Journal of Cleaner Production 78 (2014) 216–225

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Assessing the integration of torrefaction into wood pellet production

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A R T I C L E I N F O

Article history:
Received 15 November 2013
Received in revised form
24 April 2014
Accepted 29 April 2014
Available online 9 May 2014

Keywords:
Bioenergy
Forest biomass
Torrefaction
Simulation modeling
Supply chain analysis
Wood pellets

A B S T R A C T

In this study a dynamic simulation modeling approach is used to assess the integration of torrefaction into the wood pellet production and distribution supply chain. The developed model combines discrete event and discrete rate simulation approaches and allows considering uncertainties, interdependencies, and resource constraints along the supply chain which are usually simplified or ignored in static and deterministic models. It includes the whole supply chain from sources of raw materials to the distribution of the final products. The model is applied to an existing wood pellet supply chain, located in British Columbia, Canada, to assess the cost of delivered torrefied pellets to different markets, energy demand, and carbon dioxide emissions along the supply chain and compare them with those of regular pellets. In the presented case study, integration of torrefaction leads to lower delivered cost to existing and potential markets due to increased energy density and reduced distribution costs. In comparison with regular pellets, the delivered cost of torrefied pellets ($/GJ) to Northwest Europe is 9% lower. Also, the energy consumption and the emitted carbon dioxide along the supply chain are decreased due to more efficient transportation of torrefied pellets. Integration of torrefaction into the wood pellet production and distribution supply chain could result in less expensive and cleaner biofuel. The feasibility of such integration depends on the trade-off between the higher capital and operating costs and the reduced transportation costs.

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1. Introduction

Fast depletion of fossil fuels and environmental concerns related to their extraction and consumption have promoted the use of alternative sources of energy (Panepinto and Genon, 2012; Shirazi et al., 2013). Bioenergy has been regarded as a promising substitute for fossil fuels, mainly due to its renewable and carbon neutral nature (Mizsey and Racz, 2010; Nguyen et al., 2013). As a result, in biomass-rich countries, such as Canada where forests cover around 34% of the entire area of the country (The World Bank, 2013), the bioenergy industry has been growing. Today, forest biomass contribution to Canada's energy supply is 5–6% (NRCan, 2012), while its potential contribution is estimated to be 18% (Paré et al., 2011). The low contribution of forest biomass to energy supply is mostly related to its physical characteristics. Forest biomass is irregular in shape, has low bulk density, low energy density, and high moisture content that contribute to a complex supply chain and high transportation and logistics costs (Demirbas, 2001).

Pelletization is a densification process in which biomass is compressed into cylindrical shape with a diameter of 6–8 mm and a length of 10–12 mm (Mani et al., 2006). Pelletization provides consistent quality, low moisture content, high energy content, and homogenous shape and size that facilitate the logistics of biomass. These properties stimulated rapid expansion of the wood pellet industry around the globe such that wood pellets are recognized as an internationally traded commodity and further expansion of the market for wood pellets is expected (Sikkema et al., 2011; Spelter and Toth, 2009; Beekes, 2014).

Although pellets have desirable characteristics, they are expensive and still cannot compete with fossil fuels in many cases. To further improve the properties of wood pellets, torrefaction of biomass prior to densification has been suggested as a pretreatment step (Gold and Seuring, 2011; Miao et al., 2012). Torrefaction is a thermal treatment that increases bulk and energy densities by removing oxygen and other volatiles (van der Stelt et al., 2011; Peng, 2012). Higher bulk density of torrefied biomass

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http://dx.doi.org/10.1016/j.jclepro.2014.04.071
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improves transportation, storage, and handling processes. Furthermore, torrefied pellets have very low moisture content, are hydrophobic and easily grindable (Pirraglia et al., 2013b). Because of these coal-like characteristics, storage, handling and feeding infrastructure at the coal power plants require minor alternation for co-firing (Schneider et al., 2012). Production of torrefied pellets is, however, more complex and capital intensive than the production of conventional pellets, and the thermal treatment leads to a loss of dry matter.

Torrefaction of different types of biomass and the effect of different processing conditions on biomass properties, such as grindability, energy content, moisture uptake, and particle size were investigated in previous studies. Li et al. (2012) showed that the hardness and moisture adsorption of torrefied pellets are less than that of regular pellets. Peng et al. (2013) studied torrefaction of different softwood species under different temperatures and residence times. Larsson et al. (2013) investigated the effects of die temperature and moisture content in the production of torrefied wood pellets and showed that increasing the die temperature positively affects the pelletization rate and negatively affects the bulk density of the pellets. Economic viability of production and consumption of torrefied wood pellets is addressed in different studies. Chiueh et al. (2012) developed a spreadsheet model integrated with a geographical information system (GIS) to study the production and consumption of regular and torrefied pellets in Taiwan. Pirraglia et al. (2013a) developed a spreadsheet-based model that includes mass balance, energy consumption, and financial analysis of the supply chain. They studied the integration of torrefaction in the U.S. pellet industry using their developed model. Techno-economic analysis of torrefied biomass production was conducted by Shah et al. (2012). They evaluated the sensitivity of the cost and energy consumption of torrefied biomass against changes in biomass type, its moisture content, and the required capital investment. Svanberg et al. (2013) developed a static model representing the supply chain that included sub-models for raw material supply to the torrefaction plant, mass and energy balances for pellet production, capital and operational cost estimations, and distribution system. The model was applied to a case study of supplying torrefied pellets to a Combined Heat and Power (CHP) plant. Beekes (2014) compared the production and consumption of regular and torrefied wood pellets and estimated 15% lower logistics costs for torrefied wood pellets.

Effective management of the supply chains is a critical factor in the success of biofuel and bioenergy applications (Gold and Seuring, 2011; Mafakheri and Nasiri, 2014). Different supply chain modeling approaches have been used to design and plan biomass supply chains including mathematical programming, simulation, queuing theory, and agent based models (Miao et al., 2012). Mathematical programming of the supply chain is usually used in solving strategic and tactical planning of the supply chains (Sharma et al., 2013). Schmidt et al. (2010) developed an optimization model to determine the optimum location and capacity for a bioenergy plant while minimizing the total cost of the supply chain. Strategic planning of biofuel production and distribution was modeled in An et al. (2011). The scope of the model includes feedstock suppliers, preprocessors, refineries, distributors, and customers. The logistics of supplying agricultural biomass to a biorefinery plant was modeled by Ebadian et al. (2013). An optimization model was developed to optimize the inventory planning and the results were validated through simulation of the logistics system. A hierarchical methodology for integrated portfolio design and supply chain network design for forest biorefinery industry was suggested by Mansoornejad et al. (2010). Integrated supply chain design of ethanol and gasoline was studied by Andersen et al. (2013) and Tong et al. (2014). There are many other applications of mathematical programming in the supply chain planning of biomass supply chain. Recent reviews are provided by D'Amours et al. (2008), Shabani et al. (2013), Sharma et al. (2013), and De Meyer et al. (2014).

When dealing with forest biomass, uncertainty in the quality, availability, and accessibility of the material is an inherent feature of the supply chain. The performance of the equipment, their failures, and required repair time in addition to the market fluctuations and policy changes are other sources of uncertainties in this environment. Also, the interdependencies between different stages of the supply chains are an important feature of biomass supply chains. In order to include the effects of the uncertainties and the interdependencies into the analysis, stochastic simulation modeling is used in the literature. Gallis (1996) developed a simulation model of forest biomass to a wood processing facility in Greece to study the effects of changes in the equipment specification, wages, interest rate, and dry material loss on the cost of delivered biomass. Supplying forest biomass to a potential 300 MW power plant in Quesnel, BC was studied using a simulation model developed by Mobini et al. (2010). The uncertainties in availability and moisture content of biomass and their effects on the performance of the logistics system were considered in the model. The delivered cost of biomass to the power plant and possibility of demand fulfillment over the life span of the power plant were evaluated. A simulation model called Integrated Biomass Supply Analysis and Logistics model (IBSAL) was developed by Sokhansanj et al. (2006). The cost of delivered biomass was estimated considering the harvest schedule, climatic factors, and operational constraints in the model. The application of this model in designing new feedstock supply chains is explained in Sokhansanj et al. (2008). The IBSAL model was used to evaluate current and future potential technologies for production, harvest, storage, and transportation of switch grass (Sokhansanj et al., 2009). Also, it was used in Sokhansanj et al. (2010) to analyze the utilization of corn stover as the source of biomass for ethanol production. An and Searcy (2012) used IBSAL to model the biomass logistics system using a conceptual packaging system that increases the density of agricultural biomass to maximize the efficiency of transportation. Logistics planning for a potential biorefinery plant was simulated by Ebadian et al. (2011). This model is capable of including different types of biomass and incorporates the effects of weather conditions and biomass quality on the performance of the supply chain. A GIS-integrated simulation model was developed by Zhang et al. (2012) and was used to find the best option amongst a set of potential locations and capacities for development of a biofuel production facility in Michigan, US. A simulation model, called PSC (Pellet Supply Chain), was developed and used to analyze the wood pellet production and distribution supply chain by Mobini et al. (2013). The scope of the model spans over the entire supply chain from sources of biomass to the customers. The PSC is composed of several modules including suppliers of raw materials, pellet mills, customers, and vehicles. The processes and the flow of biomass inside the pellet mill are also included in the model. Raw material storage, drying, size reduction, pelletization, cooling and pellet storage are the processes included in the pellet mill's module. The PSC model is developed as a decision support tool for design and analysis of the wood pellet production and distribution supply chains.

The evaluation of torrefaction as a pre-treatment approach in a supply chain context has been identified as a research gap in the literature (Ciolkosz and Wallace, 2011; Svanberg and Halldórsson, 2013). In order to address this gap while capturing the uncertainties involved in the biomass supply chains, in the present study, the PSC model is extended by developing the torrefaction process module. The uncertainties in quality measures of biomass,

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