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Biomass feedstock supply chain network design with biomass conversion incentives

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ABSTRACT

Biomass has the potential to create sustainable energy systems, which is critical for societal welfare. A major issue regarding biomass resources is crop residues or leftover biomass that is burnt by farmers after harvesting; this happens due to high transportation costs which make burning the cheapest way to remove the residue. We develop a decision support system using a large-scale linear program with the goal of maximizing profit with and without the emission cost. This system helps identify farms that would benefit society were they to be incentivized under a biomass crop assistance program (BCAP). A case study of leftover corn stover in the state of North Dakota is analyzed to validate the model. Our results reveal that an incentive of $7.20 per ton of corn stover converted to ethanol when 20% of rail capacity is allocated is ideal, as it produces the lowest emissions of 16,784,953 metric tons with a $73,462,599 profit. Furthermore, penalizing emissions resulting from the transportation of corn stover also helps reduce emissions; a suitable value for the penalty could be $71.7 per metric ton of CO_2 emitted. Such a policy would result in reducing dependency on petroleum, thus promoting a sustainable biomass supply chain.

1. Introduction

Biofuels and biopower are forms of renewable energy directly derived from biomass, which is originally harvested from organic materials such as plants. Residues from agriculture are an important biomass source to produce bioenergy for transportation, while at the same time providing us with a better, "green" solution for the economy, society, and the environment. This growing interest in biomass for energy production has consequently led to an increase in research on biomass, especially on optimizing the overall supply chain from the initial stages of crop harvesting all the way to final consumption. In fact, biomass from agricultural residues is one of the largest biomass resources in the United States (Perlack et al., 2005). This is not only occurring in the United States, though; on the contrary, biofuel production and consumption have increased throughout the world as a substitute for fossil fuels, such as petroleum and coal (Heyne and Harvey, 2013). Lastly, biomass can transform and has indeed already had a major impact on many aspects of our everyday life, as it provides us with energy at lower costs (Mckendry, 2002) and while emitting less compared to fossil fuel (WNA, 2011). However, it is also no panacea, with high costs of production and transportation, along with greenhouse gas (GHG) emissions across its supply chain (Labriet, 2013). This raises concerns for producers and policy makers, who need to find strategies that reduce costs and at the same time address CO2 emissions in response to government objectives. According to the Renewable Fuel Standard (RFS), 138 million metric tons of GHG emissions are expected to be reduced when it is fully implemented in 2022 (Schnepf and Yacobucci, 2013). Our research aims to identify an efficient way to reduce costs and emissions across the biomass supply chain, using data from the state of North Dakota for a case study.

Research on biomass and its impact has been rapidly growing over the last years, mostly due to its ability to become an alternative power source that is both more economical and greener compared to fossil fuels like petroleum. It has also been documented that corn stover converted to bio-ethanol can lead to increased income for farmers; moreover, ethanol can help reduce the pressure of international fuel market fluctuations and help achieve energy independence (Gallagher and Johnson, 1999). It comes as no surprise then that many investigators have been looking into the adoption of operations research techniques for improving the design, viability, and effectiveness of modern biomass supply chains (Ghaderi et al., 2016). For an excellent overview of the existing results in biomass supply chain optimization

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and modeling, we refer the interested reader to the work by Yue et al. (2014).

The advantages of economies of scale for deciding the size of biorefineries was investigated Gallagher and Johnson (1999). Their analysis depicted the potential gains from adopting biofuel production from agricultural residues and materials. Their gains were shown to be not only financial, but also societal. Later, Ekşioğlu et al. (2009) analyzed the operations of the supply chain to transport biomass to biorefineries and determined the number, size, and location of the biorefineries needed and the amount of biomass shipped, processed, and stored during a time horizon. In this study, the design of long-term (supply chain) and short-term (logistics) decisions were considered and integrated with the goal of minimizing the total cost of delivery. A main insight of their work was that operators prefer to receive biomass within a 50-mile radius due to high biomass transportation costs. In a subsequent work, Roni et al. (2014) proposed the hub-and-spoke design for a biomass supply chain; therein, two models were integrated for short- and long-distance deliveries to coal plants. Moreover, Park et al. (2017) proposed a multimodal transportation scenario for switchgrass-based bioethanol in North Dakota. However, these studies do not account for incentives in their modeling frameworks. As we will show later in this manuscript, incorporating the effects of monetary incentives and emissions penalties in the decision-making process, we can help towards better streamlining the biomass supply chain.

Recently, Marufuzzaman et al. (2014) proposed a mixed-integer linear program to optimize both cost and emission components in the supply chain by employing wastewater treatment in the production of biofuel: emission components in this work focused on two modes of transportation, namely truck and pipeline, for biodiesel production using wastewater sludge. Their work also looked into regulatory policies, such as a carbon tax, carbon cap-and-trade, and other carbon offset mechanisms. In our study, we consider truck and rail transportation to move corn stover from farms to biorefinery plants either directly or through storage facilities, as well as to move ethanol from biorefineries to customer markets. We did not study emissions in more granularity by including emissions from the corn stover to ethanol conversion process. To that extent, we refer the interested reader to the work by Canter et al. (2016), in which the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (Laboratory, 2017) was used to perform a full life cycle analysis study.

In other studies related to biomass supply chain management, Cambero et al. (2015) presented a multi-period mixed integer linear programming model for converting forest residues to bioenergy. Employing mathematical programming models for better designing and planning biomass supply chain networks is also investigated in Ahn et al. (2015); such models can result in significant benefit for the supply chain. Once more, the aforementioned studies do not explore the observed supply chain benefits resulting from properly incentivizing biomass.

Other related works on optimizing modern biomass supply chains utilize simulation-based techniques. Mobini et al. (2013) developed a discrete event simulation system that considers a series of interdependencies and uncertainties across the supply chain, such as variations in moisture contents, effect of machine failure, market specifications, and costs, among others. Their model could then estimate the cost of delivery to a range of customers as well as estimate the energy inputs and CO2 emissions along the supply chain. Shabani and Sowlati (2013) used a nonlinear mixed integer program for biomass procurement, storage, and energy production and management to estimate the amount of biomass to be purchased from each supplier, and then stored and consumed on a month to month basis. Their results showed that optimal biomass procurement policies resulted in 15% lower costs. Later, the authors also proposed a Monte Carlo simulation framework coupled with their optimization model to assess the impact of uncertainty in parameters of the supply chain, such as biomass quality, availability, and electricity prices (Shabani and Sowlati, 2015). A common missing theme is the absence of monetized emission costs. Incorporating monetary incentives and monetized emissions would make these studies more comprehensive. This is one of the gaps that we aim to fill by also investigating the trade-off between the incentive and emission prices.

A study on storage systems for agricultural biomass for cellulosic ethanol production has further revealed a decline of 8% in CO2 for the logistics operations for roadside storage (Ebadian et al., 2013). Evaluation of slash recovery systems for utilizing biomass has the potential to mitigate the increases in GHG emissions, as previous studies assumed that only one recovery system would be used, with the choice being between comminution in-field and roadside (Lindroos et al., 2011). The use of renewable energy sources has also seen an increased interest for many stakeholders in district heating systems (Ghafghazi et al., 2010). Criteria considered in their work included GHG emissions, particulate matter emissions, maturity of technology, and traffic load. A fundamental result from their work was that a yearly increase of 3% or more in the prices of fossil fuels would render biomass even more attractive. The authors also employed life cycle assessment for all stages including fuel production, fuel transportation, operation, and finally demolition of the district heating system to perform a full computational study (Ghafghazi et al., 2011). However, there is a need to investigate cases of monetized incentives allocated by the government to assist biomass supply chain; such incentives programs can help towards achieving more sustainable supply chains.

Promoting sustainable energy independence is a global challenge. Renewable energy, including biomass, is one of the fastest growing energy industries which contributes towards this goal. To meet this challenge, government intervention has been crucial for supporting and promoting biomass conversion for both small- and large-scale renewable energy producers. This is usually done through incentive programs such as the Biomass Crop Assistance Program (BCAP), which was introduced by the 2008 Farm Bill as a strategy to develop and improve agricultural products in the United States and reduce reliance on foreign oil, as well as mitigate air pollution (USDA, 2016b). The program provides funds to farmers to manage logistics activity for biomass feedstock, including but not limited to operations related to harvesting and transporting biofuel ingredients. The use and generation of renewable energy has also been incentivized by the government in many countries at the state and national levels (Rosaly and Laurèn, 2013) although, as expected, there are different types of policies for each geographic location. The different responses and adoption rates of policy incentives across countries are posing a challenge for researchers to identify the reason behind them in terms of technology and settings (Bangalore et al., 2016).

More specifically, transportation seems to be the major consideration, seeing as it significantly affects the cost of converting raw material to the, ready for consumption, end product. Investigating biopower co-firing to further understand the relationship of this process with other supply chain related costs, including transportation, has recently been performed by Liu et al. (2016). Their study shows that a reduction in transportation costs indeed leads to increased feasibility of reasonably-priced biomass feedstock. For other renewable energy sources, such as wind energy, financial incentives have been shown to be important at both federal and state levels (Black et al., 2014). There are significant positive impacts on the wind energy growth in the U.S. from the tax incentives: Black et al. (2014) discovered that removing this incentive in the state of Idaho would result in tax revenue reduction as well as a decrease in other significant economic metrics such as total output, employment, and state income.

It is becoming increasingly clear that government intervention in the form of incentives for renewable energy are potentially beneficial. They can prove transformative in our efforts to foster the development of renewable energy that benefits our societies, economies, and the environment. As mentioned by Simsek and Simsek (2013), renewable energy is crucial in bettering energy security and independence, and its