_{w.b}$ = 16.7 MJ/kg., which combined with a 28% electricity efficiency, would result in the generation of 1,268 kWh/t_{marabu}. Furthermore, harvesting and transporting marabu result in net specific emission of 15.9 kg_{CO2}eq./t_{marabu}, and 1,263 kWh/t_{marabu} of surplus electricity, thus resulting in the emission of 0.01 kg_{CO2}eq./kWh of surplus electricity.

3.3. Potential scenarios

Most of the electricity generated in the sugar industry is consumed during the sugar production itself, resulting in only 1 to 2% of the electricity provided to the national grid. However, sugarcane biomass has a significant potential to contribute to the electricity production in Cuba. Moreover, 'state-of-the-art' biomass-based electricity units can be used to enhance the currently low electricity efficiency. Sugarcane yield can be improved, and in this way the quantity of biomass will be increased. As individual sugar plants operate only between 60 and 126 days (1440 to 3024 h) during the sugarcane milling season, depending on the availability of sugarcane (González-Corzo, 2015), marabu could support the electricity generation from some 5,400 to 6,600 h per year, after the milling season. In this study the average length of the milling season in the sugar factories was assumed as 110 days per year.

For 2030 the government forecasts an electricity need of 30,500 GWh, of which 24% should come from renewable sources. Scenarios, combining sugarcane, marabu and energy cane, as well as the government scenario for renewable energy are discussed.

1. Government scenario (24% renewables based electricity by 2030).
2. Biomass-based electricity from sugarcane during the milling season + marabu after the milling season.
3. Biomass-based electricity from sugarcane during the milling season + energy cane after the milling season.

Sugarcane biomass includes bagasse and filter cake, while energy cane biomass includes bagasse and trash. In general, electricity in Cuban sugar factories is produced using counterpressure turbogenerators of up to 8 MW. This outdated and inefficient technology supports production of 41 kWh per ton of milled sugarcane (tc), with an efficiency of about 8% (Sagastume et al., 2016b). Currently, the system produces less than 30 kWh/tc of electricity (which is less than 6% of electricity efficiency), while 'state-of-the-art' technology (with 28% of electricity efficiency) could generate up to 140 kWh/tc (Pereira et al., 2012; Deshmukha, et al., 2013). The use of state of the art biomass-based electricity generation technology is analyzed in scenarios 2 and 3.

A fourth scenario might describe today´s electricity matrix, with minor production of renewable energy. This scenario is outdated and was not discussed in this study.

3.3.1. Scenario 1

The Cuban government targets 24% of renewable electricity by 2030 (REN 21, 2016). To this end, a policy developing renewable energy sources and increased energy efficiency was established. The renewable sources in this policy, include biomass, eolic, solar and hydraulic energy. Table 6 describes the renewable energy based electricity targets of the government.

Table 6. Renewable energy based electricity generation targets by renewable source by 2030 (ONE, 2015b).

The policy includes the installation of small biomass-based generation units (from 15 to 60 MW) in nineteen sugar factories, thirteen small Eolic turbine fields generating from 36 to 51 MW, 74 small hydroelectric power plants (from 0.5 to 10.4 MW) and an unspecified number of solar panels (to produce over 1,000 GWh of electricity per year). Similar investments are foreseen for biomass, eolic and solar renewable sources (between 1.05 and 1.29 million USD). However, biomass is foreseen to support the generation of about three times more electricity as compared to eolic and solar energies. This shows the benefits of, at least initially, focusing the investments on biomass-based power generation.

In total, the government plans to invest 3,570 million USD to achieve this target, which would reduce the 2012-level GHG emissions by 20%.

3.3.2. Scenario 2

This scenario considers the electricity generation in state of the art units from bagasse and filter cake during the sugarcane milling season, and the use of marabu after the milling season. To this end, both the current and upgraded yields were considered. This resulted in a minimum and a maximum potential of biomass-based electricity and GHG emissions for this scenario.

With 70 to 80% of moisture, filter cake needs to be dewatered before it can be used as fuel. Belt filter presses are preferred for dewatering filter cake to about 40% of moisture, which consumes up to 0.8 kWh/m^3 of filter cake (Federal Environment Agency, 2014). For a density of around 500 kg/m^3, 1.6 kWh/t of electricity is required to dewater filter cake. Dewatered filter cake can be mixed with bagasse and combusted to generate both heat and electricity (Ochoa et al., 2010b).

Equation (1), revealed that filter cake with 40% of moisture results in a $LHV_{w.b}$ of 7.7 MJ/kg. With 28% of electricity efficiency, 601 kWh per ton of filter cake can be produced.

The production of bagasse and filter cake is summarized in Table 5. Considering state of the art biomass-based power generation technology, the current yield of 43 t/ha would produce 1,854 MW, while an optimized yield of 90 t/ha would support 3,853 MW. In addition, to support the power generation for 5,400 h after the sugarcane-milling season is finished, some marabu would be required (see Table 7). To this end, between 234,000 and 447,000 ha of marabu need to be harvested every year, summing up to 0.7 to 1.46 million ha for the three years cycle of marabu (41 to 86% of the actual area of marabu). The potential to produce electricity and the corresponding decline in GHG emissions is summarized in Table 7.

Table 7. Electricity generation potential for scenarios 2 and 3

In total, some 14,463 to 30,061 GWh could be generated via scenario 2 (depending on the sugarcane yield). This scenario can produce from 47 to 97% of the electricity generation planned by the government for 2030, representing from 71 to 148% of the electricity generated in 2015. In addition, reducing the fossil fuel based electricity in the same amount that biomass-based electricity is increased, would reduce 39 to 81% of the GHG emitted in 2012.

Considering the specific investment costs for biomass-based power generation, included in Table 6, from 3,168 to 6,585 million USD are needed (depending on the sugarcane yield) to realize this scenario.

3.3.3. Scenario 3

An alternative to scenario 2 is to clear enough marabu and to plant energy cane, for the electricity generation after the sugarcane milling-season. In this scenario, the amounts of bagasse and filter cake are the same as in scenario 1. No marabu, but energy cane bagasse and trash are used instead, after the sugarcane-milling season has ended. Similar to scenario 2, the current and optimized yields were both considered to obtain a minimum and a maximum potential of biomass-based electricity and reduced GHG emissions for this scenario. From 238,000 ha to 494,000 ha of energy cane are needed every year (which coincides with 14 to 29% of the actual area of marabu). Table 7 shows the potential to generate electricity from energy cane while avoiding GHG emissions.

In total, some 14,259 to 29,638 GWh could be generated in scenario 3 (depending on the sugarcane yield). This scenario could produce from 46 to 96% of electricity generation planned by the government for 2030 (which coincides with 70 to 146% of the electricity generated in 2015). Furthermore, reducing the fossil fuel based electricity in the same amount that biomass-based electricity is increased, would reduce the 2012 GHG emission levels in 36 to 76%.

This scenario results in the same power generation capacity as scenario 2. Thus, the same investments of 3,168 to 6,585 million USD are required in this case.

4. Discussion

Scenario 1 accounts for around 24% of the electricity potential of scenarios 2 and 3. In scenario 1, biomass-based power generation units are foreseen for 19 of the 70 sugar plants which operate in the country. Therefore, in this scenario, sugar plants where no generation unit is foresee, most of the biomass remains unused for electricity generation, or more likely is produced inefficiently. Moreover, scenario 1 does not consider an upgrade of the sugarcane yield. The limited number of biomass-based power generation units either result from the limited access of the Cuban government to state of the art technology (because of the economic embargo) or from its limited investment capacity.

Scenario 1 considers different renewable sources, while scenarios 2 and 3 consider only biomass sources. As compared with other renewable sources, biomass presents advantages:

1. Unlike solar panels, biomass-based systems can sustain 24 h a day power generation.
2. Unlike solar and eolic energy, biomass can be stored.
3. Biomass power generation can be regulated, while solar and eolic based power generation strongly depend on climate variations.
4. As compared to hydraulic energy, in Cuba, biomass has a larger potential; while the specific investment costs are lower (Table 6).
5. Biomass is used to cogenerate heat and electricity in sugar plants, resulting in a higher energy efficiency.

Scenario 2 uses marabu, which is a lower cost biomass not necessitating farming. Furthermore, the risk of further expansion of this invasive species exists. Scenario 3 also includes energy cane that requires farming; this generates employment, which as compared to using marabu is a social strength. Furthermore, energy cane is less land intensive than marabu, which requires 2.6 ha to obtain the electricity obtained from 1 ha of energy cane.

Implementing any of the discussed scenarios has different benefits for the country. Cuba's current energy matrix strongly depends on energy imports: increasing renewable energy production will contribute to the energy independency and security. The economic benefits will depend on the market price of oil. During the last 10 years the fuel oil price varied between 144 and 33 USD/barrel (http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=D) while the natural gas price varied between 55.4 and 466.1 USD per 1000 m^3 (https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm). In the scenario where the current electricity mix, is dominated by fossil fuels (Fig. 5), remains unchanged up to 2030, with the fuel costs varying between the highest and lowest prices of the last 10 years, the country will have sizable costs to support the electricity generation. Considering average electricity efficiencies of 10.99 MJ/kWh for fossil fuel based electricity and 18.83 MJ/kWh for natural gas electricity (ONE, 2015a), Fig. 10 shows the yearly estimated costs of fuel to support fossil fuel generation, considering that the electricity generation/consumption yearly increases by about 2.75%. It also shows the yearly investments required to realize each scenario by 2030. In scenarios 2 and 3 the costs of the biomass was added to the investments costs.

Fig. 10. Estimated costs in fossil fuels to support power generation between 2017 and 2030.

In total, the fuel costs of the electricity production between 2017 and 2030 vary between 20,600 and 95,000 million USD. Average yearly investments require 255 million USD per year for scenario 1 and 470 million USD per year for scenarios 2 and 3 (considering the installation of 3,853 MW of biomass-based electricity generation capacity). Additionally, scenario 2 requires from 3 to 48 million USD per year during this period to harvest and transport marabu. These costs increase yearly with the increased demand of marabu to support the biomass-power generation. Moreover, scenario 3 requires from 13 to 188 million USD per year to produce and harvest energy cane. In total, scenarios 2 and 3 require some 7,280 to 7,950 million USD (i.e.). Therefore, the fuel costs are 3 to 14 times higher than the investments for scenarios 2 and 3, while they are 6 to 27 times the investments in scenario 1.

As compared to scenario 1, scenarios 2 and 3 require about twice as much investments. However, scenarios 2 and 3 could support over 96% of the electricity mix planned by 2030 on biomass basis (given an upgrade of the sugarcane yield), as compared to the 24% of renewable energy electricity in scenario 1. This is a significant step towards a low-carbon economy and an increased energy security and independency of the country, which strongly depends on fuel imports. Furthermore, scenarios 2 and 3 reduce the GHG emissions between 36 to 81% as compared to the 20% of scenario 1. No doubt, implementing scenario 1 is a significant step towards a low-carbon economy, but implementing scenarios 2 or 3 would make Cuba a leading low-carbon economy. However, the higher investments required by scenarios 2 and 3 are an obstacle in particular in the current economic situation of Cuba, although important reductions in the fuel costs would result from replacing fossil fuels in the electricity matrix as shown in Table 8. In this case was considered the renewable energy based power that can be yearly installed with the average yearly investments (i.e. 255 million USD for scenario 1 and 470 million USD for scenarios 2 and 3), which are added to the fuel costs and the biomass costs, subtracting the fuel savings once the power plants start operations:

$$EC = FFC + BC + REI - FFS \quad (2)$$

where:

EC –costs of the electricity generation per year

FFC – Fossil fuels costs

BC – Biomass costs (bagasse, marabu, etc.)

REI – Yearly investments in renewable energy

FFS – Fossil fuel savings (resulting from replacing fossil fuel based electricity with renewable based electricity)

The investment costs (USD/kW) shown in Table 6 are used in this case. It is considered that the power plants (or the eolic or solar panel fields for scenario 1) are in operation 2 years after the initial investments. In scenarios 2 and 3, the costs of producing and harvesting biomass are included in investments, as a way to consider their impact on these scenarios. To this end, was considered a production cost of 11.4 $/t of energy cane and 98 $/ha of marabu (Sagastume et al., 2016b). The energy cane juice was considered to be marketed at 15 $/t. Estimations up to 2032, the year in which all the biomass power facilities would be operative, are included.

Table 8. Estimated evolution of the fuel costs for the electricity generation scenarios

The results showed that implementing scenario 1 could reduce the yearly costs of electricity by 2032 (see Table 8). However, in this scenario the costs of fossil fuels continue rising over time. Realizing scenarios 2 and 3 results in significant reductions of the fossil fuels costs, which are replaced by renewable energy sources. In both scenarios, the reductions of the fossil fuel costs (between 4,200 and 49,400 million USD as compared to business as usual) are between 0.5 and 6.7 times the investments required in each case. This encourages a more detailed assessment towards increasing the use of renewable energy sources in Cuba.

Compared to a business as usual attitude, realizing scenario 1 by 2030 would reduce the costs of electricity in 10% in a HFC scenario, while it will increase costs in 2% in a LFC scenario by 2032. Moreover, realizing scenarios 2 or 3 in the same period reduces the costs of electricity from 17 to 44% as compared to business as usual in both, the HFC and the LFC scenarios. Therefore, although highest investments are required for scenarios 2 and 3 there implementation can potentially result in a better economic outcome as compared to scenario 1. However, implementing any of the discussed scenarios represent a step toward both energy security and a low-carbon economy with better environmental benefits.

As could be expected, higher economic benefits are obtained in a HFC scenario as compared to the LFC.

5. Conclusions

The scenarios discussed in this study show a high potential to move Cuba towards a leading low-carbon economy. Realizing scenarios 2 and 3 will reduce 81% of the net GHG emissions as compared to 2012-levels, while scenario 1 will only reduce GHG emissions in 20%. Although, scenarios 2 and 3 could derive over 96% of the electricity from biomass, a more conservative alternative would retain a fraction of the electricity mix using fossil fuels, or keep some fossil based power plants operational in case the biomass falls short. Existing fossil fuel plants could also be modified to operate with biomass, although the economic practicability depends on the distances between the power plants and the biomass sources.

Further research is needed to estimate the actual biomass potential of Cuba more accurately. To reduce the uncertainty on the actual potential of marabu, Geographic Information Systems could be used, to define suitable areas for harvesting marabu. A multi-factorial approach can be used for taking into account among others, accessibility, and distance to existing or future generation units. Further research is also needed to address the use of other biomass sources including, among others, municipal solid waste, pig manure and agricultural waste. Moreover, other applications of renewable energy like transport (using electricity, ethanol or biogas) or cooking (using biogas), which can further reduce fossil fuels use, should be taken into account.

The economic situation in Cuba is of major importance in the transition towards a low-carbon economy. On the one hand, the current economic situation prevents higher GHG emissions by limiting/precluding new economic developments (i.e. industries, manufacturing companies, service companies), energy consumption, and GHG emissions, but also makes investments in the power generation sector difficult. On the other hand, the consumption of goods and services by the Cuban population is limited by their purchasing power, preventing consumption patterns associated with higher GHG emissions. Developing the Cuban economy will have at least two effects on the GHG emissions: first, it is likely that the consumption patterns of the population will move towards more carbon intensive practices, and new industries and other GHG emitters will be developed. Moreover, more funds will be available to invest in biomass and other renewable energy sources. Furthermore, the biomass-based energy policy will allow expanding the sugar industry to its former size, and increasing the capacity of these industrial sectors to use other biomass sources. Actually, most Cuban sugar plants produce sugar, molasses and bagasse (which could be used as raw material to produce electricity, bagasse boards, paper or ethanol). However, they could be further used by including the production of ethanol from molasses, animal feed, chemicals, etc. Developing the sugar industry is an economic alternative to improve the economic performance and the energy security of Cuba. Additionally, this can bring back the thousands of job lost after over more than half of the sugar plants were closed and dismantled in 2001.

References

Abreu, R., 2012. Utilización energética de la biomasa ligno-celulósica obtenida del Dichrostachys cinerea mediante procesos de termodescomposición. PhD thesis. Università Politecnica delle Marche.

Abreu, R., Conesa, J., Foppa, E., O., Romero, 2012. Kinetic analysis: Simultaneous modelling of pyrolysis and combustion processes of dichrostachys cinerea. Biomass and Bioenergy. 36, 170–175.

Acaravci, A., Ozturk, I., 2010. Electricity consumption-growth nexus: evidence from panel data for transition countries. Energy Economics. 32, 604-608.

Al-mulali, U., Fereidouni, H.G., Lee, J.Y., 2014. Electricity consumption from renewable and non-renewable sources and economic growth: Evidence from Latin American countries. Renewable and Sustainable Energy Reviews, 30, 290-298.

Alonso-Alonso-Pippo, W., Garzone, P., Cornacchia, G., 2007. Agro-industry sugarcane residues disposal: the trends of their conversion into energy carriers in Cuba. Waste Management. 27, 869-885.

Alonso-Alonso-Pippo, W., Luengo, C.A., Alonsoamador, L., Alberteris, M., Garzone. P., Cornacchia, G., 2011. Energy recovery from sugarcane-trash in the light of 2nd generation biofuels. Part 1: Current situation and environmental aspects. Waste and Biomass Valorization. 2, 1-16.

Alonso-Alonso-Pippo, W., Luengo, C.A., Koehlinger, J., Garzone, P., Cornacchia, G., 2008. Sugarcane energy use: the Cuban case. Energy policy. 36, 2163-2181.

Altinay, G., Karagol, E., 2005. Electricity consumption and economic growth: evidence from Turkey. Energy Economics. 27, 849-856.

Amores, M.J., Mele, F.D., Jiménez, L., Castells, F., 2013. Life cycle assessment of fuel ethanol from sugarcane in Argentina. The International Journal of Life Cycle Assessment. 18, 1344-1357.

Anderson, J.E., DiCicco, D.M., Ginder, J.M., Kramer, U., Leone, T.G., Raney-Pablo, H.E., Wallington, T.J., 2012. High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States. Fuel. 97, 585-594.

Apergis, N., Tang, C.F., 2013. Is the energy-led growth hypothesis valid? New evidence from a sample of 85 countries. Energy Economics. 38, 24-31.

Berriel, S.S., Favier, A., Domínguez, E. R., Machado, I. S., Heierli, U., Scrivener, K., Martirena F., Habert, G., 2016. Assessing the environmental and economic potential of Limestone Calcined Clay Cement in Cuba. Journal of Cleaner Production, 124, 361-369.

Bildirici, M.E., 2013. Economic growth and biomass energy. Biomass and bioenergy. 50, 19-24.

Bridge, G., Bouzarovski, S., Bradshaw, M., Eyre, N., 2013. Geographies of energy transition: Space, place and the low-carbon economy. Energy Policy. 53, 331-340.

Browne, C.A., 1919. The composition and calorific value of sirups and molasses derived from sugar cane. Journal of the American Chemical Society. 41, 1432-1440.

Burch, S., 2010. In pursuit of resilient, low-carbon communities: an examination of barriers to action in three Canadian cities. Energy Policy. 38, 7575-7585.

Cabello, J.J., Garcia, D., Sagastume, A., Priego, R., Hens, L., Vandecasteele, C., 2012. An approach to sustainable development: the case of Cuba. Environment, development and sustainability. 14, 573-591.

Cabello, J.J., Sagastume, A., Hernández, D., Hens, L., Vandecasteele, C., 2013. Improving the environmental performance of an earthwork project using cleaner production strategies. Journal of Cleaner Production. 47, 368-376.

Carraro, C., Favero, A., Massetti, E., 2012. Investments and public finance in a green, low-carbon, economy. Energy Economics. 34, S15-S28.

Casas, Y., Arteaga, L.E., Morales, M., Rosa, E., Peralta, L. M., Dewulf, J., 2010. Energy and exergy analysis of an ethanol fueled solid oxide fuel cell power plant. Chemical Engineering Journal. 162, 1057-1066.

Contreras, A.M., Rosa, E., Pérez, M., Van Langenhove, H., Dewulf, J., 2009. Comparative life cycle assessment of four alternatives for using by-products of cane sugar production. Journal of Cleaner Production. 17, 772-779.

Dagoumas, A.S., Barker, T.S., 2010. Pathways to a low-carbon economy for the UK with the macro-econometric E3MG model. Energy policy. 38, 3067-3077.

Deshmukha, R., Jacobsona, A., Chamberlina, C., Kammenb, D., 2013. Thermal gasification or direct combustion? Comparison of advanced cogeneration systems in the sugarcane industry. Biomass Bioenergy. 55, 163–174.

Ekins, P., Anandarajah, G., Strachan, N., 2011. Towards a low-carbon economy: scenarios and policies for the UK. Climate Policy. 11, 865-882.

Enoch, M., Warren, J.P., Ríos, H.V., Menoyo, E.H., 2004. The effect of economic restrictions on transport practices in Cuba. Transport Policy. 11, 67-76.

Federal Environment Agency, 2014. Technical Guide on the Treatment and Recycling Techniques for Sludge from municipal Wastewater Treatment with references to Best Available Techniques (BAT). Umweltbundesamt. Dresden. Germany.

Figueroa, V., 1989. Experiencias cubanas en el uso de las mieles de caña para la alimentación porcina. Livestock Research for Rural Development. 1, 1-14.

Font, M., Jancsics, D., 2015. From Planning to Market: A Framework for Cuba. Bulletin of Latin American Research. 35, 147–164.

Font, M.A. Larson, S., 2006. Cuba: In Transition? Pathways to renewal, long-term development and global reintegration. The Bildner Center for Western Hemisphere Studies. New York. United States.

Foxon, T.J., 2011. A coevolutionary framework for analysing a transition to a sustainable low-carbon economy. Ecological Economics. 70, 2258-2267.

Fuller, M.C., Portis, S.C., Kammen, D.M., 2009. Toward a low-carbon economy: municipal financing for energy efficiency and solar power. Environment: Science and Policy for Sustainable Development. 51, 22-33.

Ghosh, S., 2002. Electricity consumption and economic growth in India. Energy policy. 30, 125-129.

González-Corzo, M., 2015. La agroindustria cañera cubana: transformaciones recientes. Bildner Center for Western Hemisphere Studies. New York. USA

Hillier, J., Walter, C., Malin, D., Garcia-Suarez, T., Mila-i-Canals, L., Smith, P., 2011. A farm-focused calculator for emissions from crop and livestock production. Environmental Modelling & Software. 26, 1070-1078.

Hu, Z., Yuan, J., Hu, Z., 2011. Study on China's low-carbon development in an Economy–Energy–Electricity–Environment framework. Energy Policy. 39, 2596-2605.

IPCC, 2014. Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp

Johnson, E., 2009. Goodbye to carbon neutral: Getting biomass footprints right. Environmental Impact Assessment Review. 29, 165-168.

Käkönen, M., Kaisti, H., Luukkanen, J., 2014. Energy revolution in Cuba. Pioneering for the future. Finland futures research centre. FFRC eBook 4/2014 University of Turku, Finland.

Kim, M., Day, D.F., 2011. Composition of sugar cane, energy cane, and sweet sorghum suitable for ethanol production at Louisiana sugar mills. Journal of Industrial Microbiology & Biotechnology. 38, 803-807.

Körner, I., Saborit-Sánchez, I., Aguilera-Corrales, Y., 2008. Proposal for the integration of decentralised composting of the organic fraction of municipal solid waste into the waste management system of Cuba. Waste management. 28, 64-72.

Kurchania, A.K., Panwar, N.L., Pagar, S.D., 2011. Development of domestic biogas stove. Biomass Conversion and Biorefinery. 1, 99-103.

Laino, L.D., 2016. El aprovechamiento energético en la industria azucarera Cubana. Población y Desarrollo, 20, 29-35.

Lopez, J.M., Gomez, A., Aparicio, F., Sanchez, F.J., 2009. Comparison of GHG emissions from diesel, biodiesel and natural gas refuse trucks of the City of Madrid. Applied Energy. 86, 610-615.

Maegaard, P., Krenz, A., Palz, W., 2013. Wind power for the world: international reviews and developments (Vol. 3). CRC Press. Florida. United States.

Melo, C.A., Junior, F.H.S., Bisinoti, M.C., Moreira, A.B., Ferreira, O.P., 2016. Transforming sugarcane bagasse and vinasse wastes into hydrochar in the presence of phosphoric acid: an evaluation of nutrient contents and structural properties. Waste and Biomass Valorization. DOI 10.1007/s12649-016-9664-4

Menéndez, J., Coello, A.L., Tijonov, O.N., Rodríguez, M.A., 2006. Implementation of energy sustainability concepts during the comminution process of the Punta Gorda nickel ore plant (Cuba). Powder Technology. 170, 153-157.

Montiel, J.L.R., 2003. La biomasa cañera como alternativa para el incremento de la eficiencia energética y la reducción de la contaminación ambiental. Centro Azúcar. 30, 14-21.

Moraes, B.S., Zaiat, M., Bonomi, A. 2015. Anaerobic digestion of vinasse from sugarcane ethanol production in Brazil: Challenges and perspectives. Renewable and Sustainable Energy Reviews. 44, 888-903.

Mundaca, L., Markandya, A., Nørgaard, J., 2013. Walking away from a low-carbon economy? Recent and historical trends using a regional decomposition analysis. Energy Policy. 61, 1471-1480.

Muthu, S.S. (Ed.). (2015). The Carbon Footprint Handbook. CRC Press. Florida. USA.

Nixon, J.D., Dey, P. K., Ghosh, S.K., Davies, P.A., 2013. Evaluation of options for energy recovery from municipal solid waste in India using the hierarchical analytical network process. Energy. 59, 215-223.

Ochoa, P.A., Cabello, J.J., Sagastume, A., Hens, L., Vandecasteele, C., 2010a. Residue from sugarcane juice filtration (filter cake): energy use at the sugar factory. Waste and Biomass Valorization. 1, 407-413.

Ochoa, P.A., Sagastume, A., Cogollos, J.B., Vandecasteele, C., 2010b. Cleaner production in a small lime factory by means of process control. Journal of Cleaner Production. 18, 1171-1176.

Olivier, J.G.J., Janssens-Maenhout, G., Muntean, M., Peters, J.A., 2015. Trends in global CO2 emissions 2015 report. PBL Netherlands Environmental Assessment Agency. The Hague. Netherlands.

ONE, 2009. Estadísticas energéticas en la revolución. Oficina Nacional de Estadísticas. La Habana. Cuba. Available in: http://www.one.cu/50aniversarioEstadisticasEnergeticas.htm (20.01.2017)

ONE, 2014.Informe nacional censo de población y vivienda 2012. Oficina Nacional de Estadística. La Habana. Cuba. Available in: http://www.one.cu/informenacional2012.htm (20.01.2017)

ONE, 2015a. Anuario estadístico de Cuba 2014. Oficina Nacional de Estadísticas. La Habana. Cuba. Available in: http://www.one.cu/aec2014.htm (20.01.2017)

ONE, 2015b. Acceso a una energía asequible, segura, sostenible y moderna para todos. In proceedings of: Taller Desarrollo de Capacidades para la Integración de Objetivos de Desarrollo Sostenible de Energía, Metas e Indicadores en los Programa Nacionales de Estadísticas en Países de América Latina. Panamá. Panamá. Available from: https://sustainabledevelopment.un.org/content/documents/13097Cuba.pdf (20.01.2017)

ONE, 2016a. Anuario estadístico de Cuba 2015. Oficina Nacional de Estadísticas. La Habana. Cuba. Available in: http://www.one.cu/aec2014.htm (20.01.2017)

ONE, 2016b. Electricidad en cuba indicadores seleccionados: Enero - Diciembre 2015. Oficina Nacional de Estadísticas. La Habana. Cuba. Available in: http://www.one.cu/publicaciones/04industria/prodconselectricidad/ProdConsElectDici15.pdf (20.01.2017)

ONE, 2016c. Panorama uso de la tierra Cuba 2015. Oficina Nacional de Estadísticas. La Habana. Cuba. Available in: http://www.one.cu/panusotierra2015.htm (20.01.2017)

Ortiz, E.M., 2010. Las variedades energéticas de caña de azúcar (Saccharum spp.) como una alternativa sostenible frente a los riesgos de cambio climático. Unidad Académica de Ciencias Administrativas y Humanísticas. UTC. Thesis. Latacunga. Ecuador.

Osmani, M., O'Reilly, A., 2009. Feasibility of zero carbon homes in England by 2016: A house builder's perspective. Building and Environment. 44, 1917-1924.

Padrón, R., Paredes, L., Leyva, R., 2011. Generación de electricidad con biomasa de marabú como combustible en el central céspedes, provincia Camagüey. Revista Forestal Baracoa. 20, 1-5.

Papadias, D.D., Ahmed, S., Kumar, R., 2012. Fuel quality issues with biogas energy–An economic analysis for a stationary fuel cell system. Energy. 44, 257-277.

Pedroso, D.T., Kaltschmitt, M., 2012. Dichrostachys cinerea as a possible energy crop—facts and figures. Biomass Conversion and Biorefinery. 2, 41-51.

Pereira, M., Camacho, C., Vasconcelos, M., da Silva, N., 2012. The renewable energy market in Brazil: current status and potential. Renew. Sustain. Energy Rev. 16, 3786–3802.

Premalatha, M., Tauseef, S.M., Abbasi, T., Abbasi, S.A., 2013. The promise and the performance of the world's first two zero carbon eco-cities. Renewable and Sustainable Energy Reviews. 25, 660-669.

Rabl, A., Benoist, A., Dron, D., Peuportier, B., Spadaro, J.V., Zoughaib, A., 2007. How to account for CO2 emissions from biomass in an LCA. The International Journal of Life Cycle Assessment. 12, 281-281.

REN21, 2016. Renewables 2016 global status report. Available from: http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf (09.08.2016)

Sagastume, A., Cabello, J.J., Billen, P., Vandecasteele, C., 2016a. Environmental assessment of pig production in Cienfuegos, Cuba: alternatives for manure management. Journal of Cleaner Production. 112, 2518-2528.

Sagastume, A., Cabello, J.J., Hens, L., Vandecasteele, C., 2016b. The biomass-based electricity generation potential of the province of Cienfuegos, Cuba. Waste and Biomass Valorization. DOI 10.1007/s12649-016-9687-x.

Sagastume, A., Van Caneghem, J., Cogollos, J.B., Vandecasteele, C., 2012. Evaluation of the environmental performance of lime production in Cuba. Journal of Cleaner Production. 31, 126-136.

Sagastume, A., Vandecasteele, C., 2011. Exergy-based indicators to evaluate the possibilities to reduce fuel consumption in lime production. Energy. 36, 2820-2827.

Salomon, K.R., Lora, E.E.S., 2009. Estimate of the electric energy generating potential for different sources of biogas in Brazil. Biomass and Bioenergy. 33, 1101-1107.

Salomon, K.R., Lora, E.E.S., Rocha, M.H., Almazán, O.O., 2011. Cost calculations for biogas from vinasse biodigestion and its energy utilization. Sugar Industry. 136, 217-223.

Seifried, D., 2013. Cuban Energy Revolution – A Model for Climate Protection?. Büro Ö-quadrat. Germany. 32 pp. Available from: http://www.oe2.de/fileadmin/user_upload/download/Energierevolution_Cuba_eng.pdf (01.08.2016)

Shahbaz, M., Rasool, G., Ahmed, K., Mahalik, M.K., 2016. Considering the effect of biomass energy consumption on economic growth: Fresh evidence from BRICS region. Renewable and Sustainable Energy Reviews. 60, 1442-1450.

Shariff, A., Aziz, N.S.M., Abdullah, N., 2014. Slow pyrolysis of oil palm empty fruit bunches for biochar production and characterisation. Journal of Physical Science. 25, 97-112.

Shimada, K., Tanaka, Y., Gomi, K., Matsuoka, Y., 2007. Developing a long-term local society design methodology towards a low-carbon economy: An application to Shiga Prefecture in Japan. Energy Policy. 35, 4688-4703.

Shirvani, T., Yan, X., Inderwildi, O.R., Edwards, P.P., King, D.A., 2011. Life cycle energy and greenhouse gas analysis for algae-derived biodiesel. Energy & Environmental Science. 4, 3773-3778.

Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M. J. Figueroa Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J. J. Schauer, D. Sperling, and G. Tiwari, 2014. Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, Unated States.

Skowroñska, M., Filipek, T., 2014. Life cycle assessment of fertilizers: a review. International Agrophysics. 28, 101-110.

Spielmann, M., Bauer, C., Dones, R., Tuchschmid, M., 2007. Transport services. Econinvent report no. 14. Swiss Centre for Life Cycle Inventories, Dübendorf.

Stern, N.H., 2007. The economics of climate change: the Stern review. Cambridge University Press. United Kingdom.

Suarez, J.A., Beaton, P.A., Faxas, R., Luengo, C.A., 2016. The state and prospects of renewable energy in Cuba. Energy Sources, Part B: Economics, Planning, and Policy. 11, 111-117.

Sutter, J., 2010. Life cycle inventories of pesticides. Final report ecoinvent v2.0, No. 15. Swiss Center for Life Cycle Inventories, St Gallen.

Travieso, D, Cala, R., 2007. Perspectivas de la generación de electricidad en Cuba a partir de la gasificación de biomasa; Perspectives of Electricity Generation in Cuba from Biomass Gasification. Ingeniería Energética. 28, 15-18.

UNFCCC, 2016. Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Framework Convention on Climate Change. Available at: http://unfccc.int/resource/docs/2015/cop21/eng/10.pdf (05.06.2017)

Vantuono, W.C., 1999. Cuban railways: Coming out of the cold?. International Railway Journal. 39, 67-68.

Vazquez, L., Luukkanen, J., Kaisti, H., Kākönen, M., Majanne, Y., 2015. Decomposition analysis of Cuban energy production and use: Analysis of energy transformation for sustainability. Renewable and Sustainable Energy Reviews, 49, 638-645.

Verbong, G.P., Beemsterboer, S., Sengers, F., 2013. Smart grids or smart users? Involving users in developing a low-carbon electricity economy. Energy Policy. 52, 117-125.

Williams, A.G., Audsley, E., Sandars, D.L., 2010. Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. The International Journal of Life Cycle Assessment. 15, 855-868.

Wood, S., Cowie, A., 2004. A review of greenhouse gas emission factors for fertiliser production. IEA bioenergy task. 38, 1-20. Available in: www.ieabioenergy-task38.org/ (20.01.2017)

Yunhua, L., Boqian, W., 2014. Study on the approaches and policy recommendations of low-carbon economy development in Hubei Province. In proceedings of: International Conference on Biotechnology, Agriculture, Environment and Energy (ICBAEE 2014). CRC Press. Beijing. China.

Zhang, Z., 2010. China in the transition to a low-carbon economy. Energy Policy. 38, 6638-6653.

Zhang, Z., 2011. Energy and environmental policy in China: towards a low-carbon economy. Edward Elgar Publishing. Cheltenham. United Kingdom.

Annexes

Annex 1: Carbon uptake of sugarcane

Table 9. Annual carbon uptake per ton of sugarcane milled (dry basis)

Annex 2: GHG emissions of diesel, fertilizers and pesticides

Table 10. GHG emissions of diesel consumption

Diesel consumption includes the consumption by agriculture as well as by the mechanical harvest and the biomass transport to the sugar plant. For both sugarcane and energy cane, the diesel consumption per ha increases with the yield because of the more cane harvested and transported to the sugar plant, the higher the amounts of diesel used. On the other hand, the relative consumption and GHG emissions per t of biomass are reduced. Marabu consume less fuel than sugar cane because it does not require planting or tillage.

Table 11. GHG emissions of fertilizers (Contreras et al., 2009; Hillier et al., 2011)

Table 11 shows that 8.1 kg/tc of fertilizers are consumed during sugarcane crop (Contreras et al., 2009), in total emitting about 8.4 kg_{CO2}eq.

Table 12. GHG emissions of a pesticide (Sutter, 2010)

The CO_2 equivalent emissions of pesticides are calculated using the emission factors of CML 2001. About $2.8{\cdot}10^{-3}$ kg/tc of pesticides are used growing sugarcane (Contreras et al., 2009) causing about $1.36{\cdot}10^{-3}$ kg_{CO2}eq./tc of GHG emissions.

Figure

Figures

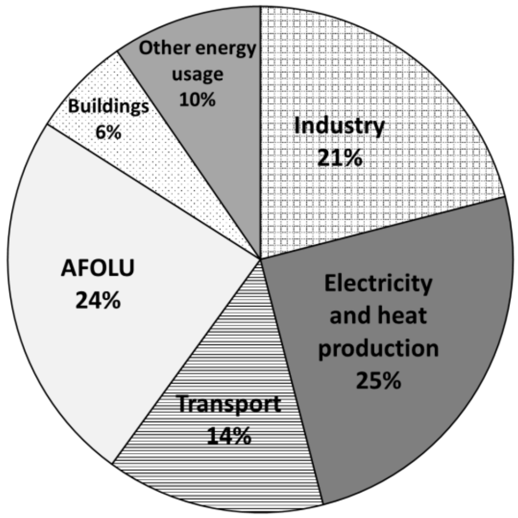

Fig. 1. Global warming by source (IPCC, 2014). AFOLU = agriculture, forestry and other land use

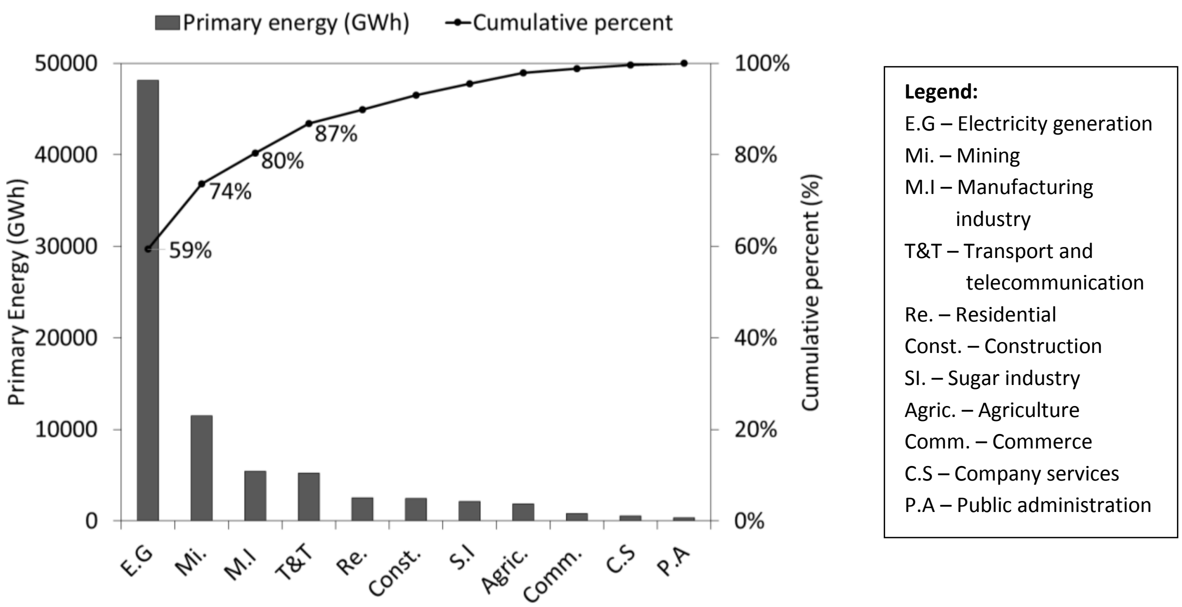

Fig. 2. Primary energy consumption by sectors (ONE, 2016a).

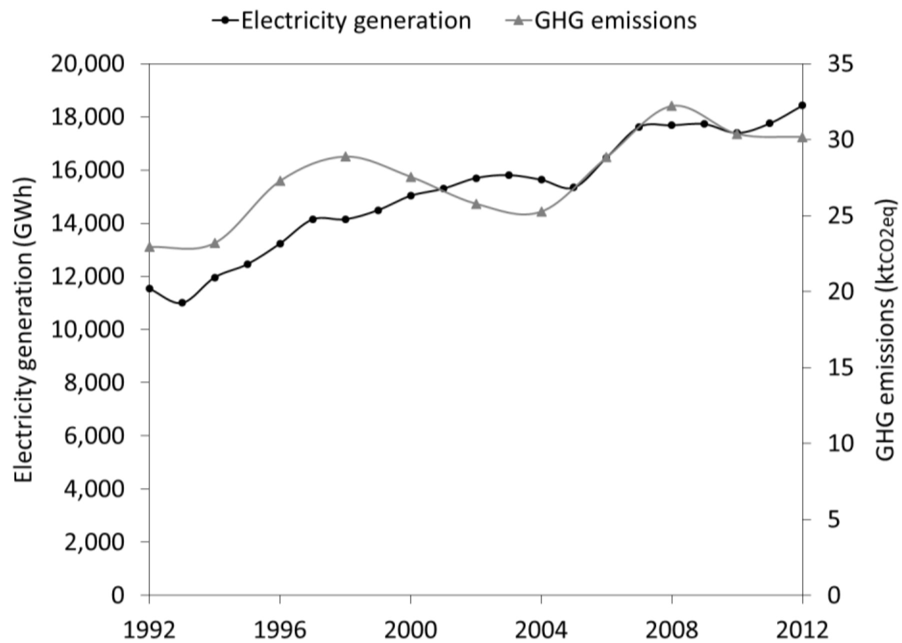

Fig. 3. Evolution of the electricity generation and the GHG emissions in Cuba (1992-2012) (ONE, 2015a; ONE, 2016a)

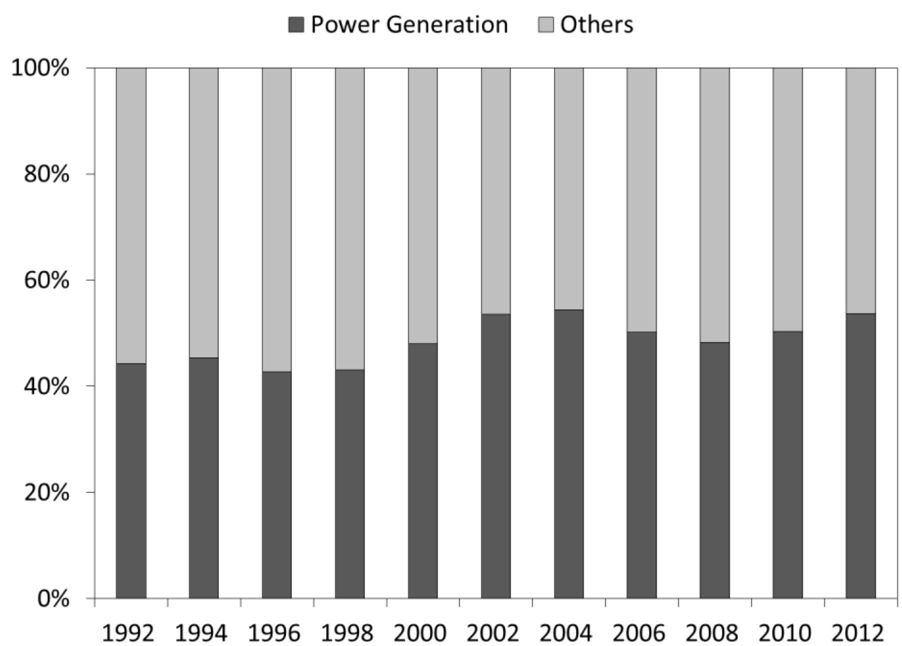

Fig. 4. Fraction of Cuba's GHG emissions resulting from power generation in the overall GHG emissions.

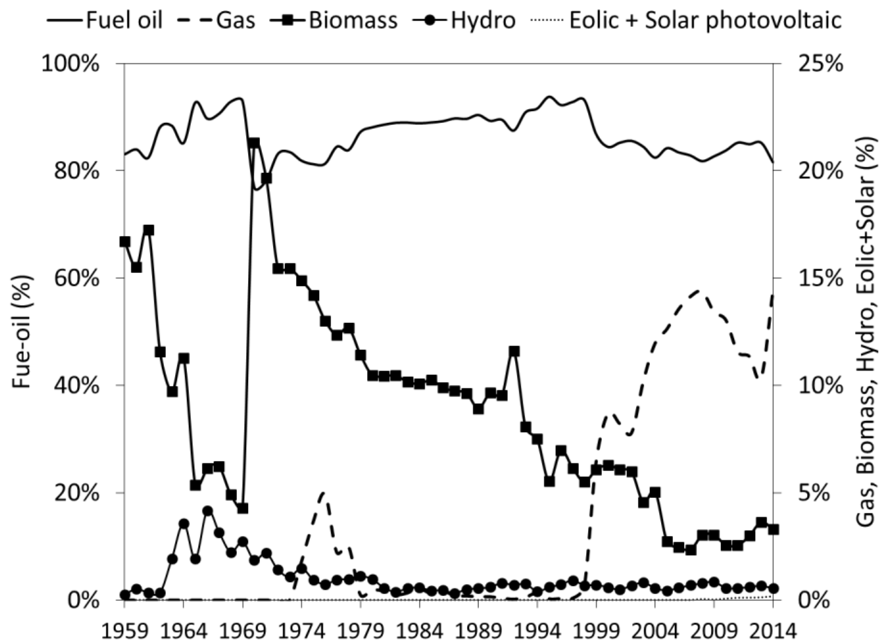

Fig. 5. Evolution of the electricity mix in Cuba (ONE, 2009; ONE, 2015a; ONE, 2016a)

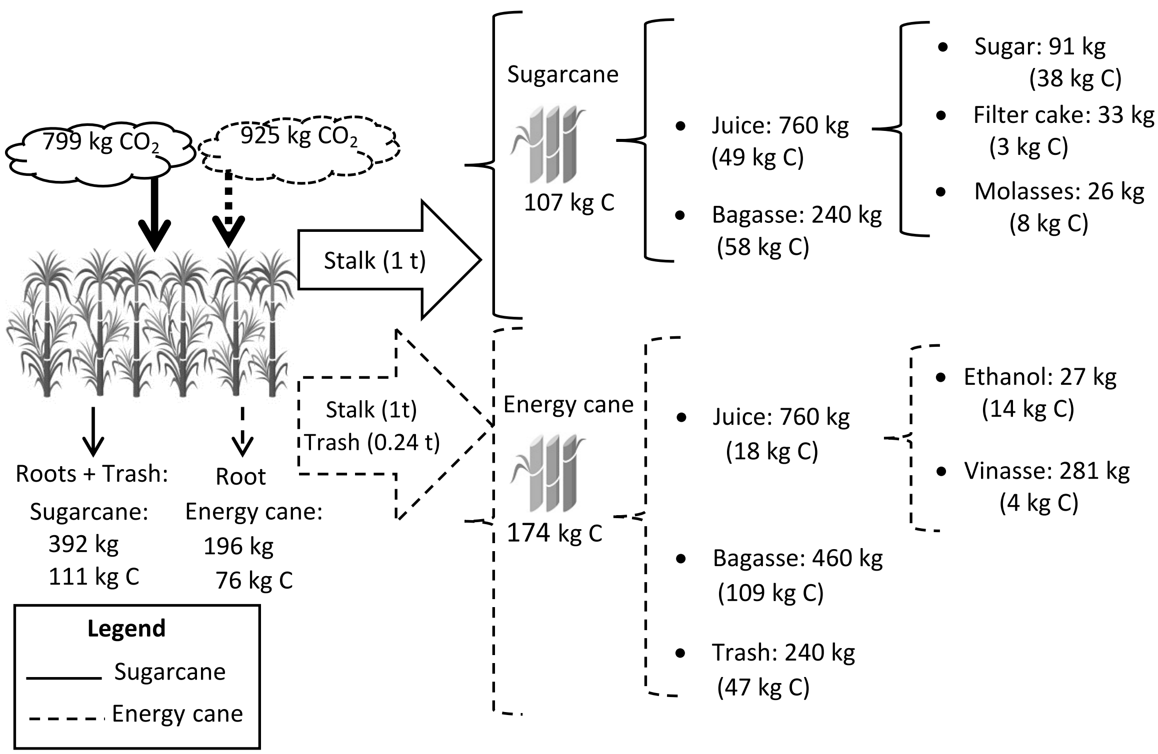

Fig. 6. Carbon balance of the wastes and products resulting from sugarcane and energy cane (per t of stalks (tc))

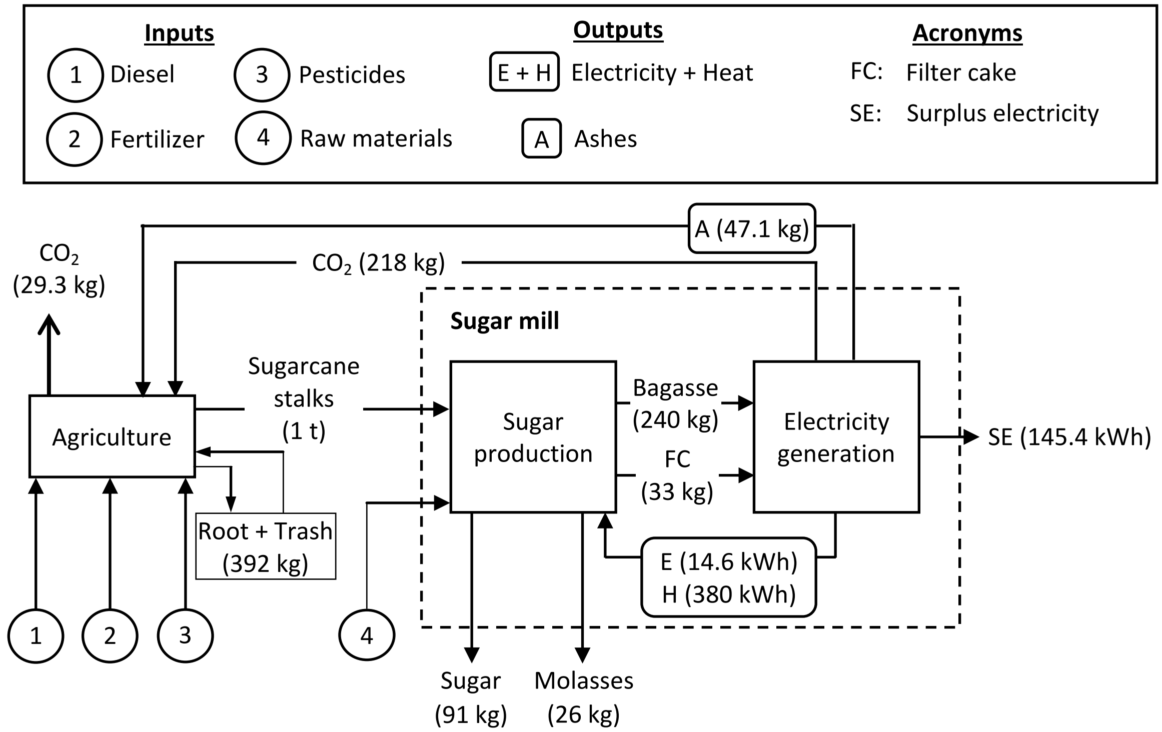

Fig. 7. GHG balance of sugarcane based electricity production in sugar plants (90 t/ha yield) in Cuba.

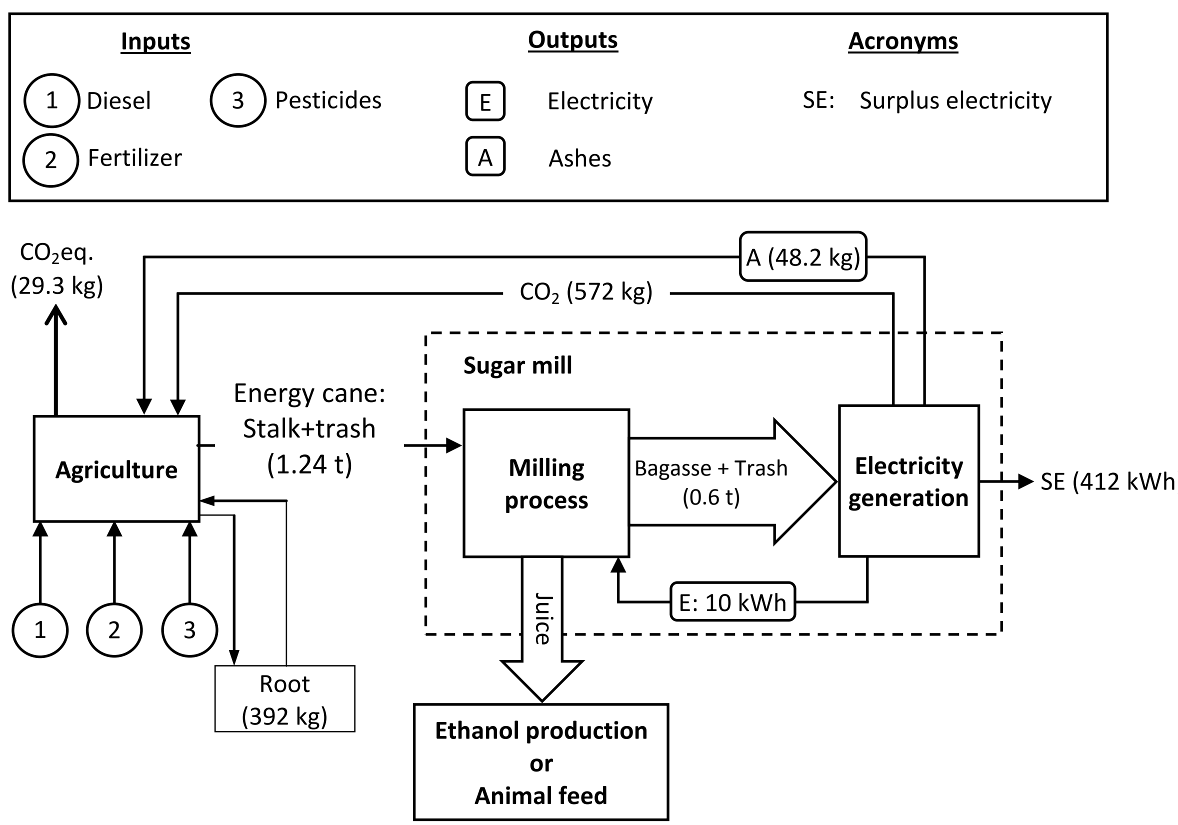

Fig. 8. GHG emission balance of energy cane in Cuba.

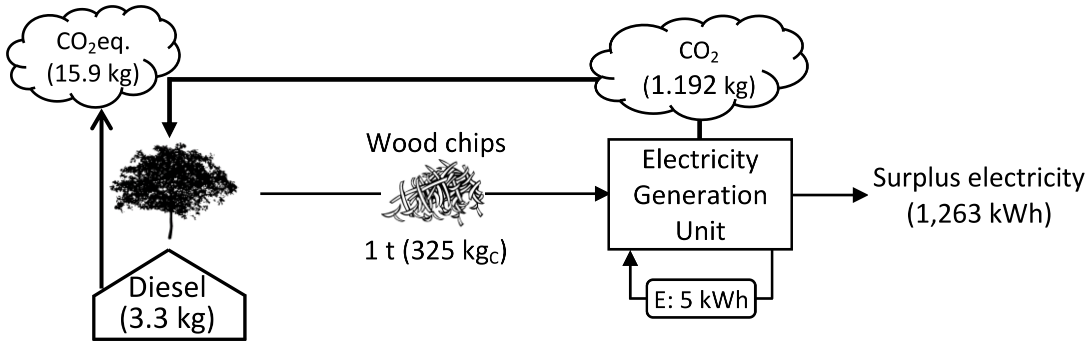

Fig. 9. GHG and electricity balance of marabu for electricity production in Cuba.

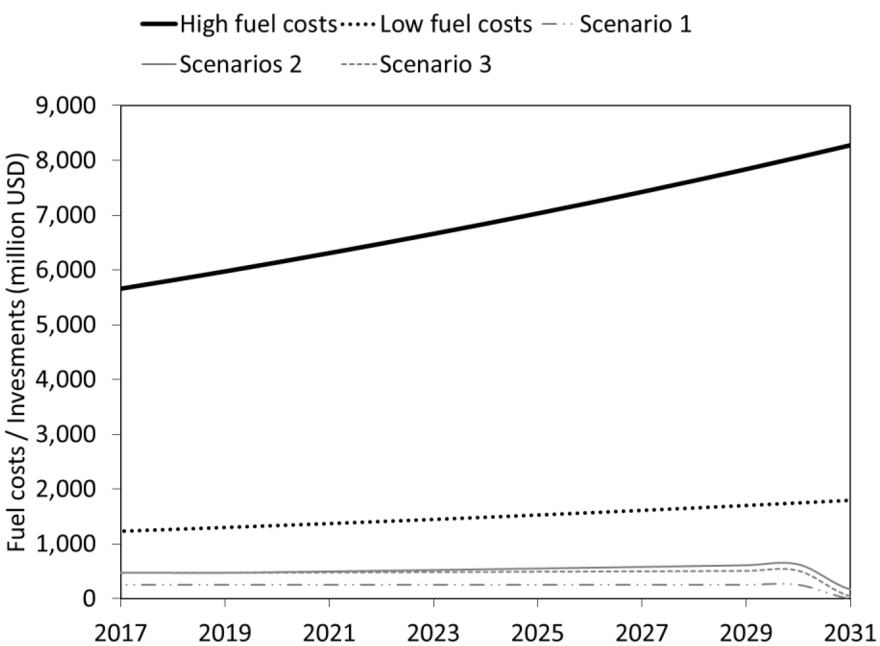

Fig. 10. Estimated costs in fossil fuels to support power generation between 2017 and 2030.

Tables

Table 1. GHG emissions in Cuba in 2012 (million t CO_2eq.) (ONE, 2016a)

GHG	CO_2	CH_4	N_2O	CO	Net GHG emissions (CO_2eq.)
Energy related emissions	28.0	0.10	$5.2\cdot10^{-4}$	0.09	28.2
Industrial processes	1.3	-	-	$10\cdot10^{-4}$	1.3
Agriculture	-	0.19	$73\cdot10^{-4}$	$2.8\cdot10^{-4}$	0.2
AFOLU	-14.2	0.03	-	$90\cdot10^{-4}$	-14.2
Wastes	-	0.13	$5.8\cdot10^{-4}$	-	0.1
Net emissions	**15.1**	**0.45**	$\mathbf{84\cdot10^{-4}}$	**0.09**	**15.6**

Table 2. Electricity generation systems in Cuba (ONE, 2009; ONE, 2016b).

Generation system	Units	Electricity generated (GWh)	Share (%)
Thermoelectric power plant	7	11479	56
Internal combustion engine generation units	>2800	4538	23
Combined cycle	2	3203	15
Others	-	1068	6
Total		**20,288**	**100**

Table 3. Chemical composition and heating values of Cuban biomass (on dry basis) (after: Suarez et al., 2000; Ochoa et al., 2010a)

Biomass	C (%)	H (%)	O (%)	Ash (%)	Moisture (%)	$LHV_{d.b}$ (MJ/kg)	$HHV_{d.b}$ (MJ/kg)
Bagasse	47.2	7.0	43.1	2.7	50	15.8	17.3
Sugarcane trash	43.5	6.1	41.1	9.3	45	15.7	17.2
Filter cake	32.5	2.2	2.2	14.5	70 ÷ 80	8.8	14.5
Marabu	48.6	6.3	43.6	1.5	19	19.3	20.7

* $LHV_{d.b}$ – Low Heating Value on dry basis; $HHV_{d.b}$ – High Heating Value on dry basis

Table 4. Electricity potential of biomass

Biomass source	Yield (t/ha)	Growing period (year)	Electricity (kWh/(ha·year))
Energy cane	100	1	38,432
Marabu	36	3	15,046
Sugarcane	90	1	12,477

Table 5. Estimated production of sugarcane based products at current and improved yields

Product	Production (kt)	
	Current	Optimized
Yield $\left(\frac{t}{ha\cdot year}\right)$	**43.3**	**90**
Sugarcane	30,890	64,206
Sugar	2,811	5,843

Bagasse	7,414	15,409
Molasses	803	1,669
Filter cake	1,019	2,119
Net GHG emissions (kg$_{CO2}$eq./tc)	29.9	29.3
Net GHG emissions (kg$_{CO2}$eq./kWh)	0.22	0.21

* tc – ton of sugarcane milled

Table 6. Renewable energy based electricity generation targets by renewable source by 2030 (ONE, 2015b).

Renewable source	Power (MW)	Electricity (GWh/year)	Share (%)	Power plants	Investment (million USD)	Cost (USD/kW)	Saved emissions (kt$_{CO2}$eq.)
Biomass	755	4,357	14	19	1,290	1709	3,700
Eolic	633	1,636	5	13*	1,120	1769	1,400
Solar	700	1,088	4	-	1,050	1500	900
Hydraulic	56	238	1	74	110	1964	200
Total	**2144**	**7,319**	**24**	**-**	**3,570**	**-**	**6,200**

*Eolic fields

Table 7. Electricity generation potential for scenarios 2 and 3

Scenario	Biomass	Yield (t/ha)	Mass (kt)	Power capacity (MW)	Surplus electricity (GWh)	Saved emissions ($ktCO_{2eq}$)	Power generation period (h)
2 and 3	Bagasse	43.3*	7,414	1,854	3,881	2,575	2,640
	Filter cake		1,019		610	535	
2 and 3	Bagasse	90*	15,409	3,853	8,066	5,386	
	Filter cake		2,119		1,269	1,114	
2	Marabu	35.6	7,896	1,854	9,972	8,640	5,400
			16,411	3,853	20,726	17,959	
3	Energy cane	100	23,738	1,854	9,768	7,908	
	Energy cane		49,341	3,853	20,303	16,436	

*Sugarcane yield

Table 8. Estimated evolution of the fuel costs for the electricity generation scenarios

Year	Scenario: Business as usual (Million USD/year)		Scenario 1 (Million USD/year)			Scenario 2 (Million USD/year)			Scenario 3 (Million USD/year)		
	HFC	**LFC**	**HFC**	**LFC**	**Inv.**	**HFC**	**LFC**	**Inv.**	**HFC**	**LFC**	**Inv.**
2017	5,657	1,228	5,912	1,483	255	6,127	1,699	470	6,127	1,699	470
2018	5,813	1,262	6,068	1,517	255	6,283	1,733	470	6,283	1,733	470
2019	5,973	1,297	6,090	1,522	255	6,443	1,767	470	6,443	1,767	470
2020	6,138	1,333	6,117	1,528	255	6,043	1,683	483	6,061	1,694	470
2021	6,307	1,369	6,148	1,535	255	5,648	1,600	496	5,683	1,622	474

2022	6,480	1,407	6,183	1,542	255	5,241	1,514	509	5,294	1,548	477
2023	6,659	1,446	6,224	1,551	255	4,825	1,426	522	4,896	1,472	480
2024	6,842	1,486	6,269	1,561	255	4,398	1,336	536	4,488	1,394	484
2025	7,031	1,527	6,320	1,572	255	3,959	1,244	550	4,069	1,314	487
2026	7,225	1,569	6,375	1,584	255	3,510	1,149	564	3,640	1,232	491
2027	7,424	1,612	6,436	1,597	255	3,049	1,052	579	3,199	1,148	494
2028	7,628	1,656	6,503	1,612	255	2,576	952	594	2,748	1,062	498
2029	7,838	1,702	6,575	1,627	255	2,092	850	609	2,284	973	502
2030	8,054	1,749	6,653	1,644	255	1,595	746	625	1,809	883	506
2031	8,276	1,797	6,482	1,407	0	614	168	171	852	319	510
2032	8,504	1,847	6,572	1,427	0	91	58	188	352	224	44
Total	**111,851**	**24,287**	**100,925**	**24,710**	**3,570**	**62,496**	**18,976**	**7,837**	**64,230**	**20,082**	**7,328**

* HFC – High fuel costs, LFC – Low fuel costs, Inv. – Investments

Table 9. Annual carbon uptake per ton of sugarcane milled (dry basis)

Component	**Yield (kg/tc)**	**C (%)**	**Reference**
Bagasse	240	47.2	Suarez et al., 2000
Trash	242	49.0	Alonso-Pippo et al., 2007; Beeharry, 2001
Rooth	150	49.0	Beeharry, 2001
Sugar	91	42.1	Ochoa et al., 2010
Molasses	26	39.5	Browne, 1919
Filter cake	33	3.3	Ochoa et al., 2010
Ethanol*	27	52.1	Ochoa et al., 2010
Vinasses*	281	35.1	Melo et al., 2016

* Per ton of energy cane

Table 10. GHG emissions of diesel consumption

Crop	**Yield (t/ha)**	**Diesel (l/ha)**	**Diesel (kg/$t_{biomass}$)**	**GHG emission (kgCO_2eq./$t_{biomass}$)**
Sugarcane	43.3	319.2	6.13	29.4
Sugarcane	90	641.5	5.93	30.4
Energy cane	100	710.3	5.91	30.6
Marabu	35.6	164.6	3.85	15.9

Table 11. GHG emissions of fertilizers (Contreras et al., 2009; Hillier et al., 2011)

Fertilizer	**Consumption (kg/tc)**	**GHG emission (kgCO_2eq./$kg_{fertilizer}$)**	**Specific emissions (kg_{CO2}eq./tc)**
Urea	2.8	1.907	5.4
Triple super phosphate	2.3	0.997	2.2
Potassium chloride	3.0	0.265	0.8

Table 12. GHG emissions of a pesticide (Sutter, 2010)

GHG	**Emission**

	(kg/kg$_{pesticide}$)
CO	$8.21 \cdot 10^{-5}$
CO_2	$4.93 \cdot 10^{-1}$
CH_4	$7.19 \cdot 10^{-5}$
CO_2eq.	**$4.93 \cdot 10^{-1}$**