Multidisciplinary Journal of TUM 4(1) 2025 105-117 **https://doi.org/** 10.48039/mjtum.v4i1.93.g111 **Research Article**

Energy Balances and Greenhouse Gas Emissions of Bagasse-based Electricity Production in Kenya

Fridah Mwanyasi*, Joseph Mbothu, Sameer Kamrudin Bachani, Gideon Kidegho

School of Engineering and Technology, Technical University of Mombasa, P.O. Box 90420 Mombasa, 80100 – Kenya

Corresponding aiuthor's email: fridah.mwanyasi@gmail.com

Abstract

Biofuels have been advocated in many nations to solve environmental issues, energy security, and the socio-economic well-being of rural residents. This study assessed energy consumption, energy balances, and lifetime net greenhouse gas emissions in Kenya's bagasse-based electricity generating chain. Production of electricity from bagasse involves the cultivation of sugarcane, milling the cane, and cogeneration. By conducting a Life Cycle Assessment, the study used the economic allocation model to partition energy inputs and their respective greenhouse gas emissions. The life cycle greenhouse gas emissions were estimated to be 24.53 $kgCO_{2eq}$/MWh of electricity generated, while the total energy consumption from both renewable and non-renewable energy sources inputs was evaluated as 181.26 MJ/MWh. The information from the energy balances computed per MWh of electricity revealed a net energy value (NEV) of 9,349 MJ, a net renewable energy value (NREV) of 9,387 MJ and a net energy ratio (NER) of 84. The high positive values of NREV and NER are indicators that minimal amount of fossil fuel is required to produce 1 MWh of electricity. Bagasse-based cogeneration offers great promise for application in electricity production in Kenya, as can be deduced from the results presented here.

Key Words: Energy balances, Life cycle assessment, Sugarcane bagasse, Greenhouse gases, Kenya

Introduction

Renewable technology and research are being driven by the worldwide need for environmentally friendly power sources. Sugarcane bagasse (a fiber used for fuel or paper), a by-product of sugarcane processing, presents a significant opportunity for renewable energy generation. This fibrous residue is abundant in sugarcane-producing regions, offering a readily available and relatively low-cost feedstock for power generation. However, the environmental performance of bagasse-based electricity generation is not uniform and depends on several intertwined factors, including the specific agricultural practices, the efficiency of the electricity generation process, and the overall management of bagasse waste (Ghani et al., 2020). The history of bioenergy in Kenya's sugar industry is deeply linked to the development of the sugar sector, which began during the colonial period (Mati & Thomas, 2019). Sugarcane farming was introduced in Kenya in the early 1900s by Indian settlers who initially used the crop for jaggery production. Large-scale sugar processing started with the establishment of Miwani Sugar Mills in 1922, followed by Associated Sugar Mills at Ramisi, south coast Kenya in 1927. After independence, the Government of Kenya expanded the industry by establishing several sugar factories, including Mumias in 1973, Sony Sugar, and Nzoia in 1978, among others (Amukoya et al., 2023).

Sugarcane thrives in warm, sunny climates and is a key agricultural crop in countries like Brazil, India, China and, South Africa. Consequently, its processing into sugar, ethanol (biofuel) and molasses (a syrup used in food and fermentation) generates significant amounts of biomass residue (Ajala et al., 2021). One promising renewable energy source is bagasse, the fibrous by-product of crushing sugarcane stalks to extract juice. South Africa and Brazil, two of the world's leading sugarcane producers, are among the many countries investigating the potential for domestic bioenergy production feedstocks

Published June 2025

derived from sugarcane crop waste (Mokomele et al., 2018). Sugarcane bagasse, left after extracting juice from sugarcane, is the most commonly used biomass component for electrical cogeneration. In this process, bagasse is burned in boilers to produce steam, which in turn generates electricity (Takase et al., 2021).

Structurally, bagasse consists of two main parts: a fibrous outer layer and hygroscopic parenchymatous tissue. Its composition includes sugars, minerals, wax, cellulose, hemicellulose, pentosans, and lignin. The specific properties of bagasse can vary depending on several factors, such as the lignin and hemicellulose content, the type and maturity of the sugarcane, and the methods used during harvesting (Andrade et al., 2017). In sugar mills, the steam and electricity produced from bagasse are critical to operations such as juice treatment and fermentation. These processes typically consume about half of the bagasse generated, making it a key element in the energy self-sufficiency of the sugar industry. However, excess bagasse can pose significant challenges if not effectively utilized. Prolonged storage may lead to issues such as spontaneous combustion and fermentation, posing safety and health risks. In conventional sugar factories, excess bagasse is often disposed of through inefficient combustion in boilers, which not only wastes its energy potential but also contributes to environmental pollution (Kabeyi & Olanrewaju, 2023). To mitigate these issues, exploring alternative applications for surplus bagasse could enhance sustainability. Implementing efficient combustion technologies or adopting closed-loop systems in sugar factories may also optimize bagasse utilization and minimize associated risks. Electricity production from sugarcane-based bagasse consists of three key areas: sugarcane growing, milling, and the cogeneration steps that take place in the boilers. The fundamental processes in sugarcane farming include land preparation, planting, crop management, and harvesting. Human labor is utilized for all farming activities except for land preparation, which is done using machinery. This division of labor contributes to efficiency while maintaining the economic viability of farming practices. Additionally, sugarcane is typically replanted after it has been harvested two to four times, reducing the need for frequent replanting cycles (Wang et al., 2023).

Bagasse (roughly 45 % cellulose, 28 % hemicellulose, 20 % lignin, 5 % sugar, 1 % minerals, and 2 % ash) is put to use in bioenergy production through a variety of methods. One common method is combustion, where the cellulose component of bagasse ($C_6H_{10}O_5$) reacts with oxygen (O_2) to produce carbon dioxide (CO_2), water in the form of steam (H_2O) and the release of energy in the form of heat. The simplified reaction for cellulose combustion is presented in Eq. (1).

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O + \text{Heat Energy} \tag{1}$$

Bagasse has a calorific value (heating value) ranging from 7,500 to 9,500 kJ/kg on a wet basis (including the moisture content of the bagasse). For complete combustion, bagasse requires an air-to-fuel ratio of approximately 3.0 to 4.0 kg of air per kg of bagasse (Kana-Donfack et al., 2024).

Anaerobic digestion is another technique for generating energy from bagasse, relying on the absence of oxygen and the activity of anaerobic bacteria. The process unfolds in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the hydrolysis phase, cellulose in the bagasse reacts with water to produce glucose (Eq. (2)).

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6 \tag{2}$$

In acidogenesis, complex organic molecules are broken down into simpler volatile fatty acids (VFAs) and other byproducts, while in acetogenesis certain anaerobic bacteria convert carbon dioxide (CO_2) and other compounds into acetate (acetic acid). Acetogenesis is a key step in the anaerobic digestion of organic matter, where it follows fermentation and precedes methanogenesis (Lee et al., 2022). Therefore, bagasse hydrolysis (Eq. (2)) forms the basis for further energy conversion. During the final stage of methanogenesis (Eq. (3)), glucose is transformed into carbon dioxide and methane (CH_4) by microbes known as methanogens.

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \tag{3}$$

Published June 2025

The resulting biogas, primarily composed of methane, is a sustainable energy source that reduces reliance on traditional fossil fuels and supports renewable energy solutions.

Previously, the study of Seabra and colleagues conducted a life cycle assessment (LCA) regarding Brazilian cane-derived products to assess their environmental benefits. The main objective of the work was the assessment of life cycle energy use and greenhouse gas (GHG) emissions related to cane sugar and ethanol, considering bagasse and electricity surpluses as coproducts. For the reference case, fossil energy use and GHG emissions related to sugar production were evaluated as 721 kJ/kg and 234 g CO_2eq/kg, respectively. For the ethanol life cycle, these values were 80 kJ/MJ and 21.3 g CO_2eq/MJ (Seabra et al., 2011).

In more recent studies, bioenergy development within the sugar sector has focused on energy cogeneration from bagasse. Mauritius is one of the most advanced countries in the use of waste from sugar processing (bagasse) to simultaneously generate heat and electricity (cogeneration) to feed into the grid, but developments have evolved over several decades with complex dynamics between different actors. Using Mauritius for a case study, a multi-level analysis by Long Seng To and others revealed how policies influenced the development of the bagasse cogeneration niche and changes in the sugar and energy regimes over time. The formation of independent power producers, centralization of sugar mills, the use of a complementary fuel (coal) in the off-crop season, and targeted financial incentives were important for the development of bagasse cogeneration in Mauritius (To et al., 2018).

In Kenya, Mumias Sugar Company led this initiative in the 2000s, using bagasse for electricity generation, which supplied energy to both the factory and the Kenya national grid. This was part of broader efforts to enhance sustainability and reduce reliance on fossil fuels. The cogeneration facility uses a traditional steam power cycle, which involves burning bagasse directly in the boiler to produce steam and thermal energy that is then transferred to a steam turbine. The company utilized LCA, a robust and widely accepted scientific method for evaluating the environmental impact of products and services throughout their entire life cycle (Marabu, 2011). However, it has not been a smooth sailing regarding sugarcane bagasse cogeneration power plants for Mumias Sugar company and other similar factories in Kenya. While it was established that the Mumias sugar factory invested in a 34 MW cogeneration power plant to export 26 MW excess electricity to the national grid, reliance on bagasse alone as the boiler fuel placed the plant at the mercy of the sugar factory operations and availability of cane.

The performance analysis by Olanrewaju and Kabeyi on Mumias sugar company’s sugarcane bagasse cogeneration power plant in grid electricity generation showed that after three years of profitable operation, the cogeneration power plant became unsustainable and export to the grid was stopped. The plant faced challenges like low load factor and capacity factors occasioned by unsustainable milling of cane. This meant irregular bagasse fuel supply to the power plant hence capacity underutilization and availability of the plant which attracted huge penalties from the utility company. It was recommended that policy initiatives to encourage export of electricity from the sugar industry be explored, while development of multi-fuel plants could delink the co-generation from the challenges of sugar cane factory operation (Olanrewaju & Kabeyi, 2022). With the aforementioned revelations from both scholars and industry in hand, biofuel sector stakeholders and policymakers should be better placed to make informed decisions. Ultimately, the aim of this present study was to evaluate the potential of sugarcane bagasse in the production of renewable energy in Kenya.

Methodology

This study assessed Kenya's bagasse-based electricity production's energy balances and GHG emissions, primarily focussing on South Nyanza Sugar Company (SONY sugar). One megawatt-hour (MWh) of electricity produced was the functional unit used in the production of electricity from bagasse. An average yield of 80-ton/ha/year was used as the basis for the analysis. Estimates of GHG emissions, energy balances, and consumption are given for each megawatt-hour of electricity generated. The LCA employed a methodology grounded in the ISO 14040/44 (2006) guidelines (Finkbeiner et al., 2006). Data for this study was collected from Sony Sugar company and this included information on sugarcane farming, milling, and electricity cogeneration. Data registration, emission calculations, energy consumption, and energy balances were all performed in Microsoft Excel spreadsheets. To determine energy consumption and emissions, coefficient factors were utilized. These factors, also known as emission factors, are applied to activity data (like fuel consumption or electricity usage) to estimate the associated emissions. This allows for a standardized way to quantify energy use and its environmental impact (Chen et al., 2022).

Sugarcane Bagasse-Based Electricity System Boundary

The system boundary defines the set of processes that are taken into account in LCA for the product system under analysis (**Figure 1**). Farm input production, sugarcane farming, transportation, milling, steam, and electricity cogeneration are the primary processes. The energy from fossil fuels used by agricultural and manufacturing machinery was not considered, since it is spread out across the equipment's lifetime and hence, the embedded energy has minimal impact on LCA of such a cogeneration plant (Khatiwada et al., 2016).

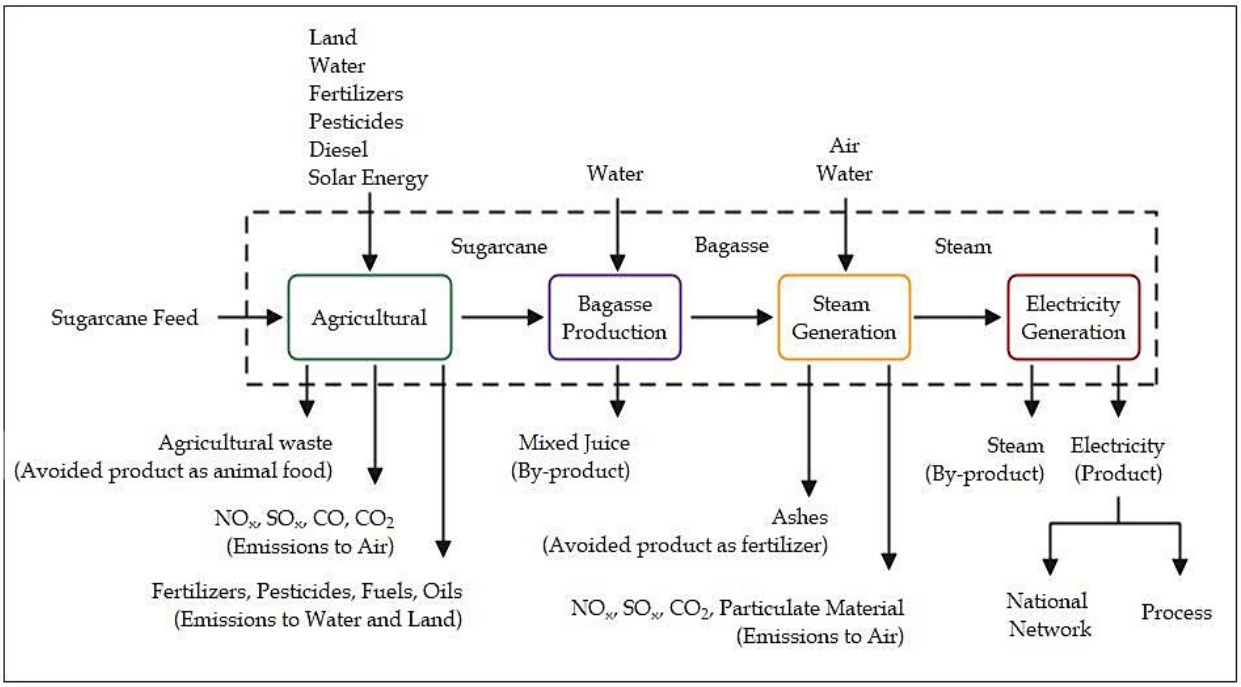

Figure 1. System boundary for sugarcane bagasse-based electricity

As illustrated in Figure 1, the main inputs and outputs of the electricity generation process are bagasse, steam and electricity. The input and output values presented in Table 1 are those that were applied in the calculations of the current study.

Table 1. Data for inputs and outputs during electricity production

Input/Output	Unit	Value
Bagasse	kg/t_{cane}	300
Steam	kg/t_{cane}	500
Electricity	MWh	110

kg/t_{cane}: kg per tonne of cane

MWh: megawatt-hour, the amount of energy produced or consumed by a power source

This present study examined farm inputs such as herbicides, fertilizers, insecticides, and pesticides all of which generate emissions during their production. The production of sugar cane also results in emissions. Emissions due to human labour (EP, $kgCO_{2eq}/ha/yr$) took into account, the amount of substance/ chemical used (M_S, kg/ha/yr), associated Emission factor/ coefficient (EF_S, $kgCO_{2eq}/kg$), and were calculated using Eq. (4).

$$EP = M_S \times EF_S \tag{4}$$

On the other hand, land preparation, planting of cane, crop management, and cane harvesting all include human effort. To determine emissions caused by human activity/ labour (EL, $kgCO_{2eq}/ha/yr$), the number of man-days per hactere (N_{md}, man-days/ha) and the respective emission factor/ coefficient (EF_{md}, $kgCO_{2eq}/kg$) were considered. The EL were computed by Eq. (5).

$$EL = N_{md} \times EF_{md} \tag{5}$$

Emissions from bagasse-based electricity ($kgCO_{2eq}/ha/yr$) accounted for both the amount of fuel consumed (F_C, kg/ha/yr) and the appropriate emission factor (EF_G, $kgCO_{2eq}/kg$). These emission were calculated using Eq. (6).

$$Emmissions = F_C \times EF_G \tag{6}$$

As mentioned in the calculation of EP, EL and *Emissions*, several emission factors that quantify the amount of a pollutant released into the environment per unit of activity are employed. Additionally, these emission coefficients are assigned energy coefficients that relate energy consumption to the emissions produced. The emission factors/ coefficients and energy coefficient values presented in **Table 2** are those that were applied in the calculations of the current study.

Table 2. Emission and energy coefficients for inputs in milling and electricity production

Substance	Emission Coefficient	Energy Coefficient
Lime production	0.7 $kgCO_{2eq}/kg$	0.10 MJ/kg
Bagasse combustion[a]	0.025 $kgCO_{2eq}/kg$	16.80 MJ/kg
Electricity[b]	–	3.60 MJ/kWh
Steam[c]	–	3.12 MJ/kg

– : Data not available

[a](Kummamuru Venkata, 2013), (Khatiwada et al., 2016); [b](Sahu et al., 2015a); [c](Bilha Eshton et al., 2013)

To quantify the GHG emissions associated with human labor, the study adopted an emission coefficient of 5.59 kg CO□-equivalent/man-day (Khatiwada et al., 2016). The corresponding energy equivalent of agricultural human labor was estimated using the Life-Style Support Energy (LSSE) technique, originally proposed by (Odum, 1993) and later applied by (Nguyen et al., 2007). Thailand, like Kenya, is a developing country with limited industrialization. Therefore, the study adopted the estimate of 12.1 MJ/h reported by (Nguyen et al., 2007) for Thailand, as it was considered relevant and comparable to the Kenyan context. In 2020, Kenya's primary energy consumption was mainly derived from fuel sources. To better understand the energy mix, these sources were categorized into two types: fossil fuels and non-fossil fuels. According to the International Energy Agency's Energy Statistics (IEA, 2020), this year's consumption of fossil fuels was 17.2%, while that of renewables was 82.8%.

Sugarcane Farming and Harvesting

Ploughing, harrowing, and furrowing are the tra ditional techniques used in land preparation.
Land preparation also required 12 man-days of effort per hectare.
After 18 months of field planting, sugarcane is h arvested once a year for three ratoons (5-year cycle period).
The management of the ratoons determines their respective yields.
Cane trash is created when cane stalks are cut d uring harvesting to remove the leaves and tips.
To make organic fertilizer, the cane waste is spread out along the root stumps in the fields.
Harvesting cane is a manual process that takes 40 man-days per hectare. Large trucks with a carrying capacity of 27 t per trip or tractors with

Published June 2025

a carrying capacity of 25 t per trip are used to transport sugarcane. Table 3 presents the data gathered from the sugarcane cultivation field.

Table 3. Field data for farm inputs of sugarcane growing and harvesting

Item	Units	Value
Nitrogen fertilizer as N	kg/ha/yr	69
Phosphate fertilizer as P_2O_5	kg/ha/yr	23
Potash fertilizer as K_2O	kg/ha/yr	53.5
Herbicides	L/ha	1.6
Insecticides/ Pesticides	L/ha	0.01
Sugarcane seeds	kg/ha	7000
Sugarcane yield	kg/ha	80000
Cane trash	kg/ha	16000
Human labour	Man-days/ha	64
Diesel used for land tillage	L/ha	45[a]
Diesel used for transportation	L/ha	101.3

[a](B Eshton & Katima, 2012)

The emission and energy coefficients for cane cultivation are as shown in Table 4.

Table 4. Emission and energy coefficients of farm inputs for sugarcane cultivation

Particulars	Emission Coefficient ($kgCO_{2eq}/kg$)	Energy Coefficient (MJ/kg)
Nitrogen (N) production[a]	3.97	56.3
Phosphorous production[a]	1.3	7.5
Potash (K_2O) production[a]	0.71	7.0
Herbicide production[a]	25	355.6
Sugarcane seed production[a]	0.0016	0.02
Insecticide production[b]	29	358
Diesel[c]	–	43.33

[a](Khatiwada et al., 2016), (Kummamuru Venkata, 2013); [b](Macedo et al., 2008); [c](IPCC, 1996), (Institute for Global Environmental Strategies, 2006)

Published June 2025

Inputs and Outputs of Sugarcane Milling

The sugarcane milling process consists of several key steps: cane pretreatment, cane juice extraction using a diffuser, clarifying, boiling, seeding, and crystal sugar extraction by centrifugation. Lime, molasses, power, steam, and chemicals are the main ingredients in milling. Sugar, molasses, bagasse, and filter mud are the by-products of sugar cane processing. The results showed that for every ton of sugarcane that was ground, 33% of it came out as bagasse, 10% as sugar, 4% as filter cake, and 3-4% as molasses. The alcohol sector is assumed to be the primary user of molasses in the basic case. Boilers burned the bagasse to create steam and power, which were utilized throughout the factory. Lime and flocculants are two of the substances used to clarify the water. The milling and electricity production stages' estimated emission amounts were determined using Eq. (7), which considered the quantity of material (A_{mb}), the material related emission factor (EF_{mb}) and the yield of sugarcane (Y_c).

$$Emmissions = A_{mb} \times EF_{mb} \times Y_c \tag{7}$$

The associated data for sugarcanemilling are presented in **Table** 5.

Published June 2025

Table 5. Data for milling inputs

Item	Units	Value
Lime	kg/t_{cane}	1.14
Molasses	kg/t_{cane}	30
Sugar	kg/t_{cane}	100
Phosphoric acid	kg/t_{cane}	0.06
Bagasse	kg/t_{cane}	300
Imbibition water	m^3/t_{cane}	0.382[a]
Filter cake	kg/t_{cane}	40[a]
Electricity	kWh/t_{cane}	10.67[a]
Wastewater	m^3/day	1200
Steam	kg/t_{cane}	500[b]
Juice flocculants	kg/t_{cane}	0.001

[a](B Eshton & Katima, 2012); [b](Ramjeawon, 2008)

Net Energy Balances

When tracking the energy balances of bagassed-based power generation, it is important to consider how much less non-renewable fossil fuel was used across the entire manufacturing chain. The net energy yield ratio (*NER*), net renewable energy value (*NREV*), and net energy value (*NEV*) were utilized to evaluate the energy balances of bagasse-based electricity. The *NER* is a metric that compares the total energy output of a process or resource to the total energy input required to produce it. It essentially indicates whether a process results in a net energy gain or loss, and is crucial for evaluating the efficiency and sustainability of energy production. In the calculation of *NER*, the current study considered the energy content of bagasse (E_B) and the fossil fuel energy input (E_F) of the process (Eq. (8)).

$$NER = \frac{E_B}{E_F} \tag{8}$$

An *NER* larger than 1 means there is a net gain in useable energy whereas an *NER* smaller than one means there is an overall energy loss (Collet et al., 2014).

The net renewable energy value (*NREV*) refers to the total amount of energy generated from renewable sources, minus the energy used to produce and maintain that energy, as well as any energy losses. It represents the net contribution of renewable energy sources to the overall energy supply. Several factors influence this value, including the type of renewable energy source, the efficiency of the generation and distribution infrastructure, and the energy storage capacity (Ritchie et al., 2020). The *NREV* was calculated using the E_B and the fossil fuel input (E_F) as in Eq. (9).

$$NREV = E_B - E_F \tag{9}$$

If *NER* and *NREV* are positive, then less fossil fuel is required to generate the same amount of power per functional unit. Both *NER* and *NREV* give information of how bagasse-based power, when viewed as a replacement for fossil fuels, affects energy security.

The *NEV* refers to the amount of energy remaining for useful purposes after accounting for all losses and energy expenditures associated with obtaining, processing, or utilizing a resource. In the calculation of *NEV*, the current study considered the E_B and the total energy inputs (E_T) of the process (Eq. (10)).

$$NEV = E_B - E_T \tag{10}$$

The net energy value of bioenergy refers to the energy remaining after subtracting the energy required to produce, process, and transport the biofuel from the total energy content of the biofuel. Essentially, it's a measure of whether a bioenergy system is actually producing more energy than it consumes (Markussen et al., 2015).

Using a mix of renewability and net energy ratio, this study evaluated the efficiency and effectiveness of switching to renewable energy sources from fossil fuels. The study calculated the energy flows of the complete bagasse-based electricity production chain, which includes the following steps: feedstock production; transportation; milling; cogeneration; and steam/electricity production. It also included an estimate of the energy consumption for each feedstock stage. The lifecycle energy balances were calculated by identifying the inputs of fossil fuels and renewable energy sources for each process in the production chain.

Co-Product Allocation

Among the co-products of sugarcane processing are heat, electricity, and animal feed. Thus, co-products must be considered to accurately assess the effects of bioenergy. The economic value, mass, energy content, or substitute of each additional co-product can determine how its energy and/or emissions are allocated. Economic valuation takes into account the quantity and market price of items and co-products. This study utilizes economic allocation as its approach to divide the material flows, energy inputs, and emissions among electricity, sugar, and molasses according to their respective yields and market prices (Dominguez Aldama et al., 2023). The data utilized in the current study is presented in

Table 6.

Table 6. Data for calculation of the allocation ratio

	Item		
	Sugar	Molasses	Electricity
Yield	300 kg	30 kg	110 kWh
Price	KES 205/ kg	KES 62.5/ kg	KES 25.20/ kWh

Respectively, the allocation ratio is computed as in Eq. **Error! Reference source not found.**.

$$Allocation\ Ratio = \frac{(Electricity\ yield \times price)}{(Sugar\ yield \times price) + (Molasses\ yield \times price) + (Electricity\ yield \times price)} \quad (11)$$

Results and Discussion

Life Cycle of GHG Emissions

The results of GHG emissions are presented in Table 7. The total GHG emissions across the entire lifecycle chain was 24.53 kg CO_2eq/MWh. Among all life cycle stages cane cultivation accounts for 73.2 % of these emissions making it a dominant contributor. Within cane cultivation, the primary source of emissions is the production and application of nitrogen-based (N and N_2O) fertilizers, which alone contributes 60.5 % of cultivation emissions, equivalent to about 44.3% of the total GHG emissions. The next major contributor was bagasse combustion in boilers for energy generation, responsible for 21.5%.

Table 7. Results of the LCA of GHG emissions from various processes

Process	**Emissions (kg CO_2eq/MWh)**
Cane Cultivation	
N-fertilizer production	2.41
P-fertilizer production	0.26
K-fertilizer production	0.33
Herbicides	0.35
Pesticides	0.59
Seeds production	0.10
N_2O (direct and indirect) emissions	8.45
Human labour	2.32
Diesel (tillage)	3.15
Cane Transportation	
Diesel (transport)	1.28
Cane Milling	
Lime production	0.01
Co-generation	
Bagasse combustion	5.28
Total	24.53

As shown in Figure 2, the main five contributing processes of GHG emissions were human labour, *N*-fertilizer production, diesel for tillage, bagasse combustion and N_2O emissions, in an ascending order.

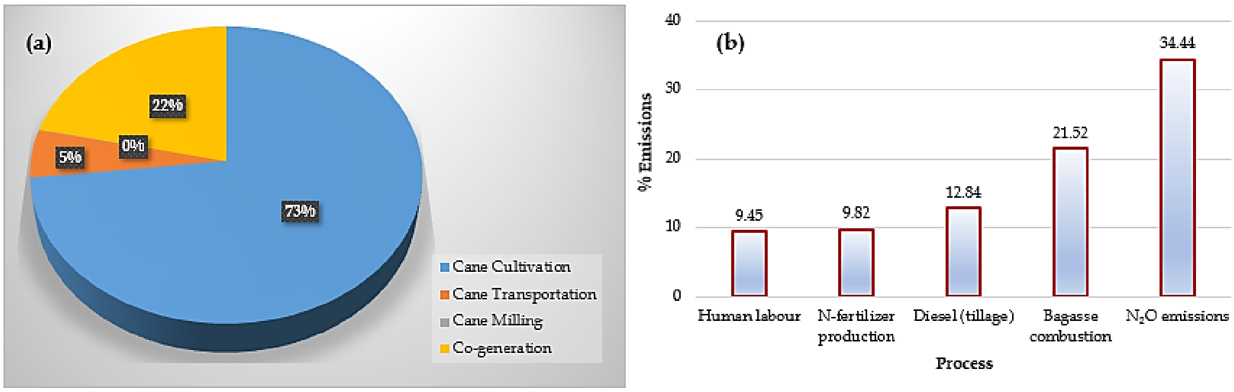

Figure 2. Percent GHG emission contribution of (a) main activities, (b) various processes

Lifecycle Energy Consumption and Balances

The energy consumption for bagasse-based electricity production was found to be 62.4 % fossil fuel and 37.6 % renewable energy-based, respectively. From the fossil fuels used, 63.5% are for cane cultivation, 34.1% for transportation, and 2.3% for milling. Table 8 presents the energy balance and consumption information for the whole bagasse-based electricity production lifecycle chain. It covers the energy used for cogeneration, cane milling, cane transportation, and cane cultivation. The total energy input was 181.261 MJ /MWh of electricity produced. From the energy balances, the net energy value (*NEV*) was found to be 9318.73 MJ, the net renewable energy value (*NREV*) was 9386.82 MJ per megawatt-hour (MWh) of power, and the net energy ratio (*NER*) was 84. The high positive values of NREV and NER indicate that the system produces significantly more renewable energy than it consumes non -renewable energy or rather to produce bagasse-based electricity in Kenya requires less nonrenewable input resulting in less GHG emissions.

Published June 2025

Table 8. LCA of energy consumption from renewable and nonrenewable sources

Process	Renewable Energy Input (MJ/MWh)	Fossil-Fuel Input (MJ/MWh)
Cane Cultivation		
N -fertilizer production		34.153
P -fertilizer production		1.517
K - fertilizer production		3.293
Herbicide production		5.002
Insecticide production		0.032
Sugarcane seed production		1.231
Human labour	45.088	9.472
Diesel (tillage)		
Cane Transportation		
Diesel (transportation)		17.142
Cane Milling		
Lime production		0.010
Bagasse combustion		2.638
Steam	21.100	
Electricity	0.450	
Co-generation		
Electricity	0.278	
Steam	1.266	
Energy input	68.182	113.079
Total energy input = 181.261 MJ/MWh		
Energy content of bagasse = 9500 MJ/MWh		
Net energy value (NEV) = 9318.73 MJ/MWh		
Net renewable energy value (NREV) = 9386.92 MJ/MWh		
Net energy ratio (NER) = 84		

Life cycle assessment (LCA) case-studies on generating electricity from bagasse has been conducted globally in nations including Iran (Mohammadi et al., 2020), Pakistan (Ghani et al., 2020), India (Hiloidhari et al., 2021), Jamaica (Contreras-Lisperguer et al., 2018), and Thailand (Silalertruksa et al., 2017). Several studies' results on greenhouse gas emissions and energy balances were compared with this study's conclusions. The reported GHG emissions per megawatt-hour of electricity include Mauritius at 35.60 kgCO_2eq (Ramjeawon, 2008), Thailand at 25.00 kgCO_2eq (Silalertruksa et al., 2017), and India at 29.00 kgCO_2eq (Sahu et al., 2015b).

The findings of this present study, which reports 24.53 kg CO_2 equivalent, are notably lower than those reported in other contexts. These differences can be explained by variations in agricultural practices, system boundary definitions, energy sources, and geographic conditions. For example, in Mauritius, pre-harvest burning of sugarcane significantly increases emissions, while irrigation powered by diesel-based electricity from the grid and coal usage as an energy source further amplifies GHG emissions. Similarly, in Thailand, diesel use for irrigation and emissions from nitrogen-based fertilizers are major contributors to greenhouse gas emissions. The reduced GHG emissions seen in this present study, on the other hand, are due to a combination of variables: the absence of pre-harvest cane burning, the exclusion of coal as an energy source, and the lack of irrigation in sugarcane cultivation. Additionally, emissions resulting from fuel combustion in vehicles were considered, though their contribution was relatively minor. While GHG emissions vary across countries, Thailand's reported emissions are closely aligned with the findings of this present study.

Published June 2025

Conclusions

Kenyan energy generated from bagasse has a net lifecycle greenhouse gas output of 24.53 kg CO_2eq/MWh. Of this overall energy usage, fossil fuels account for 62.38 %. A total of 63.5 % of the fossil energy consumed is attributable to cane cultivation, with 34.1 % coming from transportation. Promising values were computed from energy balances per megawatt-hour of electricity: 84 for the net energy ratio (*NER*), 9,387 MJ for the net renewable energy value (*NREV*), and 9,340 MJ for the net energy value (*NEV*). Given the very high positive values of NREV and NER, it appears that minimal amount of fossil fuel is needed to produce one megawatt-hour of electricity.

Acknowledgement

For supporting this study, the authors wish to express utmost gratitude to the Technical University of Mombasa's Office of Partnerships, Research, and Innovation (PRI).

References

Amukoya, J.A., Lilechi, M.C., & Moindi, K.M. (2023). Socio-Economic Impacts of Sugarcane Production from 1900 to 2020 in Bungoma County, Kenya. *African Research Journal of Education and Social Sciences (ARJESS), 10*(3), 25 - 40.

Andrade, L.P., Crespim, E., de Oliveira, N., de Campos, R.C., Teodoro, J.C., Galvão, C.M.A., & Maciel Filho, R. (2017). Influence of sugarcane bagasse variability on sugar recovery for cellulosic ethanol production. *Bioresource Technology, 241*, 75-81. doi:https://doi.org/10.1016/j.biortech.2017.05.081

Chen, Y., Wu, Y., Chen, N., Kang, C., Du, J., & Luo, C. (2022). Calculation of Energy Consumption and Carbon Emissions in the Construction Stage of Large Public Buildings and an Analysis of Influencing Factors Based on an Improved STIRPAT Model. *MDPI - Buildings, 12*(12), 2211. doi:https://doi.org/10.3390/buildings12122211

Collet, P., Spinelli, D., Lardon, L., Hélias, A., Steyer, J.P., & Bernard, O. (2014). Chapter 13 - Life-Cycle Assessment of Microalgal-Based Biofuels. In A. Pandey, D.-J. Lee, Y. Chisti, & C. R. Soccol (Eds.), *Biofuels from Algae* (pp. 287-312). Amsterdam: Elsevier.

Contreras-Lisperguer, R., Batuecas, E., Mayo, C., Díaz, R., Pérez, F.J., & Springer, C. (2018). Sustainability assessment of electricity cogeneration from sugarcane bagasse in Jamaica. *Journal of Cleaner Production, 200*, 390-401. doi:https://doi.org/10.1016/j.jclepro.2018.07.322

Dominguez Aldama, D., Grassauer, F., Zhu, Y., Ardestani-Jaafari, A., & Pelletier, N. (2023). Allocation methods in life cycle assessments (LCAs) of agri-food co-products and food waste valorization systems: Systematic review and recommendations. *Journal of Cleaner Production, 421*, 138488. doi:https://doi.org/10.1016/j.jclepro.2023.138488

Eshton, B., & Katima, J. (2012). *Energy Balances of Molasses Based Bioethanol Production in Tanzania.* Paper presented at the World Resources Forum Conference on Resources and Green Energy.

Eshton, B., Katima, J.H. Y., & Kituyi, E. (2013). Greenhouse gas emissions and energy balances of jatropha biodiesel as an alternative fuel in Tanzania. *Biomass and Bioenergy, 58*, 95-103. doi:https://doi.org/10.1016/j.biombioe.2013.08.020

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment, 11*, 80-85. doi:https://doi.org/10.1065/lca2006.02.002

Ghani, H.U., Mahmood, A., Ullah, A., & Gheewala, S.H. (2020). Life Cycle Environmental and Economic Performance Analysis of Bagasse-Based Electricity in Pakistan. *MDPI - Sustainability, 12*(24), 10594. doi:https://doi.org/10.3390/su122410594

Hiloidhari, M., Banerjee, R., & Rao, A.B. (2021). Life cycle assessment of sugar and electricity production under different sugarcane cultivation and cogeneration scenarios in India. *Journal of Cleaner Production, 290*, 125170. doi:https://doi.org/10.1016/j.jclepro.2020.125170

IEA. (2020). *Energy Technology Perspectives 2020*. Retrieved from Paris: https://www.iea.org/reports/energy-technology-perspectives-2020

Institute for Global Environmental Strategies. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

IPCC. (1996). *Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*: Cambridge University Press.

Kabeyi, M.J.B., & Olanrewaju, O.A. (2023). Life cycle assessment of energy sources and applications. *AIP Conference Proceedings, 3018*(1). doi:https://doi.org/10.1063/5.0171603

Kana-Donfack, P., Tientcheu-Nsiewe, M., Tcheukam-Toko, D., & Kapseu, C. (2024). Prediction of Low Heating Value of Sugar Cane Bagasse as a Fuel for Industrial Boilers in the High Relative Humidity Region: Case of Cameroon. *Open Journal of Applied Sciences, 14*(6), 21. doi:https://doi.org/10.4236/ojapps.2024.146105

Khatiwada, D., Venkata, B.K., Silveira, S., & Johnson, F.X. (2016). Energy and GHG balances of ethanol production from cane molasses in Indonesia. *Applied Energy, 164*, 756-768. doi:https://doi.org/10.1016/j.apenergy.2015.11.032

Kummamuru Venkata, B. (2013). Life cycle assessment and resource management options for bio-ethanol production from cane molasses in Indonesia. In (pp. 57). Stockholm, Sweeden: Digitala Vetenskapliga Arkivet (DiVA).

Lee, H., Bae, J., Jin, S., Kang, S., & Cho, B.-K. (2022). Engineering Acetogenic Bacteria for Efficient One-Carbon Utilization. *Frontiers in Microbiology, Volume 13 - 2022*, 17. doi:https://doi.org/10.3389/fmicb.2022.865168

Macedo, I.C., Seabra, J.E.A., & Silva, J.E. A.R. (2008). Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy, 32*(7), 582-595. doi:https://doi.org/10.1016/j.biombioe.2007.12.006

Marabu, A.W. (2011). *The potential of life cycle management for sustainable production of sugar at Mumias sugar company, Kenya.* Kenyatta University,

Markussen, M.V., Pugesgaard, S., Oleskowicz-Popiel, P., Schmidt, J. E., & Østergård, H. (2015). Net-Energy Analysis of Integrated Food and Bioenergy Systems Exemplified by a Model of a Self-Sufficient System of Dairy Farms. *Frontiers in Energy Research, Volume 3 - 2015*. doi:https://doi.org/10.3389/fenrg.2015.00049

Mati, B., & Thomas, M. (2019). Overview of Sugar Industry in Kenya and Prospects for Production at the Coast. *Agricultural Sciences, 10*, 1477-1485. doi:https://doi.org/10.4236/as.2019.1011108

Mohammadi, A., Venkatesh, G., Sandberg, M., Eskandari, S., Joseph, S., & Granström, K. (2020). A Comprehensive Environmental Life Cycle Assessment of the Use of Hydrochar Pellets in Combined Heat and Power Plants. *MDPI - Sustainability, 12*(21), 9026. doi:https://doi.org/10.3390/su12219026

Mokomele, T., da Costa Sousa, L., Balan, V., van Rensburg, E., Dale, B. E., & Görgens, J. F. (2018). Ethanol production potential from AFEX™ and steam-exploded sugarcane residues for sugarcane biorefineries. *Biotechnology for Biofuels, 11*(1), 127. doi:https://doi.org/10.1186/s13068-018-1130-z

Nguyen, T.L.T., Gheewala, S.H., & Garivait, S. (2007). Fossil energy savings and GHG mitigation potentials of ethanol as a gasoline substitute in Thailand. *Energy*

Policy, 35(10), 5195-5205. doi:https://doi.org/10.1016/j.enpol.2007.04.038

Odum, E.P. (1993). *Ecology and Our Endangered Life-support Systems*: Oxford University Press, Incorporated.

Olanrewaju, O., & Kabeyi, D. (2022). *Performance analysis of a sugarcane bagasse cogeneration power plant in grid electricity generation*. Singapore: IEOM Society International.

Ramjeawon, T. (2008). Life cycle assessment of electricity generation from bagasse in Mauritius. *Journal of Cleaner Production, 16*(16), 1727-1734. doi:https://doi.org/10.1016/j.jclepro.2007.11.001

Ritchie, H., Roser, M., & Rosado, P. (2020). Renewable Energy. *Our World in Data*. doi:https://ourworldindata.org/renewable-energy

Sahu, S., Ohara, T., Beig, G., Kurokawa, J., & Nagashima, T. (2015a). Rising critical emission of air pollutants from renewable biomass based cogeneration from the sugar industry in India. *Environmental Research Letters, 10*(9), 7. doi:https://doi.org/10.1088/1748-9326/10/9/095002

Sahu, S., Ohara, T., Beig, G., Kurokawa, J., & Nagashima, T. J. E. R. L. (2015b). Rising critical emission of air pollutants from renewable biomass based cogeneration from the sugar industry in India. *10*(9), 095002.

Seabra, J.E.A., Macedo, I.C., Chum, H.L., Faroni, C.E., & Sarto, C.A. (2011). Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuels, Bioproducts & Biorefining, 5*(5), 519-532. doi:https://doi.org/10.1002/bbb.289

Silalertruksa, T., Pongpat, P., & Gheewala, S. H. (2017). Life cycle assessment for enhancing environmental sustainability of sugarcane biorefinery in Thailand. *Journal of Cleaner Production, 140*, 906-913. doi:https://doi.org/10.1016/j.jclepro.2016.06.010

Takase, M., Kipkoech, R., & Essandoh, P.K. (2021). A comprehensive review of energy scenario and sustainable energy in Kenya. *Fuel Communications, 7*, 100015. doi:https://doi.org/10.1016/j.jfueco.2021.100015

To, L.S., Seebaluck, V., & Leach, M. (2018). Future energy transitions for bagasse cogeneration: Lessons from multi-level and policy innovations in Mauritius. *Energy Research & Social Science, 35*, 68-77. doi:https://doi.org/10.1016/j.erss.2017.10.051

Wang, M., Qi, X., Shi, Y., Zhao, J., Ahmad, S., Akhtar, K., . . . Wen, R. (2023). Sugarcane straw returning is an approaching technique for the improvement of rhizosphere soil functionality, microbial community, and yield of different sugarcane cultivars. *Frontiers in Microbiology, Volume 14 - 2023*. doi:https://doi.org/10.3389/fmicb.2023.1133973