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A mixed integer non-linear programming model for tactical value chain optimization of a wood biomass power plant

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HIGHLIGHTS

- Developed a mathematical model to optimize the supply chain of a forest biomass power plant.
- Considered supply, storage, production and ash management.
- The model provided more profit compared to the actual profit of the company.
- Biomass purchase cost had the highest share in total cost.
- Investing in a new ash recovery system has environmental and economic benefits.

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ABSTRACT

Forest biomass is one of the renewable sources of energy that has been used for generating electricity. The feasibility and cost of producing electricity from forest biomass depend on long term availability of biomass, its cost and quality, and the cost of collecting, pre-processing, handling, transportation, and storage of forest biomass, in addition to the operating and maintenance costs of the conversion facility. To improve the cost competitiveness of forest biomass for electricity generation, mathematical programming models can be used to manage and optimize its supply chain. In this paper, the supply chain configuration of a typical forest biomass power plant is presented and a dynamic optimization model is developed to maximize the overall value of the supply chain. The model considers biomass procurement, storage, energy production and ash management in an integrated framework at the tactical level. The developed model is a nonlinear mixed integer programming which is solved using the outer approximation algorithm provided in AIMMS software package. It is then applied to optimize the supply chain of a real biomass power plant in Canada. The optimum solution provides more profit compared to the actual profit of the power plant. Different scenarios for maximum available supply and also investment in a new ash recovery system were evaluated and the results were analyzed. The model in particular shows that investment in a new ash recovery system has economic as well as environmental benefits for the power plant.

1. Introduction

Using wood, or forest biomass, as an energy source is not a new idea. Before the 20th century, wood was one of the main sources of world's energy, but it has been substituted partly by coal, oil and natural gas during the past century [1]. Today, the growing demand for energy, environmental issues and the instability of the main energy producer countries make it necessary to use alternative energy sources, such as forest biomass. Forest biomass combustion is considered as a carbon neutral process if managed (produced, transported and used) in a sustainable manner since the combustion releases the CO_2 that trees captured during the photosynthesis process. Utilizing biomass for energy generation can decrease the gap between the actual emission levels and the international protocol targets such as those in the Kyoto and Copenhagen Accords [2]. Biomass is a flexible energy source, capable of generating electricity, heat, biofuels or a combination of them. It is one of the few renewable energy sources that can be stored and used to generate energy on-demand. It can also provide economic value, job opportunity and sustainable energy for communities [3]. In Canada, after hydro, the highest share of renewable energy production is contributed by biomass (2.9% in 2008 according to [4]).

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Despite the advantages of using forest biomass for power generation, there are several barriers to its efficient utilization, such as feedstock availability, cost and quality, conversion efficiency, transportation cost, and the efficiency of supply logistics system. Generally, the main concern in using biomass for energy generation is to design and manage its supply chain effectively in which it can compete with other options in the energy market [1]. The costs associated with different activities in generating power from forest biomass are highly case specific and depend on the availability of feedstock, distance of the suppliers from the plant, technology, and other factors. Generally, it is difficult to collect, transport, handle and store low-density materials. The quality of raw material (such as moisture content and heat value) also plays an important role in the performance of the production process [5]. Moreover, the effect of a decision made on one part of the supply, logistics, production and distribution would propagate to the other parts. Therefore, the whole system or "supply chain" should be considered and managed in an integrated manner.

Supply chains can generally be defined as distributed organizations where materials and information flow in many directions within and across organizational boundaries through complex business networks of suppliers, manufacturers, distributors, and final customers [6,7]. A supply chain model can be developed to help decision makers in their decisions and manage the supply chain more efficiently. Operations research and mathematical modeling have been used in supply chain planning and management including forestry related production/distribution design and management problems. There are also studies on design and/or management of forest biomass supply chain for energy generation. Most of these studies were done on biofuels, heating or combined heating and electricity plants. There are some studies which used simulation for modeling the biomass supply chain design or management such as [8–10]. Since the focus of our research is on optimization of forest biomass supply chain, we provide brief review of previous studies using optimization techniques in bio-energy supply chain design and management.

Several authors developed optimization model to determine the optimal material flow, transportation, storage and chipping location of energy systems, mainly heating plants [11–15]. Eriksson and Björheden [11] developed a model with decision variables related to storage and the chipping location for a heating plant. Gunnarsson et al. [12] developed a mixed integer programming model for tactical-strategic supply chain management of forest fuel used in a heating plant in Sweden by focusing on supply procurement decisions rather than the production process. In [12], the raw material were kept separated in the storage and multiple time steps were considered in model. The developed model was used to solve six generated problems rather than being applied to a real case study and the results of using different solution methods (LP and IP, and IP heuristic) to solve the problems were compared. The model developed by Kanzian et al. [13] included 16 combined heat and power plants and eight terminal storages in Austria. Freppaz et al. [14] used geographic information system (GIS) along with mathematical modeling to develop a decision support system for energy (thermal and electricity) production from biomass with a case study in Italy. In another study, done by Van Dyken et al. [15], a linear mixed-integer model was developed for biomass supply chain with transportation, storage and processing operations over 12 weekly time steps considering supply, constant demand, three different biomass products and two demand loads for chips and heat. This study focused on operational supply chain planning and the developed model was not applied to a real case study. A truck scheduling optimization model was developed in [16] for transportation of four types of forest biomass to energy plants in Oregon, US. This study only considered the transportation part of the supply chain.

Strategic decisions such as plant size and location were studied in [17–19]. The most profitable configuration (plant size) of a multi-source biomass district heating plant in Italy was considered in [17]. Optimum locations of bio-energy plants were studied in [18] with a case study in Austria. In [19], the authors used GIS to determine the optimal locations, sizes and number of bio-energy facilities (pellet plants) in Alberta, Canada while optimizing the transportation cost. Some studies evaluated the conversion technology and the possibility of co-generation in the district heating system supply chain design using mathematical programming such as [20–25]. Some previous studies considered biomass supply chain management for generating biofuels. An optimal configuration of a biofuel supply chain was studied in [26] with a case study in Italy. Ekşioğlu et al. [27] developed a model for cellulosic ethanol bio-refinery supply chain to determine the number, size and location of bio-refinery plants. The considered raw material was agricultural and woody biomass and the case study was located in Mississippi, US. Another study [28] used optimization methods to determine the optimal location, biomass supply area, and the size of a power plant that used olive tree pruning residues for energy generation. The trade-off between economic and environmental objectives in an optimal planning of a bio-refinery in Mexico was evaluated by Santibañez-Aguilar et al. [29]. In this study, different types of raw material including agricultural biomass, wood chips, sawdust, and commercial wood were considered to be used for producing ethanol, hydrogen, and biodiesel (generated only from agricultural biomass). The authors developed a multi-objective optimization model to make decisions about feedstock, processing technology, and products in a bio-refinery supply chain. Kim et al. [30] developed an optimization model for supply chain design of bio-gasoline and biodiesel production from six forestry resources (logging residuals, thinnings, prunings, inter-cropped grasses, and chips/shavings). Their case study was based on an industrial database related to a case in the Southeastern United States. The same authors [31] also performed a global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty and identified the most effective uncertain parameter on profit. The authors then developed an optimal model to maximize the expected profit of all the defined scenarios. Chen and Fan [32] developed a mixed integer stochastic programming model to incorporate uncertainty in strategic planning of bio-energy supply chain systems and optimal feedstock resource allocation. Their case study was located in California, US. They considered bioethanol production, feedstock procurement, and fuel delivery in an integrated model. Zhang et al. [33] designed an optimal switchgrass-based bioethanol supply chain using a mixed integer linear programming model with a case study in North Dakota, US. The objective function of their model was to minimize the total annualized cost which included marginal land rental cost, switchgrass cultivation, harvest, storage cost, different transportation costs, preprocessing and operational cost, and annualized fixed cost of preprocessing facilities and biorefineries. They also evaluated the effect of changes in bioethanol demand and harvest methods, bio-refinery locations, switchgrass yield on the results using sensitivity analysis.

None of the above mentioned studies considered the supply chain of forest biomass for electricity generation. The only study that considered a biomass power plant in an optimization framework is [34]. In this study, a multi-objective optimization model was developed to minimize the procurement and transportation costs and maximize the biomass quality (moisture content) for a biomass power plant. The first priority was given to procurement; the second priority was given to distance of procurement, and the third priority was given to biomass moisture content. Their single time-step model optimized the amount of each individual biomass type, including harvesting residues and poplar trees from different harvesting zones. Their case study was a 50 MW h biomass power