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# An integrated approach for modeling the electricity value of a sugarcane production system

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## HIGHLIGHTS

- Electricity value of a sugarcane industrial ecosystem is modeled using a SSD model.
- Bagasse and trash can provide highest efficiency in electricity generation.
- Projected bio-derived electricity generation can substantially reduce emissions.
- Proposed approach broadens the understanding of bio-derived electricity generation.

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## ABSTRACT

The spatial system dynamics model (SSDM) of sugarcane industrial ecosystem presented in this paper is towards an integrated approach to simulate a bio refinery system suggesting directions for bagasse and trash-derived electricity generation. The model unpacks the complexity in bio-derived energy generation across the conversion pathways of the system from land use change, sugarcane production, and harvesting and electricity production amid a plethora of challenges in the system. Input data for land use and sugarcane production in the model were derived from remote sensing and spatial analysis. Simulated and validated results indicate that the alternative scenario of combined bagasse and trash with enhanced mechanisation and technology efficiency provides the highest efficiency in terms of electricity generation and emission avoidance compared to the business as usual or base case scenario. The applied SSDM demonstrates that modeling of feedback-based complex dynamic processes in time and space provide better insights crucial for decision making. This model provides a foundation for the broader study for cost benefit analysis of electricity production from a sugarcane industrial ecosystem.

## 1. Introduction

The increasing demand for biofuels and bio-energy has motivated the use of lignocellulosic materials as feedstock [1,2]. Sugar cane, grown widely in African countries including Mauritius, is known to be one of the most productive species in terms of its conversion of solar energy to chemical potential energy [3,4]. However the sugar industry faces a plethora of threats, challenges and complexity in bio-electricity generation hindering the deployment and diffusion of this technology option on large scale. Among these has been the decline in sugar prices, which witnessed the reformation of the sugar industry in countries such as Mauritius, and inefficient production plants [5], which have stalled the potential of sugarcane in electricity generation. The situation has been worsened by massive competing priorities for land and water resources [6], which are required for biomass production. The latter has also witnessed debates over food security versus energy over the past decades [7]. More-so many projects have been blamed for undermining the social and environmental equity promises of biofuels development [8]. Others fear that such development could undermine ecological systems and traditional egalitarian land use in many African countries, which could lead to greater vulnerability for the majority of the population [9]. In some instances macroeconomic factors, and inadequate regulatory regime, and land

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policies such as the case of Zimbabwe have subsequently affected the sugarcane production trends [10]. The array of factors highlighted is not only a cause for concern to the sugar industry but have a significant bearing on the feedstock required for electricity or biofuel generation. Let alone the aforementioned challenges demonstrate that bio derived energy encompasses a highly heterogeneous set of socio-technical systems (land, water, energy, finance and human capital) [11] each requiring different structures in production, distribution and consumption as well as financial relationship therein. In every sector, there are different requirements for human resources, know how, natural resources and capital [11,12]. Concurrently planning, decision and policy making often occurs in separate and disconnected institutional entities [6,13]. As such often the analytical tools used in support of the decision making process are equally fragmented [13].

Commonly used tools for energy analysis include MESSAGE [14], MAKRAL [15], and ETP TIAM [16] and LEAP [17,18] Models. For water resources analysis WEAP [19] is often used. The models however tailored to focus on specific aspects of the energy systems hence they lack components required to conduct integrated policy assessment [6]. The focus of the models is on one resource ignoring the interconnectedness with other resources. According to Loulou [16] existing models assist with scenario analyses that are impractically long term. The CLEW modeling framework propounded by Welsch et al. [20] attempted to respond to this issue. However the framework heavily depends on the aforementioned individual models described above. Approaches such as Life cycle assessment [4,21], and eco-efficiency [22] of bio-refineries have also responded to the aforementioned interconnected challenge. Lessons drawn include the fact that trash and bagasse can enhance or maximise electricity production sufficient to meet industrial phase demands. However the work does not show feedback based complex dynamic processes which are critical for decision making for sustainable future expansion of sugarcane based electricity production [2] if not second generation ethanol [23]. This paper demonstrates how this interconnectedness and complexity challenge can be addressed using spatial systems dynamics approach. Closely linked to this is the work of Ahmad and Simonovic [24] and Scheffran and Hannon [25], who modeled feedback based complex dynamic processes in space and time. While Scheffran and Hannon study focused more on high yield perennial grasses, no study focused on the complexity and feedback processes around the conversion pathways from biomass production to electricity production and the net environmental benefits thereof, on sugarcane production systems.

This paper seeks to demonstrate the electricity value of sugarcane production systems using an integrated model based on systems dynamics and spatial analysis to:

- Examine the effects of land use change dynamics on the current and future potential of cogeneration.
- 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.

In order to demonstrate the usefulness of the model and its user friendliness in decision support, it is applied in Mauritius' sugarcane industrial ecosystem to provide insights for other emerging economies. Not only does this decision support tools aid in broadening the understanding of electricity generation but provide ways of enhancing the energy value of sugarcane production systems in an integrated manner.

The remaining content of the article is structured as follows. Section 2 provides background context on Mauritius and its energy sector landscape. Section 3 presents the input data, requirements and constraints for the systems dynamics demonstration model. Based on the requirements, Section 4 defines the constructional components (four sub models) of the system dynamics demonstration. Sections 5 and 6 present results and a discussion, concluding in Section 7 with suggestions for future work.

## 2. Background on mauritius and the energy sector landscape

Mauritius is a small island developing nation with a total area of 1860 km$^2$ and a population of 1.3 million. Approximately 90% of the arable land is under sugar cane and produces around 600,000 tonnes of sugar a year by processing around 5.8 million tonnes of cane [4]. The sugar recovery process produces the fibrous fraction of the cane stalk in the form of bagasse, which is composed of 50% fibre, 48% moisture and 2% sugars. When bagasse is burnt, steam and electricity could be produced to meet the energy requirements of the cane sugar factory.

As in many emerging and developing economies, the energy sector has been identified as a major pace setter for social and economic development in Mauritius. Like other Small island developing states, Mauritius has limited known exploitable energy sources; hence approximately 83% of its energy is derived from imported fossil fuels in the form of fuel oil, diesel and coal. Among these, coal and oil still play a significant role and are the dominant sources of energy [26]. The principal energy needs include electricity production and transportation, and these are purported to have driven the island's economic growth. The stability of the energy sector is, however, threatened by the declining stocks of fossil fuels with ever-fluctuating prices, exacerbated by the current global financial crisis and the high cost of transportation, which make the import process very expensive.

The country's power plants are owned by either the Central Electricity Board (CEB) or private companies. Approximately 52 MW of Mauritius' 364 MW installed capacity resides as independent thermal capacity at sugar estates. CEB is currently managing Power Purchase Agreements with 5 independent power producers 3 of which employ the take or pay principle. This means CEB pays for the contractual energy amount produced by the power plant even if the energy is not dispatched. The other option for the remaining two is a negotiated part tariff model which treats plant capacity and energy charges as two different cost elements. In 2011 the Independent Power Producers produced 55% equivalent to 1337 GW h, of the total electricity consumption in Mauritius [26]. CEB estimated that peak electricity demand will grow on average by 3.5% per year in areas such as Rodrigues, and this trend will reach 8.83 MW by the year 2022. No doubt efforts and innovations in increasing the generation capacity from sugarcane will go a long way in ameliorating the energy demand. Matching the electricity demand with generation capacity forecasts shows that IPPs will still play a major role in the energy sector providing over 60% of the national demand by 2022 [26].

## 3. Input data, requirements and constraints

This study used remote sensing data and systems dynamics modeling principles. Requisite statistical data both from published and unpublished literature and documents from recognised institutions were in Mauritius were collected. Apart from statistical data, unstructured interviews with policy makers, independent power producers, academics provided an in-depth understanding and holistic view of the sugarcane industrial ecosystem in Mauritius. Subsequent to information gathering was parameterization of the major control factors influencing electricity generation in the sugarcane industrial system. These were thus considered in the model development.

### *3.1. Assessing land use change using earth observation*

Land use change dynamics was considered to be one of the salient factors that determine sugarcane production, a proxy for feedstock production. Therefore mapping and monitoring sugarcane production systems is essential in planning bio-electricity production. Satellite imagery in the form of Landsat data, with a spatial resolution of 30 m was used to depict the changes in land-use patterns. Fig. 1 illustrates the schematic framework and methodology for land use change mapping applied in this study. Essentially the images were pre-processed using ERDAS imagine software [27] to select the best images free from clouds and also for geo-referencing. Both supervised and unsupervised classifications were applied on the land cover mapping. Classification is an abstract representation of the situation in the field using a well diagnostic criteria [28]. The unsupervised classification an iterative self-organising data analysis technique (ISODATA) cited in [29] was used. This approach uses minimum spectral distance from clusters. Supervised classification uses a sample of known identity (pixels already assigned to classes) to classify pixels of unknown identity [30]. The maximum likelihood classifier was used, given that it is a well-known parametric approach based on the assumption that data may be modeled by a set of multivariate normal distributions [31]. Prospective users of maps and data derived from remotely sensed images quite naturally ask about the accuracy of the information they use [29]. Accuracy defines the correctness measuring the agreement between a standard assumed to be correct and a classified image of a known quality. In this regard a confusion matrix [29] was used to identify not only the overall errors for each category (classified land use/cover) but also misclassifications due to confusion between categories. Site specific accuracy of the classified maps relied on field based GPS coordinates and their attributes. On mapping the land use change primary focus was on changing patterns in sugarcane production land over the years 1972, 1991 and 2010.

The datasets derived from land use spatial mapping was used for modeling and simulation of the land sub model described in the later subsection of this study. The methodology applied for modeling and simulation is discussed in the next section and is grounded on systems analysis concepts and approaches.

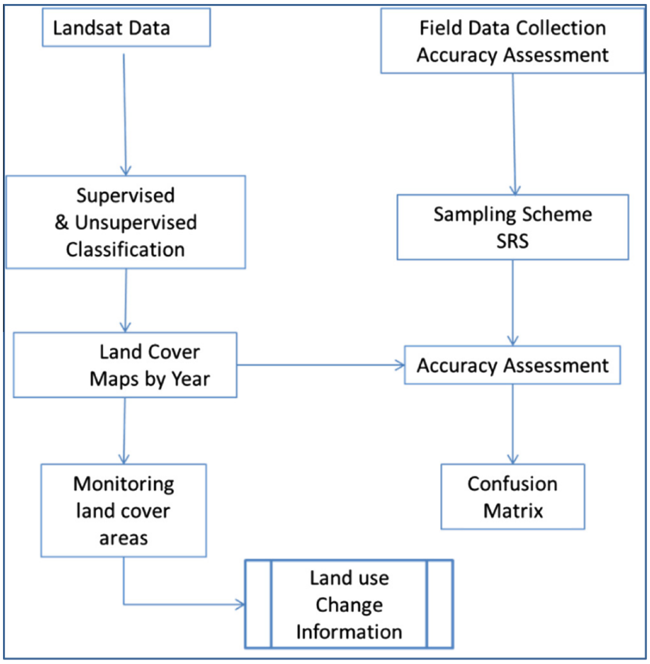


**Fig. 1.** Schematic framework for land use change mapping.

### *3.2. Systems applications and systems dynamics in energy modeling*

Systems thinking make explicit causal-effect assumptions between related variables in a system, enabling independent assessment and improvement of mental models behind particular thinking [32]. Therefore at the heart of the methodological framework for this paper is systems analysis which can be defined as a structured way of analysing complex interrelationships that are problematic or simply of interest to mankind. In this context system dynamics is observed to be one of the most suitable to analyse complex socio-economic systems, having cause and effect and feedback relationships among the variable influencing the system. Systems dynamics is epitomized by the use of causal loop diagrams which bring causal relationships between different elements of the systems. System dynamics propounded by Forrester [33–35] provides means to capture complex relationships and feedback effects within a set of interrelated activities and processes [36]. For quantitative representation of the relationships systems dynamics [37] grounded in the control theory [38] and modern theory of nonlinear dynamics [11] has been applied and represented using the stock and flows diagrams. Inputs of changing sugarcane land dynamics captured during the preceding phase are also taken into account in this phase. This follows the key principle that at the heart of systems thinking factors behind the problematic situations are interdependent, while the causal effect between these factors is often two-way, and that the impact of action is neither instantaneous nor linear. Application of system dynamics provides policy makers with a practical tool that they can be used to solve important problems [39]. System dynamics is therefore a useful simulation tool to understand the complex adaptive processes and to experiment with scenarios and policies for sugarcane production systems.

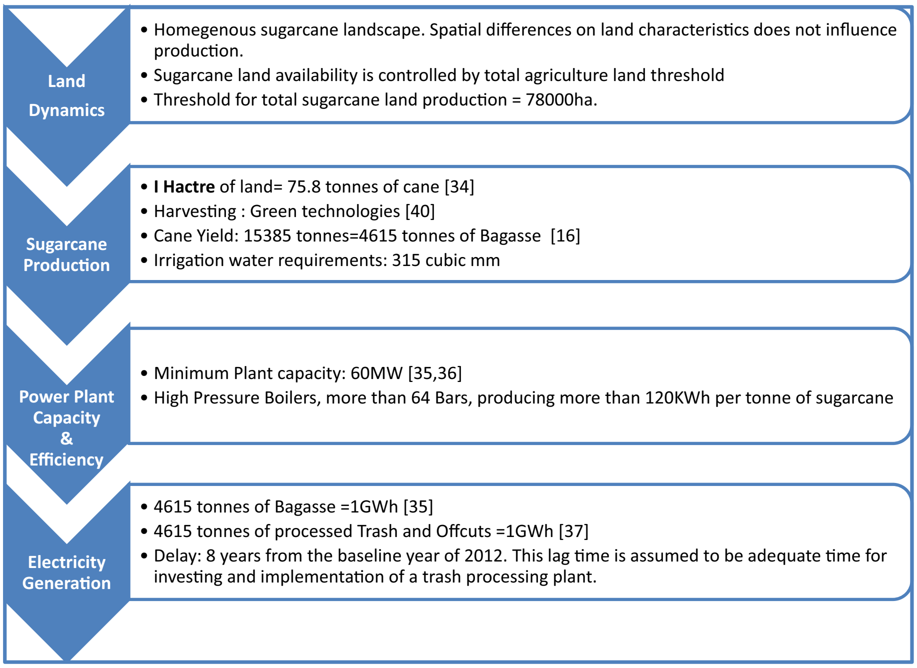
## 4. Model development

Based on the above premise system dynamics models were developed to optimise electricity value of the sugarcane production system in Mauritius. Fig. 2 presents the models assumptions and boundaries. The next section provides the key assumption and the constructional elements of the model.

### *4.1. 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 [4] on life cycle assessment of sugarcane production systems in Mauritius as illustrated on Figs. 2 and 3 respectively.



- Homegenous sugarcane landscape. Spatial differences on land characteristics does not influence production.
- Sugarcane land availability is controlled by total agriculture land threshold
- Threshold for total sugarcane land production = 78000ha.

- **I Hactre** of land= 75.8 tonnes of cane [34]
- Harvesting : Green technologies [40]
- Cane Yield: 15385 tonnes=4615 tonnes of Bagasse [16]
- Irrigation water requirements: 315 cubic mm

- Minimum Plant capacity: 60MW [35,36]
- High Pressure Boilers, more than 64 Bars, producing more than 120KWh per tonne of sugarcane

- 4615 tonnes of Bagasse =1GWh [35]
- 4615 tonnes of processed Trash and Offcuts =1GWh [37]
- Delay: 8 years from the baseline year of 2012. This lag time is assumed to be adequate time for investing and implementation of a trash processing plant.

**Fig. 2.** The main assumptions and constraints of the model [40–43].

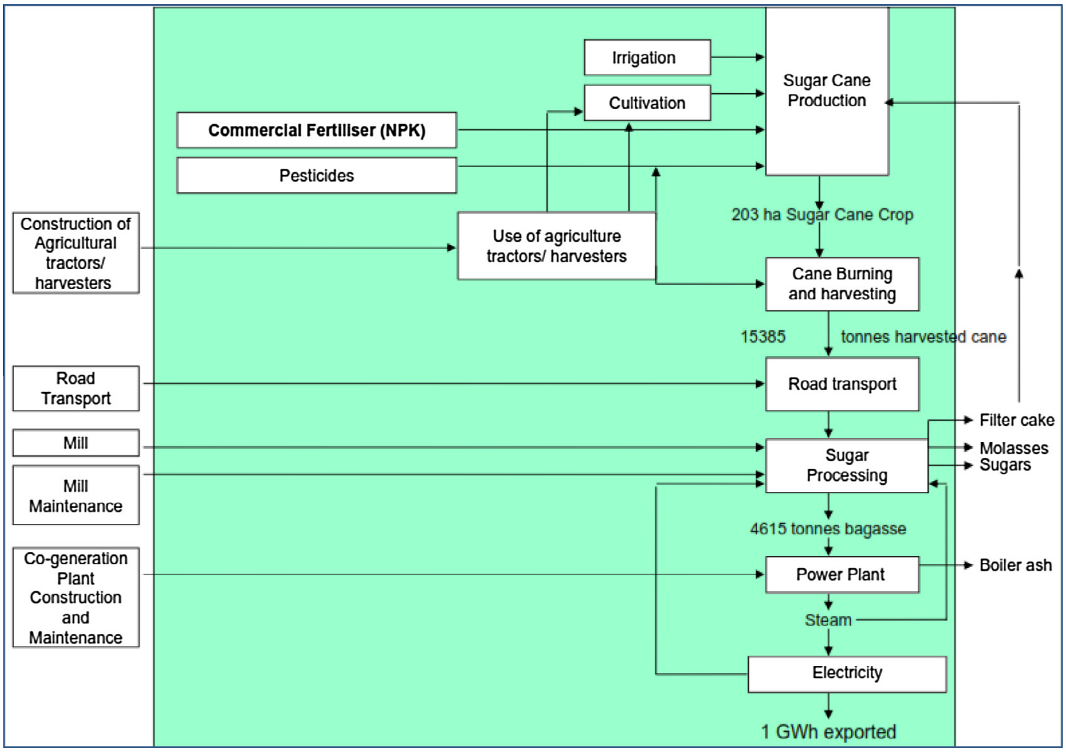


**Fig. 3.** Process flow diagram for electricity generation from sugarcane bagasse [4].

### 4.2. Parameterization for identifying major indicator/variables for the model

The spatial mapping process and estimation of feedstock provided a basis for the identification of indicators or variables for bio-electricity production. According to Hardi and Zdan [44], the selection of indicators should be based on policy relevance, simplicity, validity, availability of time series data, good quality, affordability and the ability to aggregate information. It has been evident from the validation of remote sensing component that bio-fuels production and development involves diverse actors including among others policy makers, technology developers, investors, the community and assessment practitioners [11]. Variables for the model therefore encompass heterogeneous factors which are not limited to social, economic, environmental and political factors. These factors display characteristics of a complex system. The inter-connected sectors and variables provided a basis for the development of a multi-paradigm energy model using spatial systems dynamics. Table 1 illustrates some of the identified variables for the constructional components of the SSDM.

The variables identified were used for mental modeling capturing the feedback relationships between the variables and represented them using causal loop diagrams. The next section provides the constructional components of the model and how the identified parameters have been interlinked.

### *4.3. Constructional components of the spatial systems dynamics model*

The model is divided into three key sub components namely land use change dynamics, sugarcane production, and feedstock supply-electricity generation. The first section presents the qualitative dimension through causal loop diagrams and infers or considers some quantitative aspects as it describes the linkages between the selected variables. This followed, by the quantitative dimension represented through stock and flow diagrams and the contribution of the stock and flow in the systems dynamics model.

### *4.4. Mental modeling: the use of causal loop diagrams*

This section presents causal loop diagrams a technique for mapping feedback loop structure of a system. The polarity of the feedback loops is labelled using either positive feedback loops also known as reinforcing loops and are denoted by a+ or **R**, while negative loops sometimes called balancing loops are denoted by a− or **B**. The determination of loop polarity is basically the calculation of what is known in control theory as the sign of the open loop gain [45]. The term gain referring to the strength of the signal returned by the loop. The identified sub sectors of the model are deemed sufficient to provide an illustration of the complexity in bio-electricity production. To note causal diagrams can never be comprehensive, neither are they final but they evolve and improve understanding as the purpose of the modeling effort evolves.

#### *4.4.1. Land use sub model*

*Land* has been identified as one of the major constraints in any bio-electricity production system. The model development classified land into two major classes of land namely agriculture and other land use for simplicity reasons. The *agriculture land* was further classified into sugarcane, land, *abandoned sugarcane land* and other crops land. The total land and elasticity of *agriculture land* available determines the total agriculture land, which subsequently determined the land available for sugarcane production. The above land categories were considered as stocks except for the total land which was considered as an auxiliary, in the model development. Essentially the model considers that with time there is land use conversion particularly from agriculture to other land use, hence the need for policy intervention to restrain the conversion rate in consideration of the need for sugarcane production land to meet the bio-electricity land demand.

**Table 1**
Selected indicator variables for the model sub-components.

*Land use sub model*
- Agriculture land
- Sugarcane land
- Abandoned sugarcane land
- Sugarcane market price
- Policy interventions
- Other land use

*Sugarcane production*
- Sugarcane land
- Total agriculture land
- Normal yield rate
- Policy interventions
- Water availability and high yield variety seed
- Fertilization, crop intensity, de-rocking
- Delay

*Feedstock supply and electricity production*
- Trash/offcuts/bagasse
- Green harvesting
- Traditional harvesting (burning)
- Preservation
- Distance to mill
- Feedstock quality
- Plant power capacity
- Steam power plant efficiency
- Boiler pressure
- Total electricity generated
- Emission avoidance

Despite the strength in modeling complex feedback processes, systems dynamics' ability to represent spatial processes is weak and cannot describe the spatial factors in the system. This sub model incorporated the cellular automata model as applied in He et al. [46] where the process of land use dynamics can be defined as an iterative probabilistic system [47], in which the probability of $P(_{x;y})$ that cell $(_{x;y})$ is occupied by a land use $(K)$ in a time $(_t)$ is a function of the concerned factors of land suitability $S(_{k,x,y})$, land policy $({}^tI_{tk})$, land use profitability effect $({}^tN_{k,x,y})$ and stochastic perturbation $(_{vt})$. The stochastic perturbation is approached from a probability point of view.

$$ {}^tP_{K,x,y} = f\left({}^tS_{K,x,y}, {}^tN_{K,x,y}, {}^tI_{K,x,y}, \upsilon^t\right) \tag{1} $$

Considering this approach, the probability that an area change its land use is a function of the aforementioned factors working together in a time plus the stochastic perturbation. The various factors are captured in the causal loops diagram presented in Fig. 5.

Fig. 4 presents a conceptual diagram indicating the causal and feedback relationships among the variables. *Sugarcane land* being a fraction of the *agricultural land*, is influenced by the conversion to other uses, and is considered as a function of its initial value and the conversion rates. The *political will* to convert *agricultural land* may reduce the decline in availability of sugarcane land through a positive feedback loop (R1). Various exogenous factors such as reduced *sugar market price* can lead to *land abandonment* or can influence the conversion of sugarcane land to *other land use* through a balancing loop (B1 & B2). Essentially the drop in market price hinges on the sugar industry as sugarcane farming becomes an un-lucrative or unviable practice. The model development considered that any increase in *other land* use reduces the *available land for agriculture* prompting the need for *policy interventions* which can ultimately provide additional land for agriculture as illustrated on balancing loop (B3). Such policy interventions may entail increasing the *desired land for sugarcane production* and thus consider *de-rocking* and provision of *incentives to farmers* increasing the conversion rate from other to *agricultural land*. The total land area is the simulation of all the sub categories of land areas and remains constant over the projected time period. The conversion rates of various land uses from one class to the other are considered as rate variables, which are functions of conversion fractions. The conversion fractions were obtained from the spatially modeled time series data and primary survey results for land area available under all the categories of land areas as depicted in the land use mapping section.

#### *4.4.2. Sugarcane production sub model*

The sub model for sugarcane production is developed by considering variables such as *available sugarcane land*, *yield rate* and various inputs influencing yield rate of sugarcane production. Fig. 5 shows the causal feedback relationship among the various variables. *Normal sugarcane production* is considered to be a function of available *sugarcane land* area for which is a part of the *total agricultural land* obtained from the land use sub model (see the reinforcing loop "R1" on Fig. 5), and the *normal yield rate*. The model considered the intrinsic yield Hertzel et al. [48]. Often there is the average yield observed as a function of the planted crop. However often the heterogeneity of the land where the sugarcane is grown influences the yield.

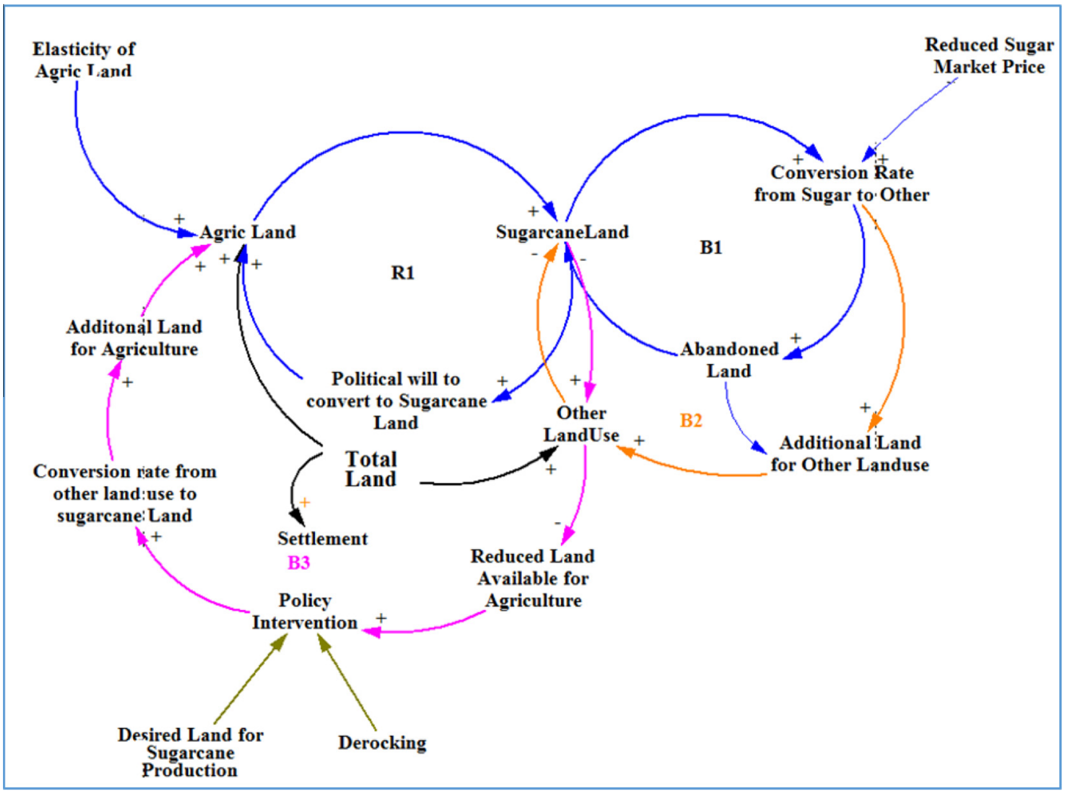


Fig. 4. Conceptual causal loop diagram for land use.

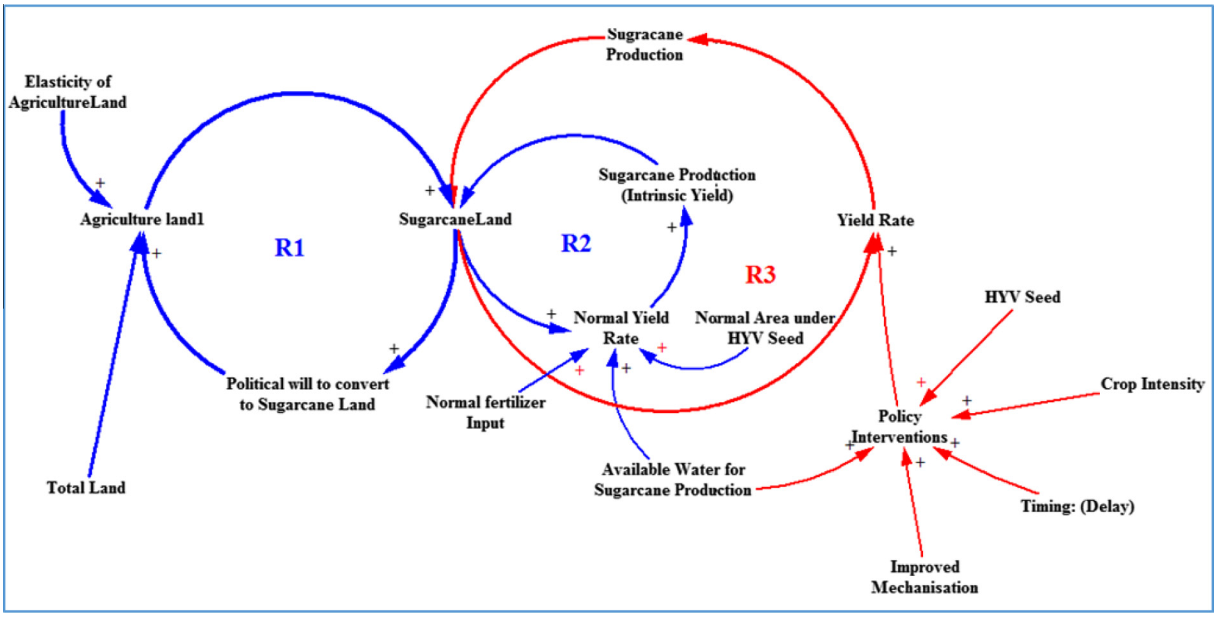


Fig. 5. Conceptual causal loop diagram for sugarcane production.

Therefore intrinsic yield is less than or equal to observed average yield. This could be represented using the following equation:

$$\bar{Y}_1 = \check{Y}_1 S_{\text{sugarcaneland}}^{\wedge 2.} \cdot S^{\wedge 1} \quad (2)$$

where S sugarcaneland is the share of sugarcaneland in total agriculture land

$S_1$ = share of land use in sugarcaneland

$\bar{Y}_1$ = observed average yield for land use

$\check{Y}_1$ = calibration parameter to match historical data on land use.

From the above equation everything on the right hand side are observed data except for $^{\wedge 2}$ and $^{\wedge 1}$.

These parameters are correlation co-efficiency parameters informed by the historical data on yield. The normal yield rate is dependent on the inputs such as *normal fertilizer input* and *normal* *area under high yield variety* (HYV) seeds. However, under the normal circumstances as a gradual reduction of *agricultural land* available for agricultural crop and with no enhanced inputs in other variables, the production is also expected to decline (see the reinforcing loop "R2" on Fig. 5). *Policy interventions* advocating for enhancements on these variables are necessary to improve the sugarcane production. *Improved mechanisation*, inputs in *fertilizer*, *increased crop intensity* and bringing a larger area under *HYV seeds* individually and compositely has a positive feedback loop characterized by a positive influence on the *yield rate*, which in turn increases the *total production* (see reinforcing loop "R3" in Fig. 5).

Similarly, an increase in *crop intensity* and in *the political will* to convert to *agricultural land* will increase the availability of *agricultural land* and *sugarcane land* respectively (R1) for production and thereby influence the *total sugarcane production* (R2) positively. Furthermore, as the production increases there will be an increase in the inputs through their feedback relations among the sugarcane production and the causal variables (R3). Thus, as understood from the causal feedback relationships, *policy interventions* which can be referred to as "*political will*" in the form of an increase in *fertiliser input* through *government subsidies*, incentives for an increase in area under *HYV seeds* and an increase in the *cropping intensity* are essential for improving the agricultural production and therefore are considered in the model. At the same time a *delay* in implementation can have a positive influence on policy intervention. The delay effect is also incorporated in the model as they practically influence the system.

### *4.4.3. Feedstock supply and electricity production sub model*

A key consideration for the feedstock supply and electricity generation sub-model is that *bio-electricity* generation is heavily dependent on the availability of *feedstock supply*. Essentially the feedstock in sugarcane production systems can be in the form of *bagasse*, *trash* or *offcuts*. Generation of electricity can be from either a combination of these though it's often *bagasse* in most sugar based electricity generation plants. The availability of the feedstock depends on the way the sugarcane is harvested, be it *green harvesting* processes which do not burn trash in the field, or the *traditional burning* of trash. There are quite a number of exogenous factors for consideration in the generation of electricity, spanning from technological to economic considerations. The sub model took into account the physical properties of the feedstock in terms of the *calorific value* of the *bagasse* and possible processing and *preservation* of the feedstock as described in Alena and Sahu [49]. In the model this has been captured as briquetting a way of preserving biomass waste. The technological efficiency took into account factors such as the effects of *boiler pressure* on *steam power plant efficiency*, and *plant power capacity* as described by Mbohwa [50]. The foundation of the sub model is based on the availability of feedstock supply.

Fig. 6 illustrates the conceptual diagram indicating the causal and feedback, relationships among the variables. Feedstock supply heavily depends on the available *sugarcane production* as determined by the causal loop (R1). Assuming that the often-used *traditional harvesting* approach of burning is used, factors such as *distance to the mill* and transportation of the sugarcane may influence the available generated feedstock i.e. bagasse at the milling plant. The generation of electricity using *bagasse* as a feedstock also has its array of requirements among which may include *bagasse quality* in terms of *moisture content.* The *moisture content* influence the *bagasse electricity* production for the standard required moisture is 50% implying the higher the moisture the lower the total electricity generated., Lower cost of production may positively influence investment in trash and offcuts processing thereby increasing trash and offcuts supply for electricity generation. On the other hand lower *cost enhances bagasse* electricity production. Cost can also positively influences the p*lant capacity* and *plant efficiency* which in turn can positively influence the *total electricity production*. These requirements can positively influence the *total amount of electricity* generated from the bagasse. An increase in electricity generation can positively influence the net profit of the technology option in terms of *emission avoidance* and cost of electricity thus promoting more *sugarcane production* as shown on the reinforcing loop (R2).

With green harvesting technologies [40,51] high *sugarcane yield* imply additional supply of feedstock in the form of trash and offcuts at the sugarcane processing mill. In addition to the factors discussed above on *bagasse feedstock*, processing trash and offcuts may require additional *investment* for processing these. Among the various options, the *trash* and *offcuts* could possibly be processed into briquettes. Briquettes can then be used to produce electricity adding more value to the total generated electricity at a plant thus closing the loop (R3). In essence the more the *feedstock supply* the higher the likelihood of *electricity generation* at the plant. Other variables that influence the supply of *bagasse* and *trash feedstock* includes the crop season and such have not been shown in the causal loop diagram.

The model built and its simulated results were validated using Sterman's approach, which considers validation as a continuous process of testing and building confidence in the model [45]. No model can be validated using a single test. Similarly the study applied structural, behavioural as well as behavioural structural tests [39]. This was done to test if any structural flaws exist in the model, and that the model does not contradict the knowledge of real systems [33,52]. This was followed by algorithm examination of their correctness. The model was then also validated against the observed trends as suggested by Forrester [34], Kumar [53], Welch et al. [54]. The built scenarios were also compared with results computed using other energy models such as LCA [4]. The next section provides the results of the changing land use patterns for Mauritius as this provides some of the spatial co-efficiencies used in the model.

## 5. Landuse change results and discussion

The first set of results presented provides the changing spatial dynamics in relation to the production trends over the years (see Fig. 7). This is followed by scenario building looking at the potential electricity generation threshold and the environmental benefits accrued from increasing electricity generation from sugarcane feedstock.

Sugarcane production land declined steadily from over 80,000 ha during the 70s to nearly 65,000 ha in 2010. This has been in-line with the country's diversification strategy first into manufacturing, and second into services sector during the 90s [45]. The decline had no systematic correlation with sugarcane production as shown on the graph of Fig. 8 [46]. The sugarcane production has been irregular as it is highly dependent on vagaries of nature. The drought of 1999 which affected the sugarcane yield could help explain this other than the change in hectorage for sugarcane production. The reformation of the sugarcane sector witnessed a decline in sugar refineries from a total of 19–11 in 2004. The fluctuations indicate that there are a number of exogenous factors that contribute to the irregular sugarcane production trends.

Notable is the discrepancy between the different figures for 2001 because not every hectare under sugar cane cultivation is harvested every year. This long term decline in hectares harvested is due to urbanisation encroaching on agricultural lands. At the same time the rockiness in some 40,000 ha of sugarcane lands hinders the adoption of advanced mechanisation in sugarcane production systems.

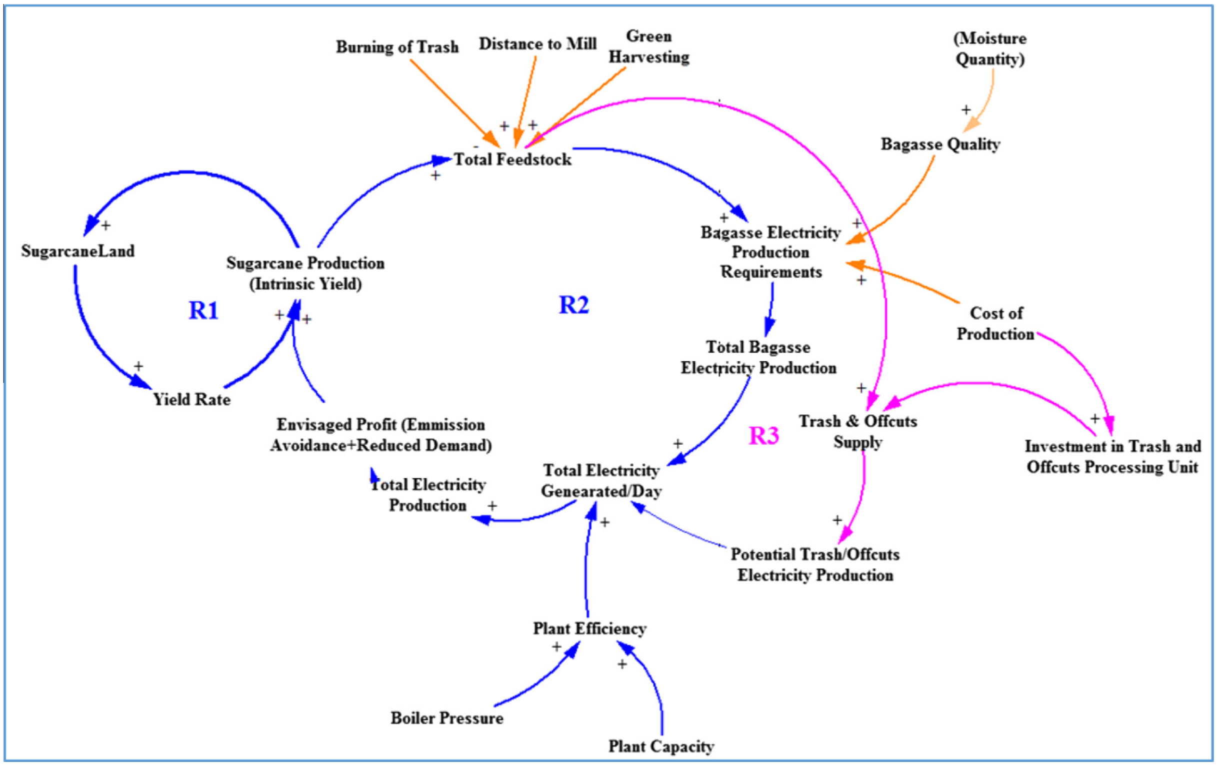


**Fig. 6.** Conceptual causal loop diagram for feedstock supply and electricity production.

To note is the abandonment of sugarcane production land. Approximately over 5000 ha have been abandoned during the last few years. The continued declining trend is a threat to the current co-generation given the risk of limited bagasse supply. While Mauritius Sugar Research Institute has noted this as an unwelcoming trend for Small Island states like Mauritius, which import most of their foodstuff to ensure food security, let alone there is a growing concern over the need for sustainable energy solutions. More-so Mauritius' GDP per capita share of the sugarcane sector has fallen from over 25% to 3.5% [56].

## 6. Simulation results and discussion

This section simulates and forecast the sugarcane industrial ecosystem complexity for the period 2012–2035 for Mauritius under different scenarios. The forecast across the different sub sectors is based on the causal effect of influential factors. Section 6 illustrates the effect on land use change dynamics. The graphical illustrations are followed with a description of the various scenarios.

### *6.1. Land use change dynamics*

The effects of land use change dynamics on the current and future potential of cogeneration is presented in three scenarios, namely, business as usual, alternative and the pessimistic scenarios. Fig. 9 depicts the different scenarios for land use change.

The business as usual (BAU) scenario in Fig. 9 shows a gloomy picture for the sugar industry of Mauritius, characterized by a continued decline in land for sugarcane production. The depicted decline from the simulation is likely to continue if no intervention policy measures in the sugar industry are put in place. With rapid population growth and growth of other sectors, such as tourism, continued conversion of agriculture land to other land uses is unavoidable. Projections show a continuous decline of land and reduction to less than 55,000 ha by 2035, if no or little intervention measures are put in place.

The alternative land use (AL) scenario in Fig. 9, simulates policy interventions in the form of de-rocking [57], and intensified incentives to farmers to protect the sugarcane farmlands in the island. Although, land converted from agriculture to other developmental priorities, such as infrastructure development cannot be reclaimed for sugarcane production, there is room for optimizing the available land resources. As illustrated on the alternative scenario alarming rates of abandoned land can be reduced. With good intervention measures the sugarcane industry may retain some of its land for sugarcane production purposes. Among the possible land retained is abandoned land, which is predicted to decline up to less than 4000 ha by 2025. Retaining abandoned land may contribute to an increase in sugarcane land of more than 70,000 ha by 2025. However the simulated threshold is not more than 75,000 ha, which is far less than the original sugarcane production land envisaged to be over 85,000 ha more than four decades ago (illustrated in Fig. 8). The construction sector is deemed to increase the infrastructure developed areas over the years.

The pessimistic scenario illustrated in Fig. 9, indicates a decline in abandoned land to less than 4000 ha. Sugarcane production land and agriculture land may decline too over the years and the expense of built up areas which is projected to reach over 40,000 ha by 2035. Despite effective intervention measures to reduce abandoned land as alluded to in the alternative that the island imports most of its food stuff from abroad. This explanation is in light of the controversial debate around food vs. energy security, coined by many scholars as the debates of first generation feedstock and second generation feedstock.

The next section provides scenarios for land use change dynamics in relation to actual crop production. In other words this provides the potential effects of land use change dynamics on the current and future potential feedstock supply for cogeneration.

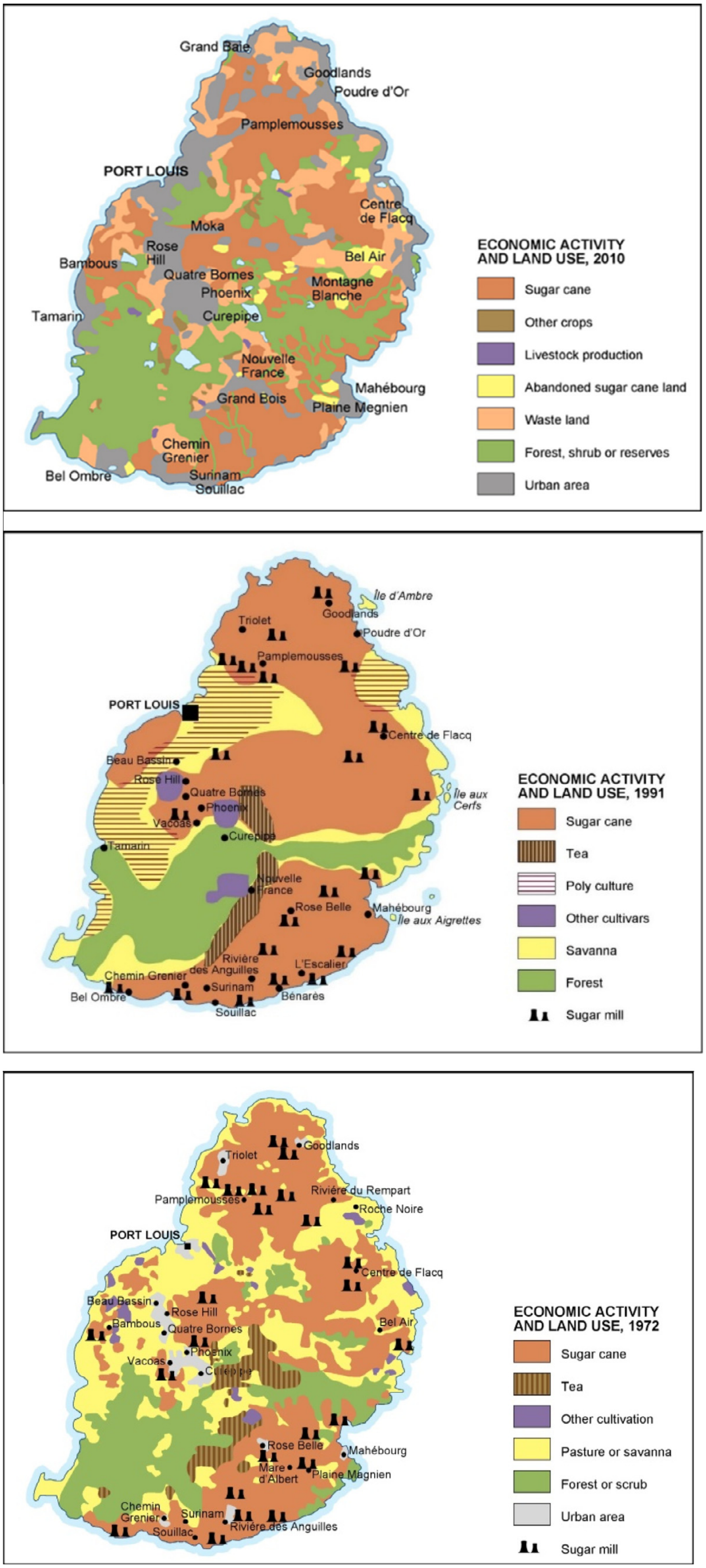


**Fig. 7.** Land use change maps for Mauritius between 1972, 1991 and 2010 [55,56].

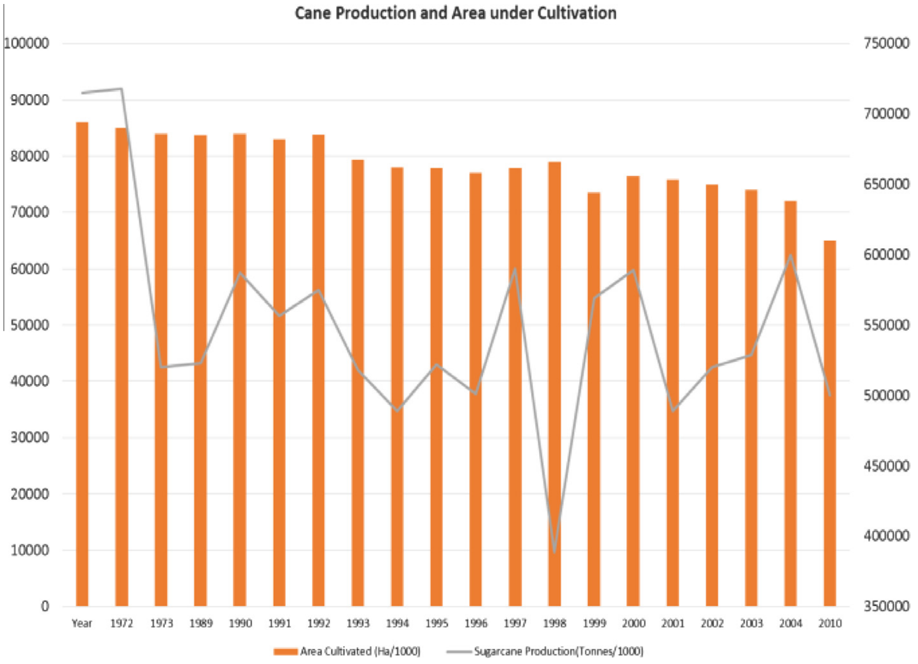


**Fig. 8.** Mauritius' total annual crop area and annual sugarcane production.

### 6.2. Scenarios for sugarcane production and land use change dynamics

The simulated scenarios partially respond to the first objective of examining the effects of land use change dynamics on the current and future potential feedstock supply for cogeneration. The effect of land use change dynamics has an influence on the dynamics in sugarcane production. This is based on the premise that land is one of the key factors required for ensuring supply of electricity production feedstock. The current and future potential of sugarcane supply required for producing feedstock needed for cogeneration is presented in three scenarios, namely, business as usual, alternative and the pessimistic scenarios.

The business as usual scenario in Fig. 10, illustrates a continued decline in sugarcane production to as little as just above 45,000 tonnes by 2035. This is not only a threat to the sugar industry but also the energy sector, which has been relying largely on the contribution of bagasse derived energy production. This decline is in tandem with the declining sugarcane production land and increased use of land for infrastructure development.

However, the alternative scenario in Fig. 10 indicates that the highest recorded sugarcane production of 580,000 tonnes can still be achieved by the year 2028 through enhanced policy interventions. More-so the projections also anticipate a rise beyond 600,000 tonnes by 2035. While production of sugarcane is not dependent on land only, other variables, such as, climate factors, improved mechanisation, change of crop varieties and improved fertilization have been considered as key factors that can improve yields. This alternative scenario factors take into account the need for monitoring and forecasting crop growth to aid in ensuring optimum yield production as explained in Section 4 for the good of the sugar industry.

The pessimistic scenario illustrated in Fig. 10 indicates a slow growth in annual sugarcane production from 50,000 tonnes with a marginal increase of not more than 15,000 tonnes over the 23 year period. Despite the policy interventions, the higher demand of land for other uses, such as infrastructure developed land, may outweigh the sugarcane production threshold. This scenario is characterized by a decline in sugarcane land to nearly 45,000 ha.

### 6.3. Scenarios for feedstock supply

Feedstock availability depends not only on the overall sugarcane production modeled in the previous sub-model, but the harvesting techniques also contribute to the type and quantity of feedstock. This sub-model primarily focuses on building scenarios for the 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. The simulated scenarios presented in Fig. 11 are based on green harvesting and traditional harvesting the latter involves burning trash in the field. This therefore provides a consolidated response to the first objective of the SSDM demonstration which seeks to *determine the future potential of feedstock supply for cogeneration*. Essentially the sub-model provides three basic scenarios namely the business as usual, alternative and pessimistic scenario.

The business as usual illustrated in Fig. 11 shows a continuous decline in bagasse supply from over 150,000 tonnes to less than 125,0000 tonnes over the simulated time frame. The decline scenario is in tandem with the simulated decline in international sugar market price predicted to be less than 15 cents by the year 2035. This scenario is based on the premise that there is limited policy intervention in the conversion pathways of sugarcane production described in the previous sub model scenarios as explained in Figs. 10 and 9. In addition the harvesting approach is assumed to be burning; hence the feedstock supply is bagasse only.

The alternative scenarios (AS) illustrated in Fig. 11 assumes intervention measures and hence demonstrates a rising supply of bagasse over the years. This is projected to be close to 158,000 tonnes by 2035. In addition to good sugarcane production is the introduction of green harvesting techniques [40]. This provides additional sugarcane waste. The preservation and processing of sugarcane waste provides the additional feedstock from trash and off cuts. As shown in Fig. 11 feedstock supply is incremental with time with an initial supply of over 250,000 tonnes in 2017 to over 1000,000 tonnes by 2035. The simulated trash and offcuts supply starts around 2017, with the consideration of building the trash processing plant and subsequent full scale running of the plant providing additional supply for electricity generation.

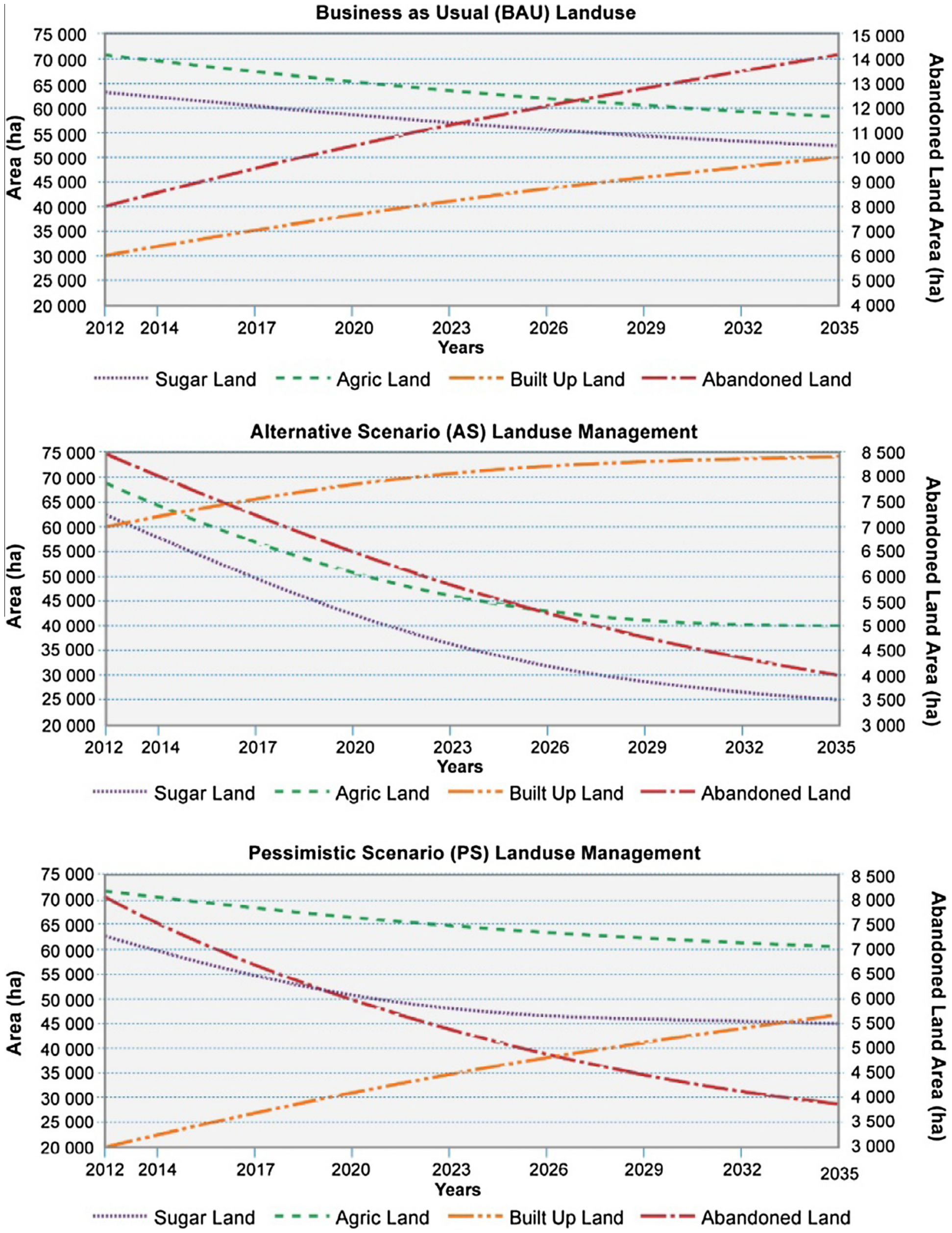


**Fig. 9.** Land use change dynamics simulation scenarios.

The total processed feedstock provides the overall bagasse and processed trash and off cuts ready to use to generate electricity. The feedstock supply shows an increasing trend over simulated time span. The scenario provides overall supply from both bagasse and trash supply.

The pessimistic scenario illustrated in Fig. 11 shows an increasing trend in total feedstock supply similar to the alternative scenario. However the total projected additional bagasse is less than the alternative scenario. Over the years between 2012 and 2035 bagasse is projected to increase by 8000 tonnes and less than 2000 tonnes between the alternative and optimistic scenario respectively. The total processed feedstock shall increase with time. However by 2035 this will be 910,000 tonnes and 850,000 tonnes between the (AS) and (PS) scenarios compared to closely 125,000 tonnes projected for the same year under the (BAU) business as usual scenario. Despite vagaries of nature together with decline in land for sugarcane production the alternative and simulated scenarios point to the potential of policies in ensuring optimum supply of feedstock over the projected time period. The next scenarios seek to determine the potential electricity generation threshold from bagasse/trash as an energy source in Mauritius.

### 6.4. Scenarios for electricity generation

Scenarios built in this sub model provide the potential electricity generation threshold from bagasse/trash as an energy source in Mauritius. The sub model takes into account an array of factors among which feedstock supply and technology efficiency are critical factors for optimum electricity production [5] The sub model builds scenarios comparing bagasse feedstock based plants including trash and offcuts feedstock, taking into account other competing priorities for this feedstock. Essentially the sub model provides three basic scenarios namely the business as usual, alternative and pessimistic scenario.

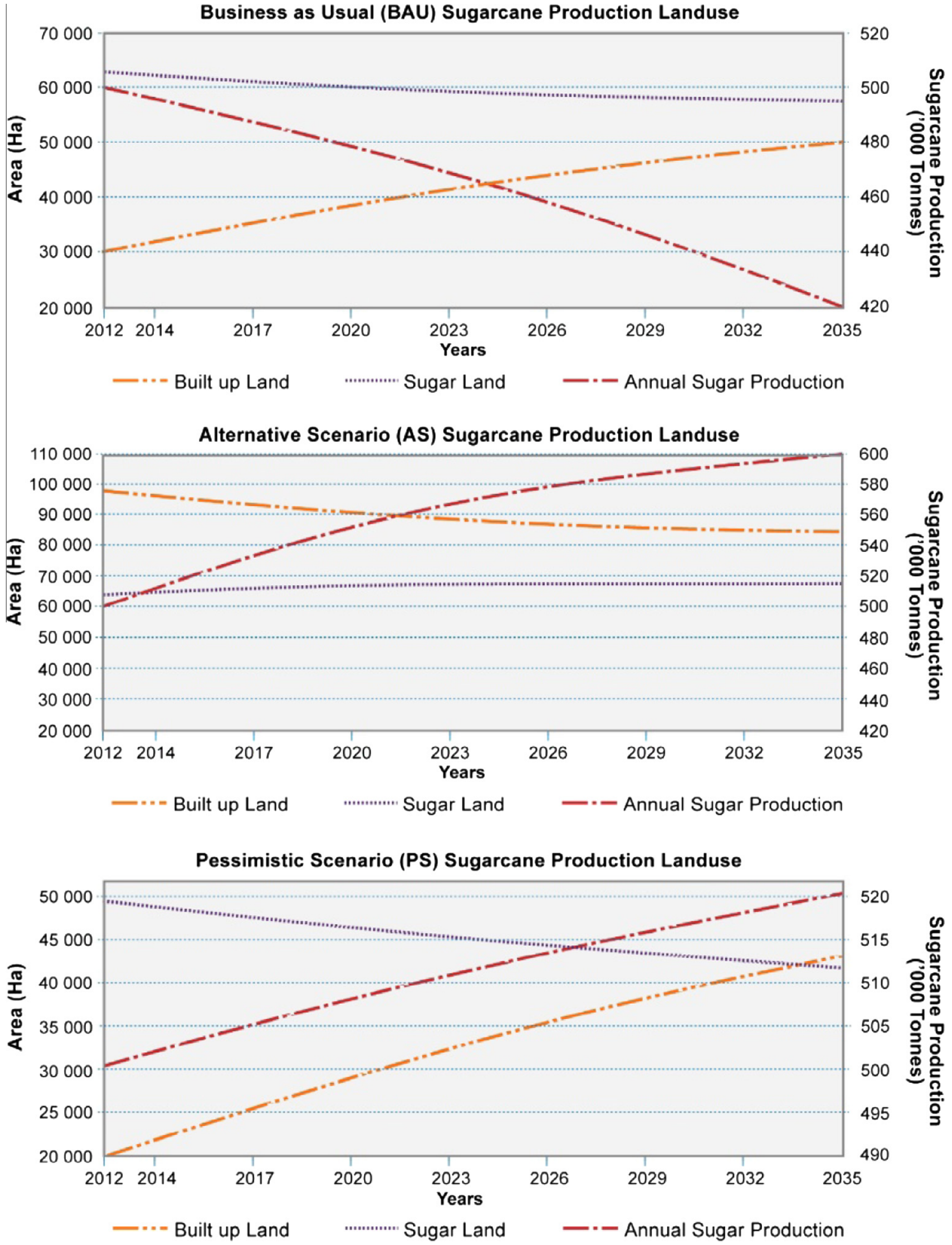


**Fig. 10.** Land use change dynamics and sugarcane production.

The BAU presents current electricity generation from bagasse only as a feedstock. The bagasse supply is anticipated to decline with time from about 300 GW h to as little as 50 GW h by 2035 as illustrated on Fig. 12. This projection assumes no intervention measures at all to protect and promote sugarcane production in the sugar industry. The slight increase in the year 2021 and 2027, from 135 GW h to 150 GW h and 60 GW h to about 70 GW h respectively and this is far less than half of the current generation. In essence the decline in electricity production is in line with the declining trend of bagasse supply projected to be less than 125,000 tonnes by 2035. In essence this scenario shows a gloomy picture for the bio-derived electricity generation industry.

In contrast assuming the current feedstock supply is retained, and intervention measures are in place, the alternative scenario illustrated in Fig. 12 shows an increase in bagasse derived electricity to more than 400 GW h per annum by 2035. This scenario is dependent on constant supply of sufficient feedstock (bagasse). The alternative scenario also provides additional electricity generated from trash and off cuts feedstock. Projections point to an additional 80 GW h of electricity by 2035, leading to a combined electricity generation total of nearly 500 GW h which is about 60% increase in electricity generation from sugar derived feedstock. Simulated projections illustrate that trash feedstock derived electricity will begin around 2017 instead of the base year and that significant generation of electricity can be around year 2022 with more than 400 GW h, owing to the given delay and time for investment and construction of trash and off cuts processing plant.

The pessimistic scenario illustrated in Fig. 12 indicates a positive future for the bio-derived electricity generation sector. The total amount of electricity generation is projected to be approximately 450 GW h by 2035. This scenario is far more encouraging compared to the business as usual scenario. The difference in the

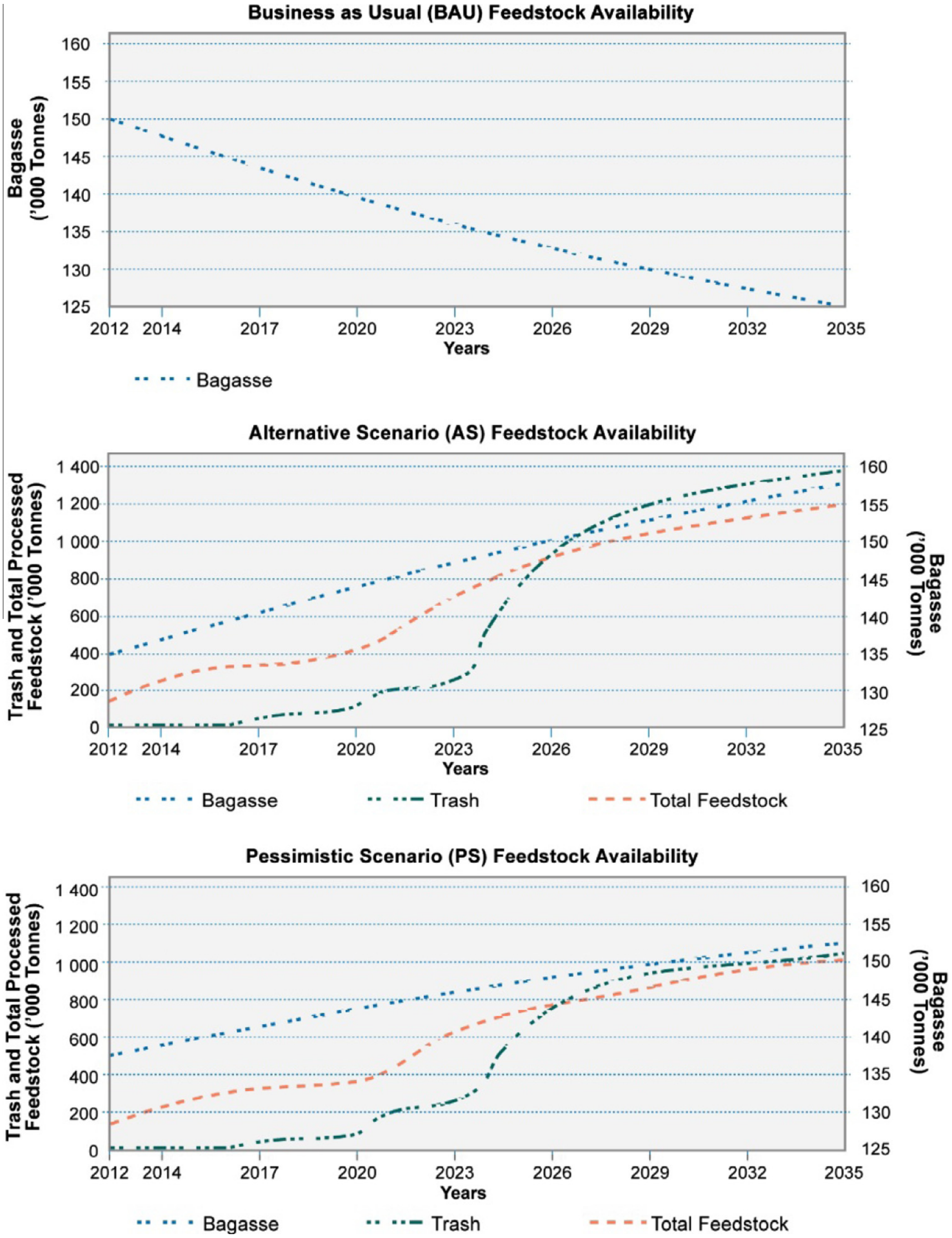


**Fig. 11.** Bagasse and trash generation potential.

two is nearly 250 GW h of electricity over the same year (2035). The scenario however shows a surge in electricity supply from trash especially around the mid-term of the simulated time frame. Bagasse derived electricity is equally on the rise although this is less compared to the alternative scenario. The cumulative effect of the various factors explained in Figs. 11, 10 and 9 including feedstock supply and the response to vagaries of nature may help explain the envisaged pessimistic scenario.

### 6.5. Emission avoidance from sugarcane derived electricity production

The simulated results of this sub section 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. In other words the scenarios extracted from the sub model thus aid in predicting the environmental benefits from optimizing electricity value of sugarcane production systems. Benefits are derived from emission avoidance from bio-derived electricity generation compared to highly fossil fuel dependent co-generation plants. Fig. 13 therefore illustrates the business as usual, alternative and pessimistic scenarios respectively.

The business as usual scenario illustrated in Fig. 13 indicates a decline in both $CO_2$ and $SO_2$ over the simulated time frame. Essentially carbon dioxide is projected to decline from 300,000 tonnes to 30,000 tonnes between year 2012 and 2035 respectively. A similar trend is projected for sulphur dioxide from 3000 tonnes to 95 tonnes over the same period. This trend is based on bagasse electricity generation only.

It is observed from the alternative simulated scenario (illustrated in Fig. 13) that bio-derived electricity generation can achieve more than 400,000 $CO_2$ tonnes and close to 45,000 $SO_2$

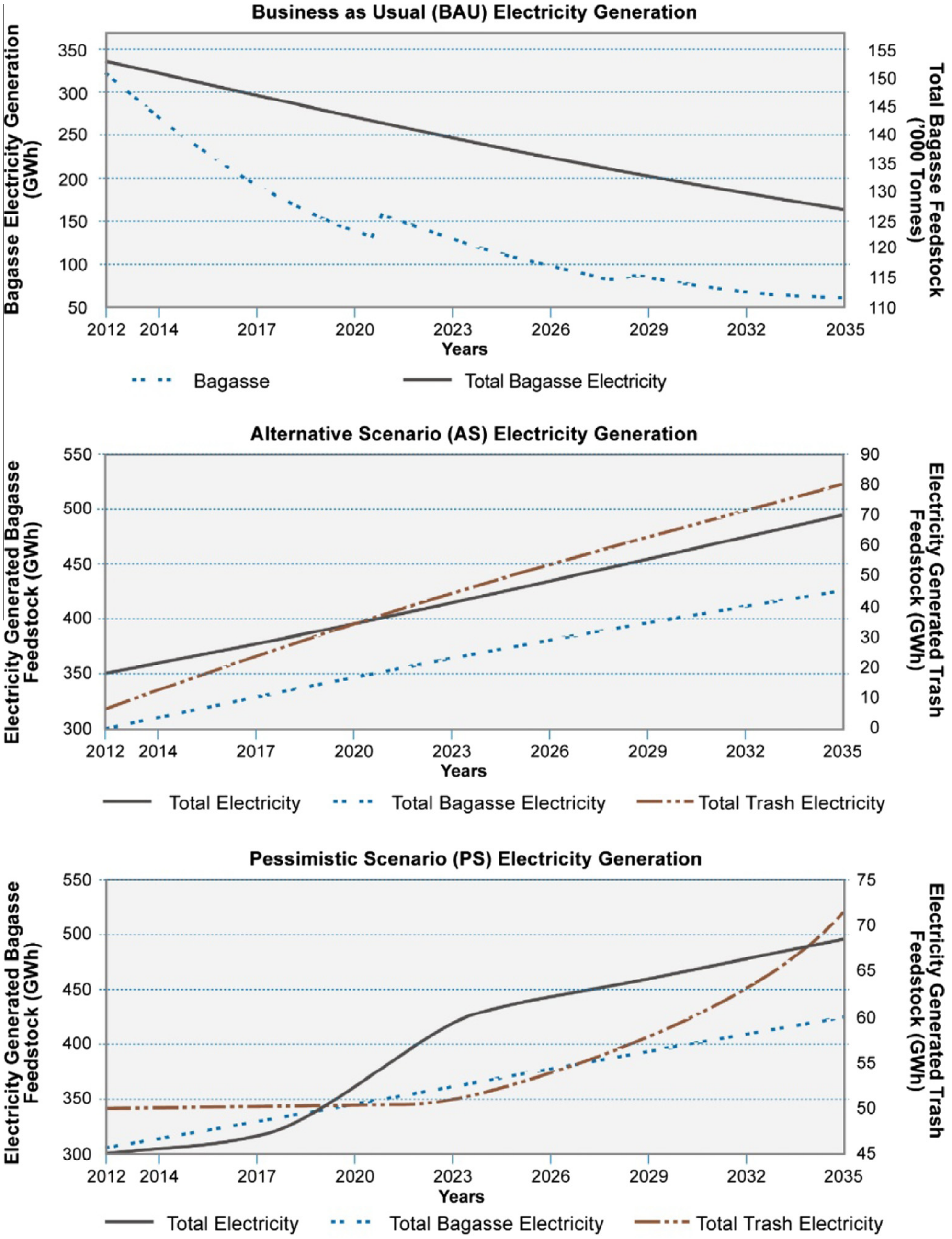


**Fig. 12.** Bagasse and trash electricity generation potential.

tonnes of avoided emissions by 2025, as illustrated in Fig. 13. This trend is anticipated to increase with time with projections rising up-to over 450000 for $CO_2$ and 50,000 for $SO_2$ respectively by 2035. Apart from the increasing trend contrary to the business as usual is the significant increase in the total emissions avoided due to increase in total electricity generation from the sugar industry.

The pessimistic scenario (illustrated in Fig. 13) similarly indicates increased emission avoidance over the total simulated time span. $CO_2$ emission avoidance is projected to increase from 310,000 to nearly 430,000 tonnes per annum. On the other hand $SO_2$ emission avoidance is projected to increase to 420,000 tonnes. Although this is comparatively less than the alternative scenario, this point to the needed environmental benefits that can be accrued from optimizing electricity produced from the sugar based industrial systems. Essentially the three simulated scenarios illustrated on this sub model illustrate the environmental benefits accrued in terms of emission avoidance over the projected time line.

## 7. Conclusion and future work

The simple system dynamics model of land use change, sugarcane production, harvesting and electricity production from bagasse and trash presented in this paper demonstrates the ability of systems analysis to simulate scenarios for bagasse and trash derived electricity generation in Mauritius. Systems dynamics coupled with GIS based data can model the complexity in bio-derived electricity generation across the conversion pathways from biomass production to the net environmental benefits. The model provides knowledge expansion on ways of optimizing bio-electricity

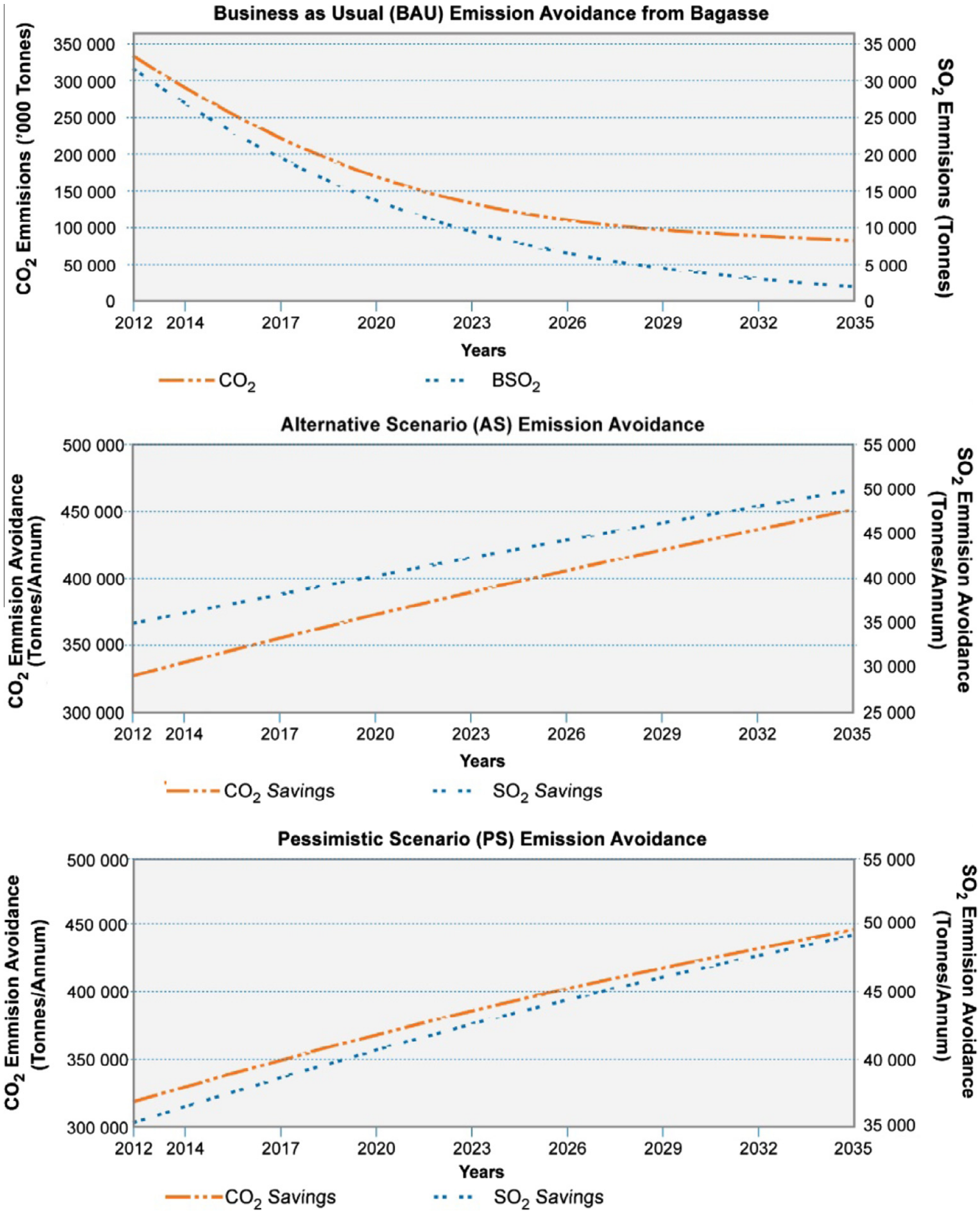


**Fig. 13.** Emission avoidance from sugarcane derived electricity production.

generation from sugarcane production systems. The 'what if' scenarios presented in the form of different scenarios evaluate the sensitivity of the system to important and realistic alterations in those factors driving not only on 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. The developed model may complement more established empirical approaches in land change science and sugarcane production, enhancing the understanding of complex interactions in sugarcane based electricity production systems. Lastly the inherent environmental benefits in terms of emission avoidance given the optimum bio-electricity produced, is key in driving the low carbon future agenda.

The systems dynamics approach presented here provides a basis for further analysis of electricity generation across the conversion pathways from sugarcane production to electricity production. Further work can focus on cost benefit analysis, net socio-economic transformation indicators such as employment opportunities. While societal perception has been incorporated in the land use sub model, a complementary analysis of the policy and institutional framework may provide a basis for determining the feasibility of and need for optimising sugarcane production systems.

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## References

[1] Sánchez-Segado S et al. Process design and economic analysis of a hypothetical bioethanol production plant using carob pod as feedstock. Bioresour Technol 2012;104:324–8.

[2] Dias MOS et al. Biorefineries for the production of first and second generation ethanol and electricity from sugarcane. Appl Energy 2013;109:72–8.

[3] Mutanga S et al. Modelling the electricity value of Mauritius' sugarcane industrial ecosystem using systems dynamics approach. In: Systems analysis. Luxembourg (Austria): IIASA; 2015.

[4] Ramjeawon T. Life cycle assessment of electricity generation from bagasse in Mauritius. J Clean Prod 2008;16(16):1727–34.

[5] Mbohwa C, Fukuda S. Electricity from bagasse in Zimbabwe. Biomass Bioenergy 2003;25(2):197–207.

[6] Howells M et al. Integrated analysis of climate change, land-use, energy and water strategies. Nat Clim Change 2013;3(7):621–6.

[7] Medina Rey JM. Biofuels and food security. Cuadernos de estrategia 2013;161:196–224.

[8] Wolde-Georgis T, Glantz MH. Biofuels in Africa: a pathway to development. International research for energy and economic development. Development Occasional Papers; 2013. p. 43.

[9] Powell N. Reconciling climate mitigation strategies (promotion of biofuels) with local livelihoods and vulnerability, undated; 2012. Stockholm.

[10] Mutanga S, Ramoelo A, Gonah T. Trend analysis of small scale commercial sugarcane production in post resettlement areas of Mkwasine Zimbabwe, using hyper-temporal satellite imagery 1. Adv Remote Sens 2013;2013 (March):29–34.

[11] Amigun B, Musango JK, Stafford W. Biofuels and sustainability in Africa. Renew Sustain Energy Rev 2011;15(2):1360–72.

[12] Amigun B, Von Blottnitz H. Operating cost analysis of an annexed ethanol distillery in a rural land locked African country. Environ Progr Sustain Energy 2011;30(3):500–15.

[13] Rogner H-H. Climate land energy and water strategies. United Kingdom: CSD Editor, IAEA; 2009.

[14] Riahi K, Grübler A, Nakicenovic N. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Chang 2007;74(7):887–935.

[15] Loulou R, Goldstein G, Noble K. Documentation for the MARKAL family of models. EA Energy Technology Systems Analysis Program; 2004.

[16] Loulou R, Labriet M. ETSAP-TIAM: the times integrated assessment model. Part 1: model structure. CMS 2007;5:7–40.

[17] Shin H-C et al. Environmental and economic assessment of landfill gas electricity generation in Korea using LEAP model. Energy Policy 2005;33 (10):1261–70.

[18] McPherson M, Karney B. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. Energy Policy 2014;68:146–57.

[19] Lempert RJ, Groves DG. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. Technol Forecast Soc Chang 2010;77(6):960–74.

[20] Welsch M et al. Adding value with CLEWS – modelling the energy system and its interdependencies for Mauritius. Appl Energy 2014;113:1434–45.

[21] García CA et al. Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico. Appl Energy 2011;88(6):2088–97.

[22] Silalertruksa T, Gheewala SH, Pongpat P. Sustainability assessment of sugarcane biorefinery and molasses ethanol production in Thailand using eco-efficiency indicator. Appl Energy 2015;160:603–9.

[23] Johnson DB, Hallberg KB. Acid mine drainage remediation options: a review. Sci Total Environ 2005;338(1–2):3–14.

[24] Ahmad S, Simonovic SP. Spatial systems dynamics: new approach for simulation of water resources system. Comput Civ Eng 2004;18(4):331–40.

[25] Scheffran J, Hannon B. A spatial-dynamic model of bioenergy crop introduction in Illinois; 2007. p. 1–20.

[26] CEB. Integrated electricity plan 2013–2022. Mauritius energy outlook. Port Louis Mauritius: Central Electricity Board; 2013. p. 1–152.

[27] TIPS. ERDAS imagine. Erdas imagine software; 2011 [cited 2014 20/05/2014]. Available from: www.tips.osmre.gov/Software/remotesensing/erdas/shtml.

[28] Ramoelo A. An innovative method to map land cover changes at a country level utilising hyper-temporal satellite images – a case study of Portugal; 2007. p. 83–3.

[29] Campbell TB. Introduction to remote sensing. London and New York: Taylor and Francis; 2002.

[30] Lillesand TM, Keifer RW, Chapman JW. Remote sensing and image interpretation. 5th ed. New York: John Wiley and Sons; 2004.

[31] Liu X, Skidmore AK, Van Oosten H. Integration of classification methods for improvement of landcover map accuracy. ISPRS, Photogramm Remote Sens 2002;56:257–68.

[32] Cabrera D, Colosi L, Lobdell C. Systems thinking. Eval Progr Plan 2008;31 (3):299–310.

[33] Forrester JW. Confidence in models of social behavior with emphasis on systems dynamics models. Cambridge (MA): MIT System Dynamics Group; 1973.

[34] Forrester JW. Lessons from systems dynamics modelling. Syst Dyn Rev 1987;3:136–49.

[35] Forrester JW. System dynamics and the lessons of 35 years. A system based approach to policymaking 1991;3(2):1–35.

[36] Vennix JAM. Group model-building: tackling messy problems. Syst Dyn Rev 1999;15(4):379–401.

[37] Forrester JW. System dynamics, systems thinking, and soft OR. Syst Dyn Rev 1994;10(2):1–14.

[38] Kirkwood CW. System dynamics methods: a quick introduction. Arizona State University; 1998. 124pp.

[39] Sterman JD. In: Barney GO et al., editors. A skeptic's guide to computer models. Westview Press; 1991. p. 209–29.

[40] Meyer E. A model to estimate combine harvester and infield transport performance and costs. In: Proceedings of the annual congress of the South African Sugar Technologists Association. South Africa: South African Sugar Technologists' Association; 1998.

[41] Mbohwa C. Energy management in the South African sugar industry 2013; I:3–8.

[42] Mbohwa C. Bagasse energy cogeneration potential in the Zimbabwean sugar industry. Renew Energy 2003;28(2):191–204.

[43] AIEA, Seeking CLEWS – climate, land, energy and water strategies – a pilot case study in Mauritius, in quatre analysis, applied systems. Atomic International Agency, Energy Joint Centre, U.S. Unit, Extension Bornes, Quatre Analysis, Applied Systems. Vienna (Austria); IAEA; 2011. p. 1–24.

[44] Assessing sustainable development: principles in practiceHardi P, Zdan TJ, editors. Assessing sustainable development. Canada: International Institute for Sustainable Development; 1997.

[45] Sterman JD. Business dynamics: systems thinking and modeling for a complex world. In: Sterman JD, editor. Systems thinking and modeling for a complex world. USA: Jeffrey J. Shelstad; 2000. p. 982.

[46] He C. et al. Developing land use scenario dynamics model by the integration of system dynamics model and cellular automata model. In: IEEE International Geoscience and Remote Sensing Symposium, October 4, IGARSS; 2004.

[47] White R, Engelen G. High-resolution integrated modeling of the spatial dynamics of urban and regional system. Comput Environ Urban Syst 2000;24:383–400.

[48] Hertzel TW, Rose SK, Tol RSJ. Economic analysis of land use in global climate change. Policy 2008:368.

[49] Alena A, Sahu O. Cogenerations of energy from sugar factory bagasse. Am J Energy Eng 2013;1(2):22–9.

[50] Mbohwa C. The energy and environmental impacts of a coal and bagasse-fired power plant in the sugar industry, vol. 82. South Africa Sugar Technology Association; 2009. p. 214–24.

[51] Jonker JGG et al. Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies. Appl Energy 2015;147:593–610.

[52] Forrester JW, Senge P. In: Tests for building confidence in system dynamics models. In: Legasto A, Forrester JW, Lyneis J, editors. Systems dynamics. New York: North Holland: TIMS Studies in Management Science; 1980. p. 209–28.

[53] Kumar DD. A system dynamics modelling for forecasting regional agriculture production. Indian J Reg Sci 2013;XXXXV(2).

[54] Welsch M et al. Supporting security and adequacy in future energy systems: the need to enhance long-term energy system models to better treat issues related to variability. Int J Energy Res 2015;39(3):377–96.

[55] Fanrpan FA, Natural resources policy analysis. Towards a regional approach to biotechnology and biosafety for national policy regarding commercial GM trade and the potential farm-level impact of adopting GM crops; 2006.

[56] CSO. Digest of agricultural statistics; 2012.

[57] Deepchand K. Sugarcane bagasse cogeneration lessons for Mauritius 2005.