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Sustainability assessment of electricity cogeneration from sugarcane bagasse in Jamaica

R. Contreras-Lisperguer [a], E. Batuecas [b, *], C. Mayo [b], R. Díaz [c], F.J. Pérez [b], C. Springer [d]

[a] *Natural Resources and Energy Unit, United Nations Commission for Latin America and the Caribbean, Av. Dag Hammarskjöld 3477, Vitacura, Santiago de, Chile*
[b] *Surface Engineering and Nanostructured Materials Research Group, Complutense University of Madrid, Complutense Avenue s/n, 28040 Madrid, Spain*
[c] *Faculty of Technical Sciences and Engineering, Open University of Madrid, UDIMA, 28400, Collado Villalba, Madrid, Spain*
[d] *Department of Sustainable Development, Organization of American States, 1889 F Street, N.W. Washington, D.C 20006, USA*

Abstract:

Cogeneration from sugarcane bagasse in Jamaica represents a significant opportunity to reduce CO_2 emissions and its dependence on a fossil fuel-based energy matrix. Generation of electricity through cogeneration is a huge opportunity in countries where the sugarcane industry is in decline. This article draws on the findings of a case-study on electricity generation through cogeneration in Jamaica to provide some key messages that may be useful for policy-makers and the private sector to make electricity generation by cogeneration a more competitive option the for investors.

To this end, this article analyses two scenarios: the first is a Baseline Scenario that assesses the impact of cogeneration technology already installed in a Jamaican sugarcane company where the cogeneration stage produces 2,2 MW; the second one considers that the cogeneration technology is changed to a new biomass-based power plant upgrading the cogeneration stage in order to produce 5 MW of power from bagasse. The assessment was carried out by using a complete Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment. The results revealed that generation of electricity from cogeneration derived from bagasse is a suitable alternative adding economic, environmental and social value

1. Introduction

Jamaica's economy is characterized by high energy intensity, low energy efficiency and dependence on imported fuels to meet its energy needs (Planning Institute of Jamaica, 2009; United Nations, 2011). Jamaica's energy matrix is composed of 91% oil imports and 9% on renewable resources, such as hydro, wind power and bagasse (Ministry of Energy and Mining, 2010; Planning Institute of Jamaica, 2009). Jamaica's Second National Communication to the United Nations Framework Convention on Climate Change showed that the island's net CO_2 emissions increased by about 46% from 2000 to 2005 (United Nations, 2011) underscoring the urgency of increasing the deployment of renewable energy technology in order to strengthen national energy security and ease the negative impacts of oil price volatility in the future (Cohen et al., 2011; Ministry of Energy and Mining, 2010; Ministry of Energy and Mining, 2010; Planning Institute of Jamaica, 2009).

Among the policy framework of the National Development Plan (NDP), the government of Jamaica published the National Energy Policy 2009e2030 (NEP) where energy security and efficiency are main outcomes associated with the goal of prosperity of the economy by 2030. Under the NEP there is a subset of policies that intent to support the deployment of biomass and biofuel and the development of energy from waste as the National Biofuel Policy (Ministry of Energy and Mining, 2010) as well as the Jamaica Country Strategy (JCS) for the Adaptation of the Sugar Industry (2015e2020). JCS highlights the need to strengthen economic diversification, social resilience and environmental sustainability of sugar-dependent areas (Ministry of Energy and Mining, 2010). In this context, the sugar industry has crucial role to play. As an example of success, in Brazil the ethanol as a byproduct of sugar production along cogenerated electricity from bagasse accounts for 15.7% of the national energy mix (Schlindwein et al., 2018). Nowadays, the largest sugarcane producers are Brazil and India and both countries have well established bagasse electricity plants with capacity of 10877 MW and 4500 MW respectively. Comparatively,

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Jamaica has only 2 MW of this bagasse electricity plants (IRENA, 2017). In this research work the key priority for authors was to assist a transition to sustainable energy in Jamaica, through the assessment of a study case of the use of bio electricity production from bagasse understanding the Jamaican context of sugar production.

Jamaica's sugar industry accounts for 4% of the direct labor force in Jamaica and 1% of the Gross Domestic Product. Sugar cane industry expansion in Jamaica has potential biomass crops for either biofuel production and/or cogeneration. There is availability of suitable land (47,000 ha) for the production of sugarcane. Likewise, ethanol from sugarcane can be sustainable but requires the optimization of production processes to achieve greater efficiency i. e cogeneration from bagasse (Bandy and Lindo, 2013; Winrock and Organization of American States, 2011). Several initiatives were started to produce excess electricity from the Jamaica's sugar sector; some studies (Joint UNDP/World Bank, 1988; USAID, 1980) were focused on the financial feasibility stage; others (Da Costa et al., 2006; Landell Mills, 2011; Winrock and Organization of American States, 2011) estimated 402,376 tonnes bagasse output and the potential interconnection of sugarcane cogeneration to the grid in the range of 220e300 GWh per year.

Literature review revealed studies with techno-economic appraisal of renewable energy an efficiency applications in general (Esen et al., 2006, 2007; Patel and Singal, 2018) and biomass in particular (Esen and Yuksel, 2013; Ekener et al., 2018).

Electricity generation from cogeneration facilities depend very much on process and technology characteristics (Morato et al., 2017). Mandegari et al., 2017 determined that coal co-combustion with biomass improves the economic and environmental benefits.

Regarding social approaches, there are also studies without a complete sustainability approach but reporting on social impacts of the sugarcane production: in Brazil (Madlener and Hayley, 2000; Silva et al., 2014; Schlindwein et al., 2018; Walter et al., 2008), in Pakistan (Arshad and Ahmed, 2016), in Africa (Maconachie and Fortin, 2013; Mashoko et al., 2013; To et al., 2017, 2018). Social benefits in terms of employment were also highlighted (Maconachie and Fortin, 2013; Souza et al., 2018). Likewise, environmental Life Cycle Assessment (LCA) studies of bagasse cogeneration and ethanol were conducted in Latin American countries providing their governments policy-making tools for project investments and the introduction of biofuels in the market (Amores et al., 2013; Caldeira-Pires et al., 2018; Cavalett et al., 2013; García and Manzini, 2012; Macedo et al., 2008; Quintero et al., 2008; Regis et al., 2014). At this respect, it was emphasized the need to establish a clear framework to generate information that is representative of the situation in the sugarcane producers countries (United Nations, 2011).

There are environmental LCA studies of bagasse (Guerra et al., 2014) and both economic and environmental LCA studies in Brazil (Palma-Rojas et al., 2017). However, no study has been reported on three social, economic and environmental issues means integrated sustainability assessment of bagasse cogeneration in Jamaica. For this purpose, this research gathers and analyzes the data for a sugarcane factory, namely Golden Grove in St. Thomas. We assessed the impacts of the bagasse cogenerated bioelectricity for a year using the Life Cycle Sustainability Assessment (LCSA) which quantifies the impacts in the tree pillars of sustainability: economy, environment and social. At this respect, LCSA maximizes the triple bottom line (Finkbeiner, 2012). Hence, the results will be useful to assist government agencies in identifying the environmental, economic and social cost and benefits to produce electricity through bagasse cogeneration and to support decision-making process of generating bioelectricity with updated technology using bagasse as a primary energy source in the sugar mills in Jamaica.

For the three analyses (LCA, LCC and S-LCA), data were collected from direct sources during visits to Jamaica, including from publicly-available statistics and interviews with stakeholders.

2. Methodology

The field based research required gathering data on the inputs and outputs in the value chain of energy cogeneration, considering already operating scenarios in the sugar factory, as well as those scenarios of electrical co-generation. The field based research also included interviews plus field observation, with groups in focal areas. Data on perceived and evidential social and economic costs and benefits in terms of health, education, working conditions, human rights, community organization and governance have been gathered.

The field-based research was carried out during three missions to Jamaica. In the first one relevant stakeholders provided their inputs. The second mission involved field-based research related to the environmental and social dimensions of sustainability. The third mission involved interviews and visits to the factory to gather data relative to the economic dimension and to validate some of the data gathered in the second mission.

Subsequently, the Life Cycle Sustainability Assessment was conducted. LCSA is a methodology that assesses the environmental, economic and social aspect of a project, or a product. The methodologies used are:

- Environmental: LCA.
- Economic: LCC.
- Social: S-LCA

While LCA and LCC are well developed methodologies, S-LCA and LCSA are in the development phase (Hannouf and Assefa, 2016; Sandin et al., 2016). The reference document for elaborating this LCSA is: "Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products," by UNEP/SETAC Life Cycle Initiative (Ciroth et al., 2011).

The function of a bioelectricity system is to generate power for fulfilling the energy needs in a sugar mill and/or to provide electricity to the external grid. In this work, two scenarios are analyzed:

- Baseline Scenario consists in the actual cogeneration technology installed in the Jamaica's Golden Grove enterprise. It considers an agricultural stage for the production of 63697.74 t of sugarcane annually. In the bagasse production stage the sugarcane is milled to extract the juice and bagasse. In this study, the mass-based allocation method was applied for the products (bagasse and mixed juice) obtained in the bagasse production stage. This distribution was used to assess its real impact, bagasse represents about 27% of the total mass of the products and mixed juice about 73%. When the allocation cannot be avoided, physical properties (mass, energy, exergy, etc.) of products can be used as the best allocation methods (Ekvall and Finnveden, 2001; Kim and Dale, 2002; Dewulf et al., 2005; Dewulf and Van Langenhove, 2005; Jungbluth and Frischknecht, 2006; Curran, 2007; Grillo et al., 2011).
- In the baseline scenario, power and steam is generated by an out-dated cogeneration system (2.2 MW) using bagasse and wood, and electricity from the external grid is used to complement the energy needs from the sugar mill.
- Scenario 1: This scenario considers the agricultural stage and bagasse production stage with the same characteristics as for the Baseline Scenario. In this scenario, the cogeneration technology is increased to produce up to 5 MW of power from bagasse. In this scenario it is also assumed the electricity

generated will satisfied on-site needs and the surplus (2.1 MW) is fully sold to the national grid. In scenario 1, a new 5 MW cogeneration system adequate to use bagasse as a fuel is used in the sugar mill installations. It is important to highlight that the new cogeneration system is capable of generating 5 MW with the same amount of bagasse currently produced by the sugar mill and the same 2942 h per harvesting year.

The functional unit for LCA is to generate bioelectricity for a year in a sugar mill in Jamaica in the two scenarios above mentioned. Fig. 1 shows the life cycle of the process and the boundaries of the system (discontinued lines). It considers three stages included in the system boundary for the life-cycle inventory: agriculture stage (sugar cane production); bagasse production stage (include transport of sugar cane from plantation to sugar mill, bagasse and juice extraction from sugar); and cogeneration stage (include steam and electricity generation).

2.1. *Environmental Life Cycle Assessment*

The Environmental LCA was conducted according to ISO 14040 and 14044 (ISO, 2006a; ISO, 2016b). For environmental LCA, the evaluation method was Recipe midpoint (H), using SimaPro software. The impact categories studies are shown in Table 1. While it accomplishes the mandatory elements of classification and characterization, it does not take into account weighting. Recipe and the categories that it uses are internationally-accepted, and the methods used are scientific and technically-valid (Hauschild et al., 2011). Data requirements and sources of data were taken into account as follows.

For the sugar cane production data on the use of land, raw material, water consumption, and transportation of materials in cane production, were obtained from report in Golden Grove. The diesel input was estimated from Ecoinvent database as average harvesting process consumption. However, for the fertilizer United States Life Cycle Inventory (USLCI) and Agri-footprint Database were used. Data related to solid waste generated at the production stage was provided by Golden Grove. The dataset of transport from Ecoinvent was used for modeling fertilizer and pesticide transportation considering average distance.

For the Bagasse production, in the industrial stage the material and energy balances in the mill were reported from Golden Grove enterprise. The cogeneration process from bagasse and the electricity generation from diesel for fulfillment the electricity demand were modeled as near process. For the electricity consumption from the grid, the electric mix from Jamaica, according to the relative contribution of 93% fossil fuels (oil and gas) and 7% renewable (hydropower and wind) was modeled.

Furthermore, the following assumptions were conducted:

- For the production of 1 t of cane sugar in the chosen mill it is necessary to produce 12 t of sugar cane that requires an area of 0,1579 ha.
- Diesel fuel is used for land preparation, crop maintenance, e.g., irrigation and fertilizer/herbicide application, and harvesting in sugar cane farming.
- All pesticides that were not included in the database were analyzed as generic pesticides.
- The air pollution control technologies in the process of steam generation are not considered in this analysis because it is not common practice in Jamaica's sugar mills.
- Mixed juice and steam are byproducts of the bagasse production, but the use of steam in the sugar process was considered in order to have a real assessment of the electricity consumed in the process.

2.2. *Social Life Cycle Assessment*

In S-LCA, social impacts are understood as consequences of positive or negative pressures on social endpoints, caused by social relations weaved in the context of an activity and/or engendered by it and/or by preventive or reinforcing actions taken by stakeholders (UNEP, 2009). For S-LCA the categories analyzed were those suggested in the document "Guidelines for Social Life Cycle Assessment of product" (UNEP, 2009).

The complexity of social impacts suggests that sub-categories should be assessed by Inventory Indicators that are both designed by using a stakeholder categorization and drawn widely and then revised in the light of interviews, site visits and new documentation.

Subcategories are classified according to Stakeholder and Social Impact categories and are assessed using of inventory indicators, measured by unit of measurement (or variable). The classification of sub-categories according to stakeholder groups match the goal and scope of the study (Benoît et al., 2007).

As in the environmental assessment, SCLA is a powerful tool to compare production alternatives (Siebert et al., 2018). Three main stages are included in the system boundary: agriculture stage (sugar cane production); bagasse production stage (include transport of sugar cane from plantation to sugar mill, bagasse and juice extraction from sugar); and cogeneration stage (include steam and electricity generation).

Following a site visit, using a layered case study consisting of interviews by type (individual and group), document analysis and participant observation, site findings were triangulated. All indicators were reviewed, with in-depth exploration of 12 potential hot spots.

2.3. *Life cycle costing*

As in the case of an environmental LCA, the functional unit is a fundamental concept in an environmental LCC, and in both studies the functional unit must be the same. For Life Cycle Costing, the SETAC method (Ciroth et al., 2011) was used. In Table 4 the various categories are shown.

For the LCC, the primary data was collected by a survey made for the sugarcane and sugar sector. The survey included all costs associated with labour, materials, energy, fuels, maintenance and operation in each unit process of the agricultural and industrial phase. The unit processes in the agricultural phase are land preparation, planting, plantation management, ratoon management, hand-cut harvesting, mechanical harvesting, and cane transport. The unit processes in the industrial phase are bagasse production and maintenance.

To complement this information and obtain cost data from the sector, interviews were held with partners from the Sugar Manufacturing Corporation of Jamaica Limited, Petrojam Limited, JB Ethanol, and the All-island Jamaica Cane Farmers Association.

The economic LCI has been developed to satisfy the needs of the local producer.

Among the assumptions in each life cycle stage, we have:

Agricultural phase: the unit processes in this phase are land preparation, planting, plantation management, ratoon management, hand-cut harvesting, and cane transportation, all of which consider labour, materials, contract and services, diesel and material costs in Jamaica dollar per sugarcane tonnes (J$/TC). The sugarcane cost is associated only with the 33% of sugarcane needed to produce bagasse, the main energy source for the cogeneration system in the sugar mills (see allocation criteria). For this study, we have assumed a 40% of planting management and 60% of ratoon management. In addition, the hand-cut harvesting corresponds to

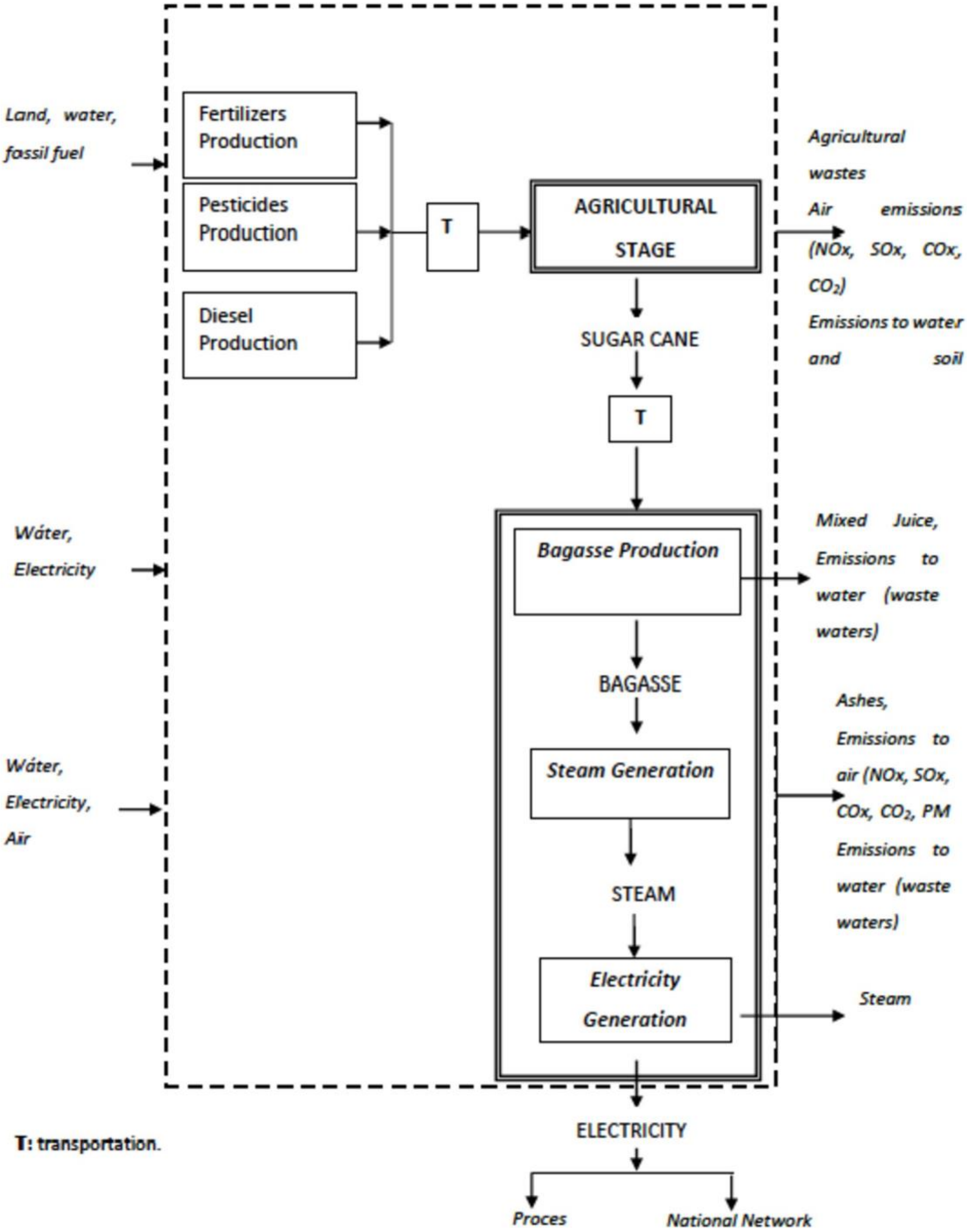

Fig. 1. Life Cycle of Cogeneration process. Source: Perez et al., 2013.

100% and no mechanical harvesting is used in the agricultural phase.

Industrial phase: the unit processes in this phase are industrial and maintenance activities. The costs are associated with materials, external energy, labor, and contract and services. Based on the current sugar industry data, 43% of the costs in the industrial activities are related to bagasse production. Only external electricity is accounted for in the industry phase in order to avoid double accounting, since the costs of cogeneration system are already part of system boundary.

Cogeneration process: in the current scenario for sugar production, the 2.2 MW cogeneration system uses bagasse as fuel and wood for ignition, and it considers the costs of operation and maintenance, labor and materials. In the scenario 1, capital and operation and maintenance costs, based on NPV, are considered, where the cash inflow is the payment received for selling the surplus electricity to the external grid.

3. Results and discussion

3.1. Environmental Life Cycle Assessment (LCA)

First, the data received from Golden Grove Company was analyzed to identify any anomalies and check the consistency of the

Table 1
Impact categories, LCA.

Potential Impact category	Acronym	Reference substance
Climate change	CC	kg CO_2 eq
Ozone depletion	OD	kg CFC-11 eq
Human toxicity	HT	kg 1,4 DCB eq
Photochemical oxidant formation	POF	kg NMVOC
Particulate matter formation	PMF	kg PM_{10} eq
Ionizing radiation	IR	kg ^{235}U eq
Terrestrial acidification	TA	kg SO_2 eq
Freshwater eutrophication	FE	kg P eq
Marine eutrophication	ME	kg N eq
Terrestrial ecotoxicity	TET	kg 1,4 DCB eq
Freshwater ecotoxicity	FET	kg 1,4 DCB eq
Marine ecotoxicity	MET	kg 1,4 DCB eq
Agricultural land occupation	ALO	m^2a
Urban land occupation	ULO	m^2a
Natural land transformation	NLT	m^2
Water depletion	WD	m^3
Metal depletion	MD	kg Fe eq
Fossil depletion	FD	kg oil eq

input and output flows by mass and energy balances and comparative analyses of release factors. It provided evidence that the data quality requirements for the goal and scope of the LCA intended application were fulfilled. The analysis demonstrated the feasibility of upgrading the cogeneration process in order to increase the electricity generation thus helping to avoid the use of fossil fuel in the process and to export electricity to the grid.

Fig. 2 and Table 2 show the comparison of the analyzed processes, actual and future cogeneration processes in Golden Grove. The comparison of Scenarios showed that Scenario 1 is better than Baseline Scenario. It shows that the actual process generates the greatest potential impact on all categories analyzed, except the agricultural land occupation where both show similar impacts because of the sugarcane production is the same in these processes.

One common result of LCA studies is that the agricultural stage is the major contributor to global warming for all types of feedstock (Wang et al., 2011, 2012).

According with these, in the actual cogeneration process in Golden Grove is observed that the agricultural stage presents the major contribution to eight categories (see Fig. 3). It contributes the most to Agricultural land occupation, Fresh Water Eutrophication, ozone depletion, Ionizing radiation, Fossil depletion, Terrestrial ecotoxicity, Marine eutrophication and Climate change. The potential impact of the eight categories mentioned is due to the process of sugar cane for the m^2 of soil used for plantation, fertilizers and herbicides use and their production and transport. Furthermore, the major contribution of the cogeneration stage is on the water depletion, photochemical oxidant formation, particulate material formation, terrestrial acidification and human toxicity, due to the water consumption and emissions from bagasse combustion process. Likewise, the bagasse extraction stage shows the major effect for the Urban Land Occupation, Natural land transformation and metal depletion, due mainly to the transportation of sugar cane from plantation to the sugar mill.

Fig. 4 shows the agricultural stage evaluation. This stage in this study considers the sugarcane necessary for the bagasse production according with the allocation considered in the extraction stage.

It is appreciated that transport contributes the most to potential impact in 14 of the 18 categories analyzed. The major contribution is to Terrestrial ecotoxicity, marine ecotoxicity, photochemical oxidant formation, climatic change, particulate material formation, terrestrial acidification, human toxicity, fresh water ecotoxicity, Ionizing radiation and fossil depletion due to the transport of fertilizers and herbicides used in the sugar cane production. On the other hand, the agricultural activities have high impact on the agricultural land occupation due to long history of sugar cane cultivation. In addition, it has a significant impact on marine and freshwater eutrophication, as for the emission produced for the use of nitrogen and phosphorous fertilizers. For that reason, together with the use of pesticides, it impacts, albeit to a lesser degree, on climatic change, terrestrial acidification, photo-chemical oxidant formation and particulate material formation.

Pesticides production and use cause significant impact on numerous categories such as: metal depletion, water depletion, natural and urban land occupation, freshwater ecotoxicity, human toxicity and ozone depletion.

Diesel consumption generates impact on several categories such as fossil depletion, ionizing radiation, ozone depletion, natural land transformation, urban land occupation, water depletion, fresh water ecotoxicity and human toxicity.

Fig. 5 shows the bagasse production stage evaluation. Transport sector has the predominant impact on all categories due to the consumption according to the activities in this stage where only the sugar cane transported from plantation to the sugar mill.

Fig. 6 shows the electricity cogeneration stage evaluation for the Baseline Scenario. It shows that the use of electricity from the grid generates the highest potential impact on 14 of 18 categories analyzed due to the consumption of electricity from fuel. All of

Table 2
Life Cycle Assessment Inventory results.

Potential Impact	Unit	Cogeneration Baseline Scenario	Cogeneration Scenario 1
Climate change	kg CO_2 eq	6424958,5	—3574623,4
Ozone depletion	kg CFC-11 eq	0,51006677	—0,10784174
Terrestrial acidification	kg SO_2 eq	53953,105	—13531,658
Freshwater eutrophication	kg P eq	142,57764	79,367819
Marine eutrophication	kg N eq	4918,8947	2924,8077
Human toxicity	kg 1,4-DB eq	212941,18	—445218,49
Photochemical oxidant formation	kg NMVOC	71772,685	32672,011
Particulate matter formation	kg PM_{10} eq	18602,628	155,51034
Terrestrial ecotoxicity	kg 1,4-DB eq	490,18143	—668,7916
Freshwater ecotoxicity	kg 1,4-DB eq	4061,9811	—1761,4207
Marine ecotoxicity	kg 1,4-DB eq	6722,9597	—9790,6754
Ionizing radiation	kg ^{235}U eq	329704,03	—177435,25
Agricultural land occupation	m^2a	8413764,8	8411085
Urban land occupation	m^2a	9638,1538	8795,4453
Natural land transformation	m^2	46,893428	41,649702
Water depletion	m^3	3286968,8	—1004437,8
Metal depletion	kg Fe eq	11428,343	10444,385
Fossil depletion	kg oil eq	2158618	—1153727,9

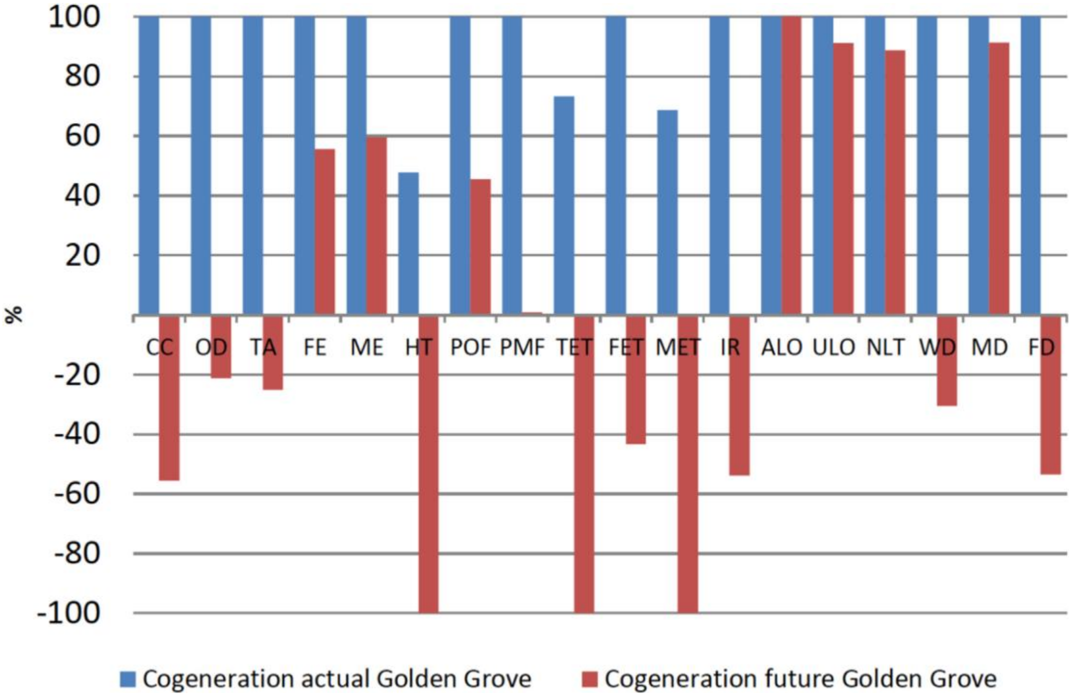

Fig. 2. LCIA Comparison between actual and future cogeneration process in Golden Grove.

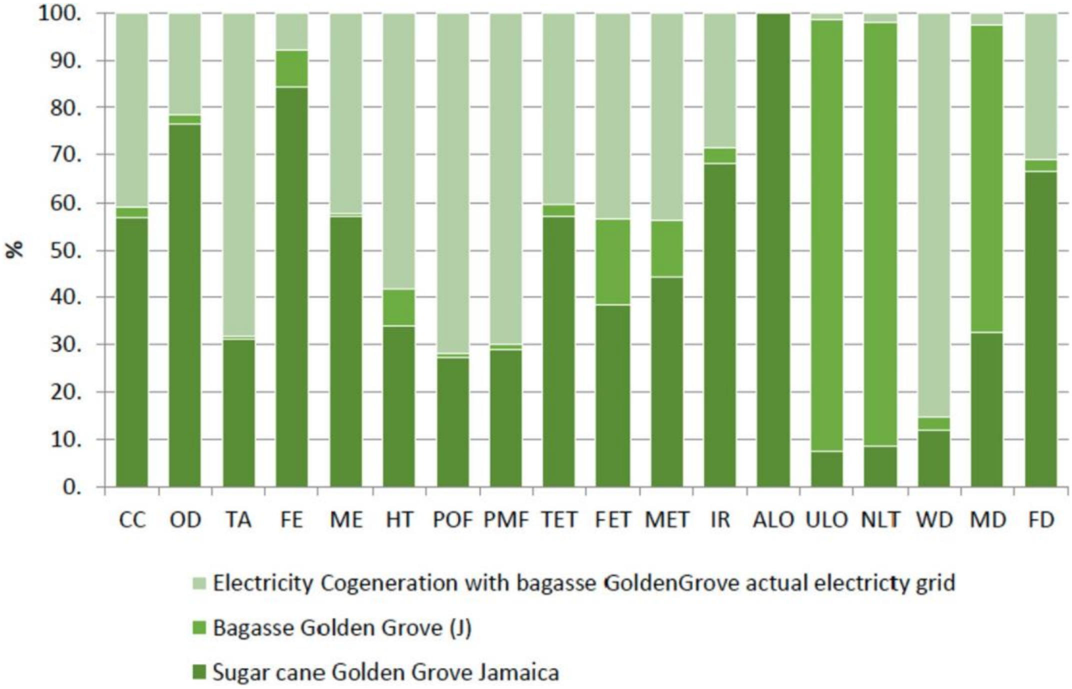

Fig. 3. LCIA of actual cogeneration process in Golden Grove.

these environmental damages are caused by the bagasse combustion, which generates significant amounts of particulate material.

Further, there are other potential impacts on metal depletion, ionizing radiation and ozone depletion caused during the water softening process by ion exchange for the steam generation. These results are similar to those from other studies witch reveal the use of residues from agricultural and industrial stages can diminish the environmental impact (Contreras et al., 2009; Chauhan et al., 2011; Dunkelberg et al., 2014; Turdera, 2013). Crop yield contributes to impact categories (Mosnier et al., 2013; Galbusera and Hilbert, 2011; Alonso-Pippo et al., 2008).

Fig. 7 shows the future electricity cogeneration stage. It is observed that similar to the actual process the cogeneration with bagasse stage present the major impact to the photochemical oxidant, marine Eutrophication, particulate material formation and terrestrial acidification caused by the bagasse combustion. But, it is

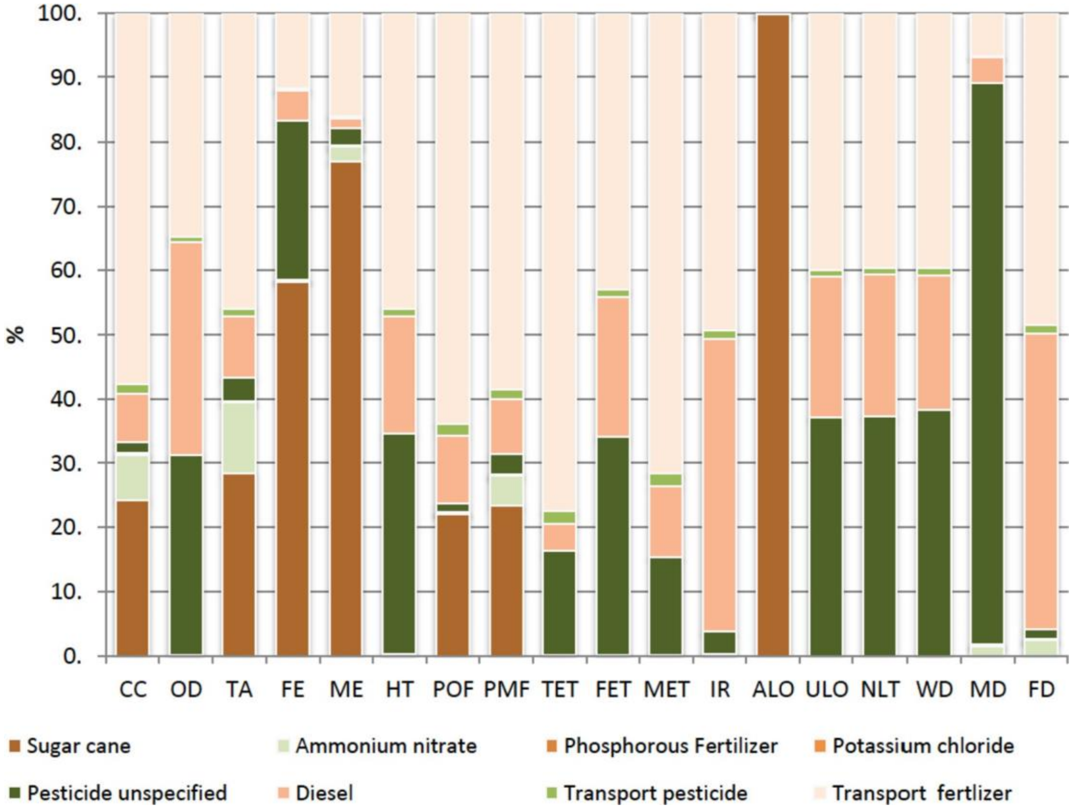

Fig. 4. Evaluation of agricultural stage of Golden Grove.

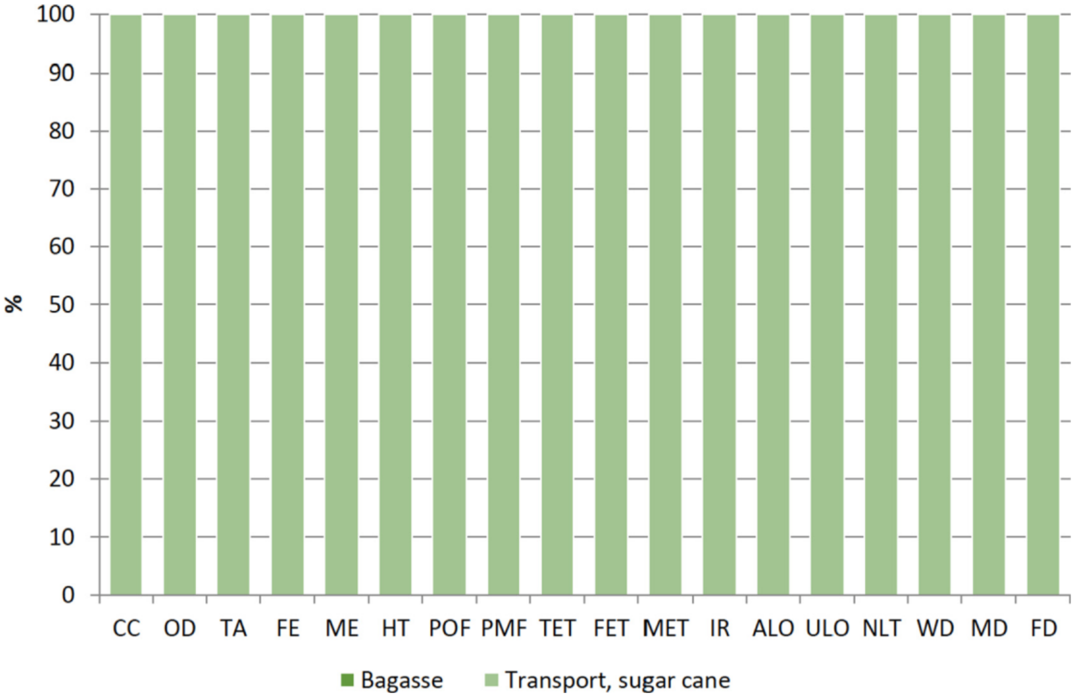

Fig. 5. Bagasse production stage in Golden Grove.

important to highlight the negative contribution (seen as a positive environmental aspect) on all categories. Is due to the electricity from fuel saved by the process and its diesel combustion associated impacts. These results are in accordance with an important conclusion of previous studies which reveal the integration of cogeneration processes as a relevant aspect to achieve the sugarcane production sustainability (Perez et al., 2013; Contreras et al., 2009; García and Manzini, 2012; Macedo et al., 2014; Wang et al.,

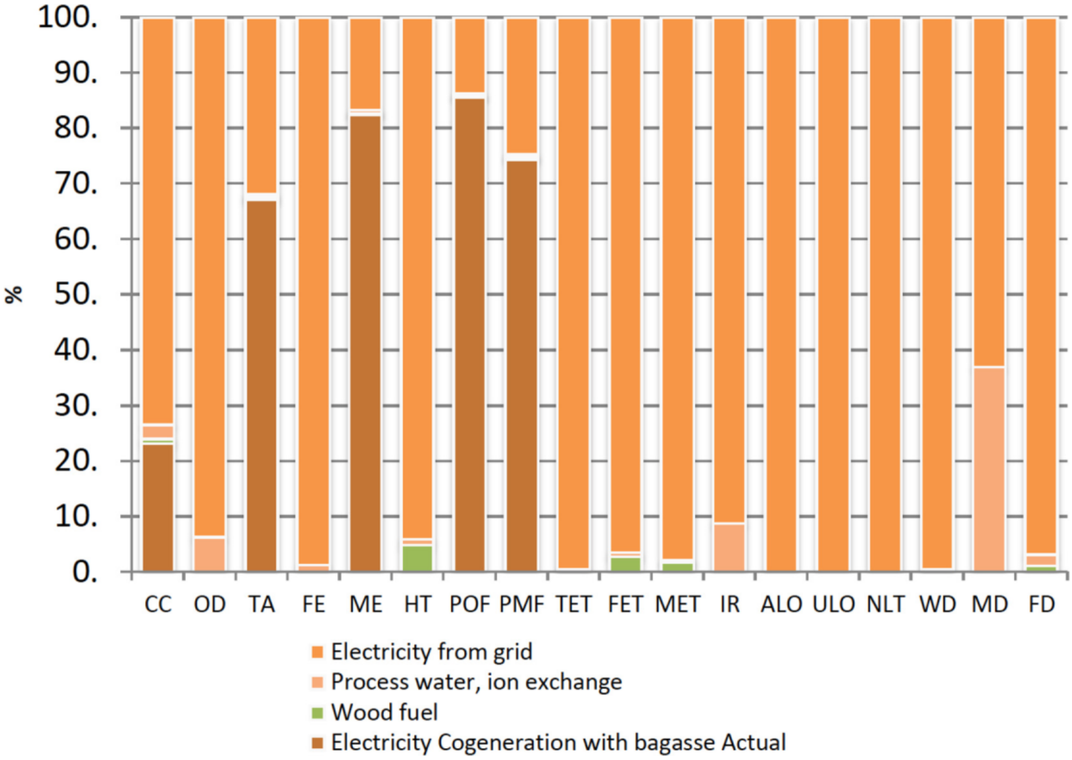

Fig. 6. Evaluation of electricity cogeneration stage for the Baseline Scenario.

2007; Wang et al., 2011; Ramjeawon, 2013; Tapia and de Souza, 2017).

In Fig. 8 is shown, per impact category that for all of outcomes, actual cogeneration has a higher score than the future cogeneration. This allows us to see whether the differences shown in the previous figure are indeed significant. In general, we can assume that if 90%e95% of the Monte Carlo runs are favorable for a product, the difference may be considered significant. Applying this rule means that only the difference between the two processes are not significant for marine ecotoxicity, freshwater ecotoxicity, human toxicity and natural Land transformation. In Scenario 1 potential impact be less in all categories of impact.

3.2. Social Life Cycle Assessment (SLCA)

St Thomas parish, where Golden Grove Sugar Factory is located, has high poverty levels relative to the rest of Jamaica and particularly poor social indicators such as, the highest teenage pregnancy and lowest male literacy rates. Social infrastructure (access to education, healthcare, energy, roads) is poor. There are few employment options outside of the sugar industry. Other agricultural products such as bananas have been severely affected by natural phenomena, particularly hurricanes. Rural to urban migration has been historically high. Government's focus, via the Sugar Transformation Unit (STU), is to improve the social infrastructure of the Parish to better serve local communities and the sugar industry, and to reduce outward migration of young people to the cities. However, in St Thomas, housing relocation has been costlier than anticipated, reducing the availability of funds for social infrastructure. This study was done in order to establish the bagasse cogeneration social impacts.

In this study, 70 indicators were selected for review. Of these, 12 were selected as key indicators of potential social hot spots. Among these 12 indicators, the results showed:

- One indicator, (Number of Jobs) was found likely to be positive in terms of potential for positive social impact through a gain in the number of full-time, low level, unqualified/unskilled jobs (a likely change of more than 200 seasonal jobs to the same number of full-time jobs) at the field level. This manpower would be necessary to produce cane or equivalent all-year round in order to produce the quantities of bagasse required for full co-generation of electricity. And these jobs are likely to be local jobs. No change likely in number of factory-based or senior level jobs was determined. These trends are in line with a recent study (Papong et al., 2017) which highlights the advantages in term of total employment in a bioethanol production plant also with bagasse cogeneration.
- Five indicators suggested positive potential, dependent on the introduction of relevant organizational policy and/or the type of certification sought. These are:
  i) Number/percentage of injuries, illness and fatal accidents in the organization by job qualification inside the company
  ii) Presence of formal policies on equal opportunities (working conditions).
  iii) Lowest paid workers, compared to the country's minimum wage (Working Conditions).
  iv) Has the organization developed project-related infrastructure with mutual community access and benefit? (More reliable electricity supply).
  v) Strength of training and (re-) qualification policies and practices (length and type of training/qualifications plus eligibility by age, experience, qualifications, local living)
- One indicator, (strength of organizational risk assessment with regard to potential for material resource conflict) was found likely to be negative because there is potential to change this to community advantage if local farmers are paid to produce raw inputs, without disadvantage to local production of other food supplies.

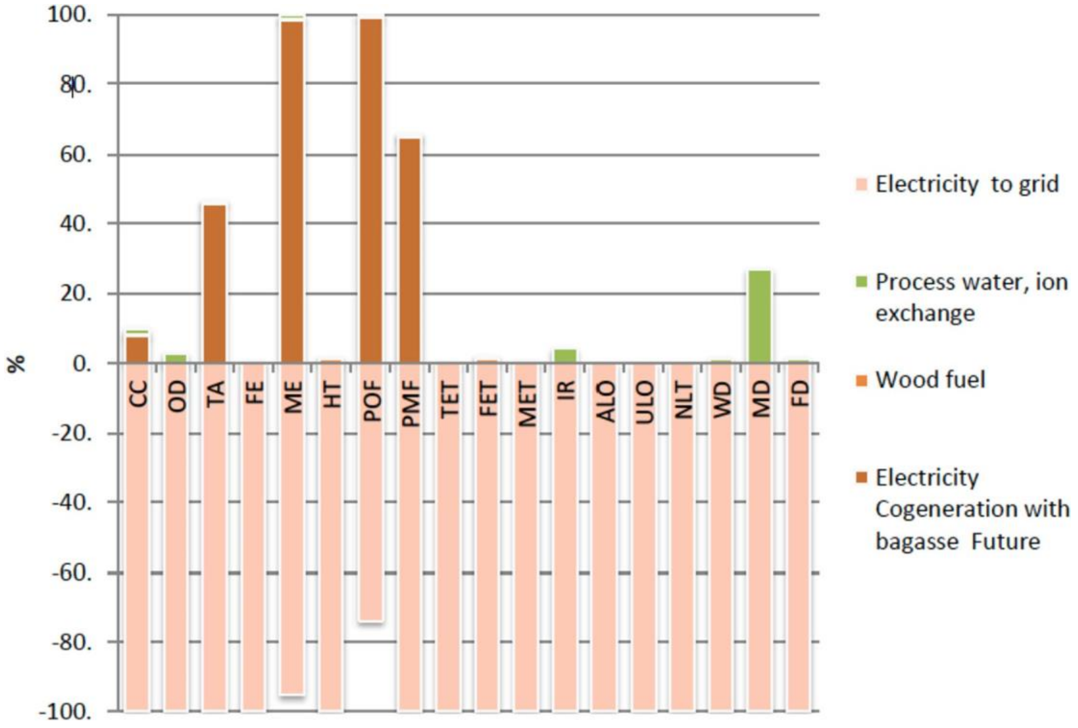

Fig. 7. Evaluation of electricity cogeneration stage for the Scenario 1.

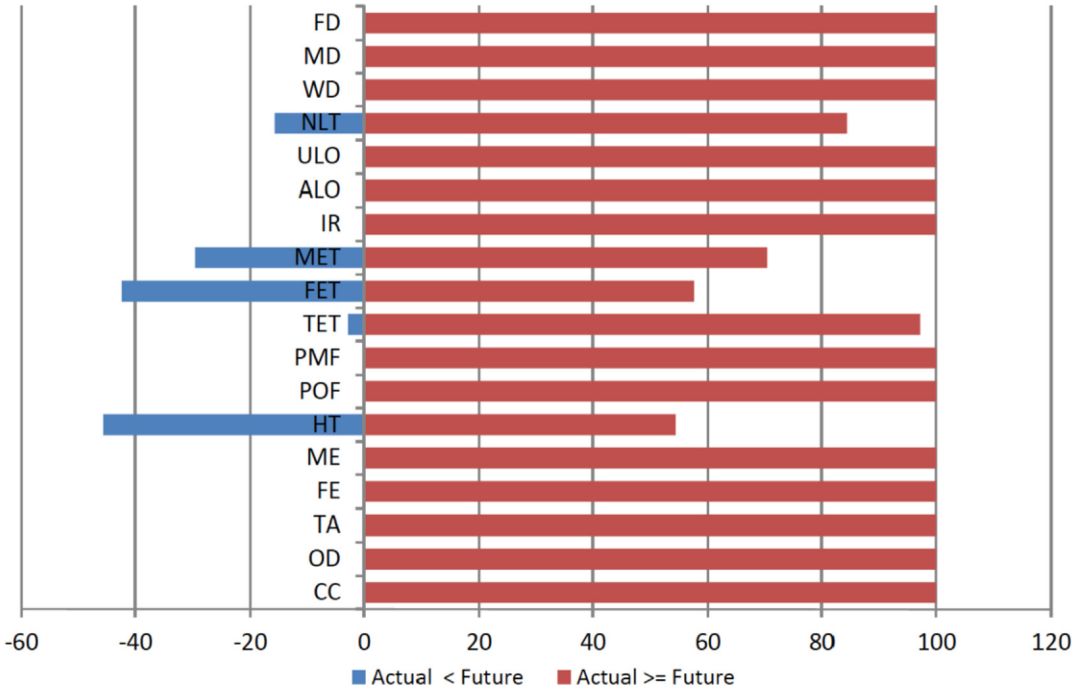

Fig. 8. Results of uncertainty analysis for scenarios comparison.

- Five indicators showed no evidence of current impact and no likely social impacts. These are:
  - i) Employment is not conditioned by any restrictions on the right to collective bargaining (Working Conditions).
  - ii) Workers voluntarily agree on employment terms. Employment contracts stipulate wage, working time, holidays and terms of resignation. Employment contracts are comprehensible to workers and kept on file.
  - iii) Absence of working children under the legal age (Human Rights - Child Labor).
  - iv) Organizational policies/efforts to reduce unpaid time spent by women and children collecting biomass.

v) Local rates of mortality and burden of disease attributable to indoor smoke.

It is important to reiterate that any potential for community conflict will likely have been considerably mitigated in the short-term by a lengthy and multi-faceted divestment process, which addresses potential problems of informal settlements and inadequate worker housing, as well as access to wider educational, social and business services.

3.3. *Life cycle costing (LCC)*

The new cogeneration system was modeled according to the technical literature (Mtunzi et al., 2012). The value of the discount rate was based on the benchmark interest rate reported by the Central Bank of Jamaica (BOJ), and the external electricity cost was informed by the sugar sector. Data associated with the cogeneration process is depicted in Table 3. Any value of the discount rate that is higher or equal to 2.88% makes the implementation of a new cogeneration system a better economic scenario than the current sectoral context. The net cash inflow is that which is expected to be received in each period. In other words, it is the periodic payment expected to be received for selling 2.1 MW to the external grid at J$34,000/MW.

Table 5 shows the main findings for LCC. These costs detailed in this study are based on the producer's perspective. This LCC study analyzed and compared two scenarios. According to the results, the installation of a new cogeneration system reduces the life cycle costs of generating bio-power in sugar mills in Jamaica.

The results reveal that agricultural activity is the main contributor to the life cycle cost of generating bioelectricity per year in a conventional sugar mill in Jamaica, followed by the cogeneration process and the bagasse production. On the other hand, the results indicate that the cogeneration process is the main contributor to the life cycle cost of generating bioelectricity per year when a new and efficient cogeneration system is introduced.

As expected, the current condition of bioelectricity generation with an outdated cogeneration technology has the worst economic performance when compared with the scenario of using an updated and efficient bagasse-derived cogeneration system. The main cost of scenario 1 is related to the cost of the new investment, representing 92% of the total cost, according to a recent techno-economic assessment (Gnansounou et al., 2015) which reveal positive environmental impacts of enhanced technology in sugarcane industry but prove to be more expensive than conventional one. But despite the high cost of a new investment, in this research, this scenario reduces the life cycle cost by about 25%.

To illustrate the context for the investment costs, a superficial exercise was carried out, and there is no investment cost for the new and efficient cogeneration system that increase its use in 127% with the new technology. Hence, the life cycle cost would drop by 78% if compared with the same scenario but with investment cost e factored in original scenario 1. The cost of the cogeneration process would be responsible for 62%, bagasse production 17% and sugarcane 21%. On the other hand, the reduction of the life cycle cost would be about 84% if compared with the baseline scenario.

Table 4
Cogeneration process modeling.

Item	Value	unit
Working hours per harvesting year	2941.18	hrs
Discount rate (*i*)	5.75	%
Exchange rate 2012	88.99	J$/US$
Equipment Capacity (5 MW)	14,706	MWh/year
Cogeneration equipment life (*n*)	20	years
Equipment Cost (5 MW)	12,000,000	US$
Miscellaneous costs 20%	2,400,000	US$
Initial Investment	14,400,000	US$
Operational and maintenance 3%	432,000	US$/year
Availability (2.1 MW)	6176	MWh/year
Cash inflow	2,359,819	US$/year
Net Present Value (NPV)	13,224,934	US$
Capital cost	52.50	US$/MWh
Operational and maintenance cost	29.37	US$/MWh
Electricity external grid cost	382	US$/MWh

It is important to highlight that the good economic performance achieved from using a new and efficient cogeneration technology is mainly related to the consumption of the same amount of bagasse for the generation 127% more power. In other words, the reduction in cost is due to a gain in energy efficiency. Thus, because with the outdated cogeneration technology less MW per year is generated with the same amount of bagasse and the cost of producing sugarcane is high in Jamaica, the driver of the life cycle costing results for that scenario is the agricultural phase, representing about 65% of the total cost.

4. Conclusions

Regarding the LCA, the Baseline Scenario is characterized by an electricity cogeneration which is not enough for fulfilling the requirements. Further, the process and the consumption of electricity from the grid generates the most important impact. The main impacts were found in the agricultural stage due to the production and use of fertilizers, pesticides and fuel and in the cogeneration stage.

On the other hand, Scenario 1 is characterized by the intensification of the generation of electricity from bagasse. We observe in all categories a negative impact due to the electricity generated from the fuel saved by the processes and its associated impacts due to emission from diesel combustion. Furthermore, the scenarios comparison demonstrated the feasibility of upgrading the cogeneration process.

In terms on Social LCA, no evidence was found on either of the Jamaica's sites of any child labor or any forced labor, nor is

Table 3
Impact categories, LCC.

Phases	Unit process	Cost categories	Perspective of LCC
Agricultural	Land preparation	Labour, land, seed cane, contract and services, diesel	Producer
	Planting	Labour, supplying seed, contract and services, diesel	
	Plantation management	Labour, fertilizer, herbicides, diesel, contract and services	
	Ratoon management	Labour, herbicides, diesel, contract and services	
	Hand cut harvesting	Labour, contract and services, diesel	
	Cane transport	Labour, diesel	
Industrial	Operation and maintenance	Labour, materials, external grid energy	Producer
Cogeneration	Process	Labour, operation and maintenance, capital, water, air	Producer

Table 5
LCC indicators.

Summary of basic costs (J$/FU)		
2012	Baseline	Scenario 1
Agricultural phase	92,807,914	4,961,316
Bagasse production	16,481,672	3,942,985
Cogeneration process	32,818,820	97,288,025
Total (J$/FU)	142,108,406	106,192,327

employment conditioned by any restrictions on the right to collective bargaining. No change is predicted with the co-generation of electricity. Moreover, no evidence was found of unpaid time spent by women and children collecting biomass or unusual levels of mortality and burden of disease attributable to indoor smoke. Hence, no change is predicted with the introduction co-generation of electricity.

From an economic perspective, a new and efficient 5 MW cogeneration technology is capable of fulfilling the energy needs of the sugar mill and the sale of 2.1 MW to the external grid, resulting in higher economic competitiveness of c of the sector.

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