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Cellulosic biorefinery portfolio and diversification: Strategies to mitigate cellulosic biorefinery risks in US Corn Belt

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ABSTRACT

Several studies have highlighted that one of the largest risks with cellulosic biorefinery investments are year-to-year variability in cellulosic biomass quantity available. Yet, strategies to mitigate these risks in biofuel development are less understood. In the absence of strategies to minimize the impact due to these variations, both biorefineries and farmers venturing into the cellulosic biofuel arena will be significantly exposed. Studies have been done on using engineering approaches, such as biomass pre-treatment and storage to address biomass supply variations. Recent studies have provided market structure and contracting strategies to manage biomass supply risks. However, storage, pre-treatment and similar engineering approaches lead to higher costs and has other limitations such as additional infrastructural requirements. There is a gap in understanding the use of feedstock (biomass) diversification and portfolio strategies to mitigate such risks. In this study a portfolio approach is developed and applied to the case of the US Corn Belt, considering various types of cellulosic biomass including corn stover, wheat straw, and switchgrass. It is found that *feedstock diversification* mitigates up to 40% of feedstock supply variations, while *biorefinery diversification* can mitigate up to 70% of feedstock supply variations although it is constrained by current cropland use patterns in the region. Overall, diversification and portfolio strategies present an effective way for mitigating risks associated with feedstock supply variations.

1. Introduction

Approximately half of the world's current biofuel supply comes from corn ethanol produced in the US [1]. Corn ethanol is found to have several disadvantages, including competition with food supply and low benefit in greenhouse gas offsets [2]. To overcome these shortcomings and expand bioenergy supply, many countries have embarked on developing second generation biofuels produced from cellulosic feedstock such as agricultural and forestry residues and perennial grasses [3]. Cellulosic biomass is primarily agricultural waste (e.g., corn stover, sugarcane bagasse, straws, etc.), forestry residues (e.g., sawdust, logging residue, etc.) or energy crops (e.g., switchgrass, elephant grass, short-rotation woody crops, etc.). For instance, the US targets to produce 76 billion litres of biofuels per year by 2022, which will require about 200 million dry tonnes of biomass annually [4], of which the US Corn Belt is by far the largest source of biomass from agricultural residues [5].

Studies have found that a major risk with cellulosic biofuel investments is variability in the annual availability of biomass by 20–30%, as a result of variations in underlying biomass yield [6]. Along with exposure to supply variations, cellulosic biorefineries will face fundamental challenge due to limitations on long-distance transport and long-term storage of biomass [6]. Its low bulk density in mass and energy prevents biomass for being transported over a long distance. As a result, unlike corn ethanol mills, cellulosic biorefineries source biomass locally, which limits their ability to effectively mitigate regional biomass supply constraints [7].

The large annual variability in local feedstock supply coupled with the constraints in long-distance transport and long-term storage of biomass points to the needs for mitigating the adverse impacts of feedstock supply variations on biofuel development. A recent review has provided the importance of managing biomass supply uncertainties and incorporating these uncertainties in modelling biofuel supply chains [8]. In the absence of a feedstock strategy, these supply variations will lead to significant regional

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supply-demand imbalances that will ultimately impact feedstock price and transform into variability of biorefinery profit or investment risk, hindering the development of a biofuel industry.

Proposed solutions to mitigating supply variations have focused on either engineering options (biomass pre-treatment and storage) or improvements in the design and management of biofuel supply chains. Pre-treatment of biomass using torrefaction, palletisation, and pyrolysis can convert biomass into denser energy carriers and improve its storability and bulk density [9–13]. Biomass storage can offset feedstock supply variations, but long-term storage remains challenging due to health, safety, and technological risks [14]. Furthermore, these engineering approaches will entail additional investments and production costs, and increase the total cost of cellulosic biofuel substantially.

Various modelling approaches, particularly mathematical programming, have also been used to identify the optimal logistics and management strategies for biofuel supply chains under uncertainties including variability in feedstock supply. Several studies have suggested a stochastic approach for managing biofuel supply chains under demand and price uncertainties [15–17]. Some others have used linear programming based optimization models [18], and a dynamic, spatially explicit, and multi-echelon Mixed Integer Linear Programming framework [19–21] for minimizing variability in biomass supply chains and in making biofuel investment decisions.

A recent study has progressed understanding of market structures and contracting strategies to address large year to year variability in biomass supply. Using Game Theoretic analysis the studies have found that a 'Derisked' supply market structure, where biorefineries maintain a buffer supply region to 'Derisk' again biomass supply shocks, would significantly reduce risk and biomass cost compared with a free market structure [6]. They find that optimizing biomass trade-offs and setting up long term biomass supply contracts between biorefineries and farmers could significantly reduce biomass cost and supply risk [7]. Another study by Dale et al. has proposed using a network of local biomass processing depots (LBPDs) for sustained supply to biorefinery [22].

However, few studies have attempted to examine portfolio strategies to mitigate biomass supply variations. One such option is through diversifying input (feedstock) blend [23]. While the concept of blending raw materials to optimize profit is widely used by the oil and gas industry [24], its applicability in cellulosic biofuel production remains to be evaluated. Further, it is unclear how diversification strategies to develop a cellulosic biofuel business portfolio can minimize risks. This study is intended to shed light on these gaps. The specific objective of this study is to examine the role and strategies of diversification in mitigating biomass supply risk.

A local diversification strategy considering corn stover, wheat straw, and switchgrass is evaluated for US Corn Belt. A modelling framework is developed, to identify optimal points of feedstock diversification using the concept of Modern Portfolio Theory. Based on the simulation results, we then identify feedstock combinations/portfolios that are on the efficient frontier (Pareto Efficient) and results in the lowest biomass supply variation for a given level of biomass premium. Although diversification may increase the primary feedstock cost (premium), as wheat straw and switchgrass are considered more expensive than corn stover [89–92], the reduction in biomass supply risk could reduce the overall impact on the biorefinery as a result of improved operation efficiency.

Historical yield data (dry t ha^{-1}) of corn stover and wheat straw is used, while *for switchgrass we use hay as a proxy for historical data* because switchgrass is still under development and there is not enough historical data available that can be used in the simulation.

This study will provide a framework for developing optimal feedstock diversification portfolios to maximize returns at a given level of risk. The strategies developed through this study can be used together with engineering and logistic options to aid in designing biomass supply chains, devising biorefinery operation plans, and developing national strategies and policy to facilitate the development of a sustainable cellulosic biofuel industry.

Although this study targets the US Corn Belt and its unique feedstock sources, the analytical approach developed here is applicable to other regions with different feedstock sources.

2. Methods

2.1. Concept of diversification

The concept of diversification can be explained using the principles of Modern Portfolio Theory [29]. Consider a feedstock supply system with n different sources of biomass (j = 1, 2, 3, …, n), where the variance of annual supply of individual feedstock j is σ_j^2, its biomass cost is E_j, and biomass from n sources is mixed in a proportion w_j for biomass source j such that $\sum w_j = 1$ for all j's to form a feedstock portfolio. The effective cost of the diversified feedstock portfolio is then,

$$E_p = \sum_{j=0}^{n} w_j E_j, \quad (1)$$

and the expected supply variance of the diversified feedstock portfolio is,

$$\sigma_p^2 = \sum_{j=0}^{n} \sum_{i=0}^{n} w_i w_j \sigma_i \sigma_j \rho_{ij}, \quad (2)$$

where ρ_{ij} is the correlation coefficient between feedstocks i and j, which ranges from +1 to −1. If the correlation coefficient ρ_{ij} is less than +1.0, the variance of the diversified feedstock portfolio σ_p can be reduced to less than the variance of any individual feedstock by mixing them in right proportions. This explains how feedstock diversification can reduce overall feedstock supply variation.

One of the key characteristics of Modern Portfolio Theory is the concept of efficient frontier, defined as a locus of portfolios that offer the highest expected return for a given level of risk or the lowest level of risk for a given level of expected return [29]. Portfolios that are not on the efficient frontier are considered suboptimal, because they do not provide the highest possible return for the level of risk. Throughout this study we define an efficient frontier as a set of feedstock or biorefinery portfolios that offer the lowest level of risk (overall biomass supply variations) for a given level of biomass premium.

2.2. Feedstock diversification

We define feedstock diversification as a system where a single biorefinery uses a diversified feedstock portfolio, instead of using a single feedstock. In the case of cellulosic biofuels, constraints with long-distance transport and long-term storage of biomass limit feedstock diversification to regional supply boundaries [28].

Research has found that switchgrass, a native perennial grass has the potential as a dedicated energy crop using marginal cropland [30–32], and produces comparable ethanol as corn stover [33]. Since switchgrass grows well in the US Corn Belt as well, it could be used along with corn stover to create a diversified feedstock portfolio. Wheat straw is also abundant in the US Corn Belt, and is another attractive alternative for feedstock diversification [34–37].

A simulation model is created using historical yield data (dry t ha^{-1}) from 2000 to 2014 to identify variations in corn stover, wheat straw, and switchgrass *(hay as a proxy due to switchgrass data limitation)*. Then the efficient frontier of feedstock diversification is