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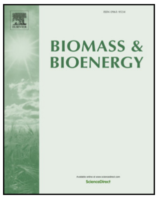

Research paper

An integrated sustainability model for a bioenergy system: Forest residues for electricity generation

Enze Jin*, John W. Sutherland

Environmental and Ecological Engineering, Purdue University, 500 Central Drive, West Lafayette, IN, 47907-2022, USA

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ABSTRACT

In the U.S., bioenergy accounts for about 50% of the total renewable energy that is generated. Biomass may be used as a source of energy in a variety of ways. Using forest residues, which would normally be treated as waste, in a co-firing power plant application is one strategy for utilizing biomass. Every stage in the life cycle of using forest residues (e.g., growing biomass, harvesting biomass, transporting biomass, and co-firing with coal) has consequences in terms of the three dimensions of sustainability: economy, environment, and society. An integrated sustainability model (ISM) using system dynamics is developed for a bioenergy system to understand how changes in the bioenergy system influence environmental measures, economic development, and social impacts. Exogenous factors such as population growth, land-use change (LUC) patterns, and renewable energy policy are considered by the ISM. Predictions, such as soil carbon sequestration, greenhouse gas savings, monetary gain, and employment, can be made for a given temporal and spatial scale. Different policy scenarios varying the bioenergy share of the total electricity generation were identified and examined via the ISM. The results of the scenario analysis indicate that an increase in the bioenergy share of the total electricity generation will stimulate the bioenergy market for bio-power. Model projections provide comprehensive insights to key stakeholders and policy makers for supporting decision-making regarding bioenergy development.

1. Introduction

Renewable energy is receiving significant attention because of its ability to meet energy demands while supporting economic growth and reducing environmental impacts relative to fossil fuel extraction and use. Bioenergy represents a significant portion of the total renewable energy that is generated. Currently, 7–10% of global energy is provided by biomass energy production [1]. The U.S. Department of Energy reports that nearly 10% of energy consumption in the U.S. is derived from renewable energy sources and in 2014, biomass accounted for 50% of the renewable energy portfolio [2]. The most common biomass-based energy is from liquid transportation fuels, which includes bioethanol and biodiesel. Biomass co-firing is another attractive option of converting biomass into power and heat. In a co-firing power plant, biomass is simultaneously blended and combusted with other fuels such as coal or natural gas in a boiler for electricity generation [3]. According to the U.S. Energy Information Administration (EIA) [4], biomass and biomass-derived gases produced nearly 1.4×10^{12} MJ, and provided nearly 2.3×10^{11} MJ of electricity across all sectors in 2015. Sources of biomass include agricultural crops, grass, wood and wood residues, other wastes from wood production, and municipal solid waste. Types of biomass fuel and associated logistics can significantly affect the performance of biomass co-firing. Forest biomass has a unique advantage in reducing net carbon emissions compared to conventional fuels. Forest biomass is a less carbon-intensive energy source compared to coal as it captures and stores carbon during growth and releases it upon combustion, so no new carbon is released [5,6]. According to Galik et al. [7], forest biomass including marketable and non-marketable wood, is a potential source of biomass supply for electricity generation. Moreover, woody biomass such as forest residues is favorable for co-firing with coal owing to its low ash, sulfur and nitrogen content [8]. In both North American and Europe, many power plants have successfully used woody biomass in co-firing applications with coal [3].

The sustainability of a bioenergy system must address three dimensions: environment, economy, and society. One environmental advantage of using forest biomass for electricity generation is that it can enhance the soil carbon sink process when agricultural land is converted to forest land (afforestation). Post and Kwon [9] observed that the average accumulation rates of soil carbon were $33.8\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ and $33.2\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in re-established forest land and grassland after agricultural use, respectively. Afforestation of former cropland was reported to increase total soil carbon stocks by 18% [10]. Moreover,

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* Corresponding author.
E-mail addresses: ejin@purdue.edu (E. Jin), jwsuther@purdue.edu (J.W. Sutherland).

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substitution of forest biomass for coal contributes to the reduction of the greenhouse gas (GHG) emissions in the co-firing system. The U.S. Forest Service also indicated that co-firing biomass with coal is the best short-term strategy for reducing GHG emissions in the electric power sector [11]. For example, Loeffler and Anderson [12] estimated that a co-firing system at a 20% displacement rate (20% of the coal is replaced with biomass), could decrease CO_2 emissions by 15%, CH_4 emissions by 95%, NO_x emissions by 18%, and SO_x emissions by 27% in southwest Colorado. In addition, removal of logging residues for energy use can avoid methane emissions from the decay and decomposition processes. In Michigan, Minnesota, and Wisconsin, Kukrety et al. [13] predicted that an annual substitution of 1.87–2.62 Mt forest residues for coal would reduce GHG emissions by 1.91–2.69 Mt $CO_{2\ eq}$ when considering the emissions avoided during the decay of forest residues. Some negative environmental impacts of bioenergy development have been examined as well, broadly considering such issues as water, soil, and biodiversity. The land-use change from forestry to agriculture can lead to a decrease in soil carbon stock [10,14], and harvesting whole trees (including branches and residues) can reduce soil nutrients [15]. Water availability is a possible constraint for large-scale biomass cultivation in several countries facing water scarcity [16]. Moreover, monocultures should be avoided to prevent pests and disease spreading into surrounding areas [15].

Socio-economic aspects of bioenergy systems have also been discussed as drivers for bioenergy development [17]. For example, potential economic impacts of forest biomass production have been analyzed in terms of regional job growth and economic development. Timmons et al. [18] estimated a total annual revenue of 57 million dollars and 440 jobs created through the operation of biomass co-firing energy facilities with a total energy generating capacity of 165 MW in Massachusetts over a five-year period. English et al. [19] ascertained that the total economic impact of co-firing bio-residues for electricity generation would be more than 7 million dollars per year, and nearly 100 additional jobs would be created based on a demand of 0.51 million tonnes of mixed biomass residues for producing 8921 MJ electricity in the Southeastern United States. Perez-Verdin et al. [20] used an economic input-output model to estimate economic impacts of logging residues recovery and bio-power operation of a 100 MW power plant in Mississippi, and the authors concluded that the bio-power industry could generate total gross output of 386 million dollars and 2343 jobs annually. Gan and Smith [21] estimated that the procurement of logging residue and the generation of electricity would contribute about 1340 new jobs and 215 million dollars in value-added to the local communities in east Texas. On the other hand, the global concerns regarding the socio-economic aspects of bioenergy development include food security and availability, land ownership changes, low wages, and child labor [22]. Very often, a bioenergy system can be beneficial to the environment, economy and society if sustainably managed.

To better understand the potential consequences of establishing bioenergy system, it is necessary to adopt an integrative perspective that considers all three sustainability dimensions. System dynamics is a comprehensive methodology that can analyze the dynamic behaviors of economic, environmental and social aspects in a complex system. Peterson et al. [23] developed a system dynamics-based Biomass Scenario Model (BSM) to better understand the impacts of biofuel policy on the biofuel supply chain in the United States. Barisa et al. [24] used a system dynamics model to analyze the biodiesel market behavior associated with various policy instruments on increasing the proportion of biofuel in Latvia. However, neither model considered sustainability performance of the associated bioenergy system. Musango et al. [25] developed a system dynamics-based model to assess the effects of biodiesel development on selected sustainability indicators for the Eastern Cape Province of South Africa. The indicators focused on the biodiesel production and profitability, biodiesel crop land, and avoided CO_2 emissions. Similarly, the economic and social impacts were not addressed in this study.

Several studies [26–28] proposed a sustainability assessment framework for bioenergy systems that employed a multi-criteria decision analysis. These frameworks sought to make sustainable decisions for bioenergy development by optimizing the performance in terms of environment, economy, and society. These efforts did not, however, endeavor to predict these impacts. Thus, a limitation of studies using this approach is that they focus only on the present situation and do not consider potential future impacts or changes that may occur within one of the three sustainability dimensions. MILESTONES, an integrated modeling framework for bioenergy strategies, incorporated three sub-models that focus on the global agricultural products market, global land-use change, and bioenergy provision and demand [29]. Two coupled sub-models manually exchanged data so the output from the source model must be adapted before it is input in the target model over multiple steps. While this approach is effective, these data exchange and feedback loops can be performed using system dynamics modeling without iterative simulation steps. Moreover, the MILESTONES modeling framework has not included the assessments of economic and social impacts.

In this paper, an integrated sustainability model (ISM) is proposed for a forest-based bioenergy system, where emphasis is placed on residues and a co-firing application. The model predicts the comprehensive performance of forest residue when utilized for energy generation. The objective of the ISM is to understand whether the use of forest residues improve the environmental, economic and societal dimensions of sustainability by using CO_2 emissions, soil carbon sequestration, monetary gain (gross output and value-added), and employment as metrics. These metrics are used to determine if the current markets for and implementations of bioenergy are favorable for the sustainability of the local environment, economy, and society. System dynamics is used to provide causal linkages between variables associated with the bioenergy system established that addresses the environmental and socio-economic impacts of forest biomass for electricity generation.

2. Methodology

2.1. Overview of integrated sustainability model

A bioenergy system is a complex system that involves multi-disciplinary interactions among human, natural and technical factors. The bioenergy system includes such activities as cultivation of biomass, harvest and pretreatment, transportation, conversion to fuels and end use of bioenergy [30]. The structure of the proposed integrated sustainability model incorporates exogenous factors, the bioenergy life cycle, and measures related to the three sustainability dimensions into a dynamic system. A variety of exogenous factors (e.g., population demographics, feedstock type, renewable fuel standard, land use policy, price of fossil fuel) are selected due to the fact that they play a highly important role in the dynamic behaviors of system indicators. For instance, the changes in population and price of fossil fuel can affect the demand of bioenergy use, different feedstock types result in different costs of bioenergy production, and incentives or tax deductions regulated by renewable energy policy can impact the structure of the bioenergy market. Several studies [24,31,32] also considered the exogenous factors, such as policy, population growth, and fossil fuel price, as important drivers for bioenergy development. Environmental, economic, and social impacts that are generated both upstream and downstream of a bioenergy system can be addressed via key indicators associated with major concerns.

A conceptual view of the model is shown in Fig. 1. Math-based sub-models focusing on environmental and socio-economic effects have been developed to describe the dynamic character of the system, and aim to anticipate such consequences as GHG emissions, soil carbon sequestration, monetary gain, and employment. Through the ISM for a bioenergy system there are two key questions that can be answered: 1) what are the potential environmental and socio-economic impacts that