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Modeling of biomass-to-energy supply chain operations: Applications, challenges and research directions

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HIGHLIGHTS

- An extensive review of biomass supply chain operations management models presented in the literature is provided.
- The models are classified in line with biomass supply chain activities from harvesting to conversion.
- The issues surrounding biomass supply chains are investigated manifesting the need to novel modeling approaches.
- Our gap analysis has identified a number of existing shortcomings and opportunities for future research.

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ABSTRACT

Reducing dependency on fossil fuels and mitigating their environmental impacts are among the most promising aspects of utilizing renewable energy sources. The availability of various biomass resources has made it an appealing source of renewable energy. Given the variability of supply and sources of biomass, supply chains play an important role in the efficient provisioning of biomass resources for energy production. This paper provides a comprehensive review and classification of the excising literature in modeling of biomass supply chain operations while linking them to the wider strategic challenges and issues with the design, planning and management of biomass supply chains. On that basis, we will present an analysis of the existing gaps and the potential future directions for research in modeling of biomass supply chain operations.

1. Introduction

There is an increasing interest in renewable and environmentally friendly energy sources. Biomass, which entails any organic matter derived from living organisms, is one of the most utilized sources of renewable energy. It is comprised of plant and animal materials, as well as residues such as wood from forests, crops, seaweed, materials left over from agricultural and forestry processes, and organic industrial, human and animal wastes (Saidur et al., 2011). Biomass has been the main source of energy in rural areas for centuries. In the past decade, biomass has been consistently ranked as the fourth greatest source of global energy, accounting for 10–14% of final energy consumption, following coal (12–14%), natural gas (14–15%) and electricity (14–15%) (Kheshgi et al., 2000; Parrika, 2004; Balat and Ayar, 2005; Demirbas, 2005; Oregon, 2010).

Climate change, dependency on foreign oil and the foreseen gap between energy supply and demand are among the main reasons behind a growing attention towards renewable energy sources. The availability of various types of biomass resources and maturity of conversion technologies has made it an attractive source of energy in the European Union (EU) (EBTP, 2006; McCormick and Kaberger, 2007; An et al., 2011). In addition to carbon mitigation and energy security, biomass energy production is associated with the creation of new jobs, the creation of a new source of income for farmers, cheaper heat supply, and reduced landfill disposal (Thornley, 2006; Saidur et al., 2011). Despite all these benefits, in practice, the use of biomass as a source of energy comes with a number of challenges, such as the potential competition with food and feed production, low energy density, high logistic costs, traffic noise and air pollution (Thornley, 2006; Saidur et al., 2011).

The most common biomass conversion-to-energy methods are: direct combustion, pyrolysis, fermentation, gasification, and anaerobic digestion. The choice of the method depends upon a number of factors, such as the type and quantity of biomass, environmental standards, and financial resources (Saidur et al., 2011).

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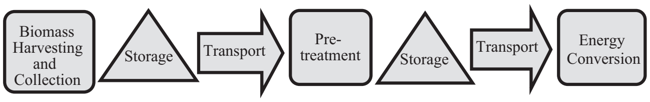

Fig. 1. Operational components of a biomass supply chain.

Supply Chain Management (SCM) plays a critical role in the management of bioenergy production processes (Gold and Seuring, 2011). Biomass Supply Chain Management has been defined as the integrated management of bioenergy production from harvesting biomaterials to energy conversion facilities (Annevelink and de Mol, 2007; Gold and Seuring, 2011). The parties involved in a biomass energy supply chain are: the supplier of biomass, transportation and distribution entities, energy production facility developers and operators, the government and utility firms who provide the incentives, and the end-users (Adams et al., 2011). In this sense, a typical bioenergy supply chain is comprised of five main components of harvesting and collection, pre-treatment, storage, transport, and energy conversion as shown in Fig. 1 (Iakovou et al., 2010).

Biomass energy supply chain differs from traditional supply chains in several ways. Among them are the seasonal availability of agricultural biomass, low energy density, demand variations due to uncertain energy production performance and the variability of biomass materials, which has implications for transport and storage (Iakovou et al., 2010). Thus, the main objectives of biomass supply chain management are to minimize costs, environmental impacts of the supply chain, and ensure continuous feedstock supply (Gold and Seuring, 2011).

This paper reviews the existing literature and research on the use of mathematical models to formulate design, planning and management decisions in biomass supply chain operations. Our review considers the research that has been conducted in relation to different operational stages of a biomass supply chain, including harvesting, storage, transport, and energy conversion. To the best of our knowledge, this paper is a first attempt to provide a comprehensive review of the existing literature in modeling of biomass supply chain operations while linking them to the wider strategic challenges and issues with the design, planning and management of biomass supply chains. A particular novelty of this research is that, based on the provided review, it presents an analysis of the existing gaps and future research opportunities in biomass supply chain operations modeling. It should be mentioned that we conduct a global review, considering the studies from different jurisdictions (USA, Asia, EU, etc.) and accounting for variations (in materials, technologies, regulations, and policies). We account for both solid and liquid biomass supply chains associated with transportation, power generation, and heating. In this sense, the review will provide an opportunity to explore the differences and similarities in challenges and issues related to biomass supply chains given the above mentioned variations.

2. Biomass supply chain modeling

Reviewing the models developed to deal with decision problems endemic in the various states of a biomass supply chain, they could be classified into five categories (according to Fig. 1), as follows.

2.1. Biomass harvesting and collection

In this component of biomass supply chains, the main decisions to deal with are allocation of land, harvest scheduling, and biomass collection planning based on the analysis of biomass soil/moisture contents, climatic conditions, land availability, and bioenergy demand.

Murray (1999) developed biomass harvest scheduling models with consideration of spatial restrictions that are due to land availability and productivity. He proposed two models called ‘Unit Restriction Model’ (URM) and ‘Area Restriction Model’ (ARM). In URM, harvest scheduling is performed in such a way that no two adjacent blocks are selected at the same time. In ARM, harvest scheduling is subject to one more constraint. Namely, each block can be harvested no more than once during each planning period. Gunnarsson et al. (2004) adopted an integer programming model to analyze 0–1 decisions regarding the harvest areas. It identified whether or not a specific land should be harvested in line with bioenergy demands downstream the supply chain. Similar cost minimization/yield maximization linear and mixed-integer programming models have been developed for land allocation and scheduling in biomass harvesting subject to various forms of area restrictions (Martins et al., 2005; Gunn and Richards, 2005; Goycoolea et al., 2005; Constantino et al., 2008). Gemtos and Tsiricoglou (1999) proposed a model to determine water and soil contents of collected cotton stalks in various farms located in central Greece over a period of two years, estimating the impact of these parameters on optimization of biomass collection costs.

Furthermore, Eksioglu et al. (2009) proposed a mixed integer programming (MIP) model with the objective of minimizing the total cost of a biomass supply chain, accounting for deterioration, seasonality and availability of biomass materials. The proposed model identifies the optimal number, size and location of collection facilities, bio-refineries, as well as the amount of biomass shipped, processed and held as inventory. In order to account for the effect of weather conditions on biomass availability, Sokhansanj et al. (2006) developed a discrete-event model that predicts the number and size of equipment needed to meet the rate of harvest, while considering the bio-refinery demand and biomass delivery cost.

2.2. Biomass pre-treatment

Pre-treatment is a mechanical or chemical process (or a combination of them) that converts biomass into denser energy carriers not only to increase its energy conversion rate but also to facilitate handling, storage and transportation, and to reduce the associated costs (Kumar and Sokhansanj, 2007; Larson et al., 2010). Processes such as drying and torrefaction (i.e. reducing the moisture content with heating in the absence of oxygen), carbonization, pelletization, chopping, shredding, and grinding are some of pre-treatment approaches adopted by biomass energy industry (Uslu et al., 2008; Stelt et al., 2011). For production of liquid fuels from lignocellulosic biomass, processes such as pyrolysis (heating biomass in the absence of air) and hydrolysis (using water to convert biomass polymers to fermentable sugars) are used for biodiesel and ethanol production, respectively (McKendry, 2002b; IRENA, 2013). It should be mentioned that not all biomass materials need to undergo a pre-treatment. For instance, maintaining a certain amount of moisture content in logs is considered a quality parameter (from a strength point of view), making them a good candidate for pelleting (Lehtikangas, 2001).

The inclusion and choice of pre-treatment processes not only influences the costing profile of storage and transport activities but also impacts the structure of biomass supply chains. Uslu et al. (2008) have compared the impact of alternative pre-treatment processes (pelletization, torrefecation and pyrolysis) on the cost efficiency of a biomass supply chain under various location scenarios for pre-treatment facilities. The findings points to the fact that combined torrefaction and pelletization could be a promising option that not only reduces the logistic costs but also