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Supply Variation of Agricultural Residues and Its Effects on Regional Bioenergy Development

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Agricultural residue/wastes are promising for producing bioenergy, despite the existing considerations, such as spatial distribution, production costs, and an unstable supply. This study quantifies the supply variance of waste biomass and explores the viability of bioenergy conversion through advanced technologies. The regional concentration of feedstock and local market needs serve as the business strategy of proposed bioenergy facilities, and a constraint profit maximization model specified for optimal production. The results of this study provide a better understanding of the distribution variation of feedstock supply corresponding to the effects of multiple factors. Resource concentration and feedstock supplements drive the production scale, and high-value bio-products under policy support handle the production uncertainty and enhance the competitiveness of bioenergy products. The method and results of this study attempt to provide a platform for other types of residual/waste biomass to adopt advanced technology and bring the value added streams on line more rapidly.

Key words: bioenergy viability, high-value outputs, optimal production, regional development, residual/waste biomass, supply variation.

Introduction

In addition to dedicated energy crops and agricultural crops, there are numerous other sources of residual/waste biomass that can also be categorized as residues of agricultural crop and forestry, biomass processing residues, and municipal and animal waste. Agricultural processes yield byproducts and waste streams collectively known as *residues*, which yield significant energy potential and are relatively conducive to utilization because they have already been collected. For example, the process of cotton ginning produces a by-product composed of bur and stem fragments, immature cottonseed, lint, leaf fragments, and dirt; this is referred to as “cotton gin waste” (CGW, also known as cotton gin trash). Using residual and waste biomass could potentially reduce the environmental impact of biofuel production by increasing energy input without increasing the total carbon emission of bioenergy production (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Roberts, Male, & Toombs, 2007; Searchinger et al., 2008). Because of existing concentration and proximity to current infrastructure, these residues/wastes could become the primary source of feedstocks, especially for regional initiative development of bioenergy. Considering both positive and negative impacts of various bioenergy technologies and feedstocks on social economics and ecological challenges, utilization of existing feedstock sources may be the most effective method to develop sustainable, renewable alternative fuel (Dale, Kline, Wiens, & Fargione, 2010). In addition, biofuel technologies make conversion possible of most biomass types into liquid and gaseous fuel, as well as electricity (Singh, Panesar, & Sharma, 2010).

Cotton represents an important cash crop in Texas, particularly in dryland crop production regions where there are few profitable, environmentally adaptable alternatives. Texas produces an average of 5.684 million bales of upland cotton annually (US Department of Agriculture [USDA], National Agricultural Statistics Services [NASS], n.d.), which equates to an estimated 1.424 million tons CGW. This waste biomass has been collected onsite with lower moisture and contains approximately 18.625 trillion Btu, which is nearly equivalent to the energy content of 1.13 million tons of corn.[1] Residual/waste biomass conversion to bioenergy has the potential to mitigate the food-and-feed-versus-bioenergy conflict. The heaviest concentration of cotton acreage is located in the northwestern regions of the

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[1] *A median energy-content value of 8,250 Btu per pound of dry matter shelled corn is used. According to Penn State University, the combustion energy content of shelled corn is a critical factor in making energy comparisons of fuels (Penn State Extension, n.d.).*

Texas High Plains, where huge dryland cotton plants are grown. Because cotton-harvested acreage varies considerably and is heavily influenced by incidents of dry weather, uncertainty exists regarding cotton production in drought-stressed Texas. Livestock manure provides another significant source of biomass, with more than 5 million tons produced annually from the 7.2 million head of feed cattle in Texas, on an as-collected basis (Mukhtar, 2007). The Texas Panhandle is regarded as the "cattle feeding capital of the world," producing 42% of the beef cattle in the United States within a 200-mile radius of Amarillo. Both the magnitude and density of the Texas cotton and cattle industries create a very large regional fixed investment in human capital, farm-level machinery, processors, compresses, and warehouses. Converting agricultural waste biomass to a source of income would be a positive strategy for cotton producers/ginners, oil mills, the textile industry, and feedlot owners.

Agricultural residues from the waste streams of commercial processes have typically been considered to have very little inherent value, mainly constituting a disposal problem in the past. Most of the waste generated by cotton gins and cattle feedlots is applied to crop production fields without first evaluating potential alternative uses. Further, a large proportion of dryland crops that are associated with an unstable supply of these waste biomasses would restrict the production scale and, consequently, diminish conversion efficiency of bioenergy. Bioenergy facilities are also confronted with the costs associated with collection and transportation for biomass (Searcy, Flynn, Ghafoori, & Kumar, 2007) in addition to the supply uncertainties of the biomass feedstock in the study region. Current empirical studies indicate that extensive research has been conducted on crop-sourced bioenergy, along with a few studies specifically conducted on agricultural residue and waste-based alternatives (Brick, 2011; McCarl, 2000). Although a geographic information system (GIS) based modeling system is commonly used to estimate potential biomass supplies, it is not likely to handle uncertainty well (Graham, English, & Noon, 2000). Cameron, Kumar, and Flynn (2007) conducted a study regarding the impact of feedstock costs on technology selection and optimum size without considering the variable of feedstock supply. Most agricultural activities result in considerable variance in output of both primary products and residues, which poses supply risks that potential bioenergy producers must consider. It would be useful for prospective bioenergy producers—as well as for policymakers—if a comprehensive study was conducted that considers the main factors of waste biomass use in order to thoroughly analyze the associated effects on regional approaches of bioenergy development.

This study seeks to explore the economic indications of utilizing existing agricultural residue/waste to generate bioenergy that will complement local nucleus businesses and meet market demands. Additional specific goals include: 1) identifying appropriate sites with a sufficient volume of agricultural waste biomass for bioenergy production; 2) identifying the variation distribution of the CGW supply for specific sites; 3) establishing economic models for optimal production scales with the feedstock variance and market scenarios; and 4) conducting relative analyses, such as a cost/benefit analysis, a sensitivity analysis, and a transportation costs versus demand analysis.

Methods and Theory

Based on agricultural production and processors' data, GIS provides the location and supply distribution of CGW and cattle manure, which are the main waste biomass sources available in the study region. To determine the supply variation of CGW at multiple locations, the Bayesian Markov Chain Monte Carlo (MCMC) method was used and combined with historical rainfall data to estimate parameters. Given the deficiency of available site-specified data, using the MCMC method is advantageous because samples can be taken multiple times with several chains from specified posterior distributions. In addition to error terms, the convergences of each parameter can be observed, which enhances the diagnostic ability and thus the confidence level for the estimated parameters. To consider the different features of variation of CGW associated with crop production practices across the geographic area, three location types (mixed/average, irrigated, and dryland) are examined and discussed.

An economic analysis was conducted for biomass gasification and pyrolysis[2] and electricity generated to meet local market demand, including the higher-value peaking power. Biomass-based gasification eliminates the need for waste disposal and reduces electricity consumption from the grid, making it a valid investment (Craig & Mann, 1996). It is commonly used to generate

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[2] *Both of the advanced technologies are near their fully maturing stage and compete with fossil fuels at $70-$75 per barrel. The gasification usually requires large production scale, and the pyrolysis can be small production scale, even on site (Campbell, 2010).*

energy and heat for internal use or sold back to the grid as it is generated, especially for those industries producing the biomass. In comparison to biomass bales, bio-oil produced from pyrolysis has 1/8 the energy density ratio. The combination of simplified handling and greater energy density significantly reduces the cost of biomass transportation and increases the feasibility for large-scale bio-refinery facilities. Biomass is commonly processed into bio-oil and other products through pyrolysis prior to being transported to a central power or refining plant. These allow biomass energy to provide base load or peaking power, which can be difficult to achieve with biomass energy (Badger & Fransham, 2006). Because real-world data for the emerging industry is lacking, lab experiment results from Texas A&M University were used in this study for the technical parameters of converting CGW to energy. Production cost information was gathered from official sources along with ongoing bioenergy commercialization plans from previous studies, and output prices are based on regional market and personal interviews. A constraint profit maximization model incorporating the distribution of feedstock supply was established, and solved for optimal production scale and associated inputs and outputs for the application of gasification. An economic feasibility analysis was also conducted to examine the entire process of a modular bio-oil plant and subsequent generation of electricity.

Data Description

The volume and location of CGW is the main consideration of the analysis. Referring to the Texas Cotton Ginners' Association *Ginners' Red Book* (2008) and individual gins, the locations and associated volumes of CGW data of 79 gins within 16 counties are identified. Next, based on the cotton production data (USDA-NASS, n.d.), the amounts of accessible CGW from these ginners are proportionately distributed across the established time period. The 16 counties covered by the identified ginners account for approximately 54% of the total cotton production in Texas. According to local ginners' records on lint, seed, and trash turnout percentages within the study region, the estimated CGW is 501 lbs. per bale of cotton, which is comparable to the turnout used by Mitchell, Johnson, and Wilde (2007). It was presumed that only about 80% of the total waste generated by the ginning process is viable for bioenergy generation (Holt, Barker, Baker, & Brashears, 2000). Rather than focusing on aggregated CGW or CGW produced by individual gins, this study grouped CGW from ginners within a 10-mile radius area based on a "closest" rule in order to better illustrate their particular geographic locations and characteristics associated with distribution. The grouping figures are used to analyze supply variance of CGW at dryland, mixed, and irrigated sites, and the economic analysis of bioenergy generation are conducted at a mixed site. The potential supplement CGW for the defined groups may come from the gins that are relatively far to join any base group.

Observed precipitation data from 1917 to 2008 (National Oceanic and Atmospheric Administration [NOAA], National Climatic Data Center, n.d.) for several locations in the study region were collected. The locations of precipitation data include the sites with a high and low proportion of irrigated cotton, as well as the joint region using mixed production practices in the study region. Energy content of CGW was 13.10 MMBtu (million Btu) per ton (Curtis, Ferland, McKissick, & Barnes, 2003). The technical parameters of gasification and pyrolysis specified for CGW are based on experimental lab data obtained by the Department of Biological and Agricultural Engineering at Texas A&M University (Capareda, 2010). A typical unit of measure used for calculating bio-gasification is one ton of dry matter CGW per megawatt (MW) of electricity produced, in which an ideal 25% efficiency for the overall conversion process from CGW to power is used.

Assumptions and Scenarios

The scenarios that reflect the possible market conditions for gasification are summarized in Table 1. Biomass feedstock is based upon onsite CGW at the base groups, where the waste biomass commonly has a disposal fee. We assumed, therefore, that the onsite biomass resource is paid for through the low prices that are set for self-supplemental electricity. Collection and transportation costs should be added for supplemental biomass. Electricity output for both peaking power contracts and regular sales are considered, in view of the mechanism and policy support (e.g., the Renewable Portfolio Standard)[3] allowing the higher-valued products of bioenergy to

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[3] *Renewable Portfolio Standards (RPS), also referred to as Renewable Electricity Standards (RES), are policies designed to increase generation of electricity from renewable resources. These policies require or encourage electricity producers within a given jurisdiction to supply a certain minimum share of their electricity from designated renewable resources. See http://www.eia.gov/todayinenergy/detail.cfm?id=4850.*

Table 1. Scenarios of input costs and output prices for gasification.

Scenarios ($/MW)	Variable range	Regular_high	Regular_low	Peak_high	Peak_low
IC price	25-40	40	40	30	25
Own price	30-45	45	45	45	30
MWP price	100-120	-	-	120	100
MWSP price	60-65	-	-	65	60
Penalty	125-140	-	-	-140	-125
TRANS ($/ton)	15-80	20	20	20	20
Fixed cost ($/MWh)	125,400-185,000	185,000	125,400	185,000	125,400

Note: 'Peak' and 'regular' are used for with and without peaking power contract (or policy support for high value bio-products), respectively; IC=the incidental sales; Own=the onsite use (self-supplemental); MWP=the electricity sold at peaking time; MWSP=the electricity sold at secondary peaking time; Penalty=represents losses on the failures of peaking power contract; TRANS=the unit cost of biomass collecting and transportation from off-site; Fixed cost=is the annual fixed cost associated with per unit of installed capacity of the facility

penetrate current power markets. Market uncertainties of facility costs and input/output prices are specified by the value ranges from "high" to "low." Therefore, the four scenarios represent 1) conservative (regular/high)—high facility costs and regular output price without policy support; 2) predicted cost reduction (regular/low)—up to one-third of reduction on facility costs and regular output price without policy support; 3) expected policy support and conservative (peak/high)—market accessibility for high-value bio-products (peaking power) and high facility costs; and 4) expected policy support and cost reduction (peak/low)—market accessibility for high-value bio-products (peaking power) and up to one-third of reduction on facility costs.

The main electricity outputs include self-supply (Own), peaking demand (MWP) and secondary peak demand (MWSP), and incidental sale (IC) to the grid. According to local vendors and secondary resources, the regional electricity prices are traded every 15 minutes according to system demand at that moment, and the local purchase price of electricity at $75 per MW in average and off peak retail is priced within $35 to $50 per MW. Also, based on the high peak-demand price and lower price paid when sold back to the grid, the electricity prices used in this study vary based on different supply purposes and are stated in speculative ranges. More specifically, the prices of MWP and MWSP were considered as the possible price for green energy with policy support, as well as the prices of natural gas or fuel oil deliveries for peaking power. A small premium was set for self-supply of electricity due to the low feedstock cost internally. The fixed costs were based on the unit capital cost of the biomass gasification power-generation system estimates of the US Environmental Protection Agency (EPA, 2007) and vendors' R&D. The higher capital cost of gasification in Table 1 is near the middle value of the four alternative technical systems defined by the EPA; this value is calculated as the annual unit cost over 15 years. The associated production and transportation costs (TRANS, per unit of biomass in Table 1) are set aside from the variable cost in the model.

To determine costs and outputs associated with preprocessing waste biomass using the pyrolysis technique, we examined a modular bio-oil plant with a capability of 100 tons feedstock per day and 330 days of plant availability. The raw feedstock consumed equals approximately 39,600 tons per year with less than 20% moisture content. According to the Cole Hill Association (2004, 2005), dry-weight yields of bio-oil and char for pyrolysis are 60% and 20%, respectively. The production capacity is 3.96 million gallons annually, and bio-oil heat content is 72,000 Btu/gal. Bio-oil plant capital cost was approximately $5.6 million, with a 20% equity investment and a loan of $4.48 million amortized over 15 years at an average interest rate of 7%. Further, the bio-oil is transported to central power plant(s), and electricity is generated for the needs of higher-valued peaking power and extreme seasons.

Model for Estimating Variation of CGW Supply

The variance of the supply variable is considered to be the ideal measure of risk in empirical work. The main factor used for estimating the probability distribution of the CGW supply is the amount of precipitation in the study region. Given the semi-arid weather in the Texas High Plain—where rainfall is insufficient and unreliable—traditionally dominant cotton production is considered the sole profitable dryland crop. Although the site-specified data of CGW is limited, data during the time period of 2001 to 2007 was available, indicating that weather fluctuated and cotton producers encountered both extremely dry and wet years in the study region. It is also assumed that the other factors of CGW, such as cotton varieties and harvest technology, are fixed at current levels for a short time period. The model is specified as

$$\log(CGW)_i = \beta_0 + \beta_1 \log(rain)_i + \beta_2 \log(rain)_i^2 + \varepsilon_i\,, \quad i = 1 \ldots 7, \qquad (1)$$

where *rain* represents the observed annual rainfall in the study region, and ε is the error term and is assumed to have a normal distribution with specific means and standard deviations.

The mean of the CGW supply is defined by Equation 1 with a quadratic form of rainfall; the unknown parameters are defined as multi-normal prior distribution with a covariance matrix. Having specified the model as a full joint distribution on all quantities, values of the unknown parameters from their conditional (posterior) distribution were sampled, given those stochastic nodes that have been observed. WinBUGS software, an interactive Windows version of the BUGS program used for Bayesian analysis of complex statistical models using MCMC techniques, was applied for the estimation.

Economic Models for Profit Maximization

Bioenergy producers are assumed to be price takers for production inputs and output. Their objective is to select a certain level of production scales and appropriate technology that can maximize their net present value of profit. For the purpose of this study, feedstock variation affects the physical scale of production; additionally, associated production inputs and outputs depend on the amount of biomass available onsite (base groups), and the possible amount of biomass supplements from nearby sources below acceptable costs.

The expected profit maximization model for gasification can be established as

$$MaxE(\pi) = \sum_{i=1}^{k} Prob_i * (Revenue - Cost)_{i,s}\,, \qquad (2)$$

subject to

(i) $MW_i + Penalty_{i,s}$ (or $MWTR_{i,s}$) $\geq MWP_s + MWSP_s + Own_i + IC_{i,s}$;

(ii) $MWP_s + MWSP_s + Own_i + IC_{i,s} \leq S*time$;

(iii) $MWP_s = T_1 *S$;

(iv) $MWSP_s \leq T_2 *S$;

(v) $VC_i = B_1 * (MWP_s + MWSP_s + Own_i + IC_{i,s})$;

(vi) $FC_s = B_2 * S$;

(vii) $Own_i \leq 0.5 * Factor * MW_i$;

(viii) $time \leq T$,

where *Prob* represents the probability of the attainable amount of CGW onsite, the suffix $i = 1...k$ along its probability distribution; the suffix S is the plant scale; *Revenue* is the production revenue; *Cost* includes fixed cost (*FC*) related with *S*, variable cost (*VC*) associated with production outputs, *penalty* occurs as failure of peaking power contract, or biomass supplements would be added on if loss from *penalty* is larger than the costs of feedstock supplements. In the constraints, *MW* represents the possible amount of convertible electricity given the distribution of onsite CGW through a specific technology; *MWTR* represents the amount of outputs (MWe) from supplemental biomass; *time* is the total operation time (hours per year) with the upper boundary of *T*, *T1*, and *T2* representing the time constraints for peak and sub-peak, respectively; *Factor* is a converting ratio representing the electricity consumption needs of the cotton ginning processes. It is assumed that only half of total electricity consumption of the gins could be supported by the bioenergy plant at the given price. Due to the lack of detailed information of associated costs of technology specified for bio-waste, it is assumed that a linear relationship exists between the amount of output and variable cost, and between plant scale and fixed costs. These coefficients are represented by B_1 and B_2 in the model. Referencing Energy Nexus Group (2002), \$5.50 of operation and maintenance cost per MW of electricity generated is assumed for B_1 as the cost of biomass supplements, which is set aside from the VC. The assumed value range of B_2 is associated with the scenarios stated in Table 1, thus suggesting the unit capital costs of a biomass gasification power system.

The economic model for gasification is established with enough flexibility to satisfy different situations or preferences of decision makers and can be run separately for all six scenarios under the assumptions of “with” and “without” supplemental biomass from off-site sources. The conducted model solves for optimal plant scale (*S*), identifying electricity output generated from off-site feedstock (*MWTR*), detecting the amount of outputs at peaking and sub-peaking time (*MWP*, *MWSP*), and electricity used onsite (*Own*) and incidental sales (*IC*). Additionally, the economic model can be used to test the model’s sensitivity on the assumptions (scenarios) made, and to detect the relationships

Table 2. Parameters estimated using MCMC method for different types of sites.

Type of site	Node	Mean	SD	MC error	2.5%	Median	97.5%	Sample
Mixed	b[0]	7.031	5.058	0.01749	-3.459	7.183	16.77	88,500
	b[1]	3.704	3.338	0.01144	-2.723	3.596	10.65	88,500
	b[2]	-0.5014	0.5483	0.001862	-1.642	-0.4857	0.5574	88,500
	ε	11.09	7.491	0.04014	1.7	9.392	29.93	88,500
Irrigated	b[0]	-0.8795	5.377	0.01972	-10.99	-1.089	10.4	88,500
	b[1]	7.367	3.602	0.0131	-0.1928	7.517	14.12	88,500
	b[2]	-1.121	0.6004	0.002162	-2.246	-1.147	0.1456	88,500
	ε	15.24	10.43	0.05613	2.266	12.83	41.78	88,500
Dryland	b[0]	1.454	6.787	0.02389	-11.75	1.417	15.05	88,500
	b[1]	4.734	4.475	0.01563	-4.243	4.766	13.44	88,500
	b[2]	-0.5993	0.7418	0.002568	-2.041	-0.6052	0.8925	88,500
	ε	2.892	1.846	0.009211	0.4936	2.5	7.534	88,500

Note: Three location sites—mixed, irrigated, and dryland—are examined. The node represents the model parameters respectively from intersection to error terms (ε).

between transportation costs and the amount of demand on biomass feedstock. LINGO 11.0[4] was used to perform operational programming for the profit maximization model.

Although a similar approach can be used for pyrolysis and subsequent electricity generation, the model development is challenged by the limitation of contemporary market and technical data information. Economic feasibility analysis was conducted generally for the entire process from preprocessing waste biomass through pyrolysis technology to bio-oil production, and bio-oil is then delivered to the power plant for electricity generation.

Results and Analyses

Location and Amounts of the Waste Biomass

Within the study region, 19 groups are specified with CGW onsite within a range of 3,603 to 74,501 tons annually based on the 10-mile-radius grouping criteria. Twelve groups owning CGW exceeding 20,000 tons are the main focus of this study, with an aggregated figure of 504,702 tons annually. Eight of the 12 focus groups are located in the southwest dryland area, and the remainder are either located in the northeast irrigated area or the adjoining area between them. The top four groups each produce more than 40,000 tons of CGW annually; two are located in an irrigated area and the others are in the dryland and adjoining areas. The supply distribution of CGW varies tremendously site by site. Beyond the focus groups, the remaining single gins—which are located too far away to join any of the base groups—produce 2,941 to 14,946 tons of CGW individually, and aggregated totals are as much as 85,029 tons annually. These ginners could become the feedstock suppliers to the base groups within a distance of approximately 25 to 35 miles. In addition, Lubbock Feeders LP—located centrally in the study region—produces approximately 52,508 tons of solid manure annually, which could also become a biomass source in the study region.

Parameter Estimation and CGW Distribution

The estimated parameters and corresponding CGW distributions identified are included in this section. The parameters estimated through the MCMC method are listed in Table 2. Among the three types of locations (mixed, dryland, and irrigated sites), all the explanatory variables contain the hypothesis signs indicating positive for rainfall and negative for its quadratic form. The convergence of each parameter was obvious, and successful Bayesian inference that uses this sampling-based approach depends on the convergence of the Markov chain. The Monte Carlo error (MC error) for each parameter is less than 5% of the sample standard deviation (SD); the MC assesses the accuracy of the procedures of posterior estimates. The significant results were obtained at the mixed site; however, the estimated parameters have larger variances.

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[4] *LINGO is a comprehensive tool designed to make building and solving linear, nonlinear, and integer optimization models faster, easier, and more efficient.*

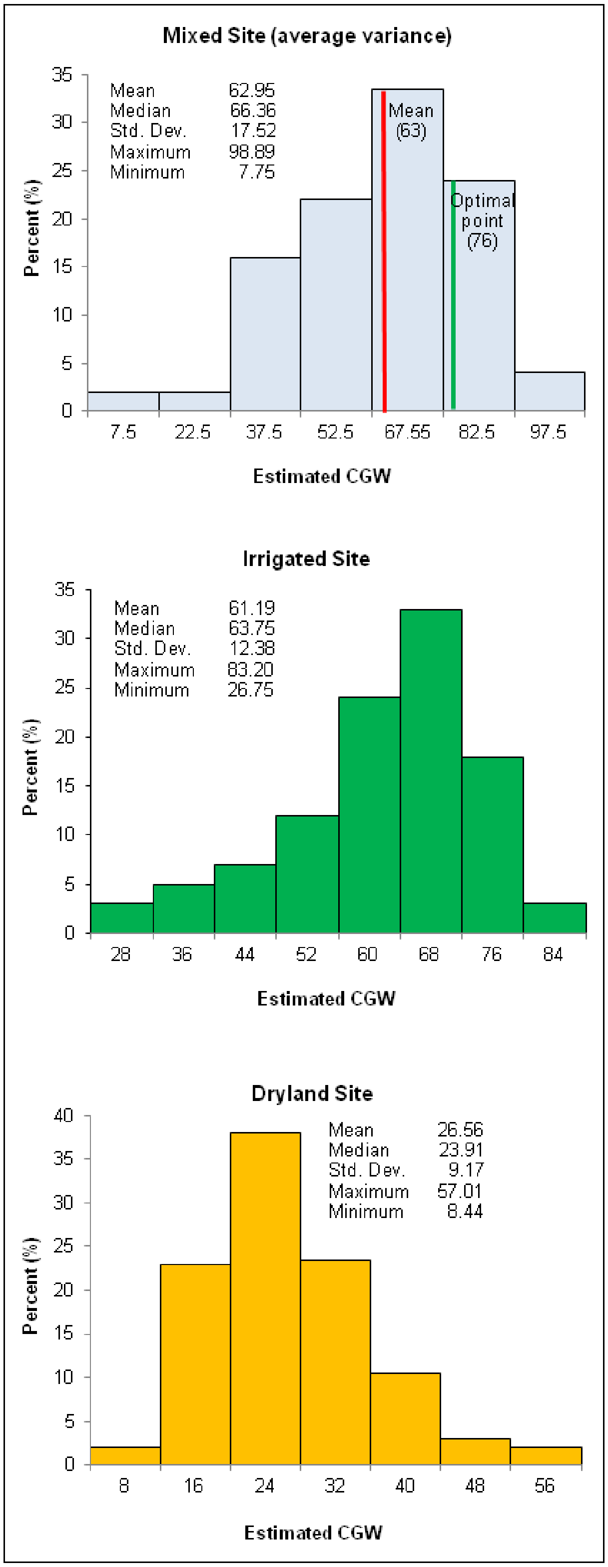

Figure 1. The estimated distributions of CGW for three types of location sites.

Figure 1 provides the distribution of the CGW supply estimated for each site type. The distribution of CGW is skewed to the right for the irrigated site and skewed to the left for the dryland site, as compared to the distribution of the mixed site. These results correspond perfectly with the empirical expectation that compare to their corresponding mean levels of relatively less biomass supply and higher variance at dryland sites, and more biomass supply and lower variance at irrigated sites exist. The location-specific features of CGW supply are demonstrated in an observable and measurable manner through such analysis. Additionally, the figure illustration of the mixed site verifies that the mean level of the CGW supply could specifically differ with the optimal points selected by the economic model under one scenario. The stochastic variation of feedstock supply with site specifics provides valuable knowledge and information and technically ensures an optimized decision under highly uncertain situations. Rather than relying only on the averages of feedstock supply, understanding the distribution of available resources is advantageous when dealing with an unstable supply of biomass feedstock.

Results of Economic Model for Gasification

The results of the economic model for gasifying CGW offer a profile of the bioenergy production possible in the study region. In this section, an aggregated view of regional CGW gasification is stated first; then, the detailed results from a mixed site are demonstrated in the following paragraphs of the section, including the result comparison from multiple scenarios, production variances and associated profit distribution, model sensitivity analysis, the impacts of acquiring costs of biomass on production scale and feedstock demand. It seems that it would be profitable for ginners' groups or other investors to gasify the low-cost waste biomass both for self-supply electricity and market needs. For the base groups identified, there are aggregated 514,360 MW of electricity and $6.3 million in profits annually under the scenario of 'peak-high' (market accessible for high value bio-products and high facility costs). The production capacities of these onsite plants could be from 3 MWh to 11 MWh individually, and total capital cost of these facilities is $13.6 million each year. Approximately 70% of electricity output is used for the ginning operation (Own) and incidental sales, and the remaining 30% meets market demands of electricity at peak power times and extreme seasons.

Table 3. Summary of economic model solutions on with/without feedstock supplements.

	Regular_high	Regular_low	Peak_high	Peak_low
		Model-onsite		
E[π] ($)	315,072	782,473	841,827	960,788
MWP (Mwe)	--	--	9,227	10,174
MWSP (Mwe)	--	--	9,764	10,766
‘Penalty’ (MWe)	--	--	0	30
Fixed costs ($)	1,114,889	999,259	1,806,393	1,350,110
Capacity (Mwh)	6.03	7.97	9.76	10.77
		Model-supplement		
E[π] ($)	373,916	933,096	882,917	964,278
MWP (Mwe)	--	--	9,227	10,174
MWSP (Mwe)	--	--	9,764	10,766
‘MWTRAN’ (MWe)	4,857	16,403	11,142	115
Fixed costs ($)	1,474,186	1,350,110	1,806,393	1,350,110
Capacity (Mwh)	7.97	10.77	9.76	10.77

Notes: Model-onsite=based on onsite feedstock only; Model-supplement=based on both onsite feedstock and external supplement MWTRAN=the energy outputs specifically from the supplemental biomass feedstock; E[π]=expected profits, and others are the decision variables described in method section. Capacity=the optimal production scales identified

Theoretically, facing the supply variation of feedstock and market uncertainty, investors want to identify the production scale that would perfectly capture the opportunity and minimize risk. To explore the impacts to production from the variation of feedstock supply, the constrained profit maximization model was run separately for both “with” and “without” external feedstock supplement. The *comparison of the solutions* under the four scenarios is summarized in Table 3, which illustrates how the variance of biomass feedstock combined with other factors affects the production capacity. The smallest production scale at 6 MWh is specified for the onsite feedstock model under the conservative scenario (regular/high), which represents the current situation of limited market access for high-value bio-products and the high facility costs of the bioenergy industry. The possible reduction of up to 30% of facility costs (regular/low) could lead to a higher production scale of nearly 8 MWh and of nearly 11 MWh if combined with external supplement of biomass feedstock. As we detected in a previous section of this article, the onsite CGW was not even-supplied annually, and a shortage of biomass feedstock may be encountered as periods of drought occur. Compared to the results of the onsite feedstock model, the solutions of the model with supplemental biomass show increased production capacities and expected profits, which implies that feedstock supplements are necessary either for reducing the production variance or for expanding the production capacity if the transportation cost is acceptable. An accessible market for bioenergy products—such as creating policy supports that would spread compliance costs among all customers—is also an important factor for establishing the new business. In this study, the peaking power contracts represent the accessible market of high-value bioenergy products. The production capacities could increase to near 10 MWh and 11 MWh, respectively, for the two scenarios of ‘peak/high’ and ‘peak/low.’ Furthermore, as the facility costs are reduced to a relatively lower level, we discovered that the production scales are the same under the scenarios of ‘peak_low’ and ‘regular_low,’ but the former’s production with policy supports has higher expected profit and relies significantly less on outsourced feedstock when compared to the production of its counterpart. On the other hand, if the facility costs remain high, a certain amount of supplemental feedstock is still critical for producing more and offsetting the production costs, even though the policy supports are available (peak/high vs. peak/low).

Corresponding to the variations of feedstock supply and market uncertainties, the production variances and associated profit distribution are analyzed as well. The high-value bioenergy products and referring policy supports would mitigate the impacts of investment uncertainty and feedstock costs of the new industry. The distributions of decision variables and associated profits with supplemental biomass are provided for the scenarios of ‘regular_high’ and ‘peak_high’ in Table 4. It is clear that the production variances of converting waste biomass to energy could be immense; a substantial loss

Table 4. Distributional results of the model with feedstock supplements (MWe, $).

Feedstock distribution	a. Scenario of regular_high: capacity 7.97 MWh; total output 55780 Mwe; VC $306,790				b. Scenario of peak_high: capacity 9.76 MWh; MWP 9227 MWe, MWSP 9764 MWe, and total output 68350 Mwe; VC $375,925			
(%)	IC	OWN	MWTRAN	Profits	IC	OWN	MWTRAN	Profits
0.05	48,406	7,374	0	$487,096	41,984	7,374	0	$1,151,000
0.05	49,121	6,659	0	$483,521	42,699	6,659	0	$1,140,275
0.15	49,511	6,269	0	$481,570	43,089	6,269	0	$1,134,423
0.25	50,094	5,686	0	$478,653	43,673	5,686	0	$1,125,670
0.25	51,140	4,640	0	$473,424	44,718	4,640	12,570	$848,077
0.15	52,271	3,509	13,595	$184,504	45,849	3,509	26,165	$547,848
0.05	52,879	2,901	20,910	$29,047	46,458	29,01	33,480	$386,305
0.05	54,089	1,691	35,450	-$279,956	47,667	1,691	48,020	$65,207
Exp.mean	50,800	4,979	4,857	$373,916	44,379	4,979	11,142	$882,917

Note: %=the probability that the solutions of decision variables could be obtained; MWTRAN=the electricity output from supplemental biomass feedstock; VC=variable costs; Exp.mean=the expected values that are weighted by their probability

Table 5. Model sensitivity analysis for the assumptions.

	Dual price ($)	Range of objective coefficient			Allowable (Mwe/yr)	
Scenario	(Shadow price)	Low bound	Current	High bound	Increase	Decrease
			Peak_high			
MWP	89.3	100	120	145	1,338	353
MWSP	34.3	46	65	89	1,338	353
Fixed cost	-	-1.1045	-1	-0.8728	-	-
			Peak_low			
MWP	69.7	95.4	100	117	11,029	611
MWSP	29.7	55.7	60	76	11,029	611
Fixed cost	-	-1.0346	-1	-0.8713	-	-

Notes: Dual price (shadow price)=the amount of expected profits which would improve as the constraint variables are increased by one unit; Range of objective coefficient=the amount of allowable increase/decrease from current coefficients of the objective function, while not causing any of the optimal values of the decision variables to change; Allowable=the right side allowable amount of increase or decrease from current value while their dual prices remain constant

could occur, although the probability is low. The profit loss in the regular sale scenario could be excluded if high-value outputs are available. In addition, the peaking power contracts not only increase the production scales, but also decrease the variance of production profit. Correspondingly, it requires more external feedstock (MWTRAN), which is 4,857 tons (or MW) at 25% of the operating years and 11,142 tons (or MW) at 50% of the operating years, respectively. Self-sufficiency (Own) is increased across the distribution as more onsite CGW is generated during the ginning process, and the ICs change reversely to it. With biomass transportation costs set aside, the VCs remain constant across the distribution.

A sensitivity analysis was conducted to evaluate the model sensitivity of the solutions to changing assumptions. The details of model sensitivity for the assumption changes under scenarios of ‘peak_high’ and ‘peak_low’ are illustrated in Table 5. The dual prices (shadow prices) of variables are interpreted as the amount of expected profits, which would improve as the constraints are increased by one unit. For example under the two scenarios, the expected profits could be increased by $89.30 and $69.70, respectively, for an additional unit of electricity sold during peaking power time. The dual prices also reflect the willingness-to-pay for additional units of a resource. The ranges of the objective coefficient specify the allowable increases and decreases from current coefficients (based on assump-

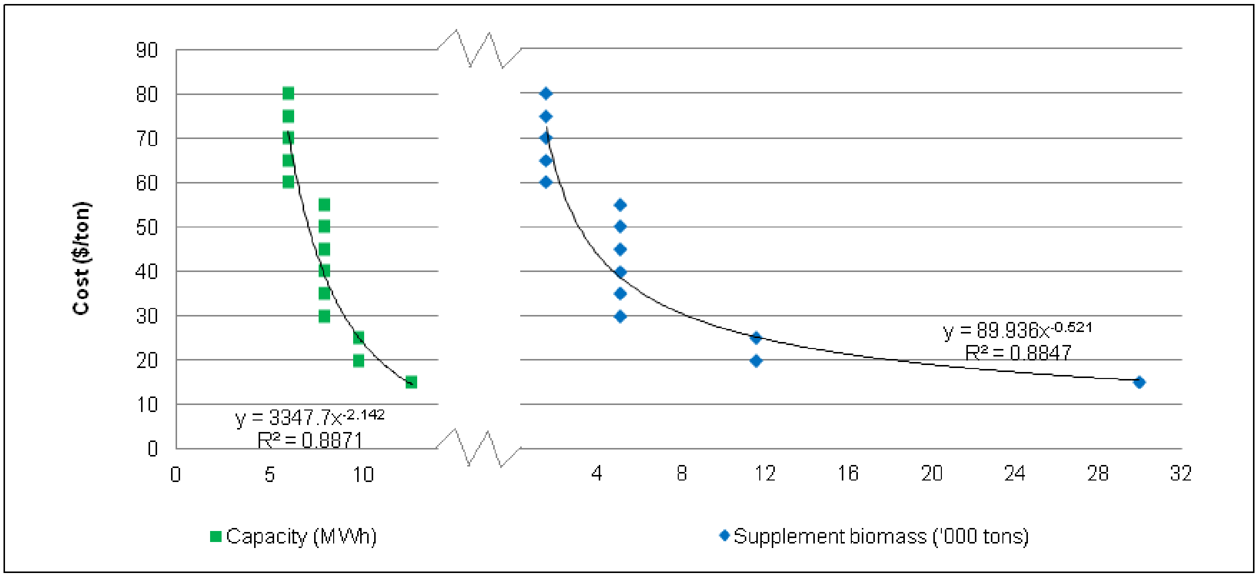

Figure 2. Unit cost of biomass vs. plant scale and demand of supplemental biomass.

tions) of the objective function without altering any optimal values of the decision variables. For example, under the 'peak_high' scenario, the objective coefficient range of MWP is [100, 145], which implies that the contract price at peaking load time could be decreased to $100/MWe or increased to $145/MWe from its assumed value $120/MWe while keeping the optimal plant scale at 9.76 MWh. Additionally, the right-hand side of allowable ranges on constraints explores the allowable amount of increase or decrease from current value while their dual prices remain constant. Obviously, when considering policy support for market acceptance and reduced facility costs (peak_low scenario), the allowable ranges constrain increased substantially, indicating that the identified production scale has potential for increased product outputs.

Finally, the impacts of acquisition costs of biomass on production scale and the demand of supplemental biomass are examined through the profit maximization model. The associated costs of collection and transportation are defined as a unit cost of feedstock in the study. Figure 2 shows the effects of unit costs of biomass on the amount of demand for supplemental feedstock (TRANS) and associated production capacities under the 'peak_high' scenario. The plant scale is selected as 9.76 MWh while unit cost is $20/ton. Nevertheless, it could be increased to 12.66 MWh as the cost drops to $15/ton, or conversely drops to 7.97 MWh as the cost increases to $30/ton. As the unit cost reaches $60/ton, the plant scale could be further reduced. During the three phases of plant scale, while the unit cost increased from $15/ton to $60/ton, the expected demands of external biomass equals 30,000 tons annually for 95% of its operating years; 11,608 tons for 50% of its operating years; and 5,060 tons for 25% of its operating years. The $45 cost increase per unit of biomass feedstock could convert an out-sourced bioenergy facility to a nearly self-sufficient bioenergy facility.

Results of Economic Analysis for Bio-oil/Power Generation

Regarding the economic analysis of utilizing CGW for bioenergy, the results for mobile pyrolysis plants preprocessing CGW to bio-oil and for bio-oil delivered to central power plants are discussed on an individual basis. A100-tons-per-day capacity bio-oil plant can produce 3.96 million gallons (19,800 tons) of bio-oil annually, at a break-even price of $0.59/gal if a cost of $7/ton is assumed for the onsite waste biomass feedstock. To attract serious investors and bank financing, a minimum 20% return on investment (ROI) would be needed, which would require a bio-oil sale price of $0.72/gal. The consequent energy-equivalent price of bio-oil could be $1.22/gal if the retail price of No. 2 fuel oil is $2.35/gal. However, as the feedstock costs rise to $47/ton, the break-even price is $1.02/gal and the required sale price is $1.23/gal, which slightly exceeds the corresponding energy-equivalent price. Obviously, since the waste biomass has been collected during the ginning process, the possible relatively lower costs of using the CGW—as well as the higher price of conventional fuel oil in the future—could result in adequate potential for profits in preprocessing CGW to bio-oil.

Nevertheless, there are concerns regarding the availability of infrastructure needed for bio-oil commercialization, along with the additional costs of delivery and storage for end-users. Compared to conventional heating fuel used at a power plant, the lesser heat content (approximately 52% of No. 2 fuel oil) of bio-oil at least doubles its delivery cost for generating the same amount of electricity output. Additional costs associated with handling bio-oil are also required, with the capital costs of equipment and installation for bio-oil handling systems at a 50 MW power plant estimated at $2.17 million (Badger & Fransham, 2006). The higher delivery cost and additional handling costs of generating electricity may ultimately result in decreased profit. Brammer, Lauer, and Bridgewater (2006) also found that relative costs of bio-oil application made it less competitive in European heat and power markets.

Summary and Conclusions

Based on a regional view, this study attempts to explore the economic potential of bioenergy generation from agricultural residue/waste by addressing the challenges and opportunities. The locations and existing volume of the processing waste biomass were identified in the central agricultural area of the Southern Plains of Texas. By using the Bayesian MCMC method, the variations and distributions of attainable CGW were specified for different location sites based on historical rainfall and observed crop production data. Incorporating the unique information on supply variance of the biomass in waste streams, an economic optimization model was developed under multiple scenarios of production inputs and outputs. We examined the production scale of utilizing the waste biomass for electricity generation through gasification technology. A sensitivity analysis was conducted to evaluate the model solutions to changing the assumptions, and the impact of biomass transportation costs were assessed as well. The economic feasibility of using the pyrolysis technique for pre-processing biomass and marketing bio-oil for electricity generation was discussed. The methods and results of this study are intended to inform the initiatives of biomass producers and other bioenergy investors—as well as policy makers—in promoting bioenergy development using waste biomass.

The potential strengths of processing residual/waste biomass to heat and power locally include: 1) the possibility of accessible market for high-value bioenergy products, in view of policy support such as the state-level RPS; 2) complementing local core businesses by utilizing facilities and available human resources, since most gins operate seasonally; 3) the power industry already has a fully developed market system and infrastructure network, as well as renewable energy initiatives; and 4) the outstanding environmental benefits in terms of total carbon emission and other factors in comparison with the use of dedicated energy crops. Approximately 70% of the electricity generated through gasification could be used for the ginning operation and incidental sale. Besides the onsite biomass feedstock, the high-value outputs and feedstock supplements seemly drive the production scale, and lead to effectively utilizing biomass resources and available human capital on hand. The initiatives of converting waste biomass to energy for self-supply and market demand could be duplicated in other similar regions.

In addition to thoroughly understanding the distribution variation of the feedstock supply across the region, it is also important to identify resource concentrations and the costs associated with supplementing onsite biomass. Both variables play an important role in reducing the variance and uncertainty of bioenergy production. Hence, in converting residual/waste biomass to energy, it would be more practical to build processing plants where fuel is available and affordable. The costs of attainable biomass feedstock and the capital investment are commonly the biggest obstacles in bioenergy production. The potential profitability is manipulated by production costs internally, as well as the external influence of the price of alternative fossil fuel and policy incentives. Policy support such as biomass boiler credits for cost sharing or state RPS must be sufficient in handling production uncertainties, enhancing the competitiveness of bioenergy products, and achieving an efficient and sustainable production scale.

Overall, this study suggests that 1) residual/waste biomass resources concentrated in a region could guide bioenergy development for regional demand; 2) production uncertainties associated with waste-based bioenergy exist widely from feedstock supply to market development; 3) market accessibility of high-value bioproducts and production costs are critical in sustaining a competitive and efficient production scale; 4) gasification could be a feasible process to generate electricity for self-consumption and incidental sales, as well as for peaking power demand; and 5) generally, most bioenergy systems are currently noncompetitive and policy supports are needed to advance the technology.

There are huge resources of residues, co-products and waste (such as oilseed residue and woody residue in processing agricultural/forest products), and manure at livestock feedlots, which could potentially become available, in quantity, at relatively low cost compared to dedicated bioenergy feedstock. The methods used and results obtained by this study would be practical to address the opportunities and challenges in other agricultural regions where sufficient residues are available. This study attempts to provide a platform for different types of residual/waste biomass in order to adopt advanced technology and to bring value-added streams online more rapidly. In the long term, technological improvements and associated production costs are the key components for bioenergy production, especially in dealing with market risks and the competitiveness of alternative fuels.

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