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A Proposed Integrated Sustainability Model for a Bioenergy System

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Abstract

The usage of bioenergy is expected to increase for at least ten more years in the U.S. owing to its environmental benefits relative to petroleum. Growing biomass, converting it to a biofuel (e.g., corn ethanol), and using the biofuel has consequences related to the three dimensions of sustainability: economy, environment, and society. An integrated sustainability model (ISM) using system dynamics is developed for bioenergy systems to understand how changes in bioenergy production influence environmental measures, economic development, and social impacts. Predictions, such as greenhouse gas emissions, biofuel price, and employment, can be made for a given temporal and spatial scale.

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Keywords: bioenergy production; integrated sustainability model (ISM); system dynamics modeling; corn ethanol

1. Introduction

Bioenergy, as an alternative energy resource for heating, electricity, and transportation fuel, provides about 10% of the current global energy demand and accounts for roughly 80% of renewable energy [1]. Smeets et al. [2] estimated the global potential of bioenergy production from agricultural and forestry residues and wastes as 76–96 EJ/year, and the total technical potential for biomass could be as high as 1500 EJ/year by 2050. The U.S. Department of Energy reports that the total projected consumption of biomass feedstocks may be roughly 330 million dry tons per year by 2030, a 54% increase over today [3]. The main reason for more biomass feedstock use is the increasing demand associated with biofuel production. Biofuels include ethanol, diesel, and methanol. The U.S. Energy Independence and Security Act of 2007 expanded the mandated use of biofuels based on the first Renewable Fuel Standard (RFS) that required the annual use of 9 billion gallons of biofuels in 2008, rising to 36 billion gallons in 2022 [4]. Global biofuel production has grown from 16 billion liters in 2000 to more than 100 billion liters in 2010. In the United States, the share of biofuels was 4% for road transport fuel and in the European Union (EU) around 3% in 2008 [5].

The use of fossil fuels for energy generation is widely linked to global warming. One of the advantages of bioenergy is that it reduces the greenhouse gas (GHG) emissions across the entire bioenergy life cycle. Using biomass to produce biofuels such as ethanol has already been proven that it can significantly mitigate CO_2 emissions when it is compared to gasoline production. For example, corn ethanol produced by a natural gas biorefinery can have a 38.9% reduction of GHG emissions relative to gasoline production and the reduction in GHG emissions could vary from 39.6–57.7% by integrating biomass to produce heat [6]. The International Energy Agency (IEA) reported that the projected use of biofuels could avoid around 2.1 gigatonnes (Gt) of CO_2 emissions per year by 2050 when produced sustainably [5].

Use of bioenergy is increasingly viewed as an opportunity, not only to enhance energy security and provide environmental benefits, but also to accelerate economic development, particularly in rural areas [7]. Solomon [8] found that existing biofuels industries have been a major contributor to rural economies and small farmers in several countries. Neuwahl et al. [9] also explored the employment impacts of biofuels development in the context of the Renewable Energy Roadmap for the European Union market and found that the biofuel

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industry has a positive impact on employment. On the other hand, there may be socio-economic concerns associated with bioenergy development, e.g., competition with food production, land ownership changes, low wages, and child labor [10].

To better understand the impacts of the increased use of bioenergy, it is necessary to consider all three dimensions of sustainability: environment, economy, and society. The bioenergy system is embedded in a complex, social-ecological system. Ostrom [11] indicated that the core challenge of assessing the sustainability of such an interdisciplinary system is the identification of relationships among the key system variables at different spatial and temporal scales. In this paper, an integrated sustainability model (ISM) is established that includes relationships for the environmental, economic, and social variables of a bioenergy system. Corn ethanol production is utilized to demonstrate the efficacy of the model.

2. Integrated sustainability model

2.1. Model conceptualization

A bioenergy system includes such activities as planting and growing biomass, harvesting biomass, processing biomass to produce a fuel, and fuel use. Such a system has associated economic, environmental, and social impacts. A variety of exogenous factors associated with the bioenergy system are highly relevant in the anticipation of the positive and negative outcomes based on a certain model. A conceptual view of the model is shown in Fig. 1. The model should be able to make predictions about how a given set of exogenous factors and decisions (e.g., population demographics, feedstock type, alternative biomass markets, land use policy, evolution of bioenergy system, tax rates, and price of oil) affect the bioenergy system.

A model for the bioenergy system has been developed that includes modules for ecosystem services and socio-economic effects. The model describes the dynamic character of the system, and aims to forecast such consequences as GHG emissions, biofuel price, employment, and quality of life. The bioenergy model was created using STELLA™ software.

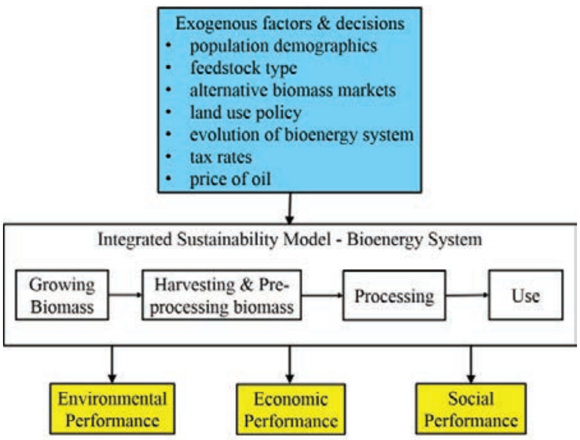

Fig. 1. Integrated sustainability model concept for bioenergy system

2.2. System dynamics modeling

System dynamics is a modeling method that can be utilized to characterize the behavior of complex, often nonlinear, systems. A system dynamics model may include feedback loops, feedforward loops, time delays, and other dynamic elements. The first stage in developing a system dynamics model is to construct a causal loop diagram (CLD). A CLD helps to visualize the interrelationships among the different elements in the system. In this study, a CLD was created that links key variables within the bioenergy system and that reflects consideration of environmental, economic, and social performances. Within a CLD, the factors connected by arrows indicate causal relationships. A sign is added to the head of each arrow, with a "+" sign indicating a positive causality, and a "-" indicating a negative causality. For example, one of the arrows in the figure relates demand for biofuel production to feedstock production. Since the indicated sign is "+", this means that when the demand for biofuel production increases, there will be an increase in feedstock production.

The proposed CLD for a biofuel system in Fig. 2 shows the relationships among key variables that influence the environmental, economic, and social impacts (e.g., reduction in GHG emissions, GDP created by the biofuel industry, employment, and tax revenue). For example, the key factor relevant to the reduction in GHG emissions is the biofuel production which is influenced by the demand for biofuel production. The level of demand for biofuel production is influenced by the economic and population growth. An increase in the demand for biofuel production leads to an increase in biofuel price in a large market. However, an increase in biofuel price negatively affects the demand for biofuel production. Such a relationship could attenuate the growth in the demand of biofuel production and make the biofuel price stable over time. Land-use change effect plays a negative role in the reduction in GHG emissions of biofuel production.

The amount of biofuel sales depends on the biofuel price and production. The biofuel price is also affected by the feedstock price which is negatively influenced by feedstock production. The economic impacts of biofuel production, such as GDP, labor income, and employment, are positively related to biofuel sales. On the other hand, the tax paid by the biofuel industry will be increased by an increase in biofuel sales. Additionally, with an increase in tax revenue, more funds will be spent on social welfare, and will increase the quality of life.

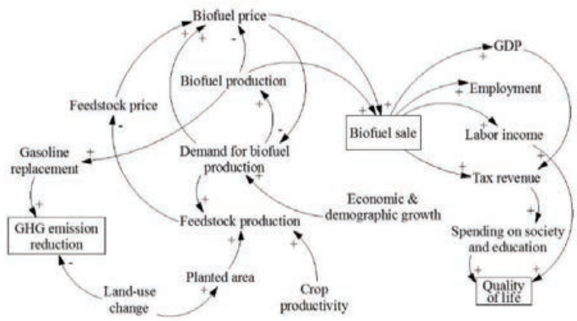

Fig. 2. Causal loop diagram for biofuel system