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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.