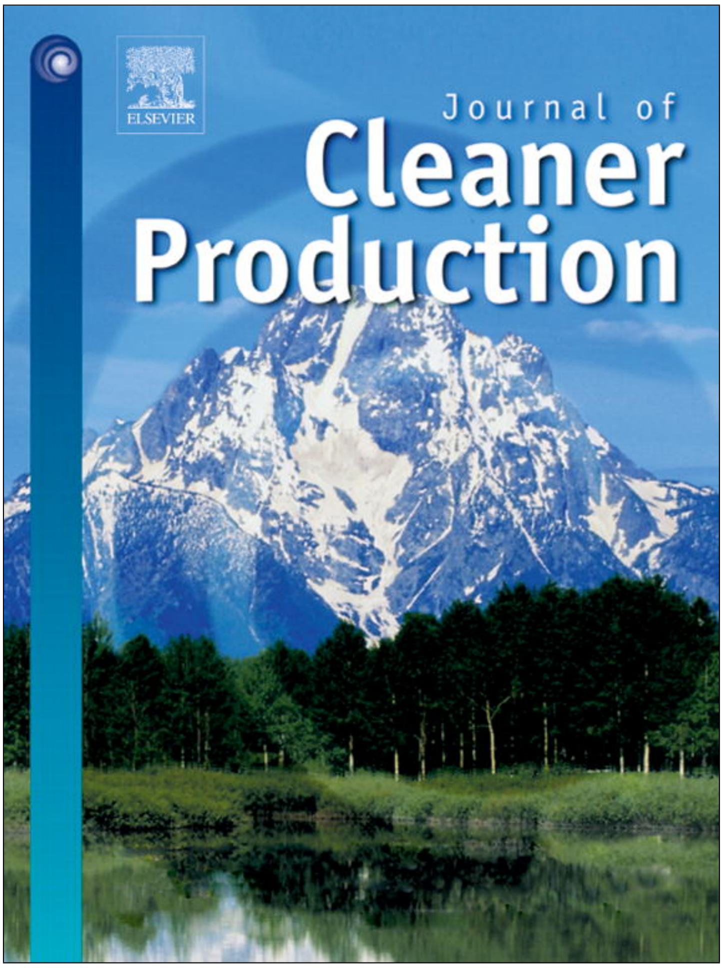

Journal of Cleaner Production 39 (2013) 42–49

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life cycle inventory of electricity cogeneration from bagasse in the South African sugar industry

L. Mashoko[a], C. Mbohwa[b,*], V.M. Thomas[c,d]

[a] Logistics and Quantitative Methods, CSIR Built Environment, Pretoria, South Africa
[b] Department of Quality and Operations Management, University of Johannesburg, Auckland Park Bunting Road Campus, P.O. Box 524, Auckland Park 2006, Johannesburg, South Africa
[c] School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[d] School of Public Policy, Georgia Institute of Technology, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 27 September 2011
Received in revised form
22 August 2012
Accepted 27 August 2012
Available online 7 September 2012

Keywords:
Bagasse power lifecycle inventories
South African sugar power
Bio power environmental sustainability
Bioenergy

ABSTRACT

The South African sugar industry has a potential for cogeneration of steam and electricity using bagasse. The sugar industry has the potential to generate about 960 MW per year from bagasse based on the average of 20 million tons of sugar cane crushed per year. Renewable energy sources like bagasse are generally regarded as cleaner energy sources as opposed to coal-derived energy. However, the environmental benefits of power production from bagasse must be verified using a systematic scientific methodology. This study develops the life cycle inventories for bagasse power production in South Africa. The life cycle inventory can help to evaluate the environmental impacts of the cogeneration throughout the life cycle. The data for this inventory stage of the research was supplied by the sugar industry, and the analysis mostly uses South African data in the inventory stage. The study presents life cycle inventories based on a functional unit of 1 GWh of bagasse-derived electricity produced in the South African sugar industry. A comparison of the current generating output with a proposed higher output shows that more energy can be produced in addition to reduced inventory levels and this has the potential to improve environmental performance of bagasse power generation in South Africa.

1. Introduction

In South Africa, coal accounts for more than 90% of electricity production. Large amounts of coal deposits coupled with lower coal prices over the years made it favourable to produce electricity using coal. As of 2010, the coal-fired plants consumed 123 million tonnes of coal per annum to supply the bulk of South Africa's electricity (Eskom Holdings Limited, 2011). The electricity generation processes result in about 225 Mt of carbon dioxide being emitted into the atmosphere per annum (Eskom Holdings Limited, 2011). The government has set up a target of 10,000 GWh renewable energy contribution to final electrical energy consumption by 2013 (Department of Minerals and Energy South Africa, 2003). The renewable energy is to be mainly generated from biomass, wind, solar and small scale hydro power. This target is approximately 4% (1667 MW) of the estimated electricity demand (41,539 MW) by 2013 (Department of Minerals and Energy South Africa, 2003). It is in this context of increased focus on renewable energy sources like biomass that this study seeks to determine the environmental life cycle inventories and benefits of generating electricity from bagasse in South Africa.

The use of bagasse for electricity generation is important in South Africa because it presents an energy security solution whilst contributing to reduction of greenhouse gas (GHG) emissions from power generation. It also contributes to economic development and poverty reduction in the rural communities in which most of the sugar factories are based (Elder et al., 2008). The South African sugar industry is one of the most important producers of sugar, producing an average of 2.5 million tonnes (t) of sugar per annum. It is an industry that combines the agricultural activities of growing sugar cane with the industrial factory production of raw and refined sugar. The sugar cane is supplied to 14 mills where it is processed to sugar; bagasse and molasses are also produced as co-products in the process. Bagasse is the fibrous biomass remaining after sugar cane stalks are crushed to extract the juice (Tongaat Hulett, 2011). Sugar industry sources indicate that every 100 t of

---

* Corresponding author. Tel.: +27 (0) 11 559 1202; fax: +27 (0) 11 559 1347.
E-mail addresses: lmashoko@csir.co.za (L. Mashoko), cmbohwa@uj.ac.za (C. Mbohwa), vthomas@isye.gatech.edu (V.M. Thomas).

0959-6526/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2012.08.034

sugar cane harvested and milled produces 10 t of sugar and 28 to 30 t of bagasse (Tongaat Hulett, 2011; Department of Minerals and Energy South Africa, 2004). This waste product can be used to produce significant quantities of electricity. Most of the sugar cane mills in South Africa are undertaking cogeneration of steam and electricity from bagasse mainly for their own consumption.

2. Methodology

The research is performed based on a methodological framework based on ISO (International Organization for Standardisation) standard 14044 in which a life cycle assessment (LCA) is divided into four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. In this study a proposed future case scenario is assessed and the focus is on inventory analysis. The case was derived from projections in a study by the Department of Minerals and Energy South Africa (2003). The scenario is assessed and inventory results are compared to conventional electricity produced from coal in South Africa. It should be noted that the future case was not considered in greater technical detail but the study assumed that the power output from one tonne of sugar cane can be increased from the current 35 kWh to 150 kWh using conventional steam plants running at higher pressures (Department of Minerals and Energy South Africa, 2003, 2004). This scenario is modelled because in the current state, the sugar mills are not exporting electricity to the national grid. The results of the study are also compared to similar studies done in other countries, which are consistent with the power output used in this study of 150 kWh per t cane crushed (Department of Minerals and Energy South Africa, 2003; Ramjeawon, 2004).

2.1. *The goal*

The goals of this study are:

- To determine the contribution of different processes to the whole life cycle of producing electricity from sugar cane bagasse in South Africa
- To compare the environmental life cycle inventory of bagasse-derived electricity in South Africa to bagasse electricity from other countries and to conventional electricity produced from coal in South Africa
- To identify the opportunities for improving the environmental performance of the system based on the life cycle inventory results

2.2. *Target group*

The results of this study are meant to be communicated to energy policy makers in government, decision makers in the South African sugar industry and to other LCA practitioners.

2.3. *The functional unit*

The functional unit for this study is 1 GWh of bagasse-derived electricity produced in the South African sugar industry.

2.4. *The scope*

A future scenario was modelled for this study that produces electricity from bagasse at a power output of 150 kWh per t. The different stages of the life cycle considered are shown in the flow chart in Fig. 1. The subsystems encompassed by the dotted line are the ones included in this system boundary.

The processes involved in the study include the growing and harvesting of sugar cane in South Africa. The following are the subsystems under consideration in the determination of the life cycle inventory:

- ■ Cane cultivation and harvesting – Most of the cane is produced in the Kwa Zulu Natal province of South Africa. Only 20% of the cane is under irrigation so most of the cane areas rely on rainfall for moisture (Pillay, 2004). Fertilizers and herbicides are applied to the sugar cane and the quantities vary from one area to the other depending on soil type and rainfall amounts.
- ■ Cane transportation to sugar mills is by both road and rail. About 6% of the cane is transported by rail and the remaining 94% is transported by road.
- ■ Fertilizer and herbicide manufacturing. The energy and other impacts of fertilizer and herbicide manufacture are included.
- ■ Sugar milling and electricity generation. There are 14 mills under consideration and on average the cane throughput at each mill is 300 t/h or 1.5 million t of cane per annum over an eight to nine month crushing season during which time the mills operate continuously (Department of Minerals and Energy South Africa, 2003).
- ■ The system boundary ends at the production of raw sugar and electricity at the factory gate.

The following subsystems are excluded from the study:

- The production, maintenance and decommissioning of capital goods such as buildings and machinery.
- The production of cuttings used in the establishment of the sugar cane plantations.
- The distribution and transmission of generated electricity.
- The road and rail transportation infrastructure.
- The transportation of sugar to consumers and storage.

3. Methodology

3.1. *Data collection*

Data for the processes were obtained from the sugar plantations in Kwa Zulu Natal in South Africa. Part of the data with regard to manufacture of fertilizers and herbicides were obtained from literature since they are imported. Efforts were made to model the system in such a way that it represents as much as possible current agricultural practices and manufacturing technology used in South Africa. The sugar mills, the Sugar Milling Research Institute (SMRI) and the South African Sugar Association (SASA) also contributed to the data. Part of the information was obtained from documents authored from the Department of Minerals and Energy in South Africa. Data were also obtained from literature and databases such as the Eco-invent database in SimaPro, and were compared to other assessments carried out in other countries. The analysis was checked using mass and energy balances. Peer review was also used to check uncertainty in data collection. Table 1 shows the data and assumptions used in the LCA.

3.2. *Fossil energy consumption*

Farming energy data include energy use for sugar cane harvesting. Data used are a combination of mechanical and manual harvest (Ramjeawon, 2008). Energy required for producing farming machinery was excluded from the system boundary. Fossil fuel energy required for farming was calculated at 44 MJ/t of cane

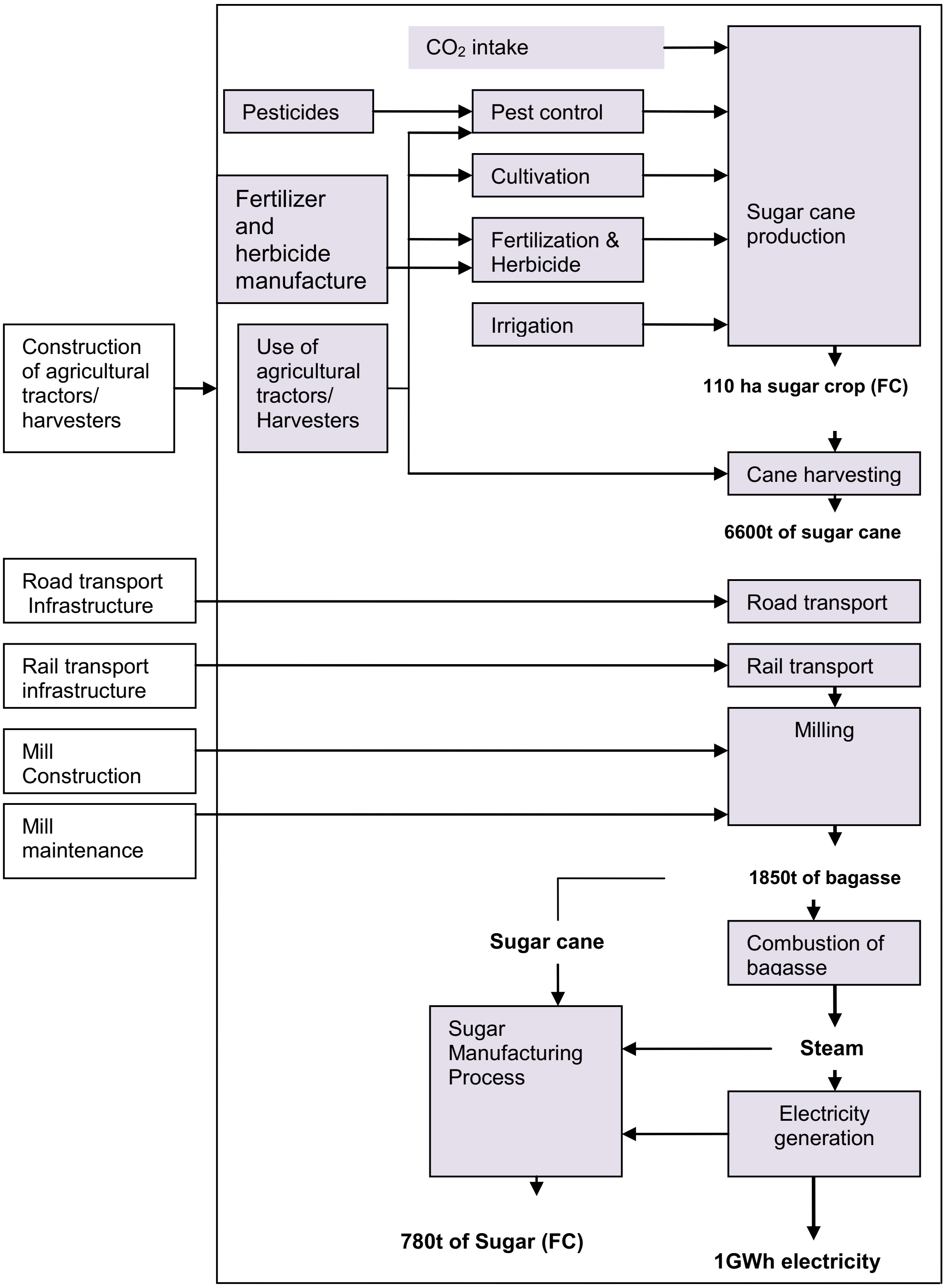

Fig. 1. System Boundary: The subsystems considered are shown inside the border line. (Adapted from: Ramjeawon, 2008; Renouf et al., 2010).

crushed. The amount of fossil energy consumed during farming to produce 1 GWh is about 48,000 MJ.

Fossil fuel energy for transportation was considered taking into account both road and rail transportation. Average data shows that about 6% of the cane is transported by rail and 94% by road. The energy consumption for rail in South Africa was assumed to be 0.68 MJ/tkm (City of Cape Town, 2005). The fuel consumption for a truck was considered to be 0.075 l per t km and the energy content for diesel was taken as 37 MJ L^{-1} based on calculations of the energy content of diesel. The fossil energy for transportation in the base case was calculated to be 112,000 MJ.

During sugar manufacture coal is used to start up boilers and to supplement bagasse supplies during off season. The coal consumed is multiplied by the net calorific value of coal (NCV). Sugar industry data show that about on average 8.37 kg of coal are required during the processing of a tonne of sugar cane. Therefore, 54.1 t of coal is required to produce 1 GWh of electricity in the sugar industry.

Table 1
Data and assumptions for sugar production.

	Value/assumptions	References
1. Sugar cane agriculture		
Cultivation area	400000 ha	(Department of Minerals and Energy South Africa, 2004)
Average cane harvest per hectare	60 t (6 t of sugar)	(Department of Minerals and Energy South Africa, 2004)
Irrigation water requirements/ha	8,000 m^3	(Nieuwoudt et al., 2005; Slabbert, 2012)
Electricity consumption /ha for irrigation	108 kWh	(Nieuwoudt et al., 2005; Slabbert, 2012; Ramjeawon, 2004 and own calculations)
N_2O emissions from soil	1.25% of nitrogen input	(Intergovernmental Panel on Climate Change, 2006)
NO_x emissions from soil	0.5% of nitrogen input	(Ramjeawon, 2004)
Fertilizer application/ha	120 kg N, 30 kg P_2O_5 and 125 kg K_2O	[South African sugar industry data]
Herbicides use	26.9 g/t of sugar cane	(Wang et al., 2008)
Pesticide use	2.21 g/t sugar cane	(Wang et al., 2008)
2. Cane burning		
Cane area burnt before harvesting	90%–360,000 ha 280 kg of leaves and tops burnt/ hectare	(Department of Minerals and Energy South Africa, 2004)
3. Inorganic fertilizer and herbicides		
Energy required for herbicide production per kg	120 MJ	(Ramjeawon, 2008)
Fuel input to produce herbicide/kg	15% diesel, 70% coal and 15% electricity	(Ramjeawon, 2004)
Energy required to produce N, P, K fertilizers/kg	50 MJ, 14 MJ, and 8 MJ respectively	(Wang, 2011)
Fuel input in production of fertilizers	Electricity, coal, diesel	(Wang et al., 2008)
4. Transportation cane		
Transportation by road average distance	90 km	[Sugar industry data]
Transportation by rail average distance	50 km	[Sugar industry data]
Diesel consumption litres/t km	0.075 l Diesel (37 MJ L^{-1})	(City of Cape Town, 2005)
Fertilizers and herbicides transport distance	60 km	[Sugar industry data]
5. Sugar processing and electricity generation		
Sugar produced/ha under cultivation	6.0 t	[Sugar industry data]
Bagasse produced	27.8% of cane	[Sugar industry data]
Molasses produced/ha	4.1% of cane	[Sugar industry data]
Filter cake produced/ha (used as fertilizer)	6.8% of cane	[Sugar industry data]
Steam consumed/t of cane	520 kg	[Sugar industry data]
Electricity consumption/t of cane	35 kWh	[Sugar industry data]
Coal consumption/t of cane	8.4 kg	[Sugar industry data]

3.3. *Co-product allocation*

Co-product allocation was done based on the economic value of sugar and electricity generated (Renouf et al., 2011). South African Sugar Industries have not yet gone to the level of electricity generation for export to the national grid. However the industry is now operating in such a way as to optimise its operations in order to generate more power and also save on the consumption of coal. Here we allocate on the basis of current and estimated economic value of the products.

ISO 14044 (2006) suggests system expansion as a preferred method, which in this case would involve expansion of the system to include electricity generation, primarily from coal in South Africa. Calculation with a systems expansion approach would result in a calculation in which bagasse-derived electricity displaces grid-derived electricity. However, here we allocate by economic value, in order to evaluate the direct environmental impact of the bagasse-derived electricity. As shown in Table 2, the electricity value is calculated on the basis of the 27.9 t bagasse per t cane, which produces 150 kWh of electricity. Electricity is valued at R1/kWh (US$0.143 per kWh), so that production of 150 kWh is valued at R150. The allocation of the proportion of bagasse to electricity is based on the material requirement for electricity production. No allocation is made to cane trash (the field residue remaining after cane harvesting) or water, which comprises 37.6% and 19.5% of the mass proportion of the sugar cane crop, respectively. On this basis 18% of the environmental impacts for cane production, harvesting, transportation and milling are allocated to electricity generation from bagasse.

Table 2
Calculation of allocation factors.

	Proportion of sugar cane crop	Economic value *R*/tonne	Value based on proportion of cane crop	% of crop value
Sugar	10.9	6000	R654	79.8
Molasses	4.1	400	R16	2
Electricity	27.9		R150	18.2

One ton of sugar can produce about 300 kg bagasse. This has a specific energy of 7620 kJ kg^{-1}, giving out 639 kWh of thermal energy (Mbohwa, 2009). The target technology results in 150 kWh of power being produced per ton of cane at about 23.5% efficiency.

4. Life cycle inventory results

4.1. *Resource consumption and emissions*

Energy consumption data were compiled for the following stages: cane farming, transportation, cane burning, fertilizer and herbicide manufacture and sugar manufacture. Sugar manufacture includes both the generation of electricity and production of sugar at the factories. All the calculations were done taking into consideration the allocation results presented before.

4.1.1. *Fossil energy inventory calculations*

The NCV of South African coal is 19.739 MJ kg^{-1} (Jeffrey, 2004) Total energy from coal required to produce 1 GWh of electricity is then calculated as 177,000 MJ.

Table 3
Calculation of energy required for fertilizer and herbicide production.

Input type	Application rate (kg/ha)	No. of hectares	Total amount/GWh (kg)	Energy consumption for production (MJ/kg)	Total energy required (MJ)
Nitrogen (N_2)	120	110	12000	50	660,000
Phosphorous (P_2O_5)	30	110	3000	14	46,000
Potassium	125	110	12500	8	110,000
Herbicide	1.6	110	160	120	21,000
Total					837,000

Fossil fuel energy for fertilizer and herbicide use was calculated taking into account the fertilizer and herbicides and application rates employed in South Africa. It was assumed that all the energy used to produce fertilizers and herbicides in South Africa is fossil fuel. Application rates and energy consumption rates for the three kinds of fertilizers mainly used in the production of sugar cane shown in Table 1 were used. One hectare of land produces an average of 60 tonnes of cane in South Africa resulting in 110 ha of land being required to produce 1 GWh of electricity. Table 3 presents a summary of the calculation used to derive the amount of energy consumed for fertilizer and herbicide production.

The fossil energy for herbicide and fertilizer manufacture that is allocated to electricity production is derived by multiplying the total energy by the allocation factor for electricity which, from Table 2 for allocation based on economic value, is 0.182. Therefore about, 147,000 MJ of fossil energy are required during fertilizer manufacture whilst 3800 MJ are also required for production of herbicides.

4.1.2. *Total fossil energy consumption*

The total fossil fuel use per GWh produced is calculated taking into consideration all the fossil energy consumed for the processes of transportation, farming, electricity generation, sugar manufacture as well as fertilizer and herbicide production. The total fossil energy required to produce 1 GWh of power is approximately 487,000 MJ. Fig. 2 presents a summary of the fossil energy consumption and the functional unit is 1 GWh of electricity produced from bagasse; the allocation of energy to electricity, sugar, and molasses production is shown in Table 4.

The graph shows that the manufacturing process is the greatest contributor to non-renewable energy consumption (37.5%). This is because of the use of coal to supplement the bagasse that is used for firing the boilers at the sugar mills in order to produce process steam and electricity. Fertilizer production is also a significant contributor to non-renewable energy consumption (28.6%). The third largest contributor is transportation with the diesel fuel used to truck most of the sugar cane (94%) being responsible for this impact. Farming and herbicide manufacture are the least contributors in that order.

4.1.3. *Net Energy Ratio*

The Net Energy Ratio (NER) for the proposed output of 150 kWh per tonne of cane is 7.63. NER is the ratio of the electric energy delivered to utility grid to the fossil energy consumed within the system. This shows that increasing the output per tonne to the future case will significantly increase the net energy ratio of producing electricity from sugar cane bagasse. The net energy ratio for electricity produced in Mauritius is about 13 (Ramjeawon, 2004) which is still higher than the one for South Africa. The probable reasons include the fact that South Africa is generally a high energy intensity country with most of its energy being derived from coal. The other reason is that in South Africa the average distance over which sugar cane is transported in order to get to the mills is significantly high at 37 km compared to an average of 7 km in Mauritius. This high road transport distance will always put pressure on the sugar industry in South Africa in terms of fossil energy consumption and greenhouse gas emissions. The average coal power plant has a net energy ratio of 0.29 (Spath and Mann, 2002). This shows that there is more to be derived from cogeneration of heat and steam in the sugar industry. The ratio for Queensland coal electricity is 0.273 and on average the ratio is 0.4 for natural gas electricity (Renouf et al., 2011).

Table 4
Energy consumption based on economic allocation for production of 1 GWh of electricity from bagasse (MJ).

Lifecycle state	Electricity	Sugar	Molasses
Farming	48,048	210,672	5280
Transportation	112,121	491,608	12,321
Sugar mill (manufacturing)	176,751	774,985	19,423
Fertilizer production	147,000	651,000	16,000
Herbicide production	3800	17,000	426
Total	487,000	2,146,000	55,600

This shows that electricity from bagasse performs much better as compared to electricity from coal in terms of net energy gain and greenhouse gas emissions.

4.2. *Emissions to air*

Emissions to air of N_2O, CO_2, methane (CH_4), sulphur dioxide (SO_2) and nitrogen oxides (NO_x) for 1 GWh of bagasse-produced-electricity, were calculated by summing up the emissions at each stage of the life cycle for all the parameters that were under study. Emissions were again compiled for all the stages under consideration: cane farming, cane burning, cane transportation, fertilizer and herbicide manufacture and sugar manufacture. Emissions for sugar cane burning were calculated with the assumption of a yield of 280 kg of tops and dry leaves at 50% moisture per metric tonne of cane harvested (Wang et al., 2008).

4.2.1. *N_2O emissions*

For the purpose of compiling the N_2O emissions in the whole life cycle, N_2O emissions were summed up for emissions from soil, N_2O

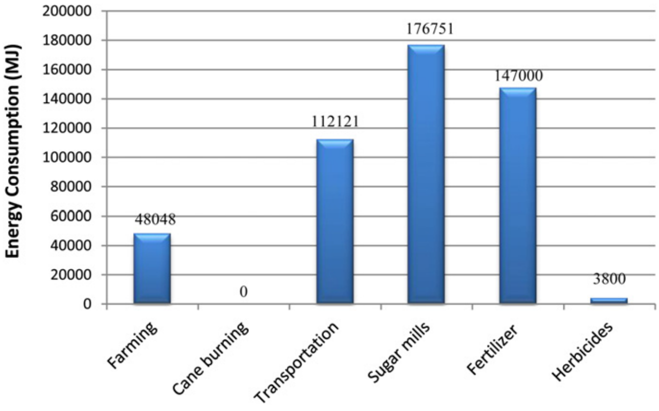

Fig. 2. Lifecycle fossil energy consumption for production of 1 GWh of electricity from bagasse.

emissions from cane burning and N_2O from bagasse combustion. The N_2O emissions from soil were calculated using an N_2O emission factor from the soil of 1.25% of the applied nitrogen (Intergovernmental Panel on Climate Change, 2006). N_2O emissions from cane burning and bagasse combustion were calculated using assumptions from Wang et al. (2008). The total N_2O emission to air for the generation of 1 GWh was found to be about 57 kg.

4.2.2. Carbon dioxide (fossil) emissions

Carbon dioxide (fossil) emissions to air were also summed up for all the stages that have a significant contribution to this parameter. The CO_2 emissions from fossil fuel combustion during farming operations, sugar cane transportation and combustion of coal during sugar manufacture were considered. The CO_2 emission from cane burning was excluded because it was assumed the sugar cane releases the CO_2 that it absorbed during photosynthesis. For farming and cane transportation the carbon dioxide produced was calculated using carbon content data obtained from Environmental Protection Agency (EPA) (United States Environmental Protection Agency, 2005). Diesel carbon content per litre is 0.734 g (United States Environmental Protection Agency, 2005). Calculations then show that the CO_2 emission per litre of diesel is 2.7 kg per litre of diesel burnt, based on the assumption that 99% of the carbon is oxidised and only 1% remains un-oxidised. For petroleum and petroleum products the oxidation factor used is also 0.99 (Spath and Mann, 2002). CO_2 emissions from cane farming, transportation and sugar manufacturing are 638 kg, 1500 kg and 28400 kg respectively. During sugar manufacture and electricity generation most of the carbon dioxide produced is from coal combustion for sugar processes steam and electricity generation. CO_2 (fossil) from coal was calculated using a carbon content of 80% because coal from South Africa is mainly anthracite. CO_2 emissions from cane farming, transportation and sugar manufacturing are 638 kg, 1500 kg and 28400 kg respectively. The total carbon dioxide emitted for the generation of one GWh is therefore 30,500 kg Table 5, shows the emission calculation results for nitrous oxide and carbon dioxide.

Most of the carbon dioxide emissions (93%) emanate from the burning of coal for electricity and process steam. Transportation has a contribution of 4.9% due to the high volumes of sugar cane moved by road and also the long distances travelled by the trucks. Use of fossil fuel to power farming machinery also results in significant carbon dioxide emissions.

4.2.3. Methane emissions

Methane emissions were calculated using the following information: 2.7 g of methane produced per kg leaves and trash burnt according to the IPCC guidelines 2006 (Intergovernmental Panel on Climate Change, 2006). An average emission factor of 30 g/1000 MJ of bagasse burnt were used for methane emission from bagasse combustion (Wang et al., 2008). The total methane emission to air for the whole life cycle per GWh of electricity is 891 kg.

Therefore, the total carbon dioxide equivalent emission is 66,900 kg, including nitrous oxide, methane and carbon dioxide.

Table 5
Nitrous oxide and carbon dioxide inventory for production of 1 GWh of electricity from bagasse.

Emission	Amount (kg)		
	Electricity	Sugar	Molasses
Nitrous Oxide (N_2O)	57	251	6
Carbon dioxide (farming)	638	2798	70
Carbon dioxide (transportation)	1489	6528	164
Carbon dioxide (manufacturing)	28,393	1,24,494	3120

4.2.4. Sulphur dioxide emissions

SO_2 emissions in the sugar life cycle emanate from the cane farming, cane burning, cane transportation and from the combustion of coal to produce steam for sugar processing. The SO_2 from cane farming was calculated considering the quantity of diesel consumed and the sulphur content of the diesel fuel. SO_2 emissions from cane farming were calculated considering the diesel sulphur content of 0.3% (De Vaal, 2004), resulting in an emissions of about 1 kg of SO_2 for every GWh of electricity produced. Using an emission factor of 0.4 g kg^{-1} of dry leaves burnt (Wang et al., 2008); the burning of sugar cane to allow for harvesting emits about 122 kg of SO_2 into the atmosphere for every GWh of power produced. SO_2 produced during transportation was calculated taking into account the amount of diesel consumed during transportation of sugar cane to mills by both road and rail. The result is 3 kg emitted per GWh of electricity produced. Most of the SO_2 emissions for sugar manufacture are from combustion of coal, with a sulphur content of 1.3% (De Vaal, 2004). With coal consumption for sugar manufacture at 8.37 kg per t sugar cane crushed, the amount of sulphur from coal burning is 233 kg per GWh of electricity produced. Overall, the total SO_2 produced per functional unit is 360 kg. The greatest contributor to sulphur dioxide emission is the burning of coal at the sugar mills for process steam and generation of electricity as illustrated in Fig. 3.

Following closely is sulphur dioxide production from burning of sugar cane fields to allow for harvesting of the sugar cane. Transport and farming are not major contributors.

4.2.5. NO_x emissions

NO_x emissions were also calculated for all the stages of the sugar life cycle. NO_x emissions from cane burning were calculated using an emission factor of 2.5 g kg^{-1} of dry leaves and tops burnt (Department of Minerals and Energy South Africa, 2004). The total NO_x emissions per functional unit amounted to 314 kg.

4.3. Avoided impacts

The use of bagasse in the sugar industry to generate electricity especially at higher efficiencies will result in significant benefits for the energy industry in South Africa. Electricity generation from bagasse will increase the amount of electricity available to consumers in South Africa but will also provide environmental benefits. The results of the life cycle are compared to electricity from coal at the power station stage only. The comparison was done to give insight into the avoided impacts at the power station stage. The generation of 1 GWh of electricity from bagasse will substitute for about 510 t of coal. This corresponds to avoided carbon dioxide emissions of 1496 t per GWh of electricity produced.

5. Discussion of results

In Table 6, the electricity from bagasse from the South African sugar industry is compared with electricity generated from coal in

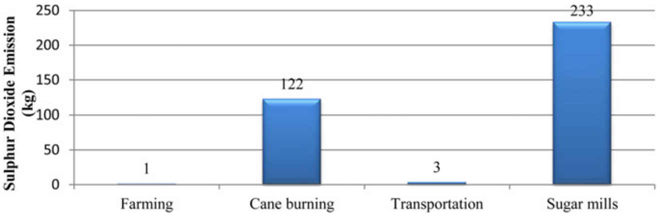

Fig. 3. Sulphur dioxide emissions from production of 1 GWh of bagasse-produced electricity.

Table 6
Comparison of 1 GWh of bagasse derived electricity with coal-derived electricity.

Parameter	Electricity from bagasse (this study)	Electricity from coal in South Africa (Jeffrey, 2004)	Bagasse electricity Mauritius (Ramjeawon, 2008)
Greenhouse gas (CO_2 eq) kg	67,000	980,000	35,600
Energy ratio	7.63	0.35[a]	13
Non renewable energy input (MJ)	472,000	11,000,000[a]	261,000
Sulphur dioxide (kg)	495	8100[a]	31.8
Nitrogen dioxide (kg)	314	4100[a]	137

[a] These values are for the power station stage only.

South Africa. The results of the life cycle inventory are also compared with the results of an LCA of bagasse electricity in Mauritius (Ramjeawon, 2008).

As expected, the net energy gain for bagasse electricity per GWh is considerably better than that for electricity produced from coal. The table shows that the sugar industry in Mauritius performs better than their South African counterpart on most of the parameters that were examined. The assessment shows that South Africa uses more fossil energy to generate 1 GWh of bagasse electricity as compared to Mauritius. Electricity from coal performs badly in most of the environmental parameters shown in Table 6.

The comparison between coal-derived electricity and co-generated electricity from the sugar industry shows that there are significant environmental benefits of cogeneration especially at higher efficiencies. The South African sugar industry can increase the power produced per tonne of cane crushed from the current 35 kWh/tonne up to 150 kWh by operating their boilers at higher pressures. According to the DME this can be achieved at relatively low capital injection (Department of Minerals and Energy South Africa, 2003). The current low power output per tonne of cane may have been a result of low electricity prices, resulting in the industry producing only for their own use and smaller communities around them. Commercial co-generation for grid export could lead to better environmental performance because the same amount of bagasse will be burnt more efficiently. Good energy management and efficiency practices in the sugar mill will also lead to increased electricity export whilst reducing environmental impacts.

There are numerous opportunities for lifecycle improvement. The agricultural stage of the sugar life cycle is worth concentrating on because it has a significant contribution to emissions, as well as to non-renewable energy consumption and water use (Mashoko et al., 2010). Transportation requires a high level of attention when it comes to energy consumption. Use of more fuel efficient vehicles and the optimisation of the sugar supply chain could reduce energy consumption and operational costs. Research into higher cane yields at reduced inorganic fertilizer input could help address the issue of fossil energy consumption. The adoption of high fibre sugar cane varieties earmarked for more energy generation could potentially also increase the power output.

In a study of sugar cane bioenergy systems in Mauritius, Beeharry (2001) has considered an option for composting some of the bagasse to increase cane yields, as well as an option for use of cane tops and leaves as well as cane trash (other cane field residue) in energy production, which showed potential for 276 kWh of electricity per ton of cane, which is approximately 80% higher than the production levels considered here. The study also used a functional unit of 1 ha and did not consider other environmental life cycle inventories other than carbon dioxide emissions.

Botha and von Blotnitz (2006) production of electricity from bagasse with production of ethanol from bagasse in the South African context, and found that ethanol production has greater benefits in terms of reduced petroleum use, since ethanol can substitute for petroleum products, while electricity production has greater benefits for fossil fuel and greenhouse gas emissions reduction. The functional unit used for the study is 1 ha of sugar cane. The study assumed that of the initial 0.3 t of wet bagasse per ton of cane processed, 0.16 t would remain for further processing, resulting in 106 kWh of exported electricity per ton of cane processed. In our study, we assumed that all bagasse is used for power generation and the export levels were based on our calculations resulting in different power export levels.

6. Recommendations

The production of 1 GWh of electricity in South Africa requires 110 ha of land at an average sugar cane harvest per hectare of 60 t. Approximately 472,000 MJ of non renewable energy is also required to generate 1 GWh of electricity in South Africa and in the process emitting 67000 kg CO_2 eq of green-house gases. The amount of avoided CO_2 emissions is very high when the results are compared to electricity produced from coal in South Africa. The results show that most of the environmental emissions are produced during the burning of coal at the sugar mills. The generation of electricity at the mills account for most of the GHG gas emissions and sulphur dioxide emissions. The process of transporting harvested sugar cane to the sugar factories is the second most significant contributor to non carbon dioxide emissions. Although the emissions are much lower than for electricity produced from coal, these values are high as compared to the energy consumption and GHG emissions from bagasse-generated electricity in Mauritius.

Most of the non-renewable energy is consumed during the production of sugar and electricity at the sugar mills. This is mainly due to the fact that there is more use of coal when bagasse is off season. However a number of energy management practices can be implemented in order to increase the efficiency of electricity generation. Some of the ways to increase the efficiency is to improve the efficiency of the equipment used to manufacture sugar so that they reduce their steam consumption thereby freeing more steam for electricity generation purposes. Some of the interventions that can be implemented include the following:

- Making use of electric DC motors as the prime movers for sugar cane milling instead of steam driven mill drives. Conventionally, steam turbines are used as the prime movers for the mills in the sugar industry in South Africa. These steam turbines are typically 25–30% efficiency whilst the DC power turbines can operate at efficiencies of about 65–70% (Peacock and Cole, 2009).
- Modifying of crystallization pans used for crystallisation in the sugar making process. This is one of the major areas of steam consumption in the sugar mills. Using low grade “recycled steam” from elsewhere in the plant instead of exhaust steam from power generating turbines enables more electricity to be produced for export to the grid (Peacock and Cole, 2009).

According to the analysis developed here, the fertilizer used in the growing of sugar cane contributes significantly to non-renewable energy consumption and greenhouse gas emissions. Renouf et al. (2010), in the Australian context, has also found that use of fertilizer in sugar cane production has substantial impacts. There could be considerable benefit if the use of inorganic fertilizers could be reduced without affecting the harvest rate per hectare of sugar cane crop. One way this has been done is through the use of filter cake as a fertilizer (Gopalasundaram et al., 2012). Filter cake, or press mud is a bi-product of sugar milling. The challenge with filter cake is its transportation from the mill to the sugar cane fields because filter cake is normally wet therefore heavier which in turn increases transport costs and greenhouse emissions during transportation over long distances. Therefore filter cake application can work for cane fields closer to the sugar mills and as the distance increases the benefits of its use can be outweighed by increased transportation costs and emissions.

There is need to find ways of reducing the amount of water used for irrigation purposes so as to reduce the overall water consumed in the life cycle of sugar production. This is further necessitated by the fact that South Africa is a water-scarce country (DBSA, 2009).

Transportation of sugar cane to the sugar mills is an integral part of the sugar industry supply chain. Inefficient transport processes result in poor quality of sugar if cut sugar cane is not delivered to the mills on time and at the right level of quality. It is necessary to ensure the efficiency of this process in order to reduce costs and its effects on the environment. Currently, only 6% of sugar cane is transported to the sugar mills by rail whilst the rest is transported by road resulting in higher energy consumption and more greenhouse gas emissions. It is recommended that as much sugar cane as is possible be moved to rail. However challenges exist in some areas due to the terrain in some areas which does not allow for use of rail. The availability of reliable rail infrastructure in South Africa is either insufficient or if available it is very inefficient. These shortcomings need to be addressed if a significant amount of sugar cane is to be moved from road to rail.

7. Conclusion

Most of the environmental impacts of bagasse-derived electricity result from the generation of electricity because of higher coal consumption used for co-firing in South African sugar plants. Cane farming is also a significant contributor to these impacts especially from energy consumed for fertilizer production. The move towards more cogeneration activities in the sugar industry will help the government in achieving its set target for renewable energy sources (Department of Minerals and Energy South Africa, 2003). An important issue is the issue of pricing of generated electricity and funding for these co-generation projects. The government could help the industry by providing tax cuts for these projects, offering higher electricity tariffs for independent power producers and opportunities for funding under the CDM mechanism should also be explored. This study shows that the adoption of electricity cogeneration in the sugar industry can improve energy security and reduce environmental impacts. Sugar industries can contribute positively towards climate change mitigation by the adoption of efficient electricity generation from bagasse.

Acknowledgements

The authors would like to thank the National Research Foundation (NRF) in South Africa, the University Of Johannesburg Faculty Of Management Research Committee and the University of Johannesburg Research Committee for their support of the project, and the Sugar Milling Research Institute (SMRI) and the Sugar Industry in South Africa for data and helpful comments.

References

Beeharry, R.P., 2001. Carbon balance of sugarcane bioenergy systems. Biomass and Bioenergy 20, 361–370.

Botha, T., von Blotnitz, H., 2006. A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life-cycle basis. Energy Policy 34 (17), 2654–2661.

City of Cape Town, 2005. Cape Town Energy and Climate Change Strategy, City of Cape Town, Environmental Planning Department.

Development Bank of Southern Africa, DBSA, 2009. Water Security in South Africa. Development Planning Division Working Paper Series No. 12.

De Vaal P., 2004. Diesel and Its Properties, Department of Chemical Engineering, University of Pretoria.

Department of Minerals and Energy South Africa, 2003. White Paper on the Renewable Energy Policy of South Africa, http://unfccc.int/files/meetings/seminar/application/pdf/sem_sup1_south_africa.pdf, (accessed 6.09.11.).

Department of Minerals and Energy South Africa, 2004. Assessment of Commercially Sustainable Biomass Resources: Bagasse, Wood and Sawmill Waste and Pulp in South Africa.

Elder, M., Prabhakar, S., Romero, J., Matsumoto, N., 2008. Prospects and Challenges of Biofuels in Asia: Policy Implications. Chapter 5 in Climate Change Policies in the Asia-Pacific: Re-Uniting Climate Change and Sustainable Development. pp. 105–131, Institute of Global Environmental Strategies.

Eskom Holdings Limited, 2011, Annual Report 2010. http://www.eskom.co.za (accessed 6.9.11).

Gopalasundaram, P., Bhaskaran, A., Rakkiyappan, P., 2012. Integrated nutrient management in sugarcane. Sugar Tech. 14 (1), 3–20.

Intergovernmental Panel on Climate Change, 2006. 2006 IPCC Guidelines for National Green House Inventories, vol. 4: Agriculture and Forestry, and Other Land Use. Hayama, Japan.

Jeffrey L. S., 2004. Characterization of the Coal Reserves of South Africa, CSIR Division of Mining Technology.

Mashoko, L., Mbohwa, C., Thomas, V.M., 2010. Lifecycle assessment of the South African sugar industry. J. Environ. Plan. Manage. 53 (6), 793–807. http://dx.doi.org/10.1080/09640568.2010.488120.

Mbohwa, C., 2009. The energy and environmental impacts of a coal and bagasse-fired power plant in the sugar industry. Proc. S. Afr. Sug. Technol. Ass. 82, 214–224.

Nieuwoudt, W.L., Gillitt, C.G., Backeberg, G.R., 2005. Water marketing in the Crocodile River, South Africa. Agrekon 44 (3), 383–401.

Peacock, S.D., Cole, M.A., 2009. Optimising imbibition in a sugar mill with cogeneration. Proc. S. Afr. Sug. Technol. Assoc. 82, 331–341.

Pillay V., 2004. Introduction to Sugar Technology. Sugar Milling Research Institute, South Africa.

Ramjeawon, T., 2004. Life cycle assessment of cane sugar on the Island of Mauritius. The Int. J. Life Cycle Assess. 9 (4), 254–260.

Ramjeawon, T., 2008. Life cycle assessment of electricity generation from bagasse in Mauritius. J. Clean. Prod. 16, 1727–1734.

Renouf, M.A., Pagan, R.J., Wegener, M.K., 2010. Life cycle assessment of Australian sugar cane products with a focus on sugarcane growing. Int. J. Life Cycle Assess. 15 (9), 927–937.

Renouf, M.A., Pagan, R.J., Wegener, M.K., 2011. Life cycle assessment of Australian sugar cane products with a focus on cane processing. Int. J. Life Cycle Assess. 16 (2), 125–137.

Slabbert M. J., 2012. Irrigation System Efficiency: a Practical Angle, Transvaal Suiker Boerdery, Mpumalanga http://www.sasa.org.za/Libraries/SA_Sugarcane_Industry_Agronomists_Association/Irrigation_system_efficiency__A_practical_angle_Martin_Slabbert.sflb.ashx (Last accessed 20.08.12.).

Spath, P.L. and Mann, M.K., 2002. Environmental Aspects of Producing Electricity from a Coal-fired Power Generation System – A Life Cycle Assessment, National Renewable Energy Laboratory, USA.

Tongaat Hulett, 2011. Sugar Manufacture Process, http://www.huletts.co.za, (accessed 6.09.11.).

United States Environmental Protection Agency, 2005. Emission Facts. Average Carbon Dioxide, Emissions Resulting from Gasoline and Diesel Fuel (EPA420-F-05-001).

Wang, M., 2011. GREET 1.8d.1. Argonne National Laboratory, US Department of Energy [online], Available from:: http://www.transportation.anl.gov/modeling_simulation/GREET/, (accessed 6.09.11.)

Wang, M., Wu, May, Huo, H., Liu, J., 2008. Life cycle energy analysis and green house gas emission Implications of Brazilian sugar cane production. Int. Sugar J. 110, 1317.