Optimal biomass-harvesting model for biobutanol biorefineries

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Long Abstract

The Energy Independence and Security Act (EISA) 2007 mandate the use of 21 billion gallons of advanced biofuels including 16 billion gallons of cellulosic biofuels by the year 2022. While much previous advanced biofuel related research has focused on cellulosic ethanol, advanced drop-in-biofuels such as biobutanol and renewable diesel are gaining significant attention because of their attractive combustion properties, compatibility with existing vehicle fleet, fuel distribution, and retailing infrastructure. While corn ethanol production has increased fast enough to keep up with the mandates, production of cellulosic and advanced biofuels has been well below the targets despite significant government support. A number of pilot and demonstration scale advanced biofuel facilities have been set up, but commercial scale facilities are yet to become operational. Scaling up this new biofuel sector poses significant economic and logistical challenges for regional planners and biofuel entrepreneurs in terms of feedstock supply assurance, supply chain development, bioefinery establishment, and setting up transport, storage and distribution infrastructure.

Economies of scale in processing mean that, future cellulosic biorefineries are expected to be large-scale facilities using multiple sources of feedstocks. Assuring a reliable supply of feedstock in adequate quantity and appropriate quality at reasonable cost and low environmental impacts is a key factor driving emergence of a sustainable bioenergy sector.

Assuming that a biorefinery is set up in a region that has more than adequate biomass potential, biorefinery managers then face the problem of contracting with producers for the actual supply quantities of feedstock over the expected operational life time of the biorefinery. These supply contracts specify the quantities of different feedstocks (e.g. agricultural crops, perennial grasses, woody biomass), the timing of the deliveries, and the geographical location of production. In other words, through these supply contracts, the biorefinery managers essentially have an opportunity to design the biomass harvest-shed both temporally and spatially. Considerations in determining the optimal mix of these supply contracts include: (i) lowering procurement costs (harvest, baling, transport, storage, and seasonal costs), (ii) maximizing fuel yields and minimizing conversion costs, (iii) reducing in greenhouse gas (GHG) emissions to qualify as a cellulosic biofuel under the federal renewable fuels standard or similar regulations, and possibly for tradable GHG credits, and (iv) meeting contracting constraints to assure supply, for example while annual crop producers may be willing to supply under annual contracts, perennial grass producers may demand longer term contracts with varying quantities matching the temporal yield patterns. In addition to the above criteria used by biorefinery managers, regional planners may impose additional constraints related to protection of ecosystem services, habitat protection, water resources, traffic patterns, and congestion.

In this article, we develop a multi-period optimization model aimed determining the optimal mix of woody biomass, annual crops and perennial grasses for a biorefinery, taking into account the necessary contract terms, feedstock costs, transport costs, GHG emissions and other environmental impacts, production capacity constraints etc. The decision variables of the optimization model are the acreages of various feedstocks (woody biomass,

annual crops and perennial grasses) that are contracted for harvesting during each month of a 25 year planning horizon. While the model is structured to be applicable to a generic biorefinery regardless of location, we parameterize the model using information for a hypothetical biorefinery located in the Midwest, producing biobutanol. Two versions of the model are developed, one optimizing the private costs faced by the biorefinery manager, and a second version taking the perspective of a regional planner with additional optimization criteria and social constraints. Mathematical programming software GAMS and solver program MINOS are used to code and solve the formulated optimization programs.

A growing body of literature has previously addressed issues surrounding the supply of biomass feedstock for biofuel production (e.g. Epplin et al., 2007; Mapemba et al., 2007; Mapemba et al., 2008; Sokhansanj et al., 2009; Khanna et al., 2010; Kang et al., 2010). While drawing on previous research, the models developed in this article have several novel features. (i) Existing studies treat the available biomass quantities in the region as exogenously given and then try to minimize procurement costs. In comparison, this model treats biomass acreage to be harvested as an endogenous decision variable subject to overall biomass availability constraints. (ii) Unlike most existing studies, in this model transport costs are endogenously determined as a function of harvesting decisions. (iii) The temporal yield patterns of energy crops are modeled explicitly unlike many other studies which use steady state average yields. (iv) GHG emissions are also endogenously determined based on feedstock sourcing decisions. (v) The legal, institutional, and ecosystem sustainability constraints that are necessary from a regional planning perspective are also incorporated. (vi) While almost all previous studies model cellulosic ethanol biorefineries, this model is specifically aimed at biobutanol biorefineries.

As a result, these models provide better insights into the realities of biomass procurement, especially for the emerging drop-in advanced biofuel production.

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1 Introduction

The Energy Independence and Security Act (EISA) 2007 mandates the use of 36 billion gallons of renewable fuels, consisting of 15 billion gallons of conventional (corn) ethanol and 21 billion gallons of advanced biofuels, including 16 billion gallons of cellulosic biofuels by the year 2022. While corn ethanol production has increased fast enough to keep up with the mandates, production of cellulosic and advanced biofuels has been well below the targets despite significant government support. Scaling up this new biofuel sector poses significant economic and logistical challenges for regional planners and biofuel entrepreneurs in terms of feedstock supply assurance, supply chain development, bioefinery establishment, and setting up transport, storage and distribution infrastructure.

While much of the extant research focused on cellulosic ethanol, drop-in fuels such as biobutanol are receiving increased attention. The focus on drop-in fuels is due to their attractive engine combustion characteristics and ‘drop in’ compatibility with existing vehicle fleet and fueling infrastructure. Thermochemical and biochemical processes for converting biomass into drop-in fuels are being developed, and the DOE has identified six technologies that can possibly be deployed to produce drop-in fuels: fermentation of lignocellulosic sugars, catalysis, catalytic fast pyrolysis, hydropyrolysis, hydrothermal liquefaction, and syngas to distillates. A few pilot and demonstration facilities are currently operating. For example, American Process Inc. (API), is building a cellulosic Bio-butanol refineryies at Alpena, Michigan. Funded in part by an $18 million U.S. Department of Energy grant and a $4 million grant from the State of Michigan, the API Alpena

Biorefinery will convert hemicelluloses extracted from woody biomass into butanol using processes developed by Cobalt Technologies. Butamax, Gevo, BP-Dupont are other companies involved in biobutanol technology development and production. Gevo is retrofitting an existing corn-ethanol plant in Luverne, Minnesota with its proprietary yeast and Gevo Integrated Fermentation Technology (GIFT) system to produce isobutanol.

All these large biorefinery facilities will use multiple sources of feedstocks due to economies of scale in processing. Assuring a reliable supply of feedstock in adequate quantity, appropriate quality at reasonable cost, and low environmental impacts are key factors driving emergence of a sustainable bioenergy sector. A growing body of literature addresses issues surrounding the supply of cellulosic biomass feedstock for biofuel production. These studies vary in scope ranging from those analyzing a single biorefinery supplied with a single feedstock, to optimal location of multiple biorefineries in a region utilizing multiple feedstocks. These studies employ a range of methods including enterprise budgeting, supply curve analysis, simulation modeling, and mathematical optimization (e.g. Epplin et al., 2007, Mapemba et al., 2007, Mapemba et al., 2008, Sokhansanj et al. 2009, Khanna et al. 2010, Kang et al., 2009).

The biorefineries locating in areas with substantial feedstock potential face the problem of contracting with producers for the actual supply quantities of multiple feedstocks. These supply contracts specify the quantities of different feedstocks (e.g. agricultural crops, perennial grasses, woody biomass), the timing of the deliveries, and the geographical location of production. In other words, through these supply contracts, the biorefinery managers essentially have an opportunity to design the biomass harvest-shed both temporally and spatially. Considerations in determining the optimal mix of these supply contracts include:

(i) lowering procurement costs (harvest, baling, transport, storage, and seasonal costs);

(ii) maximizing fuel yields and minimizing conversion costs;

(iii) reducing greenhouse gas (GHG) emissions to qualify as a cellulosic biofuel under the federal renewable fuels standard or similar regulations, and possibly for tradable GHG credits, and

(iv) meeting contracting constraints to assure supply, for example while annual crop producers may be willing to supply under annual contracts, perennial grass producers may demand longer term contracts with varying quantities matching the temporal yield patterns.

In addition to the above criteria used by biorefinery managers, regional planners may impose additional constraints related to protection of ecosystem services (hydrological flow regulation, soil formation, pollination, refugia, habitat protection, recreation, and cultural), traffic patterns, and congestion. For example, regional planners may restrict the amount of biomass removed from croplands to prevent soil erosion. Similarly the quantity of grass biomass harvests, especially from CRP lands, may be restricted for habitat protection.

In this article, we develop a biomass harvest-shed design tool to help determine the optimal mix of annual crops and perennial grasses for a biorefinery, taking into account the necessary contract terms, feedstock costs, transport costs, GHG emissions and other environmental impacts, production capacity constraints etc. While we draw on prior research, our approach has several novel features. (i) Existing studies treat the available biomass quantities in the region as exogenously given, and then try to minimize procurement costs. In comparison, the proposed model treats biomass acreage to be harvested as an endogenous decision variable subject to overall biomass availability constraints. (ii) Unlike most existing studies, in our model transport costs are endogenously determined as a function of harvesting decisions. (iii) The temporal yield patterns of energy crops are modeled explicitly unlike many other studies which use steady state average yields. (iv) GHG emissions are also endogenously determined based on feedstock sourcing decisions. (v) The legal, institutional, and ecosystem sustainability constraints that are necessary from a regional planning perspective are also incorporated. Two versions of the model are developed, one optimizing the private costs faced by the biorefinery manager, and a second version taking the perspective of a regional planner with additional optimization criteria and social constraints. As a result, these models provide better insights into the realities of biomass procurement.

2. Perennial vs. annual feedstocks:

Biorefineries constructed in the Midwest are likely to draw from two major types of agricultural feedstocks: (1) energy crop biomass derived from perennial grasses such as switchgrass, miscanthus, and mixed grasses and (2) agricultural residue biomass derived from annual field crops such as corn, wheat, and barley. According to the ‘Billion Ton Update,’ these two feedstocks would supply about 70% to 80% of biomass required for biofuel production by year 2030 (Table ES.1, (Perlack et al. 2011) p.30). There are significant differences between these two feedstocks (table 1). While agricultural residues are already produced along with feedgrains, perennial grasses are not yet grown commercially on a large scale. Energy crops have higher biomass yields, which increase the density of biomass availability (more tons per unit area) and shrink the extent of biomass collection area. The climate hardiness of energy crops allows flexible harvest that extends into winter months. The disadvantages with the perennial crops are higher establishment costs, longer time delay to achieve higher yields, long term contracts necessary due to lack of alternative markets, and potential problems in clearing the lands planted with perennial crops. While the long-term contracts provide a secure revenue stream for farmers, they are more constraining for biorefineries.[1]

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[1] While the long-term contracts enable biorefineries to secure biomass supply, the prices at which they will be purchased is expected to change over time depending on their production costs.

Table 1: Differences between agricultural residues and energy crops

Feedstock Type	Annuals	Perennials
Crops	Corn stover, Wheat or Sorghum straw	Miscanthus, Switchgrass
Available biomass for harvest (dry tons/ac)	1 – 1.25[1] (harvest limited quantities every year or larger quantities once every 2 - 3 years)	10 maximum[2] (30% year 1; 70% year 2; 100% years 3 – 7; 80% years 8 – 10)
Standard deviation of yield in percent terms	Relatively stable – depends on how much is collected	25%[3]
Typical harvest span[#]	July – December	November– February
Contracting	Farmers allow periodic harvesting[4]	Need to be harvested every year or season[5]
Cost of biomass raw materials	\$20 - \$25 per ton	\$30-\$45 per ton
Harvest costs	Low	High
Transport costs	High, due to low biomass density and large collection area	Slightly lower, due to high biomass density
Theoretical butanol conversion rate (gallons/dry short ton)	87 – corn stover[6]	93 [7]
Conversion rate at 80% of theoretical maximum (gallons/dry ton)	69 – corn stover	74
GHG emissions (based on actual conversion rate)	Byproduct residues are not allocated any GHG emissions associated with corn grain production, only conversion related GHGs are considered	48,500 g of GHG per ton of cellulosic biomass (511-653 tons of GHG per million gallon of cellulosic ethanol)[8]

[1] Assuming a collection rate of 33% of total straw produced as a coproduct with grains (footnotes continued in the next page); all tonnage refer to short dry tons (2000 lb).

[2] Maximum potential yield based on miscanthus yield

[3] Annual crop harvest starts with spring wheat harvesting in May/June and extends till corn harvesting in Oct/Nov/Dec ; energy crops are expected to be harvested by the end of the growing season and possibly into winter months

[4] Contracts can be written with an option (not) to harvest depending on the needs of the biorefinery

[5] If energy crops are grown in a field, harvesting biomass would be the only source of income from that piece of land – hence, the farmers growing energy crops would require harvesting every year

[6] Corn stover chemical composition: Arabinan (2.54% mass), Xylan (18.32%), Mannan (0.4%), Galactan (0.95%) and Glucan (34.61%) – corresponding to 44 Corn stover *Zea mays* Stalks and Leaves without cobs.

[7] Switchgrass chemical composition: Arabinan (3.19%), Xylan (23.27%), Mannan (0.22%), Galactan (1.05%) and Glucan (33.04%) – corresponding to 126 Cave-in-rock high yield variety; butanol yield from switchgrass and miscanthus are will be comparable because both are herbaceous energy crops with similar physiological traits and chemical composition.

[8] Based on the default parametric assumptions for cellulosic ethanol according to the GREET model version 1.8

In contrast, agricultural residues have a different set of feedstock characteristics. The revenues from agricultural residues are secondary to revenues from feedgrains – hence, farmers are likely to be flexible with harvesting agricultural residues. Farmers also have the option of not harvesting agricultural residues depending on whether feedstock prices more than compensate for the added production costs and the value of leaving crop residues in the field to maintain soil quality. More importantly, biorefineries may prefer agricultural residues as feedstock because they result in greater reduction of greenhouse gas (GHG) emissions. The reduction in GHG emissions is typically greater with agricultural residues because residues are allocated little or none of primary crop production related GHG emissions. A major disadvantage with agricultural residues is the lower yield of biomass per acre than that of energy crops which increases the collection area radius and transport costs. A cellulosic biorefinery also has to consider production costs, harvest costs, transport costs, short-term versus long-term contractual commitments, life-cycle GHG emissions, and other factors, such as losses in biomass storage and ethanol yield differences across the two feedstocks. These factors will affect biorefinery's spatial and temporal choice of feedstocks within the feedstock collection area termed as 'harvest shed.' Typically, a cellulosic biomass harvest shed encompasses farm fields within a 50-mile to 100-mile radius around the biorefinery. A harvest shed would be optimal if it can help reduce costs based on where (spatial) and when (temporal) the feedstocks are grown.

Thus, the biorefineries need to choose the total acreage and locations contracted for agricultural residues and perennial grass production/harvest. To address this question, a cost minimization model is developed to identify the optimal temporal and geographical composition of multiple feedstocks surrounding a biorefinery. The optimization problem accounts for the differences in characteristics between the two feedstocks (table 1).

Two versions of the model are developed, one optimizing the private costs faced by the biorefinery manager, and a second version taking the perspective of a regional planner with additional optimization criteria and social constraints. These models serve as a decision tool for any biorefinery and address such tradeoffs across multiple feedstocks.

3 Literature Review

There is a growing body of literature on issues surrounding the supply of cellulosic biomass feedstock for biofuel production. These studies vary significantly in scope. Some studies focus on supplying a single biorefinery with a single feedstock, while other studies analyze the total potential supply of single feedstock within a region. Other studies analyze supply of multiple feedstocks to a single biorefinery or to a number of refineries within a region. These studies employ various methods, such as enterprise budgeting, supply curve analysis, simulation modeling, and mathematical optimization.

Single feedstock for a single biorefinery: These studies typically focus on low cost delivery of individual feedstocks based on mathematical programming models. Wang et al. used a mixed integer linear programming model to study switchgrass harvest sheds. They evaluated how the harvest shed expands with an increase in biorefinery size (from 25 million gallons to 50 million gallons) and the impacts of weather on harvesting season, storage loss, and other related biomass supply issues such as type of baling operations (rectangular vs. round bales), transport and storage costs. Their results show that harvesting, baling and storage costs have to be included while modeling optimal feedstock combinations for biorefineries.[2]

Sokhansanj et al. (2006) developed a simulation-based optimization model called Integrated Biomass Supply and Logistics (IBSAL) model to study the supply of agricultural residues for day-to-day biorefinery operations. Kumar and Sokhansanj modified IBSAL to study switchgrass supply in alternative forms such as circular vs. rectangular bales, loaves or ensiled loafs. The IBSAL model identifies the optimal sequence of activities to harvest, transport and deliver cellulosic biomass to the biorefinery at a low cost. The biomass raw material costs were estimated at 70 – 73 cents per gallon of cellulosic ethanol. This estimate was substantially higher than US Department of Energy estimates of 40 – 45 cents per gallon reported in techno-economic studies . Currently, the

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[2] Wang et al argued that rectangular bales will preferably be used immediately after the harvest due to shorter shelf life while the round bales would be stored with plastic cover and used during lean seasons

IBSAL model is being expanded to evaluate supply decisions of multiple cellulosic feedstocks .

Single feedstock in a region: Many studies estimate the costs of crop establishment, management, harvest and transport costs of energy crops. These cost estimates for a particular enterprise, known as enterprise budgets, are commonly used to estimate the supply costs of energy crops such as miscanthus and switchgrass. These studies used agricultural input data derived from trial plots. The results from these studies showed that the potential for energy crops varied across regions depending on energy crop yields and production costs. While this approach has been adopted for many states, their results are largely limited to the region or state where the test plot sites are located. Other studies used formulas to estimate the transport costs and logistics of supplying biomass in various forms, such as chopped, rectangular bales, and round bales (Atchison and Hettenhaus, 2003; Gallagher, et al, 2003). They estimated harvest and baling costs to range from $11 to $20 per ton depending on feedstock and regional conditions. A few other studies evaluated the regional potential within the region, such as the number of biorefineries that can be supported within a state based on feedstock composition and available biomass quantity .

Multiple feedstocks for a single biorefinery: Dunnett et al. and Jacobson et al. argued that biomass yield levels of alternative feedstocks should be considered while determining the optimal supply of multiple feedstocks to a biorefinery. Epplin et al., (2007), and Mapemba et al., (2007, 2008) developed a series of linear programming models which studied the optimal combinations of naturally grown grasses and agricultural residues. Their objective was to analyze the combination of multiple feedstocks for a single biorefinery as well as multiple biorefineries in the state of Oklahoma by choosing the number of acres planted with grasses and other feedstocks as well as the number of harvesting units/machines required supplying cellulosic biomass.

Their mixed integer mathematical programming model maximized the net present value of profits for a biorefinery that used the saccharification and fermentation process over a 20 year time frame. They evaluated two major types of feedstocks: perennial grasses naturally grown on Conservation Reserve Program (CRP) lands and agricultural residues collected from prime croplands. They found that agricultural residues had a cost advantage over naturally grown perennial grasses. The energy crops (or perennial grasses) did not feature prominently in the feedstock mix due to low cellulosic biomass yield levels. The perennial grass yield considered by Mapemba et al. were 3 to 4 tons per acre under natural condictions; this is much lesser than the potential yield of 8 to 10 tons per acre when energy crops are grown using intensive cultivation practices. According to their model, agricultural residues were preferred more to energy crop biomass due to low raw material costs.

We analyze a different set of questions compared to Mapemba et al (2007, 2008) and Epplin et al (2007). Our model focuses on the optimal proportion of energy crops when energy crops are cultivated intensively (Table 1). We focus specifically on the spatial and temporal distribution of energy crops and agricultural residues within concentric circles around the biorefinery. By changing the parameters, our model can be applied to multiple locations or even different bioenergy outputs (other types of biofuels such as cellulosic ethanol, and generation of electricity from biomass).

Multiple feedstocks in a region: McCarl et al., evaluated the supply of agricultural residues and forestry biomass for electricity generation purposes. Their mathematical programming model (FASOM) was designed to maximize the objective of U.S. national social welfare defined as the net present value of the integral of biomass demand curves minus the integral of supply curves for the U.S. The FASOM model included biomass supply and harvest in agricultural and forestry sectors, the amount of land used for biomass harvesting, and shifting of lands between agriculture and forestry. The results showed that large amounts of biomass could be sourced within the United States to displace coal. Although the FASOM model does not have direct implications for an individual biorefinery's operations, it presents a set of constraints useful to model available land and required biomass for energy production.

Khanna, et al., used a mathematical programming called Biofuel and Environmental Policy Analysis Model (BEPAM) to evaluate the optimal composition of multiple feedstocks at the U.S. national level. They estimated the supply potential of perennial and annual feedstocks (energy crops and agricultural residues respectively) based on economic returns from row crops, dairy operations and available farmland in 41 states to supply one billion ton of cellulosic biomass by 2030. The BEPAM model predicted that energy crops would be economically more suitable in marginal croplands. The state level potential for energy crops varied with the regional characteristics, biomass yields (tons per acre), and relative price of alternative feedstocks.

The literature review shows that many studies focus on regional or national level biomass supply potential. While these studies are useful for policy analysis, there is a gap in identifying the optimal feedstock combination for individual biorefineries operations. The optimization models employed by Epplin et al. (2007) and Mapemba et al. (2007, 2008) partially address this issue. The results from their studies cannot be generalized because they emphasize a particular processing technology (saccharification and fermentation process), type of output (liquid biofuel), and their analysis is largely confined to the state of Oklahoma. We develop a more general model which evaluates biomass feedstock supply potential for multiple outputs, with an emphasis on the spatial and temporal patterns of harvest sheds, optimal acreage decisions and additional price premiums, if any, payable for cellulosic biomass.

The existing literature largely treats the feedstocks costs constant or exogenous. While it is a simpler approach, the biomass feedstock costs depend on acreage planting decisions and density of biomass availability. The major cost components such as harvest, baling and transport costs can potentially vary with harvest shed pattern. In this model we compute transport costs, seasonal costs, and environmental costs endogenously based on the decision variables (acreage and yield density).[3]

Biorefineries could pay a higher price to achieve a desired spatial and temporal pattern of harvest shed. The existing studies do not provide a reliable method to compute such price premiums. We derive price premiums for feedstocks using the shadow prices of binding land acreage constraints. These shadow values give an upper bound for price premiums payable for a feedstock in a concentric zone around the biorefinery at a

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[3] The models by Mapemba et al., and Epplin et al., endogenize only the harvesting costs by choosing the number of harvesting units. Their results show that the number of harvesting units was cut in half when harvesting costs are determined endogenously. But the harvesting costs remained at $11/ton irrespective of whether they are determined endogenously or whether they were treated exogenous. A possible reason for this result is the change in other assumptions: for instance, the harvesting units would have been assumed to work 24 (12) hours a day when the harvesting costs were endogenously determined (maintained exogenous).

particular time.[4] This model also helps evaluate how the inclusion of external costs associated with GHG emissions and ecosystem services affect the optimal composition of biomass feedstocks.

4 Model

Consider a generic biorefinery with butanol production capacity PC (million gallons/quarter). Its biomass raw material requirements can be met with multiple feedstocks that include annually produced crop residues ($s = 1, 2, \ldots S$) and perennials ($g = 1, 2, \ldots G$). Agricultural residue yield levels are low (about 1.5 tons per acre per year); they are annually produced as coproducts with feedgrains. Perennial energy crop yields are relatively high; they are productive for τ_g years (normally 10 years). Since the establishment costs of perennial crops are high, it is not economical to remove a perennial crop soon after establishment. Hence, the farmers would seek assured contracts to sell all energy crop biomass produced for τ_g years . This farmer requirement alters how biorefineries design their harvest shed and enter into contracts for biomass. The commitment of harvesting perennial energy crops for τ_g years is imposed as a constraint in the model. This constraint is imposed by retaining the land allocated to perennial energy crops retained under energy crops for τ_g years. All biomass produced in those fields are assumed to be purchased by the biorefinery.[5] The model is formulated over quarterly intervals (q) to study how seasonal cost differences affect biomass supply and storage. The

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[4] These shadow prices show the cost savings realized by adding or retaining one more acre for biomass feedstock supply.

[5] It is assumed that the farmers do not have any other alternative markets within the harvest sheds and rely primarily on the single biorefinery to sell the cellulosic biomass.

quarterly intervals match the harvesting pattern of feedgrains and cellulosic biomass that usually extends over three months during a crop year.[6] The quarterly intervals also help include storage and seasonal costs that help maintain regular supply of biomass during the peak and lean seasons of biomass harvests.

The harvest shed is assumed to be circular with the biorefinery located at the center (figure 1). The harvest shed is divided into concentric circular production zones ($z = 1,2,\ldots Z$), each zone corresponding to a concentric circular zone of outer radius of R_z and inner radius of R_{z-1} miles. Each zone consists of both agricultural and non-agricultural lands. I eliminate the non-agricultural and land unsuitable for producing cellulosic biomass by estimating the available fraction of the area for energy crop production or agricultural residue collection. The available area is modeled as a fraction of total geographic area in each zone and is denoted by the symbol σ (σ_{sz} for annual feedstocks (s) and σ_{gz} for perennial feedstocks (g)). The harvested acreage is assumed to be distributed uniformly within every zone of the harvest shed.

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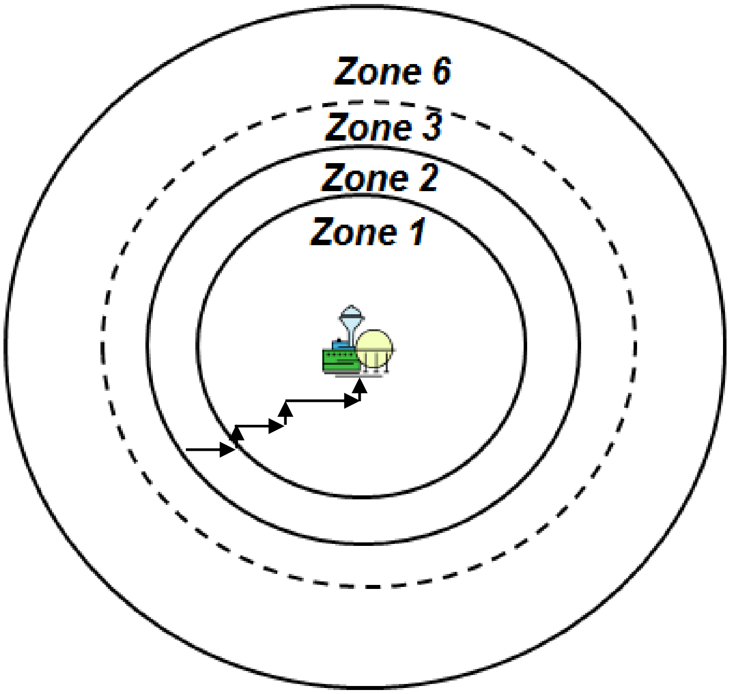
[6] Monthly intervals were not chosen due to lack of sufficient information on monthly differences in perennial energy crop yields.

Figure 1: Concentric circular harvest shed area around the biorefinery (arrows represent perpendicular roads used for transport):



Total transport costs (CT) and transport distance depends on the density of biomass availability i.e. CT is a function of (acreage planted * yield / zone area). Thus the transport costs are determined endogenously in the model. Transport costs include loading, unloading, and trucking costs. French gave an expression for transport cost calculations for circular harvest sheds. For a circular harvest shed, the total costs for transporting biomass can be written as $TC = N a_0 + \int_0^{2\pi} \int_0^R w \; a_1 D r^2 \; dr \, d\theta$ where TC is the total transport cost during a quarter (in dollars), N is the total amount of biomass required by the biorefinery (in tons), a_0 is fixed costs of transport equipment that do not depend on distance, loading and unloading (in $/ton), a_1 is variable costs ($/ton-mile), w is a constant parameter to convert air distance to road distance, D is the density of biomass within the circular harvest shed, and R is the outer radius of the circular harvest shed (French, 1960).[7] For a concentric circular harvest shed, we modify the above equation. The total amount of biomass transported from zone *z* in the quarter q is set to N_{zq}; range of radii is set to R_z and R_{z-1}; and biomass density within zone *z* is set to D_z to reflect the concentric circular zone variables.

$$TC \quad = N_{zq}\, a_0 + \int_0^{2\pi} \int_{Rz-1}^{Rz} w \;\; a_1\, D_z\, r^2 \; dr\, d\theta \qquad (1)$$

In equation (1), D_z is the density of biomass availability in tons per square mile in zone *z*. It is substituted with another equivalent expression $D_z = N_{zq} / \pi R_z^2$. Similarly, the total amount of all cellulosic biomass from zone *z* can be expressed as $N_{zq} = [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}]$. Substituting both expressions for N_{zq} and D_z, the cost of transporting biomass from zone z is calculated as following:

$$\mathrm{TC}_z = \; N_{zq} \;\; [a_0 + a_1 \, {}^2\!/_3 \; w\, \pi\, (R_z^3 - R_{z-1}^3) / (R_z^2 - R_{z-1}^2)] \qquad (2a)$$

$$\mathrm{TC}_{zq} = [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}] \; *$$

$$[a_0 + a_1 \; {}^2\!/_3 \; w\, \pi\, (R_z^3 - R_{z-1}^3) / (R_z^2 - R_{z-1}^2)] \qquad (2b)$$

Summing the transport costs across all zones, the total transport costs CT_q in quarter *q*

$$CT_q = \sum_z [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}] \; *$$

$$[a_0 + a_1 \; {}^2\!/_3 \; w\, (R_z^3 - R_{z-1}^3) / (R_z^2 - R_{z-1}^2)] \qquad (3)$$

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[7] This is obtained by combining equations (2) and (5) in French (1960)

Equation (3) is added to other costs that are minimized in the objective function. Note that CT_q is dependent on the acreage decision variables A_{szq} and A_{gztq}. Assuming transportation is done through perpendicular roads, the value of w can be approximated at $\sqrt{2}$.[8]

Current developments in pilot cellulosic plants indicate that biomass will largely be stored on field and transported to the biorefinery as and when needed for processing. Moreover, moving the entire harvest of biomass during the harvest season is difficult due to logistical issues and storage capacity limits . Transporting biomass during different seasons leads to seasonal costs. The seasonal cost fluctuations arise due to changes in diesel fuel and labor costs. The differences in labor costs are not considered because harvesting cellulosic biomass requires skilled labor that operates expensive harvesting equipment (tractors, collectors). The cost of skilled labor is relatively steady in peak or off-peak seasons; hence, there will not be much difference in costs across different seasons.[9]

The fuel costs do change over seasons affecting biomass procurement costs . The seasonal costs (CL) are computed by multiplying the transport costs and harvesting costs with a factor ω_q. This factor estimates the increase or decrease in costs over the four seasons. The base or reference season is taken to be the second quarter extending from April-June. The seasonal costs are endogenous because it depends on transport costs.

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[8] With perpendicular roads, $a^2 + b^2 = c^2$, where a = distance traveled north-south, b = distance traveled east-west, and c = air distance. Upon normalizing both a and b, $c^2 = 2$ or $c = \sqrt{2}$. That is, the sum (a+b) is also equivalent to multiplying c with $\sqrt{2}$. For example, consider the air distance of a field from the biorefinery is 10 miles. With perpendicular roads, the actual distance traveled would be 6 + 8 = 14 miles, derived from the relationship $6^2 + 8^2 = 10^2$. Multiplying 10 with $\sqrt{2}$, gives 14.14, which is an approximation of the actual travel distance of 14 miles.

[9] Unskilled labor wages is more likely to fluctuate over seasons

Material costs (CM), harvest costs (CH), and storage costs (CS) are assumed to be exogenous and treated as constants in the model. All these costs are maintained the same across all zones, expressed in terms of dollars per ton. This assumption is reasonable because these cost components are relatively the same irrespective of the field location within the harvest shed. Other parameters include biomass yield patterns of annual and perennial feedstocks (Y_s, Y_g respectively), storage costs (d_s, d_g), proportion of biomass lost in storage (ε_s, ε_g), the amount of biomass to be maintained in the inventory for continuous functioning of the biorefinery (minimum inventory required, MIR), butanol yield per ton of annual and perennial feedstocks (K_s, K_g), fixed and variable cost components of transport costs per ton mile (a_0, a_1), and the fraction of area available to plant either feedstock within each zone (σ_{sz}, σ_{gz}).

The biorefinery managersdecision problem is to minimize the net present value of cumulative biomass procurement costs over the time period of its entire operations (e.g. 15-20 years). The total biomass procurement costs include payments made directly to farmers for biomass material (CM); payments made to contractors for harvesting (CH), transport costs (CT), seasonal costs (CL); payments made to maintaining on-site storage structures (CS), The decision variables are (i) the acreage A_{szq} contracted to harvest agricultural residue s in quarter q in zone z, and the acreage A_{gztq} contracted to plant energy crop g in year t in zone z and, (ii) the amount of feedstock (s, g) processed during every quarter q. The storage quantities are implicitly determined by subtracting the amount of biomass processed from the amount produced during each quarter. Note that, if some acreage is planted with energy crops in year *t*, then that acreage will be retained with energy crops for the next τ_g years. This restriction does not apply to agricultural residues.

The social planner's decision problem is to minimize both private and external (social/environmental) costs of biofuel production. The use of cellulosic biomass for bioenergy production has both environmental benefits (such as reduced GHG emissions) and environmental costs (such as, increased soil erosion, and greater use of chemicals, herbicides and insecticides). The lifecycle accounting of GHG emissions estimates the environmental benefits; it covers biomass feedstock production, biomass conversion to butanol, and final distribution. Leading models such as Argonne National Laboratory's GREET model use this approach to compare the environmental implications of using alternative feedstocks for bioenergy production. We draw on estimates in literature of life cycle GHG emissions from butanol production. Since the objective of our study is to compare two alternative feedstocks, we consider the GHG emissions from agricultural residues as the baseline. That is, the GHG environmental cost (CE_s) of using agricultural residues is normalized to zero. We compute the environmental costs by multiplying the GHG quantity by an expected GHG price. We exclude the 'indirect' GHG emissions associated with land use changes due to lack of scientific consensus on how to estimate them.

Similarly, the ecosystem benefits derived from dedicated perennial energy crops would be different from those of annually grown agricultural residues. We include these costs in the model by calculating the net costs of ecosystem services (CP, in terms of dollars per ton) for both feedstocks. Similar to the calculation of GHG cost calculations (CE), the net costs for ecosystem services of agricultural residues (CP_s) are normalized to zero. The excess ecosystem costs of using energy crops (CP_g) are added to the objective function that is minimized.[10] A positive value for CP indicates higher ecosystem costs than benefits and vice versa. The ecosystem costs and benefits are estimated based on the literature (Power 2010, 2959-2971; Landis et al. 2008, 20552-20557). The ecosystem services and associated costs and benefits can vary widely depending on the location and practices. We conduct a sensitivity analysis for a range of CP values to evaluate the impact of ecosystem services on the costs of biomass for biofuel production.

The social planner's decision problem is to minimize the net present value of cumulative biomass procurement costs over the time period of its entire operations (e.g. 15-20 years) including the external environmental costs (CE and CP).These environmental costs depend on the amount of annual versus perennial feedstocks processed which in turn depends on the acreage decision variables. Hence, these environmental costs are also endogenously determined together with transport and seasonal costs.

5. Model Equations

The symbolic notations of the model are explained below:

Subscript notation:

s = Annual agricultural residue feedstocks such as straw or stover [s = 1, 2, … S]

g = Perennial grass feedstocks such as miscanthus, switchgrass [g = 1, 2, … G]

z = Concentric circular production zone [z = 1, 2, … Z]

q = The production/harvesting time period (quarter) [q = 1, 2... Q]

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[10] An alternative formulation is to include the ecosystem costs as constraints imposed by the social planner on the biorefinery. These constraints are simpler since the dollar value of ecosystem services need not be estimated; instead, the constraints can be written in terms of allowable soil erosion index such as RUSLE or other metric.

t = Year in which perennial crops are planted [t = 1, 2, … T]. Perennial crop *g* is assumed to supply biomass for τ_g years following establishment; hence, the perennial crop *g* established in year 3 (t=3) will supply biomass starting in year 3 until 3 + τ_g

Parameters:

CM_s, CM_g = Unit material cost of feedstocks s and g (dollars per ton, price paid to farmers)

CH_s, CH_g = Unit harvest cost of feedstocks s and g (dollars per ton)

CT_z = Unit transport cost of feedstock from zone z to the biorefinery located at the center (dollars per ton)

CS_{sq}, CS_{gq} = Unit storage cost of feedstocks s and g in quarter q (dollars per ton per quarter)

CE_{sq} = Unit greenhouse gas emissions costs of agricultural residues s in quarter q, normalized to zero (dollars per ton)

CE_{gq} = Unit incremental greenhouse gas emissions cost of perennial feedstock g in quarter q (dollars per ton)

CP_{sq}, = Unit net-costs of providing ecosystem services for agricultural residues s in quarter q, normalized to zero (dollars per ton)

CP_{gq} = Unit incremental net ecosystem costs of perennial feedstock g in quarter q (dollars per ton)

CX_{szq} = Total exogenous costs of annual feedstocks s processed in quarter ($CM_s + CS_s + (1+\omega_q)\, CH_s$, dollars per ton)

CX_{gzq} = Total exogenous costs of perennial feedstocks g processed in quarter ($CM_g + CS_g + (1+\omega_q)\, CH_g + CE_g$, dollars per ton)

Y_{gtq} = Yield of perennial feedstock g, planted in year t, for quarter q [Fixed pattern of yields in tons per acre per quarter; e.g. in scenario B, miscanthus crop planted in year t = 3 will yield 3.33 tons/acre in quarter 12, 6.67 tons/acre in quarter 16, 10 tons/acre every fourth quarter during quarters 20 – 36, 8 tons/acre every fourth quarter during quarters 40 – 48, and 0 tons in all other quarters If miscanthus crop were planted in year t = 5, then the same yield pattern will be shifted from quarters 20 through 56. The amount of biomass available in quarter q depends on the planting year (t) of miscanthus]

Y_{sq} = Yield of annual agricultural residues *s* that remains constant – harvested only once in a year either during the third or during the fourth quarter)

Ψ_{sq}, Ψ_{gq}= Quantity of feedstock (s, g) produced within the entire harvest shed during quarter q (tons)

D_{sq}, D_{gq} = Quantity of feedstock s and g processed at the biorefinery during quarter q (tons)

ω_q = Factor to compute seasonal costs related to transporting; second quarter is taken as the reference season, i.e. $\omega_{q=2}$ is normalized at 1 (see table 5)

δ = Quarterly discount factor

d = Storage cost parameter (dollars per ton per quarter)

ε_s = Rate of loss of agricultural residue due to storage (percentage per quarter)

ε_g = Rate of loss of perennial grasses due to storage (percentage per quarter)

PC_q = Quarterly ethanol processing capacity (gallons)

K_s, K_g = Butanol output for feedstock s and g respectively (gallons per ton)

MIR = Minimum Inventory Requirement (tons)

Q = Terminal time period

P_{GHG} = Price for one ton of greenhouse gas ($ per ton of CO_2equivalent)

GC_g = Greenhouse gas credit for using energy crops, in comparison to using agricultural residues (tons of GHG per million gallon of cellulosic ethanol)

ECB_s, ECB_g = Net costs of ecosystem services when agricultural residues and perennial grasses are included in the harvest shed ($/ton)

a_0 = Fixed component of transport costs ($ per ton of feedstock)

a_1 = Variable component of transport costs ($ per ton-mile)

σ_{sz} = Fraction of total land area available in zone z to harvest annual feedstock s (in percentage)

σ_{gz} = Fraction of land area available in zone z to harvest all perennial feedstocks g (in percentage)

ZA_z = Total geographic area within zone z (acres)

R_z = Outer radius of zone z (miles)

w = factor to convert radial distance to road distance; with perpendicular road network, w equals √2

Objective function:

Minimize discounted cumulative feedstock procurement costs over Q quarters:

$$\begin{aligned}\sum_q \delta^q * [\sum_g \sum_z \sum_t CX_g * Y_{gtq} * A_{gztq} &+ \sum_s \sum_z CX_s * Y_s * A_{szq} \\ &+ (1+\omega_q)\, CT_q \\ &+ d * \sum_s X_{sq} \\ &+ d* \sum_g X_{gq} \\ &+ CE_{gq} \\ &+ CP_{gq}]\end{aligned}$$

where CX refers to exogenous costs of cellulosic biomass, CT refers to endogenously determined transport costs, d*X refers to storage costs. Note that , CE refers to endogenously determined greenhouse gas emission costs, and CP refers to endogenously determined costs associated with ecosystem services. Both CE_{gq} and CP_{gq} refer to the incremental GHG and ecosystem costs of using perennial feedstocks; CE and CP terms are included only in the social planner's optimization problem, and not in biorefinery manager's optimization problem.

with respect to decision variables:

A_{szq} = Acreage contracted to harvest annual feedstock s in quarter q, zone z (in acres)

A_{gztq} = Acreage planted with perennial feedstock g in year t, zone z (in acres; yield pattern of perennial feedstocks is described in tables 1 and 5)

X_{sq}, X_{gq} = Storage levels (stock variable, either at the biorefinery or on farm fields) of feedstock s and g at the end of quarter q (in tons)

D_{sq}, D_{gq} = Quantity of feedstock (stover s, grasses g) processed/demanded in quarter q – which are implicitly determined as residuals upon choosing X_{sq}, and X_{gq}

subject to the following accounting relationships (E1-E4) and constraints (E5-E10):

Accounting relationships:

E1: Zone area ZA_z (in acres) around the biorefinery extending from zonal radius R_{z-1} to zonal radii R_z (in miles); the constant 640 converts square miles of area to acres

$$ZA_z = 640\,\pi\,(R_z^2 - R_{z-1}^2)$$

E2: Total biomass produced during every quarter (Ψ_q) is computed by multiplying the acreage harvested (A_{szq}, A_{gztq}) with yield (Y_{sq}, Y_{gtq})

$$\Psi_{sq} = \sum_z Y_{sq} * A_{szq}$$

$$\Psi_{gq} = \sum_z \sum_t Y_{gtq} * A_{gztq}$$

$$\Psi_q = \sum_s \Psi_{sq} + \sum_g \Psi_{gq}$$

E3: Transport costs (equation (3) from section 3):

$$CT_q = \sum_z [a_0 + a_1\, {}^2/_3\, w\, (R_z^3 - R_{z-1}^3)/(R_z^2 - R_{z-1}^2)] * [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}]$$

E4a: Environmental costs (CE_{gq}) of perennial feedstocks are computed based on expected GHG prices (P_{GHG}) and GHG credit (GC_g). In case of fermentation technology, this term will be positive (additional costs due to using energy crops).[11]

$$CE_{gq} = P_{GHG} * GC_g * D_{gq} * K_{gq}/1000000$$

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[11] The division by 1000000 converts ethanol gallons to million gallons.

E4b: The incremental net ecosystem costs of including perennial energy crops in the feedstocks is computed based on the exogenously determined net ecosystem cost and benefits (ECB_s and ECB_q) and endogenously determined feedstock demand. Ecosystem costs of agricultural residues (CP_{sq}) are normalized to zero.

$$CP_{gq} = (ECB_g - ECB_s) * D_{gq}$$

Constraints:

E5: Land availability constraints for perennial feedstocks:
The acreage harvested with grasses (A_{gztq}) and agricultural residues (A_{szq}) should be less than the available area from crop lands ($\sigma_{sz}\ ZA_z$) and marginal ($\sigma_{gz}\ ZA_z$) croplands. This constraint has to be satisfied in every quarter q across all zones z.[12]

$$\sum_g \sum_t A_{gztq} \leq \sigma_{gz}\ ZA_z$$

Land availability constraints for annual feedstocks

$$\sum_s A_{szq} \leq \sigma_{sz}\ ZA_z \qquad \text{for all q and z}$$

E6: Biomass mass balance constraints: Biomass supplied from fields and storage should equal the sum of biomass processed and inventoried in each quarter:

Biomass produced in quarter q (Ψ_q) + Stocks from previous quarter (q-1) = Biomass used for biofuel conversion in quarter q ($D_{gq} + D_{sq}$) + Ending stock for quarter q

$$\Psi_q + [(1 - \varepsilon_s) * \sum_s X_{s\ q-1} + (1 - \varepsilon_g) * \sum_g X_{g\ q-1}]$$
$$= D_{gq} + D_{sq} + [\sum_s X_{sq} + \sum_g X_{gq}]$$

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[12] A different formulation of land allocation is where both feedstocks can be harvested from all available lands. The restriction to source agricultural residues from prime croplands and energy crops from marginal croplands can be relaxed in the following manner. When all feedstocks can be grown in both prime and marginal croplands, the constraint E5 is replaced with the following. The total proportion of available (prime and marginal) cropland in every zone will be σ_z where $\sigma_z = \sigma_{sz} + \sigma_{gz}$. The summation over years (t) adds up the acreage allotted to energy crops that are planted at different times during the years 1 – 11. This constraint should be satisfied in every quarter q across all zones z.

$$\sum_s A_{szq} + \sum_g \sum_t A_{gzt} \leq \sigma_z\ ZA_z \qquad \text{for all q and all z}$$

E7: Biofuel produced has to meet or exceed the processing capacity (PC_q) in every quarter:

$$\sum_s K_s * D_{sq} + \sum_g K_g * D_{gq} \geq PC_q \qquad \text{for all } q$$

E8: Biomass stored at the biorefinery has to meet the minimum inventory required (MIR) at the biorefinery – only this quantity of biomass incurs storage costs. The excess biomass, if any, would be stored on field without storage costs.

$$\sum_s K_{sq} * X_{sq} + \sum_g K_{gq} * X_{gq} \geq MIR * PC_q \qquad \text{for all } q$$

E9: Terminal conditions for the last quarter (Q) are imposed by restricting the final period storage to zero after meeting the biomass processing requirements

Biomass supplied from the fields in final quarter Q + supply from the storage in quarter (Q-1) – Biomass used for conversion in Q = Ending stock for quarter Q = 0

$$\Psi_Q + \sum_s (1 - \varepsilon_s) X_{s\,Q-1} + \sum_g (1 - \varepsilon_g) X_{g\,Q-1} - D_{sQ} - D_{gQ}$$
$$= \sum_g \sum_s (X_{sQ} + X_{gQ}) = 0$$

E10: Non negativity constraints of acreage and storage decision variables:

$$A_{szq} \geq 0; A_{gztq} \geq 0; X_{sq} \geq 0; X_{gq} \geq 0$$

The cost minimization problem is coded in GAMS and solved using MINOS solver. The chosen solver helps achieve globally optimal solutions when the objective function and constraints are convex sets ; in this model, the objective function and the constraints are linear – hence, they result in globally optimal solutions. The results from the optimization model include: (i) the minimized total cost of biomass, expressed in terms of dollars per annual gallon of ethanol, (ii) acreages of all feedstocks (annuals and perennials) harvested in each quarter in each zone, (iii) variations in biomass quantities processed versus maintained in storage, and (iv) shadow prices or price premiums to expand land acreage within each zone. Additional sensitivity analyses are conducted to analyze the impact of changes in exogenous parameters (e.g., land availability, change in material costs).

6 Case Study Results[13]

We demonstrate the usefulness of the model using the case study of *Abengoa Bioenergy's* pilot plant in Hugoton, south-west Kansas. We illustrate the feedstock composition for a biofuel biorefinery of 53 million gallons or 200 million liters of annual capacity.[14,16] To simplify the analysis, only two feedstocks are considered: corn stover (an annual crop residue) and miscanthus (a perennial dedicated energy crop). Corn stover is produced every year along with corn grains; for miscanthus, We assume that cellulosic biomass will be supplied for 10 years before replanting is required. The biorefinery is assumed to operate for 20 years (80 quarters). We present the results from social planners perspective, but considering external costs associated with GHG emissions (CE_g) only; i.e. other ecosystem service (CP_g) external costs are not included.

The potential harvest shed around the biorefinery is divided into six concentric circular zones with outer radii of 5, 10, 15, 20, 30, and 50 miles. Surrounding Hugoton, KS, prime croplands account for 12% of the geographic area, while marginal crop lands account for 10% of geographic area.[15] We evaluate two scenarios where the two feedstocks are harvested in the same (simultaneous) season and in different or subsequent (staggered) seasons. These two scenarios help analyze the potential effect of harvest timing on the optimal feedstock composition (Table 2). In scenario A, both feedstocks are

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[13] These are preliminary results

[14] *Abengoa Bioenergy's* initial production capacity will be 18 MGY of cellulosic ethanol which will later be expanded to 25-75 million gallons.

[15] The remaining 78% of geographic area consists of agricultural lands where biomass is not harvested from and non-agricultural lands. For the case study, I assume that residues can be contracted only from prime croplands, while energy crops can be grown from either on prime or on marginal croplands.

harvested in the third quarter of every year (July-Sept). In scenario B, agricultural residues and energy crops are harvested in subsequent third quarter (July-September) and fourth quarter (October-December), respectively.

Table 3: Alternative scenarios based on harvesting season and harvest shed demarcation

Scenario	A	B
Agricultural residues from prime croplands; Energy crops from prime and marginal croplands	Both feedstocks harvested during the same season (third quarter) of every year	Agricultural residues harvested in the third quarter; Energy crops harvested in the fourth quarter

The results from the optimization suggest that the cellulosic biomass raw material costs range from 60 to 70 cents per annual gallon of butanol.[16] This estimate is in the ballpark of estimates from other biomass feedstock studies. Biorefineries would prefer to source a larger proportion of biomass from dedicated energy crops such as miscanthus in spite of their higher establishment and production costs. The proportion of energy crops was about 70% and 80% of cellulosic biomass raw materials in scenarios A and B, respectively. The higher proportion of energy crops in the feedstock mix was due to the benefits of higher yields and denser availability of biomass (more tons per square mile around the biorefinery). The increase in energy crops proportion in scenario B, compared to scenario A, suggests that the ability to extend biomass harvest into lean seasons would be a preferred characteristic of harvest sheds. In both scenarios the spatial distribution turned out to be similar: the energy crops were grown closer to the biorefinery, while the agricultural residues were transported from fields farther from the biorefinery. For energy crops, the higher density of biomass availability (in scenarios A and B) and staggered

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[16] The preliminary results presented here correspond to a generic cellulosic biofuel (Rhodes 2012; Pfromm et al. 2010, 515-524).

harvesting (in scenario B) offset higher production costs. The staggered harvesting reduced biomass raw material costs because it increased the proportion of energy crops in fields closer to the biorefinery which in turn reduced transport costs.

The proportion of energy crops and agricultural residues depended on two factors: the extent of marginal croplands available to grow energy crops, and the costs of sourcing either feedstock from their ‘outer margins.’ To illustrate, let the energy crops be grown within 15 miles radius and agricultural residues be grown within a 30 miles radius around the biorefinery. Energy crops would feature in the optimal feedstock mix as long as the material, transport and other costs of transporting it from a 15 mile radius were lower than the total cost of acquiring agricultural residues from a 30 mile radius. Hence, the delivered costs would determine the optimal combination of feedstocks. Such implications for individual biorefineries are similar to the economic results estimating the optimal feedstock composition at regional or national level. The environmental costs, in terms of carbon emissions, did not seem to affect the optimal biomass portfolio much. A substantial increase in the costs of greenhouse gases had only a slight impact on the optimal feedstock composition. When the greenhouse gas prices or emissions prices were raised from $15/ton to $50/ton, the proportion of energy crops decreased marginally from 73% to 69%.

The optimization results generated shadow prices for binding land acreage constraints. These shadow prices represent the value that biorefineries place on an additional acre (or ton) of energy crops or agricultural residues grown within the harvest shed. The shadow prices ranged from $2-8 per ton for energy crops grown in fields located within a 10 mile radius. The shadow prices ranged from $5-16 per ton for agricultural residues grown within a 10-20 mile radius. The salient feature of the shadow prices was that the shadow prices varied significantly over time. The shadow prices for agricultural residues were higher whenever energy crop output is lower. For example, the additional value (shadow price or premium) placed on agricultural residues was $16 per ton during the first year of operations but it declined gradually over 20 years.[17] The shadow prices for energy crops were low in the beginning years; it gradually increased over time. The type of land restrictions within the model, and the yield patterns of annual vs. perennial feedstocks were the reasons. The shadow prices for the zones with binding land acreage constraints showed similar temporal pattern. The shadow prices gradually declined with an increase in the distance of the fields/zones from the processing plant. Hence, the biorefineries could adopt a differential pricing strategy depending on the location or distance of the fields from the biorefinery. The lower material costs could justify a larger price premium (shadow price) paid for agricultural residues. Adding the shadow prices to the corresponding material and delivery costs would make both feedstocks comparable at the margin in every zone and every year.

The shadow prices for annual feedstocks declined as the supply of energy crop biomass production ramped up over time. This shows that annual feedstocks are sought after only as buffer feedstocks to meet biomass demand when the energy crop output is low due to yield pattern differences. The shadow prices for energy crops were lower due to their yield patterns and contracting limitations. During the first two years of establishment phase, the energy crop yields would only be one-third and two-thirds of the maximum potential yield (10 tons per acre per year). So, the benefits from an additional acre of

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[17] For instance, in case of scenario B, the price premiums for increasing agricultural residue by an acre fell to $6 per ton in years 2, and gradually declined with increased supply of biomass from energy crops.

energy crop would accrue rather slowly. Hence an additional acre of agricultural residues would be more valuable reflected by a higher shadow price for agricultural residues in the first few years. Moreover, the constraint that energy crop should be harvested during all 10 years created inflexibility and reduced the amount of value (shadow price) placed on energy crops.

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