Quantifying Supply Risk at a Cellulosic Biorefinery

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Abstract

In order to increase the sustainability and security of the nation's energy supply, the U.S. Department of Energy through its Bioenergy Technology Office has set a vision for one billion tons of biomass to be processed for renewable energy and bioproducts annually by the year 2030. The Renewable Fuels Standard limits the amount of corn grain that can be used in ethanol conversion sold in the U.S. Therefore making the DOE's vision a reality requires significant growth in the advanced biofuels industry. Risk mitigation is central to growing the industry beyond its infancy to a level necessary to achieve the DOE vision. This paper focuses on reducing the supply risk that faces a firm that owns a cellulosic biorefinery. It uses risk theory and simulation modeling to build a risk assessment model based on causal relationships of underlying, uncertain, supply driving variables. Using the model the paper quantifies supply risk reduction achieved by converting the supply chain from a conventional supply system (bales and trucks) to an advanced supply system (depots, pellets, and trains). Results imply that the advanced supply system reduces supply system risk from 83% in the conventional system to 4% in the advanced system.

Keywords: Risk, biofuels, cellulosic, unit cost, supply chain

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1.0 Introduction

The U.S. Department of Energy (DOE) is interested to improve security and sustainability of the nation's energy supply. Through its Bioenergy Technology Office (BETO) the DOE sponsors research geared towards that end. Recent BETO sponsored studies outlined how a bioenergy industry in the U.S. could supply one billion tons of biomass for conversion to renewable fuels by the year 2030 (Perlack, 2005; U.S. Department of Energy, 2011). The Renewable Fuels Standard limits the amount of corn grain that can be converted to fuel (15 billion gallons) to minimize the competition between food and fuel (Independence, 2007). The BETO study identified biomass types such as woody biomass, crop residues, energy crops and municipal solid wastes (MSW). In 2014 three cellulosic biorefineries, which can process crop residues and energy crops, opened for business; two in Iowa and one in Kansas (Lamers, Hansen, Jacobson, & Cafferty, 2014). The U.S. now has the capacity to process between 780 thousand and 900 thousand tons of biomass per year leaving ample room for growth in an industry envisioned to process one billion tons per year by 2030.

Research investigating supply systems to support the billion ton goal have focused primarily on logistics cost (Argo et al., 2013; Muth et al., 2014). In other work we surveyed the bioenergy industry to identify barriers in terms of risk (Lamers et al., 2014). From that high-level view we illustrate how uncertainty, market instability and costs affect profitability of the representative cellulosic biorefinery. In this paper we quantify one aspect of risk we previously identified; supply risk.

In analyzing supply risk the analysis adopts the perspective of firm owners of a cellulosic biorefinery. Part the strategic vision that BETO set includes a 2022 delivered to the biorefinery unit cost target of $80 per dry ton of biomass, which converts to $3 gallon of gasoline equivalent (gge) of delivered renewable fuel (Energy, 2012). The firm owner thus has a target by which to compare two alternative supply chains, the conventional supply system and the advanced supply system.

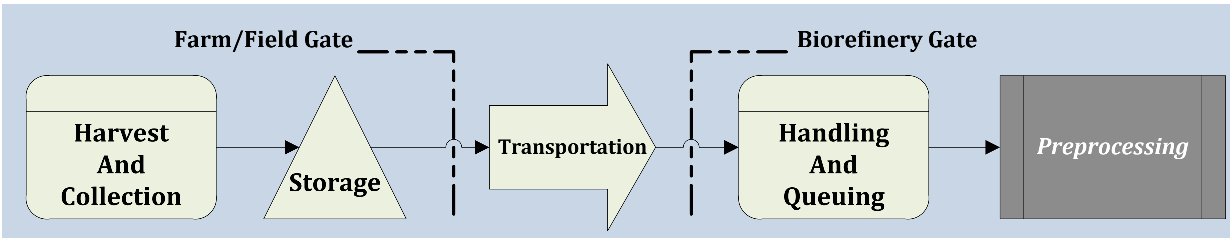


Fig 1. Conventional feedstock system for herbaceous lignocellulosic biomass

In the conventional supply system, firm owners and managers procure biomass feedstock through contracts with local growers, store it at field side and transport it to the biorefinery in low density format (see Figure 1). This "bales and trucks" system has been demonstrated to work in high yield regions of the U.S. but its success is questioned outside of resource rich regions. On the other hand, in the advanced supply system, developed by Hess, Kenney, Ovard, Searcy, and Wright (2009), feedstock is densified from large bales of biomass to small, dense pellets at regional supply depots (Figure 2). Use of depots makes possible contracting with growers that are geographically distant from the biorefinery. This supply system of depots, pellets, and trains is more costly than the conventional supply system but research shows that its benefits outweigh its costs (Jacobson et al., 2014).

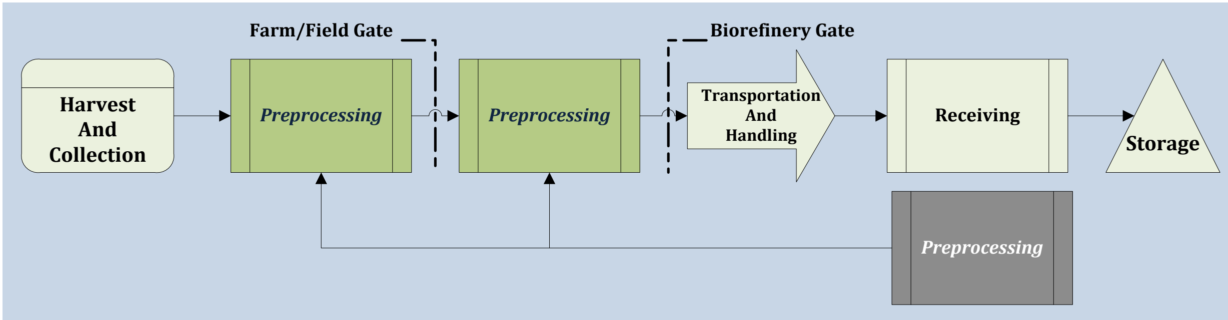


Fig 2. Advanced supply system design (Advanced Uniform) follow the model of the current grain commodity supply system, which manages crop diversity at the point of harvest and/or depot, allowing all subsequent feedstock supply system infrastructure to be similar for all biomass resources (Argo et al., 2013).

This paper compares the conventional supply system to the advanced supply system in terms of supply risk at the cellulosic biorefinery. It develops a risk assessment model that interacts the underlying causal relationships of variables driving risk on an annual basis. The analysis finds that the advanced supply system reduces unit cost of production when compared to the conventional supply system, but the larger impact is the reduction in cost variation. It decreases by 90%. The risk assessment model is preliminary in research that investigates supply risk overtime. It is built in a systems dynamic framework so that as additional risk drivers are uncovered in the research the inter-temporal feedback loops can be included. The paper proceeds with a discussion of the methods used to build the risk assessment model in Section 2. Then Section 3 presents the results with a discussion to follow in Section 4. Section 5 summarizes and concludes.

2.0 Methods

This section characterizes the supply risk that faces the cellulosic biorefinery in terms of feedstock supply variation and its impact on biorefinery costs using two feedstock alternatives, corn stover and corn stover blended with switchgrass. The amount of feedstock the biorefinery receives influences unit cost because too much (little) biomass moves production out of the target capacity range. Here we describe the theory to quantify risk and the risk assessment model, with its component parts, which is used to quantify supply risk.

2.1 Theory

We model risks according to the quantitative definition outlined in Kaplan and Garrick (1981) where they suggest a three-question approach. This seminal paper on risk asks: what can go wrong, how likely is it to go wrong, and what are the consequences if it does go wrong? We quantify supply risk at the cellulosic biorefinery by answering these questions.

2.1.1 Quantifying Risks

Supply risk is therefore defined as:

$$\Pr\left(c > C\right) \tag{1}$$

where the probability of c, the unit cost of production, exceeds C, the unit cost based on the design capacity. Unit cost overrun is the unwanted event and its likelihood quantifies risk.

Biorefinery architects and engineers design the facility with a target supply capacity in mind. Conversion efficiency, capital equipment, and other inputs into production are optimized when the feedstock supply falls within the range of engineered design specifications. Too little (or too much) feedstock at intake means the biorefinery does not produce the target level of ethanol, which means unit cost is outside of the designed range. In the case of too little biomass unit cost increase because excess capacity means fixed costs must be spread over fewer units of ethanol, or that the firm owners incur unexpected transaction costs for procuring feedstock out of contract. On the other hand too much biomass at intake means the firm incurs one of two likely outcomes. It must dispose of off-take (excess biomass) or store it for later processing when volume feedstock is short.[1] Either of these outcomes

[1] Managing storage will likely prove to be a supply risk reducing strategy. We investigate this question in the next phase of research.

increases unit cost because the biorefinery purchases, handles and stores more feedstock than it was designed to process. The primary driver to supply risk is to *receive feedstock quantities outside the target range*. This occurrence increases unit cost.

2.1.2 Supply Cost Variation

Obtaining cost data on cellulosic biorefineries is difficult for two reasons. First, only three cellulosic biorefineries exist today and their cost data is proprietary. Second, biorefineries of the scale needed for biofuel industry level development, those processing 800 thousand tons per year or more, do not yet exist. The DOE has established a unit cost target for a gallon of ethanol, based on ethanol being competitive with fossil fuel (Energy, 2012). The cost target of $3 per ethanol gge covers costs needed to produce a gallon of ethanol, including grower payment, feedstock logistics, transportation, conversion, etc. The latest design reports, where costs of converting feedstocks to ethanol are analyzed for conversion technologies, find the unit cost for thermochemical conversion at $3.11 per gge (Dutta et al., 2011) and for biochemical conversion $3.27 per gge (Humbird et al., 2011a).

The stylized biorefinery we model has the capacity to process 800 thousand tons of feedstock per year, which is consistent with operating 330 days at 2,400 tons per day. Based on research we assume a conversion ratio of 1:80 where a dry feedstock ton converts to gallons of ethanol (Humbird et al., 2011b). The assumption about conversion maps feedstock throughput to ethanol production such that the biorefinery in this example expects to produce 64 million gallons of ethanol per year.

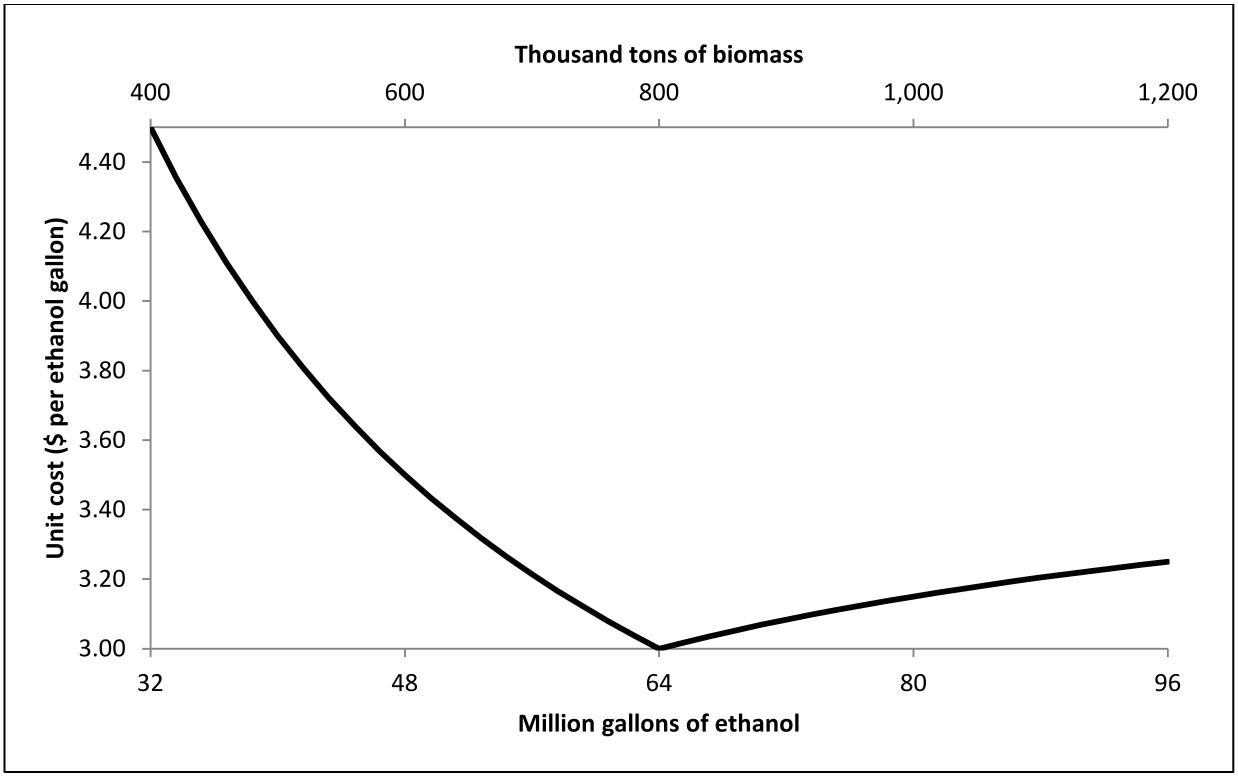


Fig 3. Average total production cost curve for a stylized biorefinery with feedstock throughput mapped to ethanol production.

Based on unit cost of $3 per gallon the firm's total cost is $192 million. This stylized biorefinery is analogous to the one modeled in Humbird et al where capacity is 61 million gallons of ethanol per year and capital costs are $232 million. With a single point on the biorefinery's total cost curve defined we use cost elasticities to estimate the average cost curve over a range of feedstock quantities. We assume economies of scale over the range of volume less than capacity so we use an elasticity consistent with economies of scale, 0.5, to estimate the corresponding total and average costs. For the feedstock range in excess of capacity we use a cost elasticity of 1.25, consistent with diseconomies of scale, to estimate total and average total costs.[2] These elasticities influence the shape of the average cost curve shown in Figure 3. Our choice for elasticities is consistent with the logic that the problem of insufficient feedstock is more costly than too much feedstock. Average total cost decrease as production increases up to the level of designed capacity at a rate greater than it increases for production in excess of design capacity.

[2] See Hirschey (p. 277, 2003) for a discussion of cost elasticities and economies of scale.

We use the average cost curve in the figure to quantify feedstock quantity risk according to equation (1), where c corresponds to the realized unit cost and C is $3 per gge.

2.2 Risk Analysis

2.2.1 Scenario

Our interest is in the future of the cellulosic biofuel industry so the biorefinery we model has capacity to process 800 thousand tons of feedstock per year. This capacity exceeds that of typical cellulosic biorefineries in production today but is consistent with the size of biorefineries needed to support a large scale biofuel refining capacity across the U.S. (Jacobson et al., 2014). Further, it is consistent with the assumption of an N^{th} of a kind biorefinery in the design case of a mature industry envisioned by the Bioenergy Technologies Office (BETO) in the DOE (Humbird et al., 2011b).

Feedstocks

The first feedstock we evaluate is corn stover, which is the residue left in the field after the corn grain has been harvested. To model it we assume independent farmers grow the feedstock so we apply farmer characteristics of a representative corn farmer in Iowa. Small biorefineries are currently in production in Iowa and good data exists for corn farms there. Consistent with the average corn farm size in Iowa, the model represents each farmer with 333 acres of corn.

The second feedstock we evaluate is a blended feedstock where switchgrass is blended with corn stover. Blending feedstocks is a method to improve quality and improve yield. Blending is useful because energy crops like switchgrass can be planted on marginal crop lands (Ian J. Bonner et al., 2014). Instead of planting corn in lands where soil quality is not conducive to good plant growth and corn yield, farmers can plant switchgrass. Switchgrass does not require the same high quality soil as corn to produce abundant yield, and it can be harvested for biorefinery feedstock at higher quality than corn stover. We model a blended feedstock assuming farmers plant 20% of their corn land in switchgrass. In the model this means that the total tons of corn stover decrease but the reduction is offset by the increase in switchgrass quantity (I.J. Bonner, McNunn, WLeirer, Muth, & Dakins, 2015).

Conventional Supply System

The conventional supply system can be thought of as one of bales and trucks, where stover is baled in the field, stored field side, then trucks transport it to the biorefinery when called for. In the conventional supply system over-contracting is the risk mitigation strategy available to managers at the biorefinery. Ensuring the biorefinery receives a sufficient amount of feedstock is critical. The contract manager over-contracts with a sufficient number of farmers to meet minimum feedstock supply requirements. Corn stover is expensive to transport and studies find that it is not economical to transport it over distances in excess of 50 miles (Hess et al., 2009). Therefore the manager issues contracts to farmers within a 50 mile draw radius from the biorefinery. Based on average characteristics for corn stover in Table 1 (yield, ash content, dry matter loss) we assume the manager contracts with 820 farmers, putting under contract over 1 million tons of corn stover. If average conditions prevail then the manager will net about 811 thousand tons of corn stover.

Advanced Supply System

The advanced supply system, which can be thought of as depots, pellets and trains, lets the contract manager mitigate supply risk through a diversified feedstock supply portfolio approach. Feedstock biomass is densified into small pellets at depots, which facilitates different storage and transportation. Instead of transporting biomass via trucks, now train transport is cost-effective because of the greater feedstock density and flowability. In the conventional system the manger contracts with 820 local farmers but in the advanced supply system the manager can contract directly with preprocessing depots. Because of reduced transportation costs depots can be either local (within 50 miles) or, because of reduced transportation costs, far removed from the biorefinery (up to 400 miles away) (Hess et al., 2009). Pelletizing corn stover at the depot makes it economical to transport the feedstock over much larger distances.

For consistency in comparing the two supply systems, now suppose that the 820 farmers belong to 10 farmer cooperatives, 82 farmers in each cooperative, where cooperatives each own a depot. The contract manager does not issue a contract to each farmer (820 contracts) but instead issues a contract to each depot (10 contracts). Depots are responsible for managing their own internal contracts and agreements among member farmers.

Because of the larger draw radius each depot can be geographically distinct from other depots. This means that the supply risk is now different. In a conventional system weather patterns, extreme events and other potential supply disruptions are shared equally amongst farmers since they are in close geographic proximity. That is in the conventional system a single set of uncertainties face each of the 820 local farmers and thus the biorefinery in the same way. However, in the advanced system 10 different locations means there are 10 sets of uncertainties so that disruptive weather patterns or other extreme events that affect the crop in one location do not affect the crop in all locations. A flood or drought that destroys some of the corn stover under the biorefinery's contract would not destroy all feedstock under contract because the feedstock is now distributed across 10 separate locations.

2.2.2 Uncertainty

With operational risk defined in terms of feedstock quantity we estimate uncertainty in order to quantify risks. In this model three random variables contribute to the set of uncertainties: yield, dry matter loss and ash content. We capture phenomena such as drought, flood, and other extreme weather or other events with the variation in yield. Dry matter loss and ash content impact the amount of usable feedstock at the biorefinery. Ash content is the dirt and other debris that collects in the biomass during harvest, storage and transport. Dry matter loss refers to the amount of rot in the biomass.

Table 1. Random variables used in simulation

	Corn Stover	**Switchgrass**
Yield (tons per acre)		
Distribution	Truncated Normal	Truncated Normal
Mean	3.86	4.01
St. Dev.	0.47	0.69
Min	2.80	2.96
Max	4.59	5.22
Ash Content (%wt)		
Distribution	Truncated Normal	Uniform
Mean	6.6	--
St. Dev.	2.75	--
Min	2.90	1.63
Max	11.4	3.32
Dry Matter Loss (%wt)		
Distribution	Truncated Normal	Truncated Normal
Mean	16.0	5.06
St. Dev.	16.5	0.78
Min	7.5	4.0
Max	38.0	6.0

Together yield, dry matter loss and ash content determine the amount of feedstock realized at the biorefinery in the simulation model.

Table 1 presents the distributions we used for each feedstock and variable of interest. To determine yield distributions we rely on the literature and empirical data. We approximate the yield for corn stover by extracting data on average bushel per acre in the U.S. from 1990 to 2013 from USDA.[3] Then we convert corn grain bushels per acre to corn stover bushels per acre with a 1:1 ratio (Kim & Dale, 2004). We use data from Adler (2006) and Aravindhakshan (2010) to approximate the distribution for switchgrass yield.

[3] http://quickstats.nass.usda.gov/results/D5445FF2-7FB3-390B-A54E-2B99CA1BA37B?pivot=short_desc last accessed 20 January 2015.

The distributions for ash content are based on estimates reported in the literature. Ash content for corn stover is based on the work of Kenney, Smith, Gresham, and Westover (2013). We approximate ash content for switchgrass based on Adler (2006) and Esteghlalian (1997).

For a conventional system we model dry matter loss in corn stover based on the work of Hess et al. (2009) for on ground storage at 7%. For switchgrass we approximate the distribution based on Mooney, Larson, English, and Tyler (2012) and Sanderson, Egg, and Wiselogel (1997) at 5%. In the case of advanced supply system we alter the distribution for dry matter loss to a uniform distribution that varies dry matter loss between 1% and 2%. Densification, which occurs in the preprocessing depot, reduces dry matter loss to almost nothing (Yancey, Tumuluru, & Wright, 2013).

2.2.3 Simulation Model

We simulate the model using Monte Carlo methods and 1,000 runs in Powersim Studio 10™ imposing the Latin Hyper Cube sampling technique. We simulate the model for each feedstock type, beginning with corn stover then simulating the switchgrass blend. Figure 4 illustrates the model.

The ‘Conventional Supply System’ forms the basis of the model; we build from it to form the advanced supply system. In the conventional supply system the biorefinery contracts with 820 local farmers within a 50 mile supply radius of the biorefinery. The uncertainty distributions for yield, dry matter loss, and ash affect each farmer in the same way because they are in the same geographic region. In each run the model determines ‘feedstock at the biorefinery’ then compares it to ‘FEEDSTOCK CAPACITY.’ The cost model computes ‘total cost’ and ‘average total cost’ based on the feedstock comparison. For feedstock less than capacity the cost model computes average total cost based on economies of scale, for feedstock greater than capacity it computes average total cost based on diseconomies of scale. The model generates a histogram for ‘feedstock quantity at the biorefinery’ then it generates the cost-risk curve (Figure 6), the cumulative probability distribution of average total cost.

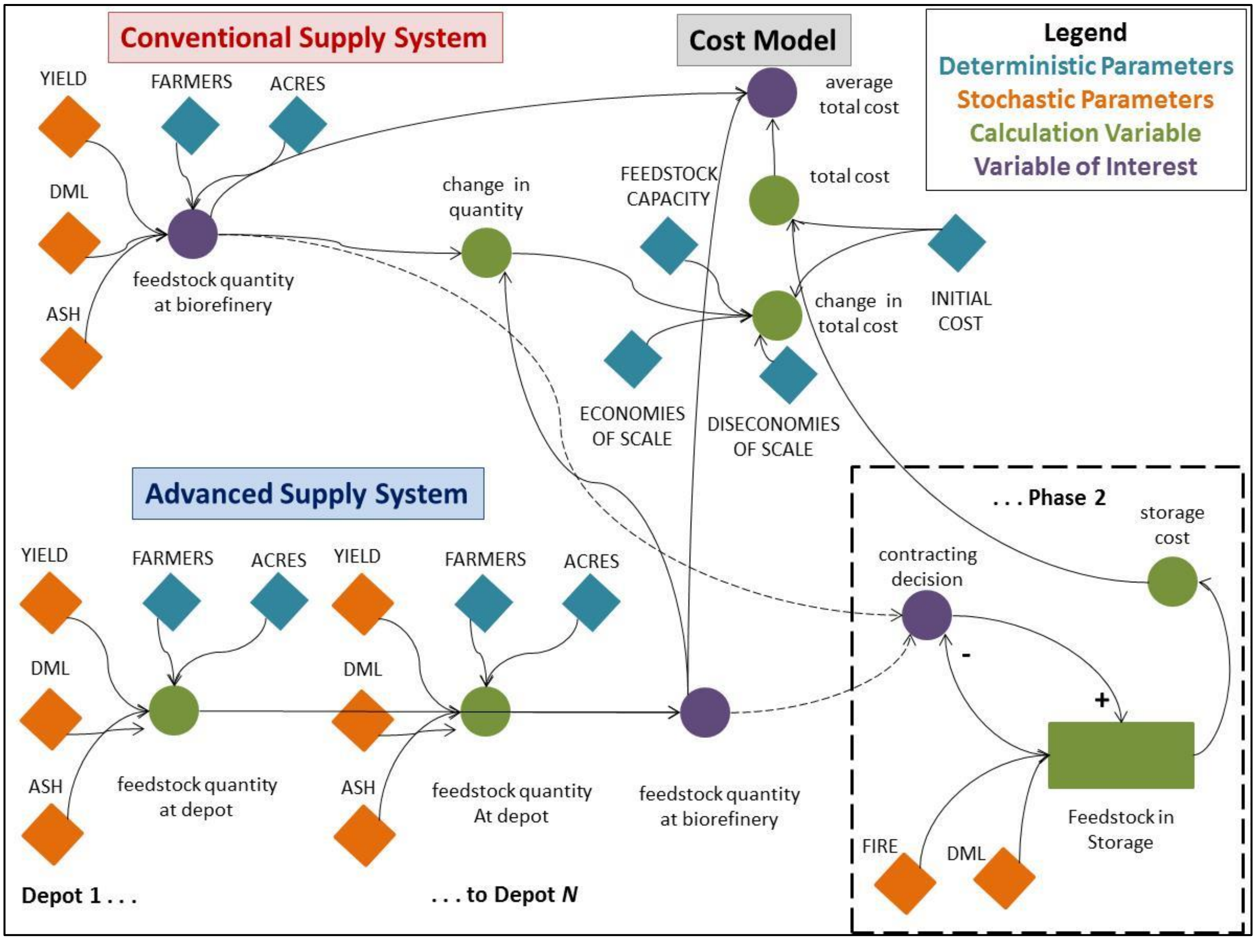


Fig 4. Feedstock Supply Risk Assessment Model

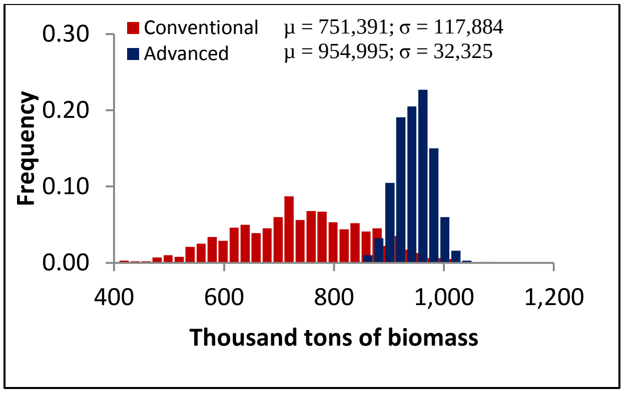
The 'Advanced Supply System' the model scales the 'Conventional Supply System' in the following ways. Whereas in the conventional case the biorefinery draws from a local supply radius, in the advanced case it draws from a much larger radius (up to 400 miles). Moreover, instead of drawing directly from 820 farmers the biorefinery draws from *N* number of depots. In the model depots are designed such that 82 farmers contribute to a single depot. The geographic difference between the two supply models is important because it influences how uncertainty is modeled. In the conventional case all 820 farmers faced the same set of uncertainties. In the advanced case farmers face *N* sets of uncertainties. In each depot region farmers face 'YIELD', ‘DML’, and ‘ASH’ equally but the model imposes separate uncertainties for each region so that farmers in region i do not face the same set of uncertainties in region j. The model scales up to N regions although our analysis begins with $N = 10$.

In Phase 2 of the analysis we will extend the risk assessment model to quantify supply risk over time. Feedstock storage is a risk mitigating strategy so we will extend the current risk model to include the storage component identified as “Phase 2” in Figure 2. This will inform on the feedback loop between feedstock in storage and the contracting decision, which determines the number of depots needed to reach feedstock supply targets.

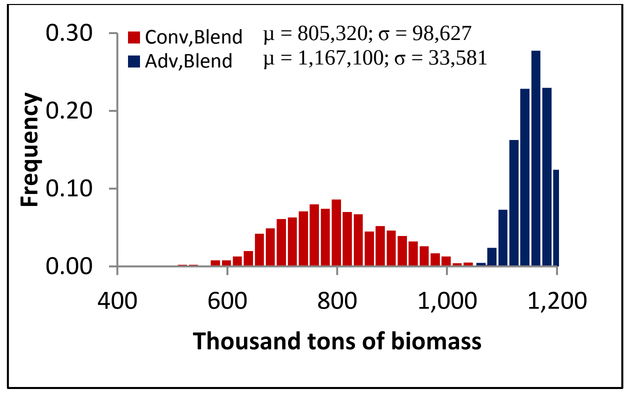
3.0 Results

3.1 Feedstock Supply Risk

Quantifying supply risk requires a measurement on the likelihood of the unwanted event, which is feedstock supply outside of design specifications. Figure 5 (a) shows the histogram for feedstock supply (corn stover) at the biorefinery. It shows the distribution of feedstock the biorefinery receives under the conventional supply system (red bars) and the advanced supply system (blue bars). In the conventional system the probability that the biorefinery receives less than capacity (800 thousand tons) is 71%, i.e. the summed area of red bars less than 800 thousand tons. In the advanced supply system the probability of less than 800 thousand tons is zero. The range of each distribution illustrates the amount of uncertainty in feedstock supply induced by variation in yield, ash content, and dry matter loss. The feedstock uncertainty in the conventional system varies from slightly more than 400 thousand tons up to nearly 1.1 million tons. The feedstock uncertainty in the advanced system varies from just less than 900 thousand tons to slightly more than 1 million tons. The width of the blue bars is less than the width of the red bars: less feedstock variability exists in advanced supply.



(a) Corn stover



(b) Blend

Fig 5. Histograms of biomass feedstock under conventional and advanced supply systems, note that (μ, σ) represent mean and standard deviation, respectively.

Figure 5 (b) shows the distribution of feedstock supply for the case of a blended feedstock. The red histogram shows the simulation results for the conventional supply system and the blue for the advanced supply system. In the conventional system the risk of getting biomass less than capacity is 58% but in the advanced supply system it is zero. Compared to Figure 5 (a) the distributions has shifted to the right in Figure 5 (b). Switchgrass has very high yields on marginal lands so by replacing low yielding corn with high yielding switchgrass increases the total quantity of feedstock. Comparing the variation in the conventional supply system under the two feedstock finds that the standard deviation decreased by about 16% but in the advanced system it increased by 4%.

Equation (1) showed the quantitative definition for supply risk; that is, the probability unit cost exceeds the unit cost based on designed capacity. The unit cost target for a large scale biorefinery is $3 per gge in order to compete with current gasoline prices. This is based on design features where deterministic parameters are assumed. But quantity is not deterministic. Figure 6 shows the unit cost risk due to variation in feedstock quantity observed in Figure 5. The vertical axis is the probability that unit cost exceeds a reference point given on the horizontal axis.

Using the relationship of feedstock supply to ethanol production cost mapped in Figure 3, Figure 6 shows how the variation in feedstock quantity translates to cost risk. The horizontal axis shows the range of unit cost based on the range of feedstock possibilities from Figures 5. The vertical axis shows probability of exceeding unit cost.[4] Given a unit cost on the horizontal axis the vertical axis shows the risk of exceeding it. Movement towards the origin indicates risk reduction.

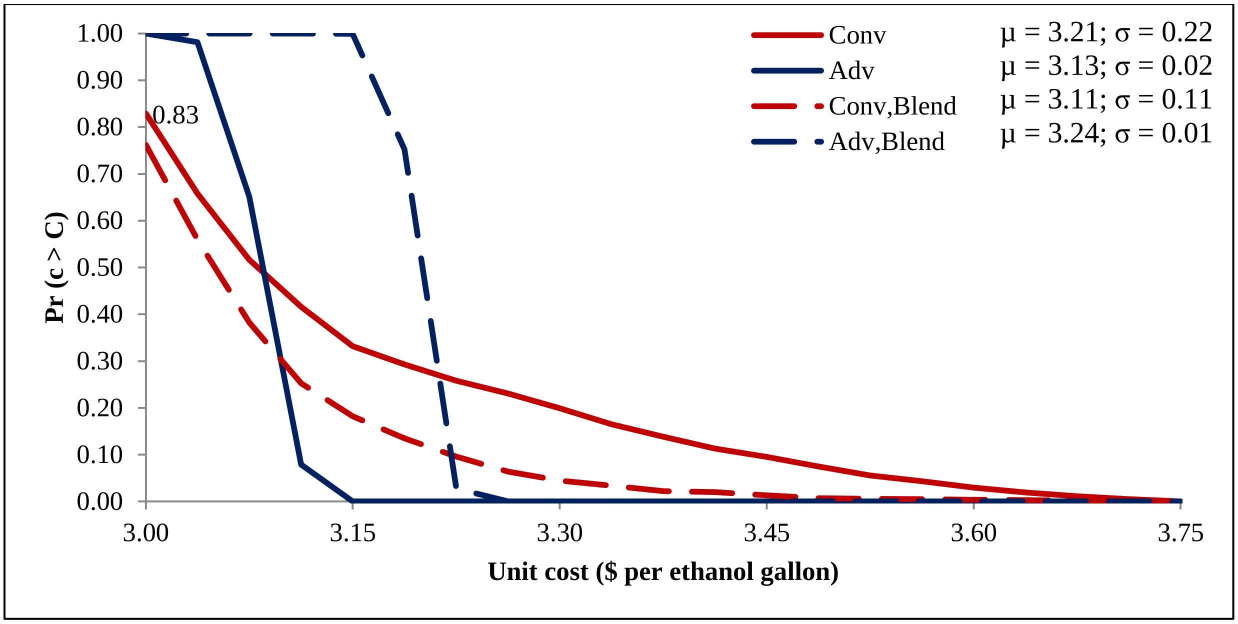


Fig 6. Supply risk curve

In the conventional supply system where corn stover is the feedstock the supply risk, $\Pr(c > \$3)$, is 83%. This translates to an 83% chance of not getting enough biomass supply. It is a bit less for the blended feedstock. Supply risk translates into unit cost up to $3.45 for the blend and $3.70 for corn stover. In the advanced supply system cost risk, $\Pr(c > \$3)$, is 100% but the risk quickly decreases to zero at $3.15 for corn stover and $3.25 for the blend. Further, the variation in cost possibilities is greater in the conventional supply system. Whereas in the advanced system the standard deviation is a penny or two in the conventional supply system it is $0.22 and $0.11 for corn stover and blended feedstock, respectively.

[4] The vertical axis is generated by computing $\Pr(c > C) = 1 - \Pr(c < C)$ for each cost listed on the horizontal axis.

To put these results in context, Figure 5 shows that the distribution of feedstock (both types) in the advanced supply system exceeds capacity. The simulation shows that in the advanced system excess costs result from the problem of dealing with excess feedstock. The biorefinery does not incur transaction costs to make up for feedstock shortfalls but instead incurs costs to dispose of off-take. In the advanced system more feedstock is under contract than is needed. By contrast, in the conventional supply system the biorefinery must sometimes buys more feedstock and sometimes disposes of off-take. The range of feedstock possibilities, and therefore cost possibilities, is greater in the conventional supply system. The sensitivity analysis tests how results change with the amount of biomass under contract.

3.2 Sensitivity Analysis

This section examines the sensitivity of the supply risk results to the underlying assumptions. The assumptions about cost elasticities change the shape of average total costs in Figure 3. In the region of *economies of scale* we assumed a cost elasticity of 0.5. Changing the elasticity to one on the interval $(0.5,1]$ decreases unit cost, which flattens the curve to the left of capacity. Increasing the elasticity in the region of diseconomies, we assumed an elasticity of 1.25, increases unit cost. Changing the shape of the unit cost curve in Figure 3 scales how the supply risk maps to unit cost in Figure 6. The shape of the curves do not change but the horizontal axis becomes more (or less) expensive with changes in Figure 3.

The scenario assumption that affects the results is the number of depots, which is to say the amount of feedstock under contract. Figure 5 shows how the advanced supply system shifts and narrows the feedstock supply distribution when compared to the conventional supply. The implication of the distribution shifting entirely above the level of capacity is that the biorefinery must deal with off-take. Figure 7 shows the sensitivity of the feedstock supply risk curve to the number of depots.

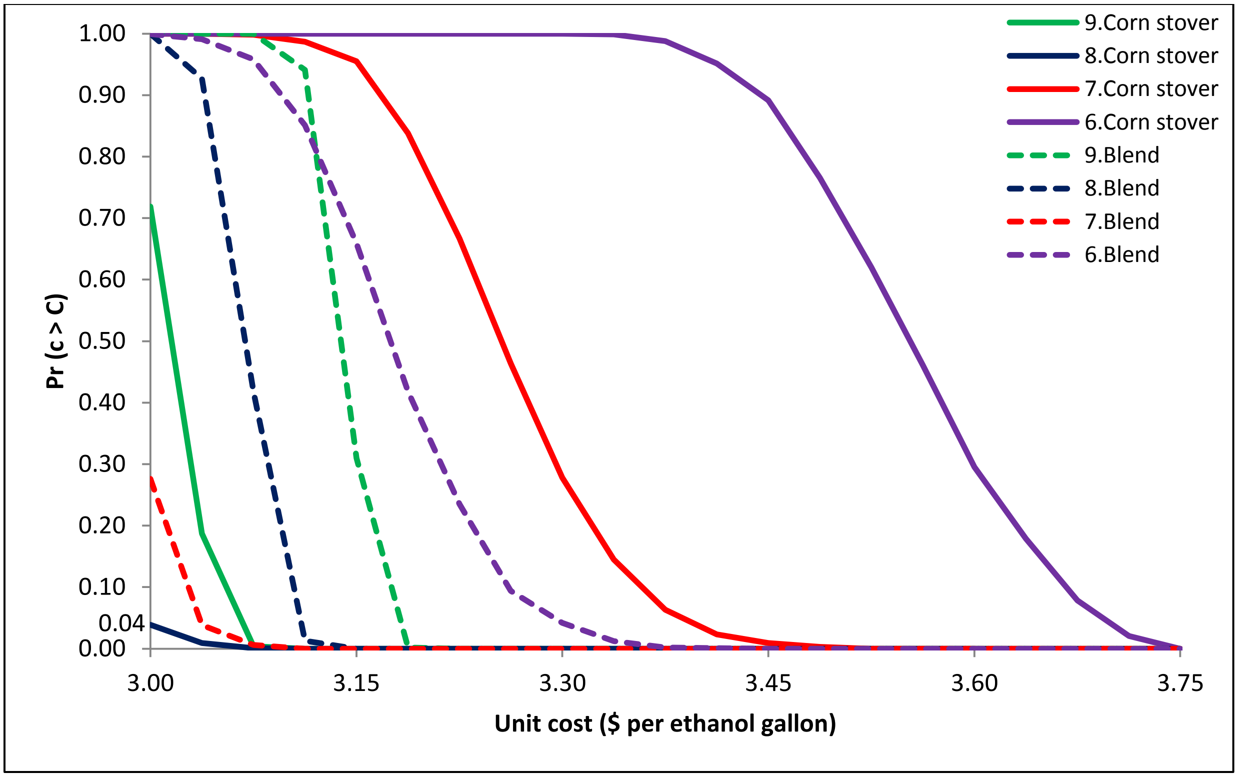


Fig 7. Supply risk sensitivity to number of depots where feedstock is corn stover and corn stover blended with switchgrass. Curves assume economies, elasticity of 0.5, and diseconomies, elasticity of 1.25, of scale in feedstock volume**.**

Figure 6 shows that in the advanced supply system, with a corn stover feedstock and 10 depots, cost risk, $\Pr(c > \$3)$, is 100% but that risk reaches zero at $3.15. Figure 7 shows that with corn stover as the feedstock and 9 depots (solid green line) the supply risk $\Pr(c > \$3)$ falls to 70% and that it reaches zero at $3.08. Again with corn stover but reducing depots to 8 (solid blue line) supply risk, $\Pr(c > \$3)$, falls to 4% and risk reaches zero at $3.04. However reducing depots again, to 7 depots (solid red line), increases risk.

Figure 6 shows that for the case of the blended feedstock in the advanced system and 10 depots risk reaches zero at $3.25. Figure 7 shows that, for blends, risk decrease with the number of depots to 7 depots. In the case of 6 depots are under contract risk increases. The least amount of risk represented in Figure 7 happens when the biorefinery contracts with 8 depots and corn stover is the feedstock.

4.0 Discussion, Conclusions, and Future Work

This paper analyzes the supply risk that faces firm owners of a cellulosic biorefinery. Variation in feedstock supply imposes cost implications at the biorefinery because design specifications call for a specific range of feedstock supply. Unit cost increases when the supply falls outside of the designed range. Using theory to quantify risk as outlined in the seminal work by Kaplan and Garrick (1981), the paper quantifies risk as the probability of a unit cost overrun on an annual basis. The analysis builds a causal relationship model of underlying variables that drive supply uncertainty and links these to cost to form a risk assessment model. The risk assessment model completes the first phase of research thereby creating a framework for a dynamic risk assessment and mitigation.

The results inform on at least a couple important points; the advanced supply system mitigates risk through diversifying the supply portfolio, and costs decrease because of the change in the management approach. Diversifying supply allows the biorefinery to reduce risk exposure to extreme weather and other supply disrupting events. Changing the approach to managing contracts reduces transaction costs.

The risk analysis illustrates how diversification mitigates risk. In the case of the advanced supply system the biorefinery is able to diversify the supply portfolio across many regions, reducing supply risk from 83% in a system of bales and trucks to 4% in a system of depots, pellets and trains. This means that if a bad year happens to hit one (or more) region(s) then supply from other, non-affected regions offsets supply disruption. Mitigating risk like this is especially important as the biofuels industry scales up and economies of scale drive towards larger biorefineries. The demand for large amounts of biomass exposes the biorefinery to greater supply risk, but it can be mitigated through the advanced supply system. The ability to diversify the supply portfolio in the advanced supply system allows the biorefinery to mitigate against catastrophic supply disruptions (drought, flood, pests, etc.) that it cannot do in the conventional system.

The risk assessment model informs on the need to investigate other aspects of risk and cost mitigation at the biorefinery. In the sensitivity analysis the model illustrates that not as much biomass is needed under contract in the advanced system as in the conventional supply system. The strategy of "over-contracting," the risk mitigation strategy in the conventional system, is not needed in the advanced system because of the diversified portfolio. This means that the biorefinery can reduce the number of procurement contracts that must be managed.

The sensitivity analysis sheds light on additional cost savings. Setting and managing contracts is costly. The advanced supply system makes possible cost savings as the biorefinery reduces the amount of contracts that must be administered. The 820 farmer contracts in the conventional supply system become N depot contracts in the advanced supply system. Figure 7 suggests that an optimal combination exists between biorefinery and depots. The analysis started with a number of depots such that the same amount of biomass was placed under contract. However, the diversified portfolio approach informs that not as much biomass is needed under contract to reach the target capacity. Moreover, contracting based on the assumptions of the conventional supply system lead to more biomass (and excess costs for off-take) than are needed.

"De-risking" the biofuels industry, particularly mitigating risk at the level of the biorefinery, is paramount to industry growth. Supply uncertainties such as those modeled in this paper tend to classify the biomass industry as a high risk investment thereby limiting the expansion of the industry. Risk mitigation on the part of the biorefinery improves the business case, making investment in biorefineries a more attractive option than at present. Reducing costs and reducing variation in costs leads to better forecasts of profitability. Risk reduction, with the corresponding improvement in profitability, leads to better financing rates so that additional cost savings result. Lamers et al. (2014) outline the cost savings that result from better financing. A better business case therefore improves the odds of industry growth.

Direction for future work emerges from this analysis. Careful examination of the optimal number of depots per biorefinery requires understanding the role that biomass storage plays in mitigating risk. Phase two extends the risk assessment model to include risk over time and storage dynamics. This will inform on how storage across months and years mitigates supply risk at the biorefinery, and the dynamic relationship between biorefinery storage, feedstock demand, and the number of depots needed. Better understanding about the combination of biorefineries and depots, and on the role that storage plays in mitigating supply risk will inform interested stakeholders on what considerations need to be addressed in order for the DOE vision of a billion tons of biomass to be realized. This analysis does not make a distinction between biochemical and thermochemical conversion pathways. In terms of the risk reduction results outline in the paper we do not expect much difference between the conversion pathways, but this may be a point for further consideration. Finally, quantifying cost savings from reducing the number of contracts is left for future analysis.

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