**Sweet energy – bioenergy integration pathways for sugarcane residues. A case study of** **Nkomazi, District of Mpumalanga, South Africa**

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**Abstract**

The South African sugar sector is making important contributions to the national economy in terms of income, employment, land reform and rural development. With fluctuating world market prices for sugar and sharp price increases for electricity the sector is facing several challenges. There is a recognised need to switch to more low carbon and renewable energy carriers and sugarcane residues are becoming of increasing interest. This paper presents exploratory research on community energy demand of integrating bioenergy from sugarcane residues into the sugar value chain. These have been identified during farm visits and stakeholder meetings in Nkomazi, District of Mpumalanga, South Africa. From these, four potential bioenergy integration pathways were highlighted and evaluated. While the pathway with centralised bioenergy generation can provide benefits to the national energy supply, local community-scale bioenergy integration can directly target the development and empowerment of communities and improve their energy security. Assessing the pathways identify that it is necessary to consider carefully: (1) what are the desired outcomes of integrating bioenergy, (2) what are the trade-offs between different sustainability aspects, and (3) who will receive the benefits. This shows the importance of considering context specific and wider socio-economic aspect to identify possible benefits and challenges.

Keywords: Sugarcane residues; bioenergy; bioenergy integration; energy security; empowerment; South Africa

# Introduction

South Africa is one of the top 15 sugarcane producers globally with the sector making important contributions to the national economy in terms of earnings and employment [1]. The world market price for sugar is fluctuating and has been decreasing over the last few years [2] leading to considerable government support and regulations [1] in South Africa. Steep increases in electricity prices [3] have added further challenges to profitably producing sugarcane. This not only affects the energy intensive sugar processing industry but also cane growers in particular in regions where the crop is irrigated and electricity is required for pumping. The government has indicated that it will introduce a carbon tax for all direct greenhouse gas (GHG) emissions from energy use and non-energy industrial processes [4]. This taxation would further increase energy prices along the whole sugar value chain [5]. Despite about 90% of the South African population currently connected to the electricity grid[6], households, businesses and industry still get affected by scheduled load shedding and blackouts.

One way of addressing inconsistent power supply, increasing electricity prices and reducing net greenhouse gas emissions is to consider the integration of bioenergy into the sugar sector. However, such integration will have wider socio-economic impacts [7, 8]. The objective of this work is to evaluate the sustainable development impacts of bioenergy integration in the South African sugar sector. It does this by examining a region with extensive sugarcane production and local energy demand, together with interviews of local stakeholders who are familiar with the local and wider contexts to explore the livelihood and energy supply aspects of a potential bioenergy integration.

Sugarcane is grown on both small and large scales in South Africa. During the 2013/14 season, 12,507 of the 21,110 small-scale growers delivered sugarcane to the mills [9, 10], approximately 9.4% of the total crop in South Africa [10]. Small-scale sugarcane farms cultivate an average of 7 ha, with 40% of small-scale farmers not producing sufficient sugarcane to deliver to the mills. The production is often characterised by low and non-profitable yields with an average of 35 tha-1 (personal communications 2015) with poor access to adequate infrastructure like malfunctioned irrigation systems and poor road networks [11]. The land of small-scale growers is classified as sugarcane land and is set up with irrigation systems; hence, they identify themselves as cane growers only as the land cannot be used for any other crop (personal communications 2015).

The 1,383 commercial growers in South Africa produce about 83.3% of the sugarcane [10] withfarms larger the 30 ha deemed commercial. Sugarcane is produced under intense management with optimised inputs of fertiliser, plant protection and irrigation [12]; personal communications 2015) with profitable yields ranging from 80 tha-1 to up to 150 tha-1 (personal communications 2015). Farms are usually connected to a paved road network with quick access to the sugar mills (personal communications 2015). In most cases, sugarcane is just one of the commercial farms’ crops as fruit production is very common in the region. Approximately 7% of the South African sugarcane is produced by the mills on company-owned and on rented land [10], the fields are located close to the mill with optimised inputs and irrigation with yields above 90 tha-1 (personal communications 2015).

The selected research location was Nkomazi in the District of Mpumalanga, where sugarcane is produced under irrigation, leading to high electricity demands for pumping. The high cost and inconsistency of power supply are obstacles, especially, for small-scale growers and have a direct impact on the yields. With this in mind, there is a recognised need in South Africa to switch to more sustainable, low carbon and renewable energy carriers to reduce emissions and improve the national energy supply [13, 14]. So far, the regulatory framework and environmental and sustainability policies and measures regarding bioenergy generation as well as the handling of farm and processing residues are either immature or do not exist [14, 15]. There are initiatives for the establishment of renewable energy applications [14, 15] and to support cogeneration [16]. Notably, most of the power produced in South Africa is provided by the state-owned power supplier ESKOM, which also owns and operates the grid [14]. The sugar sector already plays an important role in cogenerating heat and electricity by utilising bagasse for on-site energy use at the mill and if a surplus is available, by exporting electricity to the grid.

Under the current Independent Power Producer (IPP) process [17, 18] the government aims to improve the national power supply by 2030 with the application of various energy carriers, technologies and scales including bioenergy [13, 18, 19]. Nevertheless, the IPP programme for small-scale renewable energy projects are banded between 1 and 5 MW capacity [19].

As a well-investigated biofuel feedstock in terms of producing bioethanol, sugarcane is of particular interest. Apart from bioethanol production, fibrous sugarcane residues, particularly bagasse, are already used in sugar mills worldwide to cogenerate heat and power for milling and refinery processes, and export surplus electricity to the grid [20-25]. Hence, most research focuses on this type of cogeneration and as yet no local options have yet been considered, e.g. micro grids or decentralised energy supply options. Additionally, technical and economic problems are discussed widely [20-29] but social and socio-economic challenges, and actual energy demands of the local cane growing communities are often neglected. Therefore, this exploratory research provides a demand side approach and focuses on the bioenergy options for local communities and farms, such as micro grids or decentralised energy systems which suits the end-users’ need and demand, and focuses less on energy generation opportunities and efficiency improvement at mill level. This is of particular interest in the South African context where the Broad-Based Black Economic Empowerment Act [30] is implemented. This act regulates the empowerment of the black and previously disadvantaged population across all ethical groups and in public and commercial sectors [30].

Related to the structure and energy demand of the South African sugarcane sector, the utilisation of fibrous sugarcane residues can make valuable contributions by improving the energy supply, increasing the share of renewable energy and providing economic development and empowerment for cane growers. This paper identifies the key sustainability issues arising from the transition of a sector focused on sugar production to one that integrates bioenergy generation. The objectives were to highlight and identify the key parameters that need to be assessed to ensure the environmental, economic and social sustainability of the integration. Together with stakeholders, a set of potential bioenergy pathways were developed and the related benefits, opportunities and challenges of these pathways from an environmental, economic, social and policy perspective were discussed. At this stage, the research provides a qualitative assessment taking a demand side approach on the energy needs and demand and wider socio-economic impacts of the cane growing communities. It does not provide data on feedstock availability and demand, energy potential, technological feasibility, required investments or quantitatively evaluates costs and revenues nor environmental impacts.

# Methods

This research is an exploratory study and is based on data collected during fieldwork in July 2015 in Nkomazi region, District of Mpumalanga, South Africa. The main activities included visits to cane growing farms of different scale to capture the breadth of stakeholders and agricultural practices. Stakeholders along the sugar value chain were included in this process. The aim was to identify the energy needs and demands of the cane grower communities and scope from this potential bioenergy integration pathways and their wider socio-economic impact. According to the nature of an exploratory research, the data was collected through informal unstructured interviews [31] with farmers, and observations [32] of farming activities. This was important to gather unbiased and independent data as there can be a mismatch between how people perceive and actually conduct activities [33]. Additionally, in-depth interviews with key experts from the sugar industry, such as millers, grower associations and sugar association were held to discuss the bioenergy potential, opportunities and challenges of the South African sugar sector.

The farms were selected according to availability of the farmers. In total, five small-scale farms were visited, of which three are members of cooperatives, and two are individually managed lands—one by a male, and the other by a female farmer. Additionally, four commercial farms were visited, of which one is mill-owned, two are individually managed and one is cooperatively managed. A sugar mill was also visited and interviews conducted with the South African Canegrowers’ Association, the South African Sugar Association and RCL Foods Sugar and Milling (Pty) Ltd. The conversations during farm visits and meetings were not audio recorded due to their informal and unstructured character. Notes were taken during the visits and meetings, and minutes were written after [34].

The aim of the fieldwork was to develop a basic understanding of the South African sugarcane sector and from this, to elicit and prioritise key criteria regarding a potential integration of bioenergy into the sugar value chain on the basis of the cane grower communities’ energy demand and wider sustainability impacts.

The data was used to develop a set of bioenergy integration pathways. To evaluate and verify the pathways in terms of environmental, economic, social and policy aspects, the benefits, opportunities and challenges of the different options were discussed with key experts. This helped to identify the pathway, which could open up opportunities for the different actors, as well as the most challenging ones. This also allowed for a plausible comparison of the different pathways. While potential technologies were included in the conversations, no decision on technologies and application were made as it was agreed these were site and context specific and would require a detailed techno-economic assessment which was outside the scope of this study.

# Results

The section presents the findings from the fieldwork conducted in the research region in July 2015 and are backed up by existing literature.

# Sugarcane production in the research area Location of Nkomazi in the District of Mpumalanga

In Nkomazi, sugarcane is grown on about 51,000 ha producing about 4.33 million tonnes of sugarcane per annum [35], which supplies two sugar mills in the region. About 63% of the land is cultivated by commercial growers, 15% by small-scale growers and 22% is mill-managed land [35].

The typical sugar value chains are presented in Figure 1. Sugarcane (*Saccharum officinarum*) is a perennial crop, which is harvested for 6 to 10 seasons depending on variety, yields and management conditions [12]. The common varieties in Nkomazi have a seasonal cycle of 12 month and all require irrigation throughout the season (Personal communications 2015). The production systems are similar across all scales in Nkomazi. Before the sugarcane is harvested, it is common practice to burn the leaves off the stalk for easier and quicker handling [12, 23, 36]. About 80% of the leaf material is removed that way [23]. About 90% of sugarcane is burned pre-harvest in South Africa [24, 36, 37]. Currently, there are no regulations on national level for pre-harvest burning. Regulations like the Air Quality Act [38] and National Veld and Forest Act [39] regulate the conditions and standards of sugarcane burning but do not reduce or prohibit such activities. There are, however, municipal ordinances regulating burning in some areas.

After the burning, the sugarcane is cut by hand, loaded mechanically onto lorries and transported to the mill where it is processed. In Nkomazi, as the rest of South Africa, 95% of sugarcane is harvested by hand cutting and 5% is done by mechanised harvesting [24, 37]; personal communications 2015). Following good practice, the tops of the plant should stay in the field and are being spread to provide soil cover, support soil moisture, return nutrients and suppress weeds [12, 40, 41].

The sugarcane is then processed at the mill and after the extraction of sugar; bagasse is left as the fibrous residue of the sugarcane. In the case of Nkomazi, the bagasse is burned in boilers at the mill, generating heat and electricity for internal factory process and surplus electricity is fed into the grid [24, 42].

The South African sugar industry has a highly regulated structure to include everyone involved in the value chain from growing sugarcane up to marketing the sugar. The market has a set price for the recoverable value (RV) of the sugarcane calculated from the composition of the sugarcane in terms of sucrose, non-sucrose and fibre content [43]. Following this, the region-specific profitable yield threshold for Nkomazi is 60 tha-1, which many small-scale growers do not achieve due to lacking inputs (water and fertiliser), management skills and agricultural knowledge (personal communications 2015).

Currently, the utilisation of fibrous sugarcane residues such as bagasse and brown leaf is not part of the legislative measures such as the Sugar Act [44] and the Sugar Industry Agreement [45]. This means that growers do not receive any payment for the bagasse or leaf material.

**Fig 1** Sugar value chains in Nkomazi

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Currently, cane growers in Nkomazi operate in two different organisational structures: individually and in cooperatives. In particular, small-scale farmers are organised in cooperatives. This helps them with managing irrigation, sharing costs, vehicles and labour (personal communications 2015). To receive government or industrial funding, it is often a condition to be organised in cooperatives as this makes the sugarcane production on small-scale financeable and more efficient [46]. Still, there are also small-scale growers who work on an individual basis but they often struggle to find financial support, the crop management is more challenging and they produce it at a higher cost (personal communication 2015). In case of commercial growers, both cooperatives and individual farming is common and often based on personal preferences (personal communication 2015).

# Energy demand along the sugar value chain

The milling process of sugarcane and refining of sugar is very energy intensive. In the case of Nkomazi, sugar mills are already generating power and heat from bagasse mainly for internal processes. There is a potential that these cogeneration activities can be extended by improving the efficiency of the boilers and additionally, using brown leaf to generate surplus heat and electricity that can be exported to the grid. The highest on-farm energy requirements are for pumping of irrigation water as was pointed out by all interviewees. It is common practice that farms at all scales are sharing pumps and pump stations and the cost for running and maintaining the pumps is shared between users. Irrigating sugarcane is a daily activity in the research region. About 13 to 20 kWh are required per day to irrigate one hectare of sugarcane (personal communications 2015). Steep electricity price increases of over 300% in the last 6 years [47], price variations on daytime (peak and off-peak), season (high and low demand season) and locations further increase the electricity cost for sugarcane growers[3]. Additionally, the electricity supply gets more inconsistent with increasing distance to the generation plant and scheduled power cuts (load shedding) are more common. Hence, when irrigation is required during the daytime and dry season, electricity prices are usually highest and particularly affect farmers in remote locations. On household level, the most energy demanding activities identified are mainly cooking, cooling, and heating (personal communications 2015). For cooking or heating the most common energy carrier is wood and in some cases electricity (personal communication 2015).

# Biomass potential of sugarcane

There a three fibrous parts of the sugarcane plant, which are considered as bioenergy feedstock:

1. Bagasse, the fibre from the stalk after milling,
2. Brown leaf (sometimes referred to as trash), the dry leaves from the lower stalk and
3. Green leaves from the upper stalk.

Tops, which are the green top leaves and the sheath bundle to the highest fully formed node, could potentially also be considered but due to current agricultural practices and considering soil and nutrient management, there can be sustainability concerns if they are removed from the field [12].

According to different commercial farmers in the research region ((personal communication 2015) and Smithers [24]) about 15-20 tonnes of leaf material (dry basis) are produced per hectare, considering sugarcane yields of 80-100 tha-1. About 5-10 tha-1 are green leaves and tops with a moisture content of up to 70% and 10-15 tha-1 are brown leaf [22, 41].

Green leaves and tops return higher amounts of nutrients back to the soil than dry brown leaf [40, 41]. It is therefore suggested to leave fresh leaf material in the field, while the majority of the brown leaf can be removed [12, 24, 41]. Nonetheless, spreading brown leaf in the field also supports the suppression of weeds and reduces soil erosion and demand for irrigation [12, 24, 40, 41]. Fifty percent (50%) recovery rates are considered as sustainable and efficiently removable in the case of South Africa [24] when sugarcane is harvested green. In case of pre-harvest, burning the amount of leaf material will be massively reduced and all leaf material should stay in the field for soil and nutrient management and weed control [12]. Hence, a precondition to use sugarcane residues as bioenergy feedstock is harvesting green cane. The advantages and disadvantages and brown leaf recovery options are discussed in detail by Smithers [24].

One agronomic disadvantage of leaving brown leaf in the field is an increased risk of “trash worm” infection. Another disadvantage is that cane growers mentioned in regard to harvesting green cane are the increased demand in labour, handling and transport, which would increase the post-harvest cost by about 20% (personal communications 2015).

# Bioenergy integration pathways

This section is describing a set of potential bioenergy pathways at different scale and application when using brown leaf as bioenergy feedstock. Brown leaf recovery options and the bioenergy potential of sugarcane residues have been investigated by others [20-26, 28, 29, 48]. So far, these focused on energy conversion at mill level, while local options and community energy supply have been widely neglected. The aim was not to identify the most feasible technology or business models but to identify key sustainability issues arising from integrating bioenergy generation into the sugar value chain. This is done by describing qualitatively the benefits, opportunities and challenges of each of these pathways and considering environmental, economic, social and policy aspects of such an integration.

The bioenergy pathways described in this section are developed to provide guidance in improving the energy supply of cane growers and rural communities and reducing environmental and health impacts from pre-harvest burning. They are the result of engaging with stakeholders in Nkomazi, discussing energy demand and supply challenges and opportunities. An outline of the different pathways is given in Figure 3. All pathways have similar harvesting and collection practices: Cane is harvested manually as green cane, the brown leaf is stripped and the tops are cut off. Fifty per cent (50%) of the leaf residues, mainly tops and green leaves and some of the brown leaf are left and spread in the field as soil cover and to return nutrients and the other 50%, mainly brown leaf, are removed. The removed brown leaf is collected and transported to the bioenergy facilities where it is processed. The conversion technology and energy end-use have not been specified at this point of the project as this lies outside of the scope of the project and would require a feasibility and techno-economic assessment.

*Pathway (A) - Field to pump: Energy generation from brown leaf to provide electricity for irrigation (cooperative small-scale growers).* In this pathway, the brown leaf is used to generate electricity, which could be used for irrigation pumps in small-scale systems. Other available residues and organic wastes might be included as feedstocks. The energy generated, especially if only brown leaf is used, is likely to provide only a small amount of the electricity required and an additional supply from the national grid is necessary. Nonetheless, the bioenergy can substitute some of the grid electricity or provide electricity during power cuts when irrigation is needed.

*Pathway (B) - Field to community: Energy generation and use at community level (individual and cooperative small-scale growers).*In this pathway energy is provided at community level, e.g., schools, meeting halls, farm or household activities. Other organic wastes from household, farm and commercial activities could be included as feedstocks. As in Pathway (A) the amount of energy is unlikely to cover all of the required energy but could replace some of the existing fossil fuel or traditional biomass based energy or increases the local energy supply and improves energy security.

*Pathway (C) - Field to farm: On farm energy generation (commercial growers).* Commercial farms grow usually more than just sugarcane. In the research region, fruit production is very common and often the main produce. With this, farmers can utilise a variety of residues as bioenergy feedstocks. The energy generated on-farm can then be used for on-farm and household activities like irrigation, lighting, cooking or cooling. Again, a full replacement of grid-based energy is unlikely but it could possibly substitute some of it and be a backup during power cuts.

*Pathway (D) - Field to mill and grid: Power generation at mill with surplus export to grid (all growers).*Sugar mills already use bagasse and to a small extent brown leaf delivered with green cane to generate heat and electricity. The brown leaf is delivered to the mill together with the sugarcane, where it is handled and combusted together with the bagasse to produce heat and electricity. This supplies energy for mill’s internal processes and surplus electricity can be exported. This electricity is then either wheeled to growers’ pumps or fed into the grid.

**Fig 2** Outline of potential bioenergy pathways for the utilisation of sugarcane residues for energy generation

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# Discussion

# Benefits, opportunities and challenges

All four pathways provide environmental, health and economic benefits along the sugar value chain. Globally about 30 Mt of CO2eq are released annually from burning crop residues in fields [49]. Avoiding the burning of brown leaf in field reduces direct emissions and local pollution of mainly carbon dioxide, methane, carbon monoxide, oxides of nitrogen and particulate matter [50]. Utilising brown leaf as bioenergy feedstock provides a local renewable energy source., which can support community and national energy resilience. While this still releases emissions, these can be much better controlled and minimised in an application where the combustion of the biomass fuel can be controlled and optimised compared to the incomplete combustion of wet biomass during pre-harvest burning in the field. Integrating modern bioenergy technologies available at household level could also reduce the use of traditional bioenergy for cooking and heating, which has significant health impacts [51]. This would then also reduce the unsustainable sourcing of wood for cooking and heating, and reduce time for collecting fire wood [52].

Harvesting green cane also means that more leaf material stays in the field with numerous agronomic benefits such as improved soil and nutrient management, protection from erosion, reduced irrigation demand due to the soil cover, which saves water and energy required for pumping [12, 24, 40].

Green cane harvest is seen as a challenge for all pathways as it increases the harvesting and transport cost by 20% (personal communications 2015). However, integrating bioenergy into agricultural systems and replacing inefficient traditional biomass provides, apart from low carbon energy, various co-benefits such as employment, income resilience, improve poor people’s access to clean energy, reduce health and pollution impacts from residue burning and traditional biomass use, support agricultural and forestry systems, provide business opportunities and deliver social benefits [8, 52-55]. Especially in the South African context creating employment is a central political agenda under the Broad-Based Black Economic Empowerment Act [30, 56].

In case of Pathways (A), (B) and (C) some of the energy supply would be decentralised through the bioenergy integration and could reduce the dependence on the central energy system. This would allow addressing local and community energy demand in a direct way. The introduction of new agronomic and economic activities like residue collection and the management and maintenance of the bioenergy facility would further support local development of the communities. The consistency of feedstock supply (quality and quantity) will be limited by the timing and season of harvest. Adding other feedstocks such as other agricultural residues and organic household and community wastes might be required for a more consistent bioenergy energy supply. This way bioenergy integration would provide additional benefit by dealing with other wastes and residues.

The small size of fields, the bulky characteristics of the feedstock, in field collection and poor road networks could make the brown leaf collection and delivery difficult in the case of Pathways (A) and (B). Moreover, the logistics and management of additional types of feedstocks can also be challenging for these two pathways. Compared to this, commercial farms (Pathway (C)) with higher yields, larger cultivated area, and availability of different agricultural residues and machinery could find utilising different feedstocks more economically feasible in terms of energy generation and waste management.

From a practical perspective, Pathways (A) and (B) will be easier to organise and manage in cooperatives as the beneficiaries share the same infrastructures and services (personal communications 2015). Still, it is likely that there will be challenges on how the bioenergy facility is managed, operated and maintained, regarding the governance of the bioenergy system and how contributors are rewarded and reimbursed in a fair way. As the amounts and quality of brown leaf are likely to vary between growers, a system to record the quantity and quality of these would be required. This might be easier in the case of Pathway (A), where the farmers who deliver the feedstock are also the direct beneficiaries. Nonetheless, a combination of different feedstocks and extending the bioenergy system beyond the sugar value chain, like in Pathway (B), would give it a horizontal character. Hence, different value chains would be linked with each other and it would not be just a sugarcane-to-energy value chain but a ‘feedstock a’-‘feedstock b’-‘feedstock x’-to-energy value chain. New stakeholders would get involved at each level and process of the value chain and ownership rights and influence on decision-making would be extended more equally. This could significantly contribute to the empowerment of the local communities. Nevertheless, this again would require good governance and a high level of management and organisation.

Commercial growers, as in Pathway (C), would be more flexible in decision-making and the production and consumption of energy would stay within their own system. This reduces the required level of governance compared to a system reaching outside the farm boundaries. At the same time, this would make a bioenergy system exclusive to the commercial farm.

The main advantage of Pathway (D) is that infrastructure and technology for dealing with the residues at mill level already exist. Recording the amount of delivered fibre and payment of the biomass suppliers could be linked to existing monitoring mechanisms. Nevertheless, this would require a value and accounting scheme similar to a payment system for the recoverable value of sugar (personal communications 2015). If the generated electricity is wheeled to the growers’ pumps through discounted energy rates, the growers would directly benefit from the energy generation. This would only be effective for a certain tariff and reduce the actual tariff rate of the users. The discounted allocation would need to be below the actual electricity use as unused electricity will be lost to ESKOM (personal communications 2015). This would limit the actual benefits in case of malfunctioning and damaged electricity infrastructures. Additionally, the shared irrigation infrastructure makes it complicated to identify and separate which grower will receive a discount and who would not as this depends on the delivery of brown leaf to the mill.

Alternatively, surplus electricity from Pathway (D) could be fed into the grid and increase the rate of renewables in the national electricity mix and the supply of electricity as such. The recently introduced REBID (renewable energy bids) process [16, 18], would provide a valuable basis to utilise sugarcane residues on mill level and incentivise the development of large-scale bioenergy applications. Nevertheless, a better cogeneration procurement framework has to be established to utilise the total system efficiency of brown leaf in a sugar mill (personal communications 2015). Additionally, there is no guarantee that the additional bioenergy will also support and improve the electricity supply and the development of rural and remote communities and poor population groups. For this, the infrastructure and electricity supply of these areas would need to improve and the prices for electricity would need to decrease. Following Pathway (D), the electricity end-users will still depend on the central energy system with a small number of decision-making stakeholders. Moreover, most mills and the used boilers are based on old designs with low efficiencies. Investments would be required to modernise the facilities, allowing the production of more surplus energy.

For Pathways (A), (B) and (C), there is no national or local policy support for renewable energy application at a smaller scale. According to REBID, bioenergy system would need to be a dedicated energy production system with significant contribution to the national energy production to receive the necessary incentives [17]. Hence, applications at mill level (Pathway (D)) might be eligible for government support while small-scale or micro-grid options and applications are not captured. The variety of benefits of bioenergy integration in agricultural systems beyond providing energy, climate and environmental services has been discussed by others [52, 57-60], and often find that policy needs to address the synergies between agriculture and bioenergy [57, 61]. The 5th IPCC report states that small-scale bioenergy deployments are better for empowerment and local livelihood of communities, while large scale projects can undermine local development and cause land use conflicts and reduce access to productive land for local population [52].

Another issue perceived as challenge for all pathways is the high level of crime. Pumping facilities are usually in remote areas and theft, vandalism and violence are common. This is likely to affect a bioenergy facility too, if linked to the pumps.

Figure 3 summarises and compares the main aspects, benefits and challenges of the four proposed bioenergy integration pathways.

**Fig 3** Benefits and challenge of different bioenergy integration pathways

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# How sweet is bioenergy?

The bioenergy pathways presented above describe different options for integration of fibrous sugarcane residues as bioenergy feedstock into the sugar value chain. Each pathway provides opportunities to (1) increase the energy supply, (2) reduce emissions from not burning brown leaf before harvest, replacing fossil fuels with a renewable energy source, (3) modernise traditional biomass systems, (4) provide agronomic benefits from brown leaf as soil cover and (5) support economic development and employment. Nonetheless, there are also a number of challenges such as increasing cost for labour and transport, lacking infrastructures, no existing payment and benefit frameworks for stakeholders, lacking investments, no or limited policy support and challenges of protecting facilities from crime.

Considering the different pathways raises the question, which of the four options could open up most opportunities for the different actors, and which one would be the most challenging. This would depend on the main focus of the bioenergy integration and the emphasis on linking environmental, economic and social trade-offs.

Regarding environmental impacts, all four pathways provide environmental benefits in terms of local pollution, climate change mitigation, health impacts and agronomic aspects, with Pathways (B) also offering alternatives to the traditional use of biomass for cooking and heating.

Regarding economic sustainability, the benefits, opportunities and challenges vary across the different pathways. Even though the integration of bioenergy would provide economic development and create employment, the cost for labour and logistics would increase due to the higher amounts of fibrous material that need to be handled. The bioenergy integration would fit into the infrastructure of Pathway (D). This is also the pathway likely to have the highest benefit in terms of national energy security and decarbonising the South African electricity mix. Nonetheless, considering local energy security Pathway (D) could not guarantee that the renewable energy supplied reaches remote communities, while Pathways (A) and (C) and in particular Pathway (B) focus much more on the local energy supply of the directly involved community.

Due to the South African history, economic and social empowerment of disadvantaged groups has a strong political and societal agenda. Current South African political strategies advice that social sustainability and in particular, economic empowerment should be of as much concern as economic and technological feasibility [30, 56]. The empowerment of the local population is supported in Pathways (A) and (B) and to some extent in (C). Pathway (D) would be integrated into the existing fossil fuel based energy system with a vertical supply chain that includes a small number of stakeholders. While small-scale cane growers might receive a payment for the delivered fibre, the electricity and price benefits will not necessarily reach these communities. The justice and equality of electricity supply for the communities would be most supported in Pathway (B) and least in Pathway (D). This is closely linked to decentralising the energy infrastructure and adopting horizontal value chains to involve a larger number of players and beneficiaries as well as increasing ownership rights and participation in decision-making. Pathway (B) is the only one of the four options benefiting the wider community in all these points, while Pathways (A) and (C) provide benefits to a small number of players or local groups. Pathway (D) can make a valuable contribution to the national energy supply but will have few direct benefits for local communities, in particular in remote areas except in job creation and reward for brown leaf provision.

None of the bioenergy pathways receives significant policy support. Policy support for medium- and large-scale bioenergy projects is under development, which in the future could incentivise bioenergy options like Pathway (D), but smaller scale option like Pathways (A), (B) and (C) will not be included. Therefore, the support mechanisms currently being developed will not necessarily reach the poor or improve their livelihoods.

Technical considerations and issues reading energy conversion were outside the scope of this research as the project took a demand side approach focussing on energy needs and socio-economic factors and the given policy environment. Nevertheless, technical challenges can be expected and will be technology and system specific and have been discussed by others [20-29]. Once a selection on specific technologies and applications is made, a techno-economic feasibility assessment will be necessary. However, the here presented work shows that the context is much more complex than just a choice of an application with the most feasible technology, and that, independent on the final choice of technology, wider social impacts and the institutional framework will play a role in a successful bioenergy integration.

The different pathways made clear that depending on the focus of interest, the objectives of the bioenergy integration and the wider aim of the bioenergy system, one or the other of the four pathways would be relevant and could provide a possible way forward. The final decision would be based on the primary interest of the bioenergy system. If the main interest would be decarbonising the electricity mix and improving national electricity supply at low cost, Pathway (D) might be the most applicable way. If the main interest is to reduce the area of pre-harvest burning, improve agricultural practices while policy incentives and public investments are lacking, Pathway (C) might be the best option due to the large agricultural area affected, a reliable feedstock supply and availability of necessary assets including private investment. If the focus would be on local empowerment and local energy security, the best options could be Pathways (A) and (B). Pathway (B) would be also the way forward if there is a strong interest in equal energy access and decision-making contributing to equity and justice aspects of the wider local communities. This shows the importance of each of the different aspects as part of the bioenergy system integration and the dependence on how much emphasis is put on each aspect.

Most cane growers involved in this research were not aware of any bioenergy options at farm level and considered it more as an option at mill level. This was mainly due to lacking knowledge of technologies and business models. However, the above discussed pathways demonstrate that small- and medium-scale bioenergy applications on farm and community level exist and could be highly relevant supporting wider societal benefits. Integration of a bioenergy value chain into the existing agricultural production, for example, by changing practices to green cane harvest and removing a sustainable amount of the leaves for bioenergy, could add various benefits to the existing agricultural systems as described above. In South Africa, this is an important aspect because small-scale farmers are the biggest group of cane growers. For the development of these communities, diversifying their farm activities can make a valuable contribution to development and empowerment. These communities also experience high rates of energy insecurity. Integrating bioenergy could therefore diversify their agricultural system and support their development. The trade-off between additional labour and handling cost from green cane harvest and bioenergy integration has not been in the scope of this research but with continuously increasing electricity prices and the possible introduction of a carbon tax, integration at small-scale level becomes increasingly interesting.

# Conclusion

This paper presents a set of for bioenergy pathways, which show if and how bioenergy can be sustainably integrated into the sugar value chain in South Africa. Focussing on improving the supply of renewable energy to support the development of local communities and on reducing environmental impacts of current value chain activities, a change in the harvesting practice from burnt to green cane is a precondition. Even though bioenergy integration can lead to practical, technical and economic challenges, there are various environmental, economic and societal benefits from such an integration.

Sugar mills already utilise bagasse for heat and power generation and in terms of economic benefits and efficiency, this pathway can provide several benefits. Nevertheless, the results showed that this pathway is limited in terms of local development and empowerment of small-scale growers, who are the biggest group of cane growers and are the most vulnerable group in the South African sugar sector. The analysis showed that local and small-scale bioenergy pathways provide more benefits regarding local energy access and security, development and empowerment. Considering the South African past and from a development point of view, a local bioenergy integration pathway would therefore be the best way to directly target the people’s need. However, the current policy frameworks do not favour these options and mill-based bioenergy integration is more likely to become commercially viable.

To maximise the outcome of a bioenergy integration into the existing sugar value chain, it has to be considered carefully: (1) what the desired outcome of integrating bioenergy into the sugar value chain is, depending on the environmental, economic and social sustainability priorities, (2) what the consequences and trade-offs between different sustainability aspects, as well as between the different pathways are and (3) who will receive the actual benefits. The current policy agenda is focussing on energy generation and carbon reduction, but by focussing exclusively on these aspects, opportunities to deliver wider sustainability goals and the development and empowerment of communities are very likely to be missed.

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