# Modelling Electricity Generation from Sugarcane Production System Using Systems Dynamics

**Mutanga Shingirirai Savious and Marne De Vries**

**Abstract** Current global energy systems have proven unsustainable amid effects of the cumulative greenhouse emissions and climate change. The drive towards a low carbon future has precipitated the consideration of alternative energy sources. Among these sugar cane, grown widely in African countries, is known to be one of the most productive species in terms of its conversion of solar energy to chemical potential energy. However the supply of feedstock is limited to the harvest or crop season. More-so the sugarcane industry is faced with a plethora of threats and challenges. This paper seeks to broaden the understanding of the complexity in bio-electricity generation through a systems dynamics model. The model provides certain considerations for optimization of the energy value in sugarcane production systems. Among these is the use of trash as additive feedstock, and improvement in feedstock productions through enhanced sugarcane production systems. Apart from illustrating some of the policy considerations on land use change, sugarcane production, and improved technological efficiency the paper provides the effect on emission avoidance.

**Keywords** Energy · Bio-electricity · Sugarcane · Systems dynamics

## 1 Introduction

Current global energy systems have proven unsustainable amid effects of the cumulative greenhouse emissions (Jacob and Hilaire 2015; McGlade and Ekins 2015) and climate change (UNFCCC 1997). A recent surge in the area of renewable energy technologies in response to climate change (Cacho et al. 2003; Goldthau 2011; Oxfam 2010) fluctuations in international oil prices (UNIDO 2008),

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dependence on imported fossil fuels (Ramjeawon 2008) and the need for energy security (Cherp and Jewell 2014) have been witnessed in the last decade. Among the various renewable energy technology options are bio-derived fuels' in particular sugar cane, grown widely in African countries, is known to be one of the most productive species in terms of its conversion of solar energy to chemical potential energy. Similar to other renewable energy technologies sugarcane production systems generate electricity in a variable manner. The supply of feedstock is limited to the harvest or crop season. More-so the sugar industry has faced a plethora of threats and challenges which have hindered their growth across the Southern African region. One of the threats is the decline in sugar prices which affected the sugar industry in small developing islands, such as Mauritius. Competing priorities for land and water resources (Howells et al. 2013) and inefficient production plants (Mbohwa and Fukuda 2003) which have stalled the potential of electricity generation from bagasse. Despite these the opportunity of harnessing energy co-products from the sugar industry, such as ethanol and electricity is becoming increasingly attractive. This paper seeks to broaden the understanding the complexity in bio-electricity generation. Central is the drive towards optimization of the energy value in sugarcane production systems using a systems dynamic model. The demonstration model is used to:

- Determine the potential electricity and threshold of bagasse/trash as an energy source in Mauritius.
- Predict the environmental benefits from optimizing electricity value of sugarcane production systems.

The remaining content of the article is structured as follows. Section 2 defines the key terms applied in this paper and presents systems thinking as an approach to unpack the complexity in bio-electric generation. Section 3 defines the constructional components (four sub models) of the system dynamics demonstration model for Mauritius. Section 4 presents model results and a discussion; Sect. 5 is the conclusion with suggestions for future work.

## 2 Complexity Science: Sugarcane Production Systems

a. Defining salient terminology

*Complexity theory*: This can be defined as means of simplifying seemingly complex systems (Manson 2001). There is no single identifiable theory, instead a number of theories concerned with complexity system gather under the general umbrella of complexity research.

*Energy and power*: The three are often considered synonymous. Despite the fact that they are interrelated they are not the same. While energy is the ability to do work, power is its measurement, which calculates the time by which the energy has been used. In other words:

- Energy is a measure of how much fuel is contained within something, or used by something over a specific period of time.

Energy = power * time
kWh = Kw * h
**Where**: kWh is the energy
kW is the power
h is the time in hours

- Power is the **rate** at which energy is generated or used.
  kW is a unit of power.
  KWh is a unit of energy:

$$\text{Power} = \frac{\text{energy}}{\text{time}}$$

$$\text{kW} = \frac{\text{kWh}}{\text{h}}$$

*Systems*: *A system* can be defined as a ‘complex whole of related parts’ (Cabrera et al. 2008). It is the summation of different parts or entities related to each other, that constitute the observed whole. Considering a system implies cognisance that an observed phenomenon is an outcome of underlying complex interrelationships (Amigun et al. 2011). Similarly, alternative forms of energy such as biofuel encompasses a highly heterogeneous set of socio-technical systems implying there are underlying complex interrelationships too.

*Systems analysis*: System analysis is a structured way of analysing complex interrelationships that are problematic or simply of interest to mankind (Kirkwood 1998).

*Systems thinking*: At the heart of systems thinking is the recognition that factors behind the problematic situations are interdependent, that causal effect between these factors is often two-way, and that the impact of action is neither instantaneous nor linear. It is a formal, abstract, and structured cognitive endeavor on thinking about systems in general (Cabrera et al. 2008). Systems thinking make explicit causal-effect assumptions between related variables in a system, enabling independent assessment and improvement of mental models behind particular thinking (Datta 2008).

*Systems dynamics* is a methodology based on systems thinking. Systems dynamics provide the means to capture complex relationships and feedback effects within a set of interrelated activities and processes (Vennix 1999). The field developed initially from the work of Jay W. Forrester of the MIT Sloan School of Management with the establishment of the MIT System Dynamics Group (Forrester 1991). Systems dynamics (SD) therefore is a framework of modeling and simulation that can be used to understand the complex adaptive processes, also operating as a tool for experimenting with scenarios and policies for using bio-fuels as the successor of the fossil fuel regime in a virtual environment.

b. Unpacking the complexity in sugarcane production systems

Land has been identified as one of the major constraint for energy production in Mauritius. The total land and elasticity of arable land available determines the land available for sugarcane production. The cause-and-effect relationships are demonstrated in Fig. 1. The conversion rate from sugarcane land to other land use can be increased by the reduced sugarcane market price given that farmers will be reluctant to invest their time and money on an unlucrative and unviable farming practice. This can thus increase abandoned land and other land uses such as land for infrastructure development depicted as tourism land. The causal loop on Fig. 1 illustrates Policy interventions, such as provision of incentives to farmers, derocking farming practise coupled with increased desired land for sugarcane production. This shows the possibility of retaining or increasing the conversion rate from other land use to agriculture thus increasing land for sugarcane production and reduced abandoned land.

The land use for sugarcane is a key factor determining the total yield for sugarcane production. There are other factors that influence production among which includes water availability which can influence the yield rate and subsequently the total yield production. Policy intervention in the form of improved mechanisation,

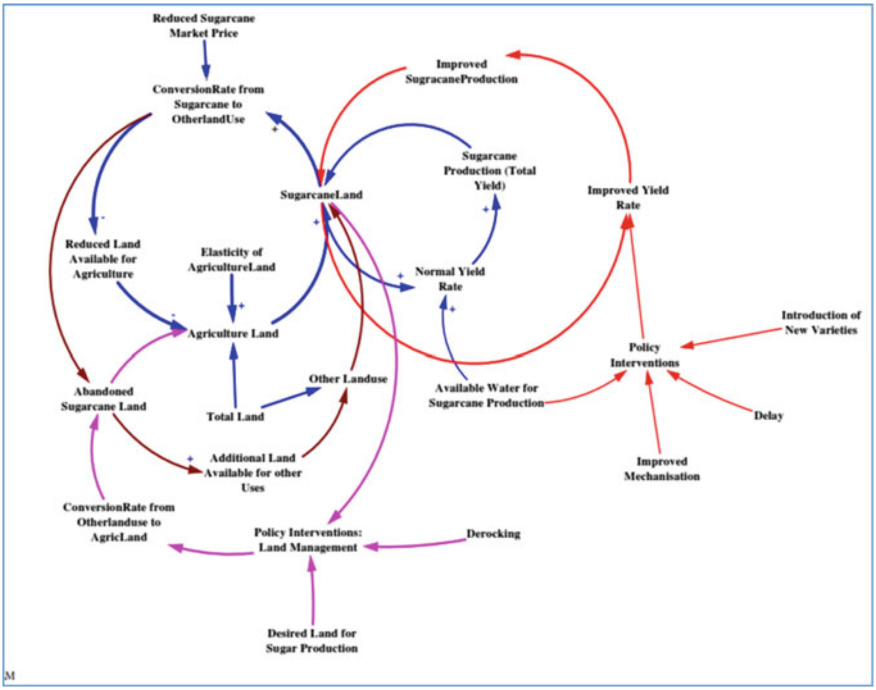


**Fig. 1** Causal loop diagram for land and sugarcane production

introduction of new crop varieties can improve the yield rate subsequently improving the sugarcane production.

Illustrated in Fig. 2, high sugarcane yield with green harvesting technologies imply good supply of sugarcane processing waste such as trash and offcuts. In addition, increased cane processing lead to the production of more sugar and other by products, such as Bagasse. Increased production of bagasse positively affects available stock for electricity generation and an increase in power generation. Bagasse availability can attract capital investment in electricity generation, hence increased power generation. There are other exogenous factors in electricity production among which includes technology costs and maintenance costs. Supply of bagasse and trash feedstock is limited to the crop season. The more the feedstock to meet the desired feedstock for electricity generation the more the chances to preserve the feedstock inform of briquettes. The higher the briquette production the more the electricity generation off crop season period. Apart from feedstock supply, exogenous factors for electricity production may include among others moisture content.

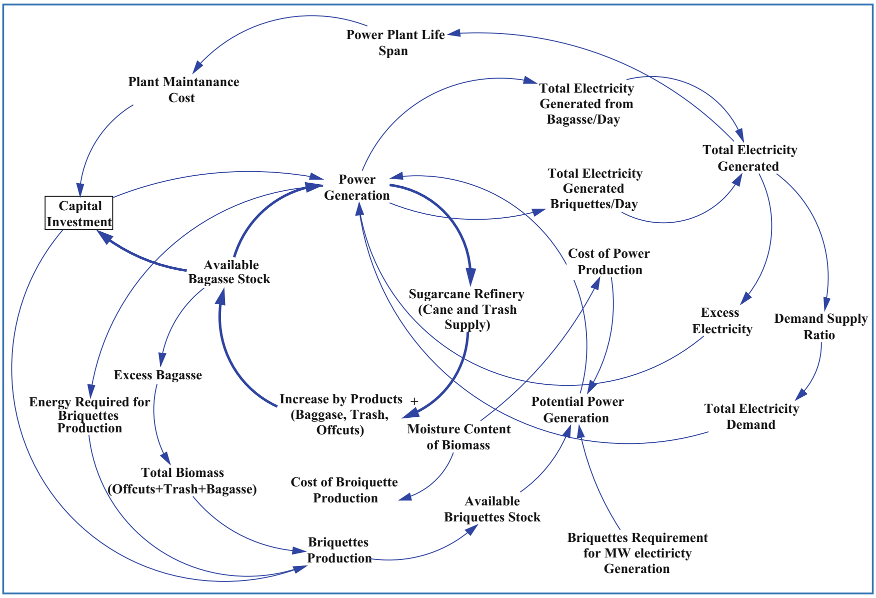


**Fig. 2** Complexity in electricity production systems

# 3 Model Development

Based on the above premise system dynamics models were developed to optimise electricity value of the sugarcane production system in Mauritius. Figure 3 presents the models assumptions and boundaries. The next section provides the key assumption and the constructional elements of the model.

A. The Main Assumptions and Constraints of the Model

The model assumes a homogeneous landscape when simulating the land use change dynamics. The spatial variations on the landscape are not taken into consideration hence the production of sugarcane is influenced by the area under cultivation. The land available for sugarcane production is controlled by the total area under cultivation. A percentage of arable land is used for sugarcane production, however the changes in land use or total arable land might vary with increase in other crops. Since this study was undertaken for the entire Island, the threshold of sugarcane area has been based on the highest area under sugarcane production of 78,000 ha.

This study extracted the electricity production process requirements and parameter estimates from a previous study by Ramjeawon (2008) on life cycle assessment of sugarcane production systems in Mauritius (Fig. 3).

Based on the input data, electricity production process requirements and constraints, the following section describes the constructional components of the demonstration model.

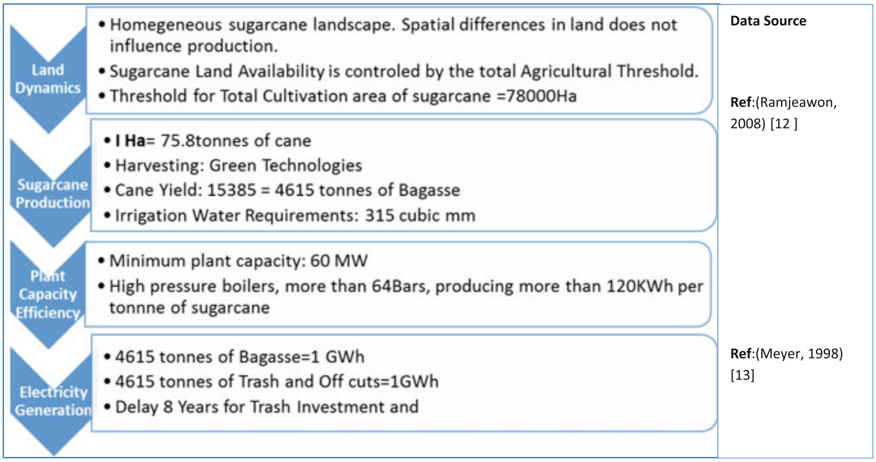


**Fig. 3** The main assumptions and constraints of the model (Meyer 1998; Ramjeawon 2008)

B. Constructional Components of the Demonstration Model

I. Land and Biomass Production Sub Model

Essentially this sub model takes recognition of the land use changes which have been identified as one of the major constraining factor in Mauritius's sugarcane and bio-fuel production sector. Most importantly the sub model captures the competing priorities on land resources and the implications thereof. The changing land-use patterns are related to the total cane production and the subsequent bagasse output as feedstock for energy production. The rate of conversion of one land use to the other is also taken into account. While other studies have used land use parameters (Musango et al. 2012) they did not evaluate the impact of changing land use on production potential. This sub model also incorporates other resource constraints, such as water and climate, which have already been captured in previous studies on the CLEWS framework (Howells et al. 2013; Welsch et al. 2014). The sub model allows for investigating policy implications, such as the reformation of the sugarcane sector in Mauritius (Mutanga 2013). Population dynamics have also been taken into account since they influence settlement, food crops, and livestock requirements.

II. Harvesting and Electricity Feedstock Supply Sub Model

This sub model primarily focuses on building scenarios for preservation of sugarcane waste, in particular bagasse and trash. The sub-model infuses the green technology options that can be undertaken to ensure better utilization of sugarcane waste. While the known by-products of sugarcane production systems include ethanol, steam and electricity, this study focuses on electricity generation, since the potential of ethanol has already been captured in previous studies (AIEA 2011).

III. Electricity Generation and Technology Sub Model

The sub model takes into account technology efficiency as a critical factor for optimum electricity production (Mbohwa 2009). The effect of cogeneration is modelled in this sub model. The sub model builds scenarios comparing bagasse feedstock based plants including trash and offcuts feedstock, taking into account other competing priorities for these feedstocks.

IV. Bio-fuel Environmental and Profitability Sub Model

The sub model takes into account the potential environmental benefits. Essentially it models the emission avoidance based on the total annual sugarcane based electricity generation. In particular predictions focus on carbon dioxide and Sulphur dioxide avoidance based on the total annual electricity generation potential. The four sub models were constructed with the aid of systems dynamics software (STELLA). The next section report on a number of scenarios that were generated to guide decision-making.

## 4 Selected Model Results

(a) Modelling the effects of land use change dynamics on the current and future potential of cogeneration
From the Systems Dynamics model two scenarios were generated. Figure 4 illustrates the business-as-usual model compared to the alternative scenario. The results indicate that the business as usual (BAU) scenario is a gloomy picture for the sugar industry of Mauritius, characterised by continued decline in land for sugarcane production.

The depicted decline illustrated on Fig. 4(a) is likely to continue if no intervention policy measures in the sugar industry are put in place. Rapid population growth and growth of other sectors, such as tourism, result in conversion of agriculture land to other land uses. Projections show a decline to less than 55,000 ha by 2035 if no or little intervention measures are put in place. However policy interventions in the form of de-rocking (Deepchand 2005) incentives to farmers need to be intensified to help protect the sugarcane farmlands on the island. Although land used for other developmental priorities, such as infrastructure development cannot be reclaimed for sugarcane production, there is room for optimising the available land resources. As illustrated on the alternative scenario [see Fig. 4, Alternative Scenario (AS)] abandoned land can be reduced to almost 300 ha by 2025. Further research is key to ensure development of optimum land use strategies for the island to contain the threatened sugarcane land from other competing priorities. These efforts will reduce the increasing abandoned sugarcane land irrespective of the drop in sugar market price and other competing priorities, which have been identified to be an indirect factor in reducing the sugarcane land.

**Land use change dynamics and sugarcane production**: From the Systems Dynamics model two sugarcane production scenarios were generated. Figure 5 illustrates the business-as-usual model compared to the alternative scenario. The BAU on Fig. 5, illustrates a continued decline in sugarcane production to as little as just above 55,000 tonnes by 2035. This is not only a threat to the sugar industry but also the energy sector which has been relying largely on contribution

**(a) Business as Usual (BAU)** **(b) Alternative Scenario (AS)**

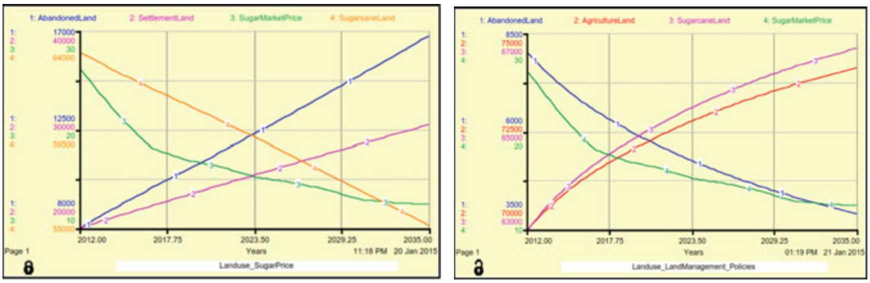


**Fig. 4** Land use change dynamics

**(a) Business as Usual (BAU)** **(b) Alternative Scenario (AS)**

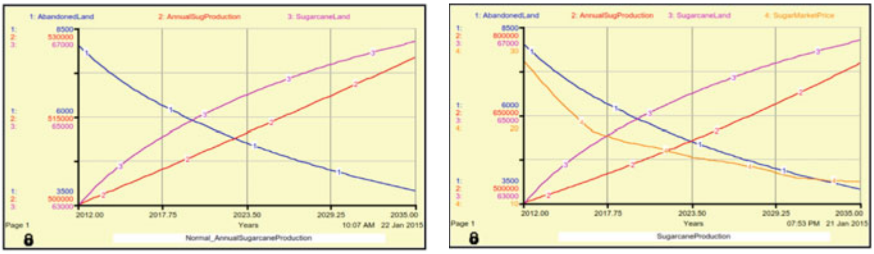

**Fig. 5** Land use change dynamics and sugarcane production

of bagasse derived energy production mainly from the Independent Power Producers within the island. However the alternative scenario with intervention measure indicates that the highest recorded sugarcane production can still be achieved by 2025 through policy interventions. While production of sugarcane is not dependent on land only, other variables may also improve yields, such as climate factors, improved mechanisation, change of crop varieties and improved fertilisation. Monitoring and forecasting crop growth can aid in ensuring optimum yield production in the sugar industry.

(b) Determine the potential threshold of sugar systems as an energy source.

From the Systems Dynamics model two feedstock supply scenarios were generated. Figure 6 illustrates the business-as-usual model compared to the alternative scenario. The current generation is mainly based on bagasse as a feedstock. The business as usual scenario illustrated in Fig. 6 anticipates a continuation of this trend. Assuming the current feedstock supply is retained, the business as usual shows an increase in bagasse derived electricity to above 400 MW per annum by 2035. However this scenario is also dependent on the constant supply of sufficient feedstock (bagasse).

As indicated in Fig. 6, the alternative scenario projects that Bagasse and Trash derived electricity can contribute close to 500 GWh per annum by 2035 with strong policy interventions. This entails investment in trash and offcuts processing for

**(a) Business as Usual (BAU)** **(b) Alternative Scenario (AS)**

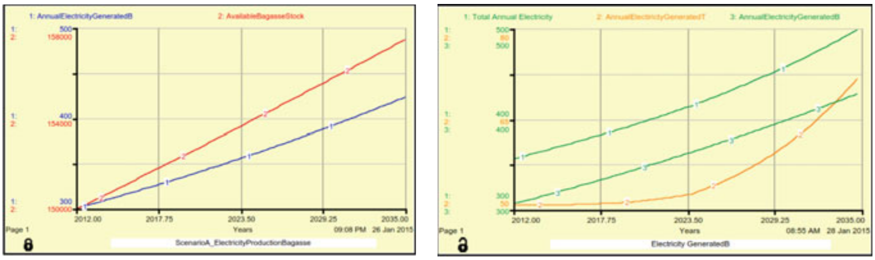

**Fig. 6** Bagasse and trash electricity generation potential

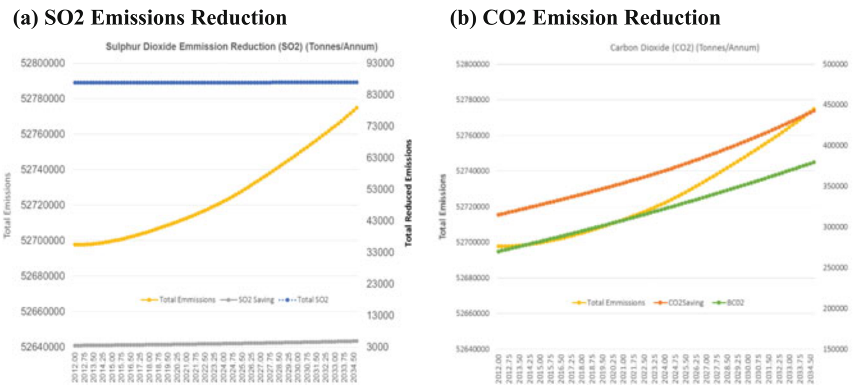


**Fig. 7** Emission avoidance from sugarcane derived electricity production

optimum electricity from sugarcane production systems. The contribution of trash and offcuts as feedstock is only anticipated to take off 3 years from the time of this writing for this has been tried and tested in countries such as Brazil. Optimisation of electricity production can also be attained through improved technology. Some of the technological considerations could include but not limited to: improving steam conditions (Mbohwa and Fzweie 2002) making use of lower grade vapour for hearting purposes, improving boiler efficiencies, as well as replacement of steam driven mill drivers with electric DC motors (Mbohwa 2009).

Investment in bio-derived electricity generation can achieve more than 400,000 $CO_2$ tonnes and over 83,000 $SO_2$ tonnes of avoided emissions by 2025, as illustrated on Fig. 7(b) and (a) respectively. This illustrates the environmental benefits that can be accrued from optimising energy produced from the sugar based industrial systems.

## 5 Conclusion

The simple system dynamics model of land use change, sugarcane production, harvesting and electricity production from bagasse and trash presented in this study demonstrates the ability to simulate scenarios for bagasse and trash derived electricity generation in Mauritius. The developed model reveals insights into electricity generation from the sugar industry, 'what if' scenarios. The 'what if' scenarios evaluate the sensitivity of the system to important and realistic alterations in those factors driving not only land use change, but also the electricity generation production process and positive environmental spinoffs. Among the insights gained, the study showed that effective policy interventions and capital investment on technological development can optimise the electricity value of sugarcane production systems throughout the simulation period.

This work provides a good foundation for further research of the energy systems of not only small developing islands but most of the developing countries. Mauritius, while more advanced than most African countries in terms of sugar based electricity generation, is not alone in its trials to ensure energy security and drive towards a low carbon future and reduced importation and use of fossil fuels. The systems dynamics approach presented here provides a basis for further analysis of electricity generation and the various conversion pathways from sugarcane production to electricity production taking into account some of the limitations highlighted in this model.

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