Co-firing in Coal Power Plants and its Impact on Biomass Feedstock Availability

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Abstract

Several states have a renewable portfolio standard (RPS) and allow for biomass co-firing to meet the RPS requirements. In addition, a federal renewable fuel standard (RFS) mandates an increase in cellulosic ethanol production over the next decade. This paper quantifies the effects on local biomass supply and demand of different co-firing policies imposed on 398 existing coal-fired power plants. Our model indicates which counties are most likely to be able to sustain cellulosic ethanol plants in addition to co-firing electric utilities. The simulation incorporates the county-level biomass market of corn stover, wheat straw, switchgrass, and forest residues as well as endogenous crop prices. Our scenarios indicate that there is sufficient feedstock availability in Southern Minnesota, Iowa, and Central Illinois. Significant supply shortages are observed in Eastern Ohio, Western Pennsylvania, and the tri-state area of Illinois, Indiana, and Kentucky which are characterized by a high density of coal-fired power plants with high energy output.

1 Introduction

Growing concerns about GHG emissions and energy security in the United States have led to policy enactments and proposals to rely more on domestic renewable energy sources. The Renewable Fuel Standard (RFS) passed with the Energy Independence and Security Act (EISA) of 2007 requires blending regular gasoline with biofuels from feedstocks such as corn or cellulosic biomass (Khanna et al., 2011a). Proposals include the American Clean Energy and Security (ACES) Act of 2009 and the American Power Act (APA) of 2010 which would have established a cap-and-trade system. The definitions of renewable energy resources in those bills include biomass and would have issued renewable electricity credits in the case of co-firing biomass with fossil fuels. In addition to federal efforts, 29 U.S. states plus the District of Columbia and Puerto Rico have enacted a renewable portfolio standard (RPS) as of May 2012 (U.S. Department of Energy - Database of State Incentives for Renewables & Efficiency, 2012). A RPS is comparable to the RFS as it demands from energy producers a predetermined level of renewable output. Eligible technologies generally include wind, biofuels, biomass, geothermal, landfill gas, photovoltaic, etc. (EPA, 2009). For example, Minnesota requires 25% of the state's power to come from renewable energy sources by 2025. Efforts to establish a federal RPS are underway but have not yet come to fruition. The renewable energy standards in the cap-and-trade systems or a federal RPS would result in dedicated biomass power plants and co-firing of existing coal power plants (EIA, 2009). Co-firing plants work in conjecture with coal and have the advantage of requiring small and low cost modifications to existing power plants and more flexibility in the short-term input mix, i.e., shortages in biomass supply can be compensated by increasing the coal percentage (Basu et al., 2011). Thus, current and proposed legislation together with low cost of switching to co-firing would affect the market for cellulosic biomass resources such as agricultural residues, energy crops, and forest residues. Biomass co-firing can be part of a larger portfolio of carbon sequestering and mitigating options such as wind or carbon capture and storage. In this paper, we focus on co-firing biomass in existing coal power plants and its impact on local biomass supply and demand. Focusing on existing coal-fired power plants allows us to identify counties and areas in which biomass feedstock is either abundant or scarce. The results can be used to evaluate the

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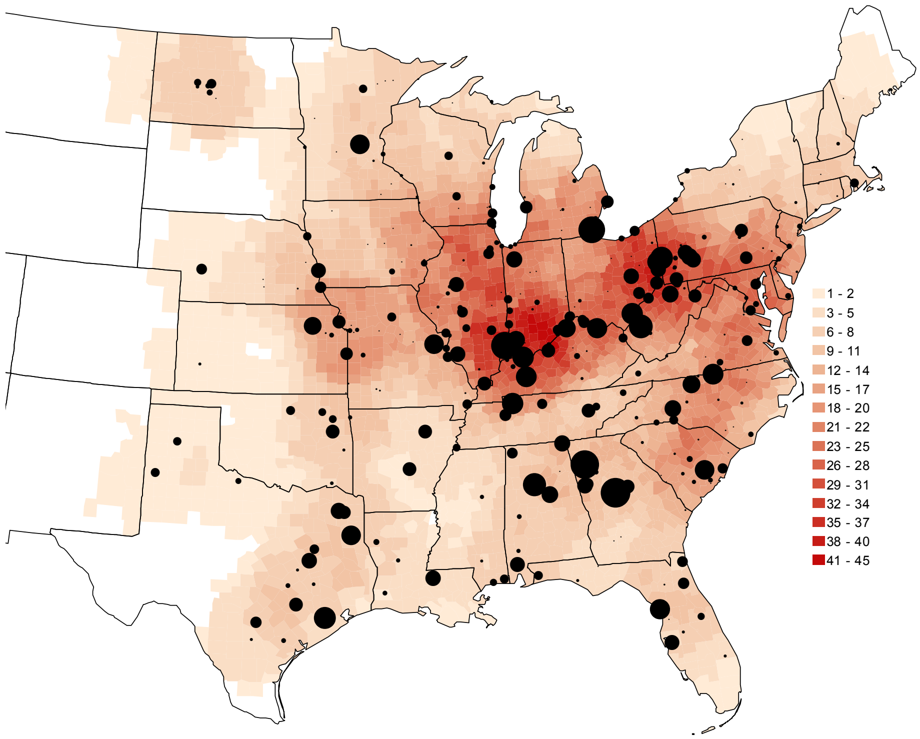


Figure 1: Coal-fired power plant location and density: Number of powerplants within 200 kilometers of a county's centroid with the marker size representing the name plate capacity. Total number of power plants in this study: 398

county-level feedstock availability for a cellulosic ethanol industry when simultaneously having a co-firing requirement. A similar scenario was analyzed by the Energy Information Administration (EIA) but not at the county level (EIA, 2007a).

Insert Figure 1: Coal-fired power plant location and density: Number of powerplants within 200 kilometers of a county's centroid with the marker size representing the name plate capacity. Total number of power plants in this study: 398

We focus on corn stover, wheat straw, switchgrass, and forest residues as sources for biomass. To supply any type of biomass, landowners need to be compensated for collection, storage, and transportation (Panichelli and Gnansounou, 2008; De and Assadi, 2009; Khanna et al., 2011a). Despite having the RFS in place, high cost associated with collection and transport of cellulosic material make the evolution of the cellulosic ethanol industry difficult to predict (FAPRI, 2012; Babcock et al., 2011). To overcome this issue, we impose an exogenous biomass price and determine how much and what type of cellulosic feedstock farmers supply. Based on the biomass price, farmers optimally allocate the agricultural land among field crops (corn, soybeans, and wheat) and switchgrass. Crop prices are endogenous to the model and depend on the land allocation of all landowners. The area of forest is assumed to be fixed and we rely on previous studies to assess the supply curve of forest residues (Perlack and Stokes, 2011). If biomass is produced from crop residues, then the effect on commodity prices should be minimal whereas a switch from field crops to energy crops should affect commodity prices much more strongly (Thompson and Tyner, 2011). The biomass supply is modeled at the county level for which we know the cropland characteristics (e.g., land availability, crop and switchgrass yields, costs, etc.) and forest residue supply functions. The model solves for the competitive equilibrium under different biomass prices.

The coal power plants are subject to an exogenously determined co-firing percentage (in percent of total electricity production) and can use any combination of the aforementioned biomass sources. We use datasets from the Energy Information Administration (EIA) and the National Energy Technology Laboratory for the location of coal power plants and to determine the characteristics (e.g., name plate capacity, fuel type, heat rate, etc.). Given data about the size and location of the power plant, the feedstock demand function under a co-firing requirement is calculated based on the power plants least cost procurement of biomass. We do not include cellulosic ethanol plants because of limited capacity (FAPRI, 2012). We focus on cellulosic biomass and hence, we do not need to include the location of conventional ethanol plants because the feedstocks are separate.

The spatial aspect plays an important role for two reasons: First, many power plants which would qualify for co-firing are already in place and second, the transportation from biomass from its production site to the plant is likely limited due to transportation cost and infrastructure. Figure 1 illustrates the issue analyzed in this paper by displaying the geographic location of the power plants analyzed, their name plate capacity, and the number of power plants within 200 kilometers of a counties centroid. A cluster of large power plants in the tri-state area of Illinois, Indiana, and Kentucky as well as the Ohio-Pennsylvania border is observed.

One of the first analysis of co-firing crop residues with coal was done for Iowa in 1981 by English et al. (1981). More recent studies mostly focus on the availability of biomass for cellulosic ethanol production (Perlack and Stokes, 2011; Mabee et al., 2011) or the effects of a renewable portfolio standard on the generating sector and consumers (EIA, 2007b,a). Others focus on co-firing in a single plant (Huang et al., 2009; De and Assadi, 2009) or a limited number of power plants in a single state (Brechbill et al., 2011). This paper focuses on the impact on biomass supply and demand at the county level by including 398 coal-fired power plants. A 2007 study by the EIA projected a threefold increase in the electricity production from biomass given a 15% federal RPS (EIA, 2007b). To the best of our knowledge, this is the first paper to analyze the county level impacts of a federal renewable portfolio on biomass suppliers with endogenous opportunity cost for changing to switchgrass. Our model examines two issues: the competition of power plants for limited biomass resources and the effect of landowners switching from field crops to energy crops and its effect on national commodity prices.

The scenarios analyzed differ in terms of co-firing requirement, i.e., 15% or 25%, biomass price, and switchgrass production cost. We pair the high switchgrass production cost with the low biomass price and vice versa to determine the upper and lower bounds of biomass supply. The results show that almost no agricultural land is dedicated to switchgrass under unfavorable biomass price and switchgrass production cost conditions. Under favorable conditions, switchgrass is grown in East Texas, Oklahoma and the Southeast of the United States. Because of high opportunity cost, in neither case is switchgrass planted in the Corn Belt. Across the scenarios, Eastern Ohio, Western Pennsylvania, and the tri-state area of Illinois, Indiana, and Kentucky face a shortage of biomass due to a high density of coal-fired power plants with high energy output. Sufficient biomass supply to serve co-firing power plants and a potential cellulosic ethanol industry is found in the northern part of Iowa, Southern Minnesota, and, depending on the biomass price, Nebraska, Kansas, and Oklahoma.

The effects on commodity prices of a low biomass price and high switchgrass production cost are moderate. The price increases ranges from 1.5% to 7.24% for corn and wheat, respectively. A larger price effect can be observed for a high biomass price and low switchgrass production cost leading to a price increases from 15.25% to 54.4% for corn and wheat, respectively.

The remainder of the paper is organized as follows: Section 2 introduces the data on coal-fired power plants and the biomass co-firing requirements. Section 3 presents the model of agricultural production and biomass supply at the county level. Section 4 reviews the transportation of biomass and the approach chosen to determine the demand schedule of biomass for each power plant. Section 5 describes the scenarios and the results whereas the last section concludes the paper.

2 Coal-fired Power Plants

The advantage of biomass co-firing in coal power plants to reduce greenhouse gas emissions is that there is no need to convert the cellulosic feedstock into an other form (e.g., ethnaol) (Aravindhakshan et al., 2010). We include power plants with coal (i.e, anthracite, bituminous, lignite, refined, sub-bituminous) as the primary source of energy according to the the 2010 Energy Information Administration 860 Annual Electric Generator Report. The co-firing requirement is imposed on electric utilities, independent power producers (IPP), and independent power producers with combined heat and power (IPP CHP). We excluded power plants from the Western Electricity Coordinating Council (WECC) of the North American Electric Reliability Corporation (NERC) regions because of limited agricultural area. In total, 398 coal power plants in the contiguous United States are included in our analysis. Basu et al. (2011) identifies three co-firing options: direct co-firing, indirect co-firing, and gasification co-firing. We assume that each those co-firing options can be used for all coal-fired power plants. Approximately 100 co-firing plants are situated in Europe, 40 in the United States, and some in Asia and Australia (Basu et al., 2011). Most of them use direct co-firing which involves pulverizing coal and biomass simultaneously before feeding it into the boiler. De and Assadi (2009) note that the investment cost are lowest when direct co-firing is used. In addition, they note that the co-firing capacity depends on the type of boiler. As opposed to coal, biomass produces residues after being burned which need to be removed and thus, add to the cost of co-firing. Because we are interested in the biomass market based on availability and power plant size, we assume that the investment decision and adjustments for co-firing have been made and do not affect the decision how much and from where to procure the biomass.

For each plant location, we determine the sum of the nameplate capacity of all the generators considered and assume that the heat input of the power plant remains unaffected by the co-firing option used (Basu et al., 2011). We assume a uniform boiler efficiency η of 88% and 8000 hours of yearly operation (De and Assadi, 2009). The average heat rate for the power plants and the location are obtained from the National Energy Technology Laboratory 2005 Coal Power Plant Database. The heat rate was not available for some power plants and thus, we assumed a value of 10,325 MJ/MWh. Based on this data, the following amount of biomass feedstock (b) in mega joule (GJ) is necessary:

$$b = \rho \times \frac{C}{0.88} \times 8000 \times \varphi \tag{1}$$

where ρ is the co-firing fraction, C represents the name plate capacity (GW) and φ expresses the heat rate in GJ per GWh.

3 Crop and Biomass Production

For each county, we assume a representative landowner who allocates agricultural land to field crops (corn, soybean, wheat) and switchgrass. In addition to the grain, corn stover and wheat straw can be harvested to serve together with switchgrass as a source for biomass co-firing and cellulosic ethanol. In our model, the land allocation and the resulting commodity prices are endogenous and depend on the exogenous price of biomass. Forest residues serve as a biomass source as well but the forest area is fixed and we rely on the county-level forest residue supply curves for 2015 modeled in Perlack and Stokes (2011). In what follows, we present the model and data for agricultural residue and switchgrass production.

3.1 Agricultural Residues

The commodity demand $Q_j = D(\mathbf{p}, e)$ for crop j is a function of the price vector $\mathbf{p}$ including the three crops and corn ethanol production (e). Food, feed, export, and biofuel sectors contribute to the total demand for each crop. With the exception for biofuel, each sector has a constant elasticity demand function of the form:

$$q_{jm} = \gamma_{ij} \prod_{j=1}^{J} p_j^{\theta_{jm}} \tag{2}$$

Table 1: Prices and price elasticities for food, feed, and export

	γ_{ij}	p_{CO}	p_{SB}	p_{WH}
Base price		\$180.70	\$419.25	\$220.46
Food Demand				
Corn	260.86	-0.389[1]	0.001[4]	0.003[4]
Soybeans	1105.17	-	-0.513[1]	-
Wheat	71.15	-	-	-0.137[1]
Feed Demand				
Corn	12575.49	-0.883[1]	-	-
Exports				
Corn	486.80	0.420[2]	-	
Soybeans	1276.81	-	-0.570[2]	-
Wheat	229.74	-	-	-0.380[2]

Notes: The elasticities for food and feed demand are calculated using the Linear Approximation Almost Ideal Demand System. Some elasticities were adjusted because the estimates from the LA/AIDS (1) were inconsistent with economic theory. The elasticities are corrected using the POLYSYS model (2), the Food and Agricultural Policy Research Institute (FARPI) model (3), and the Economic Research Service/Pennsylvania State trade model (4).

where q_{jm} is the demand for crop j from sector m, γ_{ij} is the constant, and θ_{jm} represents the price elasticity. The demand functions are calibrated to the 2015 projected quantities and prices in FAPRI (2012). The quantity of corn used for biofuel is fixed to 142.03 million metric tons in 2015 and is added to the total demand. The demand elasticities are represented in table 1.

To calibrate the model for 2015 in terms of crop area and yield, we obtain data from the United States Department of Agricultural National Agricultural Statistics Service (NASS) for yield and area harvested between 1975 and 2010 for the three field crops analyzed. Counties which did not harvest a particular crop during at least five years after 2000 were not included for that particular crop. The base area for each crop in each county was taken as the average area harvested between 2000 and 2010. To determine the yield in 2015, we fit a linear trend for each county and each crop on 1975-2010 yield data to determine the expected yield by crop and county in 2015. Based on the expected yield (y_{ij}) and the base area (a_{ij}), we can calculate the base crop production in each county. The area is adjusted to reflect total production to match the demand in FAPRI (2012). The constant as well as the prices are found in table 1.

Cost and return data are obtained from the USDA's Economic Research Service[1]. The total cost in our model is represented as $K_{ij}(a_{ij}) = \alpha_{ij}a_{ij} + (1/2)\beta_{ij}a_{ij}^2$ where $K_{ij}(a_{ij})$ represents the operating cost. Although we assume homogenous land quality throughout each county, the increasing marginal cost captures either the decrease of yields because marginal land with lower average yields is brought into production if cropland is expanded or the requirement of more fertilizer use for the same reason (Mallory et al., 2011). County specific cost data are not available and hence the direct estimation of the county specific parameters α_{ij} and β_{ij} is not possible. To obtain county specific parameters, we proceed in two steps. First, we obtain data from the USDA/ERS cost and return database on operating cost by crop and farm resource region between 2005 and 2010 and set the parameter α_{ij} equal to the total of operating cost but exclude fertilizer and chemical costs. Costs are deflated to 2008 prices using the Producer Price Index. We assume that all counties in a particular farm resource region have the same α_{ij}. The values are represented in table 2. Second, assuming profit maximizing but price taking behavior allows the calculation of the county specific parameters β_{ij} because the landowner sets marginal revenue equal to marginal cost, i.e., $p_j \cdot y_{ij} = \alpha_{ij} + \beta_{ij}a_{ij}$. Given p_j, y_{ij}, α_{ij}, and a_{ij} enables us to obtain β_{ij} for the base year.

[1] www.ers.usda.gov/Data/CostsAndReturns accessed January 15th, 2012

Table 2: Average operating cost in $ per hectare except fertilizer and chemicals

Region	Corn	Soybeans	Wheat
Basin and Range	299	205	138
Eastern Uplands	252	193	131
Fruitful Rim	299	205	255
Heartland	274	188	131
Mississippi Portal	299	264	131
Northern Crescent	304	207	163
Northern Great Plains	297	195	109
Prairie Gateway	423	252	133
Southern Seaboard	277	178	131

3.2 Crop Residues and Energy Crops

Perlack and Stokes (2011) provide a sustainable retention coefficient for corn stover and wheat straw which we apply to our yield parameters y_{ij}. Not all crop residue can be removed because certain levels of soil nutrients and soil carbon needs to be maintained in addition to controlling soil erosion (Perlack and Stokes, 2011). The residue to grain ratio on a dry basis is 1:1 and 1:1.5 for corn stover and wheat straw, respectively. In addition, the removal of crop residue requires the switch to reduced tillage or no-tillage. Because of uncertainty surrounding the effects of reduced or no-till on yield, we assume that the crop yield remains unchanged when switching to reduced tillage. The cost of producing corn stover and wheat straw includes the replacement of nutrients, harvesting, storing, and bailing (Huang et al., 2009; Khanna et al., 2011a). The average nutrient replacement for corn stover and wheat straw is $26/t and $25/t, respectively (Perlack and Stokes, 2011). The collection and harvesting cost for both crop residues is based on Perlack and Stokes (2011). Because the authors report only three yield-cost combinations, we fit a simple regression through those points which results in a cost function of the form $C(y_{ij}) = 21.036 - 7.648 \cdot \ln(y_{ij})$. Huang et al. (2009) estimates the storage cost at $8/t.

Switchgrass (*Panicum virgatum*) yield data was obtained from Jager et al. (2010) who provide the maximum of lowland and upland yield which was also used in the billion-ton study update (Perlack and Stokes, 2011). The cost of producing switchgrass is taken from Jain et al. (2010) who calculates the cost ranging from $39 to $90 per dryton for eight Midwestern states[2]. We are using the operating cost reported by Jain et al. (2010) because the opportunity cost are endogenous to our model as opposed to exogenous (Huang et al., 2009; Jain et al., 2010; Aravindhakshan et al., 2010). For states that were not included in Jain et al. (2010), we use the production cost reported by Aravindhakshan et al. (2010) which results in operating cost of $38.13 per ton. For our analysis, we assume an upper and lower bound of +/- 20% on this costs which results in $30 and $46 for the low and high cost scenarios, respectively. We also include annualized establishment cost of $43.9 per year which where obtained from Aravindhakshan et al. (2010) but by excluding the land rental cost which are endogenous to our model.

3.3 Farmer's Profit Maximization Problem

The six decision variables of the landowner in our model are the area of corn, soybeans, wheat, corn stover, wheat straw, and switchgrass. Note that corn stover and wheat straw refers to the area of corn and wheat harvested for crop residues. The profit for field crops of landowner i is written as follows:

$$B_i^f(a) = \sum_j p_j \left(a_{ij}^f + a_{ij}^b\right) y_{ij} + \alpha_{ij} \left(a_{ij}^f + a_{ij}^b\right) + \frac{1}{2}\beta_{ij} \left(a_{ij}^f + a_{ij}^b\right)^2 \quad (3)$$

[2]Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin

Table 3: Summary of key scenario parameters

Scenario	RPS	p_{bm}	Switchgrass Cost
RPS 15: Low Incentive	15%	\$3	High
RPS 15: High Incentive	15%	\$4	Low
RPS 25: Low Incentive	25%	\$3	High
RPS 25: High Incentive	25%	\$4	Low

where $B_i^f(a)$ represents the profit, a_{ij}^f and a_{ij}^b represent the area of crop j not harvested for biomass (f) and harvested for biomass (b). The profit from biomass crops is written as:

$$B^b(a) = p_{bm} \sum \delta_{ij} y_{ij} a_{ij}^b - \eta_{ij} a_{ij}^b \tag{4}$$

where δ_{ij} summarizes the country specific retention coefficients and differences in energy content of the different biomass sources. The parameter η represents the per hectare cost based on the yield in dry tons of the three biomass resources. The landowner in county i maximizes $\pi(a) = B_i^f(a) + B^b(a)$ given crop and biomass prices subject to the land constraint. Total land available is assumed to be the sum of the base area per county. Derivation of the first order conditions is straightforward.

Agriculture is a perfectly competitive market and hence, all agents are price takers and do not take the effect of their acreage decision on output prices into account. In aggregate however, the net revenue in each county is endogenous to the model. Given the biomass price p_{bm}, our model solves for the commodity prices to clear the market for crop supply and demand. Due to differences in the energy content of corn stover, wheat straw, and switchgrass, we express the biomass price in dollars per gigajoule (GJ). The heating values in GJ/t are 17.45, 17.63, and 18.51 for corn stover, wheat straw, and switchgrass respectively. For forest residues, we assume a uniform heating value of 20 GJ per metric ton.

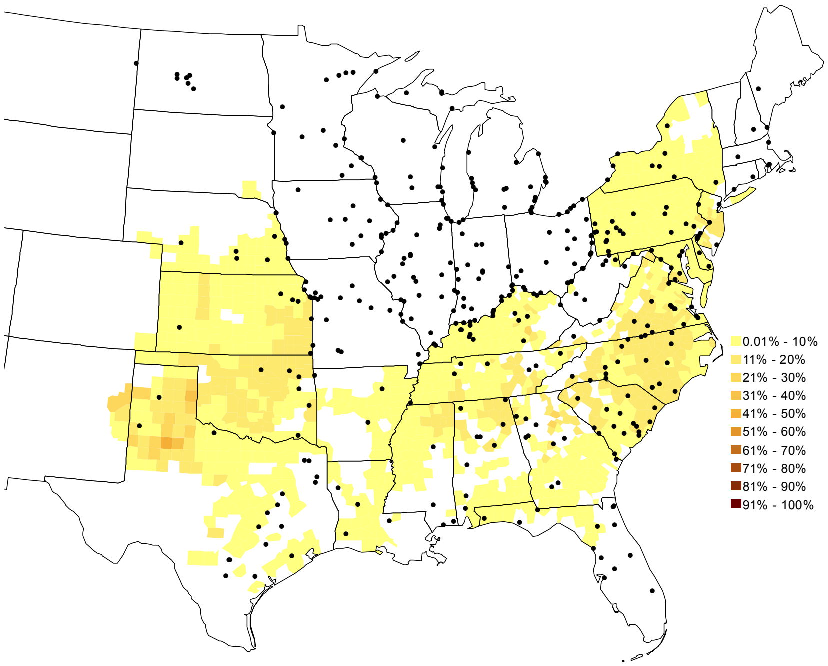
4 Feedstock Delivery

Feedstock delivery involves the transportation cost and the choice of the power plant from which county to buy the feedstock. We assume that all the biomass is available at the centroid of the county (Egbendewe-Mondzozo et al., 2011) and the transportation distance is between the centroid and the power plant. The average transportation cost of corn stover, forest residues, and switchgrass were estimated between \$0.11 and \$0.12 per dry ton per kilometer (Huang et al., 2009). Because the assumption of a direct line between the power plant and the counties centroid is likely to underestimate the transportation cost, we assume the upper cost value of \$0.12 dry t^{-1} km^{-1}.

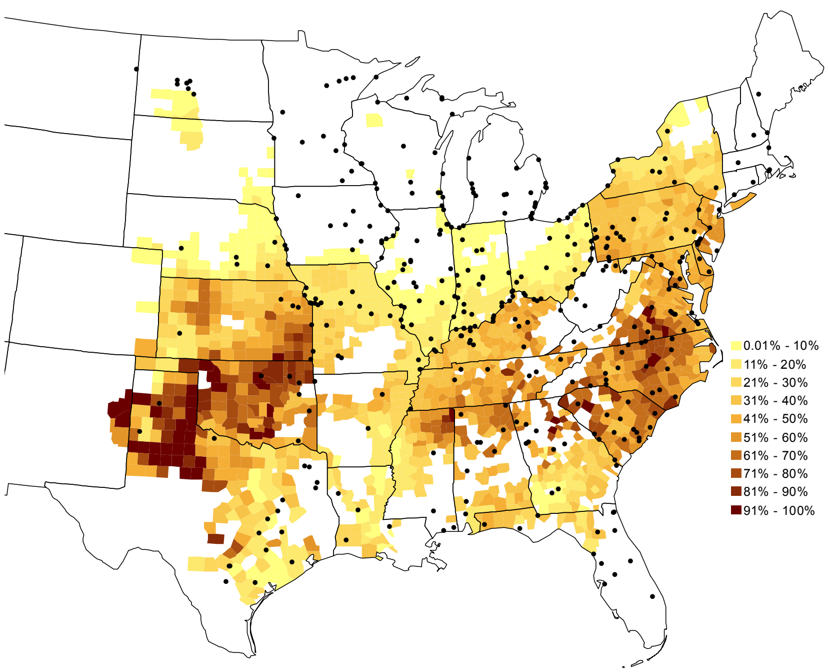
To calculate the per county demand coming from the power plants, we use the approach developed by Noon et al. (2002). Given the transportation cost, the biomass price from each county, and the biomass supply from each county, the power plant can construct a supply curve ranking the counties from lowest to highest price. The cost associated with the most expensive county supplying to the power plant is the marginal cost of biomass. This assumption implies that county closest to a power plant delivers all the biomass available to that power plant.

5 Results

We simulate four scenario as follows: First, we set an exogenous price of biomass p_{bm} and simulate agricultural production in terms of corn, soybean, wheat, corn stover, wheat straw, and switchgrass. Based on the quantity supplied, the biomass price, and the co-firing requirement, each power plant chooses the quantity demanded from each county (Noon et al., 2002). The approach by Noon et al. (2002) implicitly assumes that each power plants is the sole consumer of biomass in a particular county. If we aggregate the demand from each power plant, areas of biomass supply shortages will become evident. The co-firing standards are set to

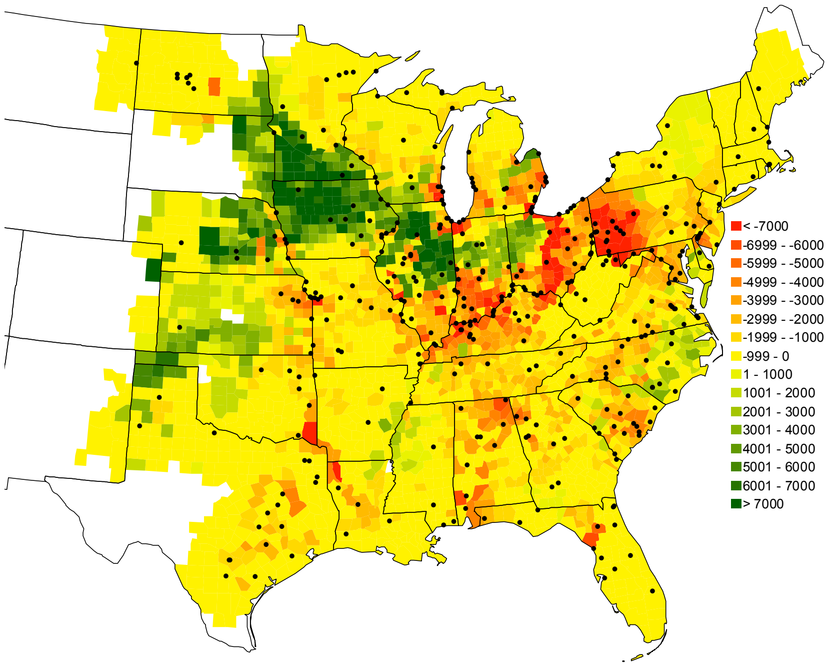


(a) Low Incentive

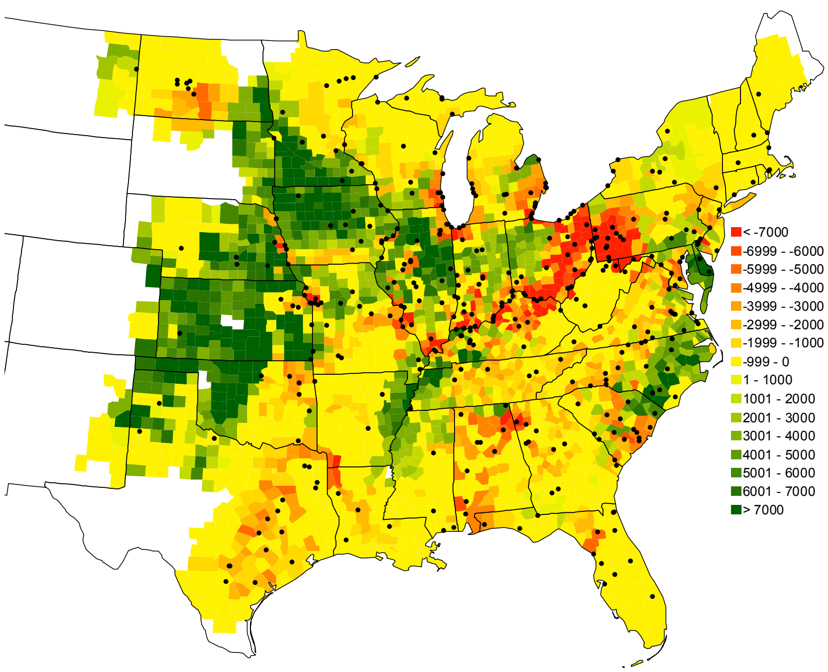


(b) High Incentive

Figure 2: Fraction of agricultural land dedicated to switchgrass. (Panel (a): Low Incentive, Panel (b) High Incentive)

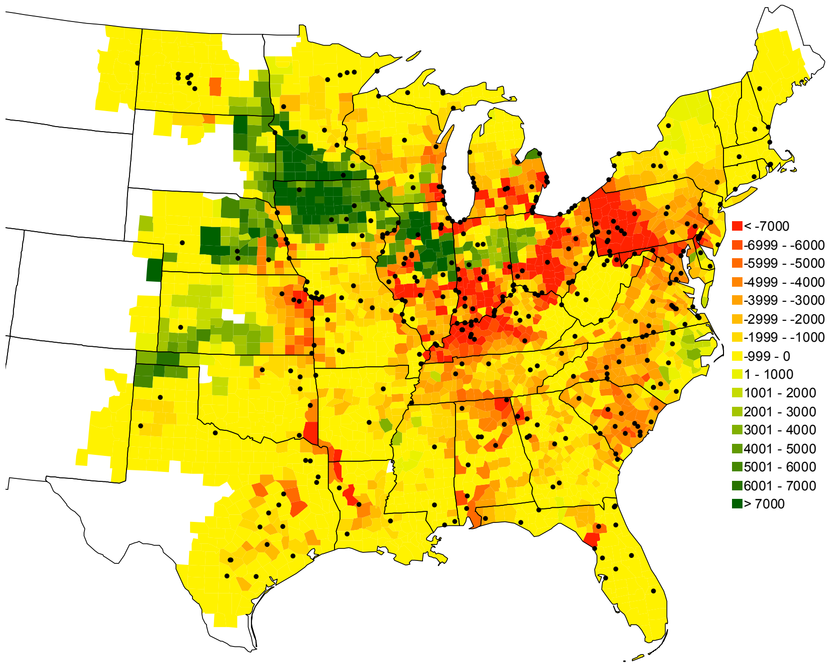


(a) Low Incentive

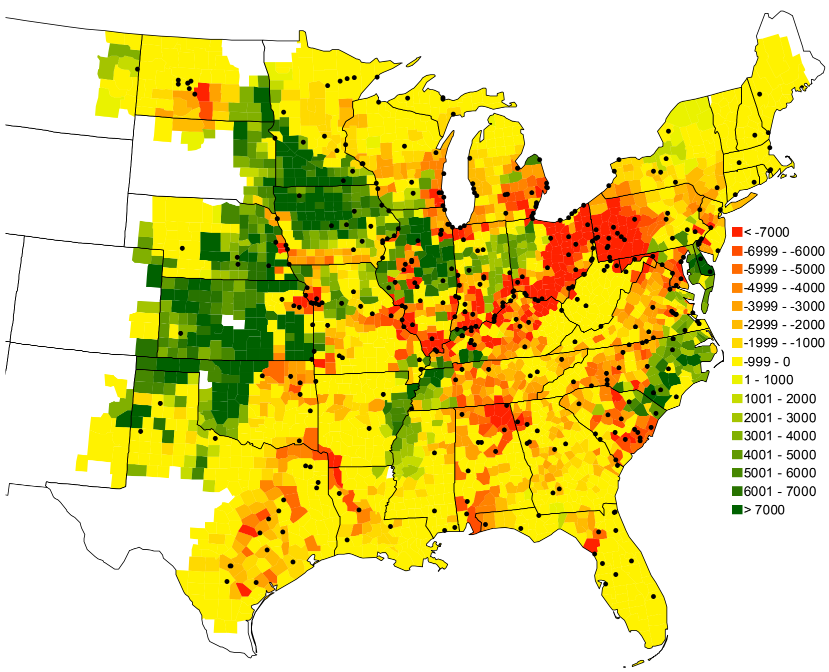


(b) High Incentive

Figure 3: Insert Figure 3: Co-Firing 15%: Excess Supply in GJ per County (Panel (a): Low Incentive, Panel (b) High Incentive)



(a) Low Incentive



(b) High Incentive

Figure 4: Insert Figure 4: Co-Firing 25%: Excess Supply in GJ per County (Panel (a): Low Incentive, Panel (b) High Incentive

Table 4: Commodity price effects (in $ per hectare) and increases for different biomass prices.

Scenario	Corn	Soybeans	Wheat	Corn	Soybeans	Wheat
$p_{bm} = 0$	180.70	419.25	220.46			
Low incentive	183.42	434.12	236.42	1.50%	3.55%	7.24%
High incentive	208.25	529.73	340.39	15.25%	26.35%	54.40%

15% and 25% which are consistent with assessments conducted by the Energy Information Administration (EIA, 2007b,a). Although a co-firing requirement of 25% might require more modifications to the boiler infrastructure. Previous literature has shown that there is almost no biomass supply for prices below $2.5 Khanna et al. (2011a,b) and thus we decided to pick $3 and $4 as reference prices. For all scenarios, we assume a switch to reduced tillage if corn stover and wheat straw are harvested. Because we are interested in the upper and lower bounds of the biomass supply and demand at the county level, we run a high and a low incentive scenario with regard to biomass price and switchgrass cost of production for the tow co-firing requirements. The "Low Incentive" scenario assumes a biomass price of $3 with high switchgrass production cost whereas the "High Incentive" assumes a biomass price of $4 with low switchgrass production costs. Key parameters for the four scenarios are summarized in table 3. There will be a positive correlation between the biomass price and the co-firing requirement in realty and thus, the price and co-firing combinations of the scenarios "RPS 15: Low Incentive" and "RPS 25: High Incentive" are more likely.

Because we assume a uniform biomass price to which not only the electricity industry is subject to but also the cellulosic biofuel industry, the share of switchgrass grown in a county as a fraction of agricultural land is independent of the RPS imposed. Figure 2 represents the area of switchgrass as a fraction of total agricultural land per county. At a biomass price of $3 and high switchgrass production cost, very little switchgrass is grown. No switchgrass is planted in the Corn Belt and and only a small fraction of cropland is dedicated to switchgrass in the Carolinas, West Texas, and Oklahoma. If the price of biomass is increased to $4 and production cost are low, switchgrass is planted in the southern part of the Corn Belt, i.e., Southern Illinois, Indiana, and southeast Ohio, in addition to the areas mentioned for the low incentives.

A co-firing requirement set to 15% together with a low biomass price of $3 and high switchgrass production cost, only counties in Iowa, Central Illinois, Central Kansas, and Central Nebraska, and northern Minnesota produce sufficient biomass relative to the demand from power plants. As aforementioned, almost all the biomass supply comes from corn stover and crop residues in this scenario. Under the more favorable price-cost scenario for landowners, Eastern Kansas, Western Oklahoma, the Carolinas, and the Mississippi Portal expand their supply of biomass sufficiently to cover the demand of local power plants. Similar results are obtained under the 25% co-firing requirement with shortages increasing in the tristate area of Illinois, Indiana, and Kentucky. County level results are summarized in figures 3 and 4.

Figure 5 summarizes the supply and demand for selected states. Only Iowa, Minnesota, Nebraska, North Dakota, and South Dakota provide sufficient biomass resources in aggregate in all scenarios. Those states are characterized by a small number of power plants and sufficient crop residue resources. Note that Kansas has a small overall shortage only in the case of low biomass price and a 25% co-firing requirement.

6 Conclusion

The Renewable Fuel Standard mandates an increase in the blending of cellulosic ethanol with gasoline over the next decade. At the same time, federal policy proposals and state renewable portfolio standards have been launched which could rival yet to be build cellulosic ethanol plants. This paper analysis the effects of

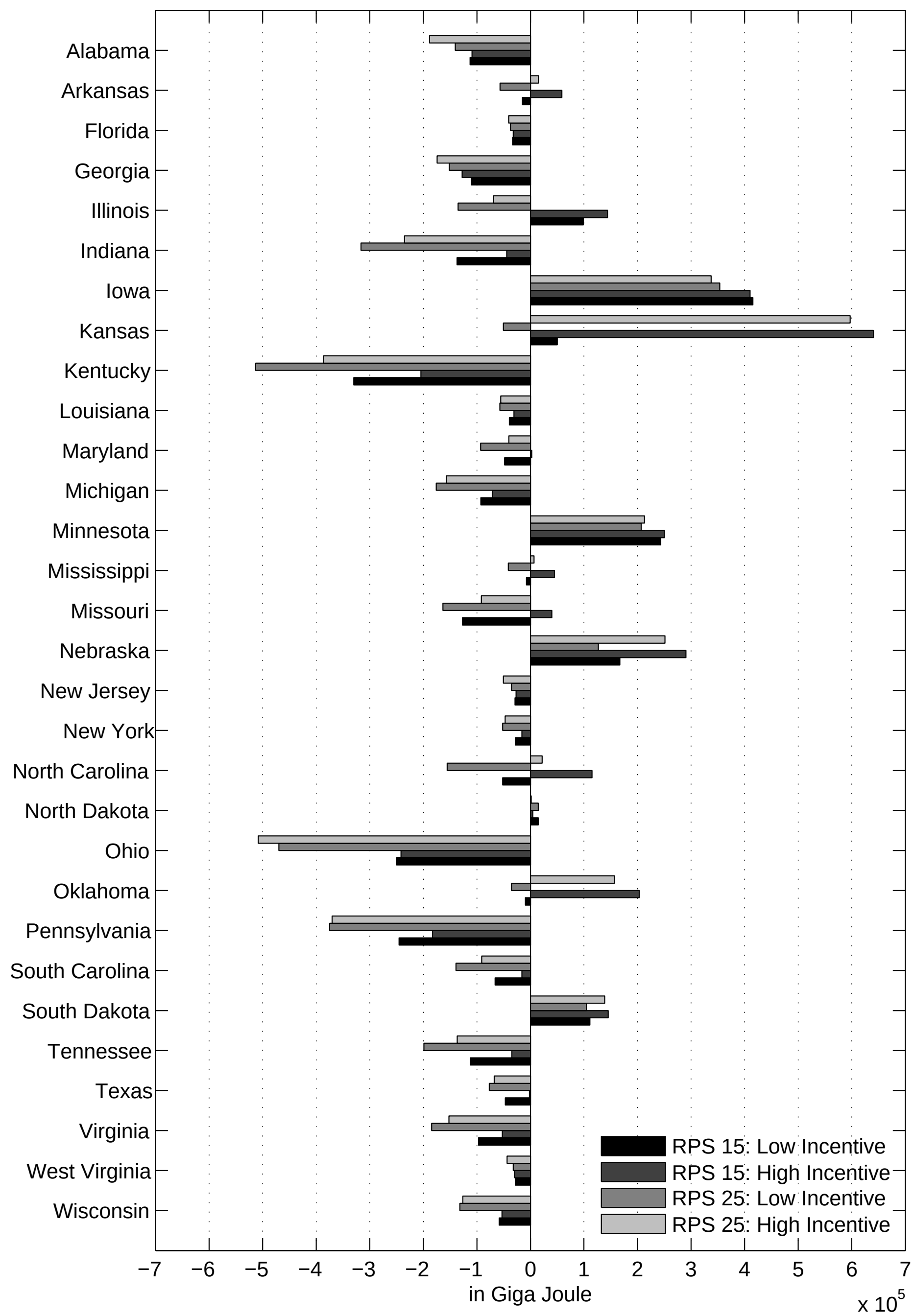


Figure 5: Excess supply of biomass in GJ by state.

biomass co-firing in existing coal-fired power plants on the market for cellulosic feedstock at the county level.

We use location and energy output of 398 power plants in the Western United States and impose a 15% and 25% co-firing requirement under various biomass prices. Based on the biomass price, individual landowners allocate land among three field crops and switchgrass. They also decide how much corn stover and switchgrass to harvest under the biomass prices. Based on their supply curve, which incorporates endogenous commodity prices, the power plants decide how much and from which landowner to purchase the feedstock. We find that states which have a high corn and wheat production, and thus have a high potential to collect the associated crop residue, are able to support cellulosic ethanol production facilities as well. Those states have also a low density of coal-fired power plants with low energy output. The exception is Illinois with large facilities in the Southern part of the state. Significant biomass shortages occur in the Eastern part of Ohio and Western Pennsylvania.

Although the scenarios analyzed in this article are hypothetical, two implications arise. First, in the case of RPS and RFS requirements, not all areas remain attractive for new cellulosic ethanol plants which would be suitable without co-firing power plants. Second, the use of perennial grasses such as switchgrass remains unlikely even at a biomass price of $4/GJ or $74/ton.

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