Energy Economics 34 (2012) 1790–1798

Contents lists available at SciVerse ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

# Internal, external and location factors influencing cofiring of biomass with coal in the U.S. northern region

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ARTICLE INFO

*Article history:*
Received 5 March 2012
Accepted 4 July 2012
Available online 14 July 2012

*JEL classifications:*
L94
Q40
Q42

*Keywords:*
Cofiring
Biomass
Logit model
Infrastructure

ABSTRACT

The use of biomass as a source of energy has been identified as a viable option to diminish reliance on fossil fuels. We parameterized the effect of selected internal (e.g. coal-fire presence), external (e.g. price and renewable energy mandates) and location (e.g. biomass availability, infrastructure) variables on the likelihood of using biomass in cofiring with coal by building a two-stage econometric model. The first stage controlled for factors driving the spatial location of coal power plants and the second stage concentrated on factors influencing cofiring. The empirical model was applied in the Northeast quadrant of the U.S. where the unit of observation was an individual county. Results of our model stress the significant effect of existing flexible coal feeding systems that permit the incorporation of biomass, transportation infrastructure and biomass availability (woody biomass in particular in the form of residues from the wood products industry). State-level renewable energy portfolio standards showed no statistically significant effect on the adoption of cofiring biomass with coal. Further developments of biomass cofiring in the U.S. northern region are most likely to take place in the Great Lakes region.



## 1. Introduction

The heavy reliance of the U.S. energy sector on non-renewable fossil fuels has motivated great interest in the utilization of renewable energy feedstocks. The combustion of fossil fuels provided about 84% of total energy and about 69% of electricity consumed in the U.S. in 2008 (Energy Information Administration, 2010). Approximately one billion metric tons of coal was used in the U.S. for electricity and heat generation the same year (EIA, 2010). Coal has steadily provided about 51% of electricity annually consumed in the U.S. since the early 1990s (Sami et al., 2001). Geographically, the U.S. Department of Energy (DOE) reports that the majority (342) of the coal-fired power plants in the U.S. (640) are located in the DOE's North Central and Northeast regions (U.S. Department of Energy, 2010).

Bioenergy (i.e. energy generated from biomass), nonetheless, is an important component of the U.S. renewable energy portfolio. Energy generated from a variety of biomass sources represented about 3% of total energy consumption including electricity, heat and liquid transportation fuels in 2008 and exceeded 4% for the first time in 2009 (U.S. Department of Energy, 2011). Although energy output from biomass is much smaller than petroleum, natural gas, and coal it is still greater than hydroelectric and other renewable sources (EIA, 2010). Among different biomass feedstocks, woody biomass supplied the greatest share of renewable energy at approximately 53% in 2008 (EIA, 2010). According to the U.S. Department of Energy (2011) woody biomass for energy consumption was estimated to occur primarily within the forest products industry (68%), for electric power generation (9%), and in the residential (20%) and commercial (3%) sectors. A relatively small fraction (less than 10%) has been used to make biofuels — although requirements under the Energy Independence and Security Act of 2007 command U.S. national biofuel use to raise to 36 billion gallons a year by 2022, with 21 billion coming from advanced biofuels (Public Law 110–140, 2007). Woody biomass currently originates primarily from two sources: (1) residues generated in the manufacture of forest products and (2) fuelwood used in the residential and commercial sectors. Residues from the forest products manufacturing sector include primary and secondary mill residues generated in the processing of roundwood, roundwood products, and pulping liquors. Fuelwood is wood harvested from forests and combusted directly for useable heat in the residential and commercial sectors, as well as power in the electric utility sector (U.S. Department of Energy, 2011). Aguilar et al. (2011) investigated factors behind wood energy consumption in these energy sectors and suggested that level of consumption in the forest industry is primarily a function of wood product output (with limited influence from energy markets or regulations), consumption in the residential sector is mainly affected by prices of alternative energies (e.g. electricity and natural gas), while the electricity sector is the one that has experienced the greatest change in output in recent years primarily driven by various federal tax incentives such as the Public Utility

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doi:10.1016/j.eneco.2012.07.005

Regulatory Policies Act, a component of the National Energy Act of 1978 (Public Law 95–617, 1978).

Various technological platforms can be used for converting biomass to usable energy. These include: (1) direct firing or cofiring biomass for electricity, heating and cooling, (2) production of liquid biofuels, and (3) gasification of biomass (Gil et al., 1999; Pimentel and Patzek, 2005). Cofiring refers to the practice of introducing biofuels as a supplementary energy source in high efficiency utility boilers (Demirbas, 2003; Tillman, 2000). There are currently 86 coal-fired power plants in the U.S. that utilize some quantity of biomass (EIA, 2010; U.S. Department of Energy, 2010). Compared to alternatives such as liquid biofuels or gasification, cofiring biomass with coal is a popular option because many coal-fired electric plants can incorporate biomass into the existing fuel storage and handling systems with relatively minor modifications (Aguilar and Garrett, 2009; Baxter, 2005; Hansson et al., 2009; Sami et al., 2001). Among biomass feedstocks, woody biomass is a less problematic feedstock to use with regard to factors such as chlorine emissions and silica contamination in coal-fired boilers than many herbaceous feedstocks such as switchgrass (Demirbas, 2004). Moreover, woody biomass contains virtually no sulfur, hence, sulfur dioxide emissions are reduced in direct proportion to coal replaced, minimizing soil and water pollution (De and Assadi, 2009; Demirbas, 2003). Ash content of woody biomass is much lower than that of coal, while ash content of non-woody biomass fuels varies widely (Sami et al., 2001).

In this study we evaluated the effect of selected industry internal, external and location-specific factors influencing the regional adoption cofiring of biomass and coal. There were several reasons for investigating this particular segment of the renewable energy sector. First, biomass is the main source of renewable energy in the U.S. and an important share is produced by the electric generation sector. Second, cofiring is already occurring in the market with success, yet little has been reported in the literature about factors driving this process at a regional scale. Third, biomass use in the renewable energy sector is one that has been reported to be influenced by regulatory approaches and not solely on alternative energy prices or output from other industries (Aguilar et al., 2011). Fourth, there is available geographically-referenced data that can be analyzed to identify salient factors affecting the likelihood of cofiring.

The remainder of the paper is structured in the following fashion. The subsequent section outlines the theoretical framework that guided model development and analysis. It is followed by a description of the empirical model applied to the northern quadrant of the U.S. and the corresponding variables used as proxies for the analysis of cofiring factors. We discuss the implications of our findings outlining the potential for additional cofiring in the region and the impact of explanatory variables in the model. We conclude with the identification of counties in the northern region that appear to have relatively high potential for cofiring and list future research steps.

## 2. Theoretical framework

Our study of location and adoption of cofiring is rooted in industrial Classical Location Theory and Regional Science. The study of factors influencing industry cofiring adoption must include location variables as this is a sector heavily dependent on the physical availability of energy sources (e.g. coal and biomass), affected by other input costs, and limited by the technical capacity to incorporate biomass in to coal feeding systems. Weber (1929) argued that there are four major factors driving industry location: (1) fixed capital costs, (2) costs of securing materials, power, and fuel, (3) costs of labor, and (4) costs of transportation. Rawstron (1958) suggested three principles governing industrial location. The first principle, physical restriction, refers to the fact that choice of location is restricted when a natural resource is the main production input, and hence, production is limited to the availability of such resource. The second principle, economic restriction, stresses the effect on the choice of sites when the cost of one of the inputs to the manufacturing process varies widely from place to place. Rawstron's third principle is related to technical restrictions and technological change. Industries that tend to undergo dramatic changes in technology that require establishing new factories will in fact consider location factors more carefully.

The study of industry location may be conducted at different levels. Helburn (1943) suggested the distinction between three different levels of "location": industry orientation, location per se, and site. The first level, industry orientation, refers to the regional placement with reference to a source of raw materials (e.g. the wood product lumber sector is concentrated around areas rich in forest resources). The second level refers to the location within a particular region because of existing favorable conditions over other similar regions. Finally, site level makes reference to the specific sitting of a plant, like a particular town. In this analysis we were mostly interested in drivers behind cofiring location rather than industry orientation or a plant cofiring at a particular site. Therefore, we investigated cofiring at the regional level, with observations gathered at the county level, as findings at other scales would either be too general (as in industry orientation) or too specific (factors particular to a single site) with limited practical implications.

Regional Science, more recent to Classical Location Industry Theory, also aims to shed light on industry location factors. Lloyd and Dicken (1992), Van Dijk and Pellenbarg (2000), and Brouwer et al. (2004) among other regional scientists, suggest that the geographic location and movement of firms are functions of internal, external and location-specific factors. Internal factors include firm specific conditions such as a particular production technology, management, ownership structure, growth rate of turnover, employment and profits. External factors include government policy and regulations, regional economic structure, technological progress. Renner (1947) also mentions ancillary factors such as adverse or favorable laws, taxation policies, climatic conditions, labor and environmental policies. Location-specific factors refer to absolute and relative characteristics of the location such as access to input materials, distance to customers and suppliers, and the presence of support services (Nicholls et al., 2006).

As a fundamental internal factor, cofiring of biomass in a coal power plant is first contingent on the physical presence of a coal-fired power plant (and subsequently, on factors driving coal firing location) and second on external and location factors encouraging or limiting cofiring such as renewable energy mandates or the physical availability of biomass materials. Therefore, in a general form, the probability of cofiring ($y$) at the $i$th location is conditional on the expected probability of a coal power plant sited within the $i$th location ($\mathrm{E}[c_i]$) given a vector of variables affecting coal-firing ($c$) and internal, external and location-specific location factors influencing cofiring captured in information matrix $X$ (that also includes an intercept). This relationship can be expressed as:

$$\mathrm{Prob}(y_i = 1|\mathrm{E}[c_i], X) = F(\mathrm{E}[c_i] + X_i\beta), \text{ and} \tag{1}$$

$$\mathrm{Prob}(c_i = 1|L) = G(L_i\alpha) \tag{2}$$

where $L$ is an information matrix (including an intercept) capturing factors relevant to coal power industry location and $\alpha$ and $\beta$ are vectors of parameters corresponding to coal power plant location factors and cofiring adoption, respectively. Probability distributions $F$ and $G$ both have a non-linear distribution taking values of 1 and 0 (1 = presence, 0 = absence). The expected probability of a location hosting a coal power plant is given by Eq. (2). Hence, the probability of cofiring can be estimated following:

$$\mathrm{Prob}(y_i = 1|X, L) = (e^{X\beta + \gamma \mathrm{E}[c_i|L]})(1 + e^{X\beta + \gamma \mathrm{E}[c_i|L]})^{-1}, \tag{3}$$

where $\gamma$ is a parameter for the expected probability of the presence of coal power plant at the $i$th location.

However, an alternative approach to study cofiring may not be contingent on the expected probability of a coal-fired plant location but on its observed presence or absence. Under this approach, the probability of cofiring is a function of information matrix $X$ as previously defined and an information vector $m$ regarding the presence (or absence) of a coal-fired plant, hence:

$$\text{Prob}(y_i = 1|m, X) = F(m\psi + X_i\beta), \quad (4)$$

where ψ is the coefficient capturing the effects of $m$ on $y$. This latter approach does not control for factors behind coal-fired plant location prior to estimating explanatory variable effects on cofiring but estimates them all in a single stage. This approach highlights the fact that co-firing may not be conditional on an existing coal-fired power plant (i.e. a new plant may be sited in a county that will use both biomass and coal, instead of the assumption that only existing coal-fueled power plants can use biomass to generate electricity).

## 3. Empirical analysis of cofiring in the U.S. northern region

### 3.1. Study area

The incidence of cofiring of biomass and coal was empirically tested using a model applied to the U.S. northern quadrant as defined by Smith et al. (2009), henceforth referred to as the U.S. northern region (Fig. 1). This region is composed of the 20 following states: Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, West Virginia, and Wisconsin. The U.S. northern region has states located in five of the electricity supply sub-regions as defined by the EIA U.S. Energy Information Administration (2010) including West North Central, East North Central, Middle Atlantic, New England, and South Atlantic. This region was selected for three main reasons. First, biomass was identified as a major potential source of renewable energy in the region (Aguilar and Garrett, 2009; U.S. Department of Energy, 2011). Second, this region hosts a large concentration of coal power plants (U.S. Department of Energy, 2010). Out of the 1037 counties in the northern region, 246 currently have at least one coal-fired power plant. Additionally, 42 of the counties containing coal-fired power plants have at least one plant which uses some quantity of biomass. Third, 19 of the 20 states in the region had adopted renewable portfolio standards (RPSs) by 2010 (DSIRE, 2011). RPSs specify the percentage of total energy or electricity generation that must come from renewable energy sources such as wind, geothermal, and solar as well as biomass (Bird and Lokey, 2008).

### 3.2. Empirical model for coal-fired power plant location and cofiring adoption

Table 1 describes the selected factors influencing both coal-fired power plant location and cofiring adoption. Notice that industry internal factors were only included as factors behind cofiring adoption since these can only be present once a coal power plant has been established (i.e. no coal plant-internal factors influencing cofiring can exist if there is no coal-fired plant in the first place). For instance, external factors are dominated by market electricity demand indicators and the adoption of RPSs. Location-specific factors encompassed a variety of descriptors that included land value, transportation infrastructure, energy feedstock resource availability and variables capturing sub-region specific conditions. In addition to these variables that were common to both coal fire location and cofiring adoption, resource availability of biomass was used as a location-specific driver for cofiring.

Table 2 provides details for the explanatory variables used as proxies for drivers of coal-fired power plant location and cofiring adoption. It is important to stress that the analysis for the regional econometric model was conducted at the county-level. It was determined that the county-level was the smallest practical observational

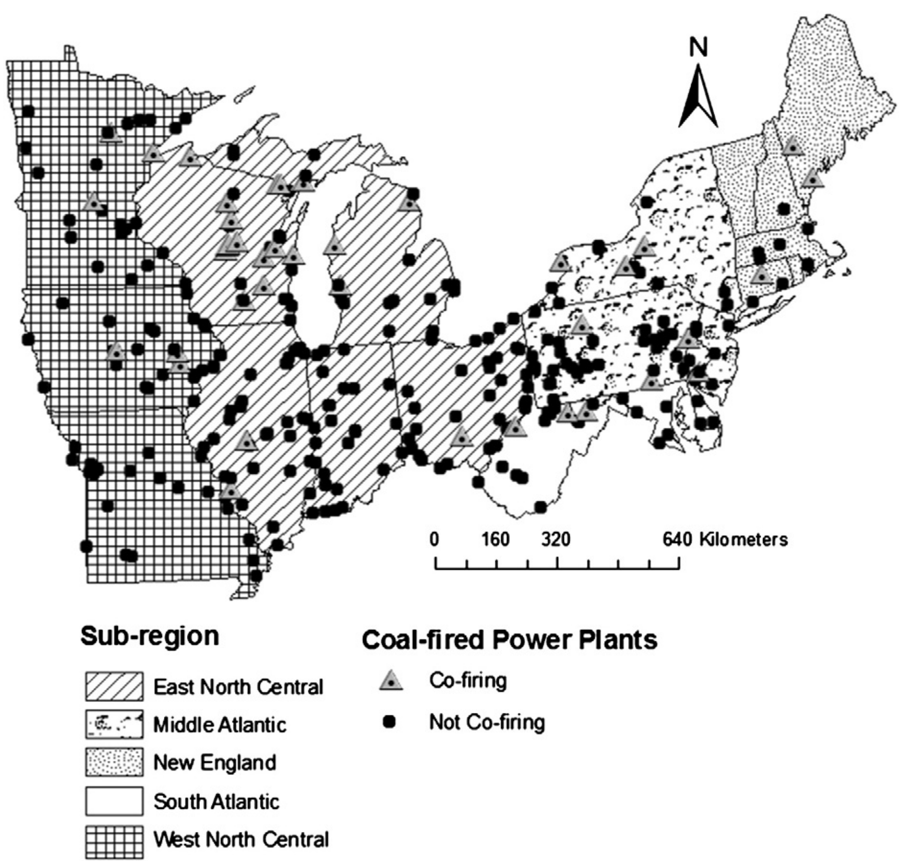


**Fig. 1.** U.S. northern region with electric sub-regional boundaries showing locations of coal-fired power plants as well as locations where cofiring with biomass already occurs. Sources: DOE (2010) and EIA (2010).

**Table 1**
Factors influencing location of coal plants and probability of adopting cofiring.

| Factors | Coal-firing location | Cofiring of biomass and coal |
|---|---|---|
| Internal | Not applicable[a] | Observed presence/estimated probability of coal-fired power plants<br>Technical cofiring feasibility |
| External | Electricity demand indicators<br>Coal price | Electricity demand indicators<br>Coal price<br>Adoption of RPS |
| Location-specific | Land value<br>Transportation infrastructure<br>Energy feedstock (coal) availability and price<br>Sub-region-level conditions | Land value<br>Transportation infrastructure<br>Resource availability of biomass<br>Wood mill operations<br>Sub-region-level conditions. |

[a] As a causality effect, internal factors were only included as factors behind cofiring adoption. Coal power plant internal factors (e.g. technology) may deter its capacity to adopt cofiring. There is no such causal effect in coal-based electricity production as the technology used in coal power plants is suited to coal utilization by design and the placement of coal power plants is primarily dependent upon external and location-specific factors.

unit in which many of the specific factors such as land value, transportation infrastructure, and resource availability of biomass could be estimated for the region. Another reason was that information is often aggregated at this level to keep some level of anonymity in the data, in particular to agricultural and timber production. Also, biomass produced in another county will often not be considered readily available for a particular power plant as the costs of long-distance transport can severely reduce the economic feasibility of cofiring (Goerndt et al., 2012; Nicholls et al., 2006). One limitation of this approach is that it may not be able to account for fine-scale variation at the city- or municipal-level.

Aside from current county-level presence or estimated probability of coal-fired power plants, the technical feasibility of cofiring per county was also controlled for. The proxy for cofiring technical feasibility was assessed by determining the boiler types used by all coal-fired power plants in the region (DOE, 2010). Stoker, cyclone, and fluidized bed boilers were deemed to be the most adaptable to cofiring due to their ability to burn fuels that are coarser than pulverized coal and fuels with higher moisture content (Baxter, 2005; Sami et al., 2001). Although cofiring is possible in pulverized coal boilers, there can be strict limitations regarding the type of biomass and quantity that can be used due to pre-existing fuel preparation and injection apparatus (Savolainen, 2003). The proxy for technical feasibility was then calculated as a dichotomous variable with a value of "1" if a county contained at least one plant using stoker, cyclone, or fluidized bed boilers and "0" otherwise.

Two external factors for placement of coal-fired plants and adoption of cofiring were proximity to electricity demand and renewable energy mandates (Hansson et al., 2009; Nicholls et al., 2006). County area and percentage of urbanized county area were included as proxies for electricity demand because of their relationship to urban population density within individual counties (Kahn, 2009; Muller and Mendelsohn, 2007). As of the year 2000, urban population comprised over 79% of the total U.S. population and is the greatest contributor to residential electricity consumption (U.S. Census Bureau, 2009). Percentage of urbanized county area was an important proxy to include in our model because it accounted not only for urban population density but also the amount of land taken up by urban development per county. Land availability can have a significant effect on biomass supply and productivity (Milesi et al., 2003). Adoption of RPSs was used as a proxy to capture the effects of state-level renewable energy mandates. States that have adopted a RPS by 2001 were identified with a '1' (and '0' otherwise) to capture the causality drawn between an earlier mandate and the subsequent adoption of cofiring, which was based upon data compiled in 2005 (DOE, 2010). This approach better accounted for the time lag from RPS adoption to actual increased renewable energy production.

Location factors included proxies for land values, transportation infrastructure, energy feedstock availability and sub-region specific variables. Land value was included as a location factor to represent the price of land that would be purchased by both an industry (coal-fired power plant) and suppliers of woody-biomass for cofiring (e.g. wood using mills, private landowners) to accommodate a plant as well as storage and feedstock handling area. Median house value was used as the proxy for relative land values by county (Aguilar, 2009). Coal availability and price were used as indicators of primary energy costs. Presence of principal highways, railways, and navigable waters by county were included as proxies for infrastructure based on the fact that coal-fired power plants require major transport routes

**Table 2**
Factor, proxies, description, units and source of information for the study of coal-fired power industry location and cofiring adoption for electrical generation in the U.S. northern region.

| Factors | Proxy | Description | Units | Source |
|---|---|---|---|---|
| Internal | Power plant presence | Number of coal-fired power plants per county | Count (know number of coal-fired power plants) | U.S. Department of Energy, 2005 |
| | Technical feasibility | Boiler type indicator | Binary (1 = desirable boiler type present, 0 = otherwise) | U.S. Department of Energy, 2005 |
| External | Electricity demand indicators | Average electricity price in (state) | US cents per kilowatt-hour | U.S. Energy Information Administration, 2008 |
| | | County area | 100 $km^2$ | U.S. Census Bureau, 1996 |
| | | Percentage county area urbanized | | U.S. Census Bureau, 2000 |
| | Implementation of RPS | RPS adopted by 2001 (state) | Binary | Database of State Incentives for Renewables and Efficiency |
| | Land value | Median house value (state) | Thousands US$ | U.S. Census Bureau, 2000 |
| Location-specific | Transportation infrastructure | Presence of principle highways (county) | Binary (1 = infrastructure present, 0 = otherwise) | U.S. Census Bureau, 2000 |
| | | Presence of principle railways (county) | | U.S. Census Bureau, 2000 |
| | | Presence of major rivers and streams (county) | | U.S. Environmental Protection Agency, 1997 |
| | Coal availability and price | Presence of coal production (state) | Binary | U.S. Energy Information Administration, 2008 |
| | | Average coal price (state) | US$ per ton | U.S. Energy Information Administration, 2008 |
| | Resource availability of Biomass | Annual corn yield | 1000 metric ton | National Agricultural Statistics Service, 2008 |
| | Wood mill residues | Total annual residues (county) | 1000 $m^3$ | U.S. Forest Service Timber Products Output Database (TPO), 2007 |
| | Subregion-level conditions | Subregional binary variables | Binary (1 = county within subregion, 0 = otherwise) | U.S. Census Bureau, 2000 |

for coal. Additionally, the technical feasibility of cofiring biomass is highly dependent upon efficient transport of the biomass from the source to the power plant (Baxter, 2005; Nicholls et al., 2006; Voivontas et al., 2001). Compared to coal, biomass is widely dispersed and has a relatively low energy content per ton making transportation cost a limiting factor. The presence of major rivers and streams was included as a proxy to indicate close proximity to water sources based on the fact that coal-fired power plants are dependent upon significant water supplies for operation (Torcellini et al., 2003). Because of the joint importance of all these transportation factors a single variable that combined road presence, rail presence, and stream presence into an interaction term (road × rail × stream presence) was used in the model.

Primary and secondary wood processing facilities can be large sources of woody biomass for energy. Mill residue is already one of the most prominent forms of biomass feedstock used for cofiring (Gregg and Smith, 2010; Hoogwijk et al., 2003). Data from the U.S. Forest Service Timber Products Output Database (TPO) were used to capture total annual residue outputs per county in the U.S. northern region (TPO, 2006). Also, corn yield by county was included as a proxy to represent availability of corn stover, which can be an important source of non-woody biomass for cofiring operations (Demirbas, 2003). It is implicit in this analysis that only existing woody and crop residues have been used in cofiring. This is a reasonable assumption as no wood harvesting systems or short-rotation crops have been established to-date to commercially supply biomass solely to the energy sector in the U.S. Future higher energy prices may trigger greater levels of harvesting as suggested by the DOE's (2011) Billion-Ton Update report but this analysis is entirely based on past observed trends.

Sub-region dichotomous variables were used to identify the five energy sub-regions utilized by the EIA: West North Central Region (MN, IA, MO), East North Central Region (WI, IL, MI, IN, OH), Mid-Atlantic Region (NY, PA, NJ), New England Region (NH, VT, ME, MA, RI, CT), and South Atlantic Region (DE, MD, WV). To avoid over-specification of the model, the fifth region was dropped and used as the base-level variable (Greene, 2003). These sub-regions add an important spatial component to the analysis as they have been identified by EIA as having gradient variations in energy profiles including energy demand and supply. The use of sub-regional variables help in capturing any effects that the explanatory variables in the model may have failed to capture within regional boundaries, thus, reducing the potential effect of spatially correlated errors (Aguilar, 2009; Anselin and Griffith, 1988; McMillen, 2003).

### 3.3. Econometric analysis

The econometric analysis was completed using two final models for estimating biomass cofiring probability at the county-level for the U.S. northern region. The first model (Eq. (3)) used the predicted probability of coal-fired power plants (Eq. (2)) to control for location factors driving coal-fired electricity generation but without restricting the analysis to only counties with existing coal-fired power plants. This two-stage approach highlights counties that lack existing coal-fired power plants but seem to have other characteristics associated with those where cofiring already occurs. The other cofiring model (Eq. (4)) was estimated using the internal factors of technical feasibility and observed presence of coal-fired power plants as explanatory variables. This approach enabled us to incorporate information from all counties in the study region and identify those with existing coal-fired electric plants deemed to have a high potential for cofiring.

Standard logistic regression models were used at each modeling stage. All models were compared based on the percentage of correctly predicted observations (presence/absence). If the predicted value (probability) for a county was $\geq$0.5 it was given a value of one and if the predicted value was $<$0.5 it was given a value of zero. The percentage of correctly predicted observations was reported as a weighted mean of the two outcomes in the data with weights being the fractions of zero and one observations from the 1037 counties. Logistic model coefficients cannot be interpreted directly because of their non-linear nature, hence, marginal effects were obtained by exponentiating each regression coefficient to generate odds ratios (Greene, 2003). Odd ratios can be interpreted as changes in the odds of a county hosting a coal power plant or adopting cofiring as a result of a unit change in an explanatory variable (Long and Freese, 2006).

Finally, counties with a high probability of observing future cofiring developments were identified. Expected cofiring probabilities were calculated for every county in the study and compared to the current value (adoption or not) of cofiring per county. The value of observed cofiring was subtracted from the expected probability of cofiring creating a new variable $y_{\text{diff}}$. An ad hoc value for $y_{\text{diff}}$ greater than 0.50 was selected to identify counties that appear to be poised for adopting cofiring as done by Aguilar (2009).

## 4. Results

Table 3 shows coefficient estimates as well as relevant summary statistics for the first stage logistic model evaluating coal-fired plant presence within a county. The regression yielded a log-likelihood ratio test with $p$-value $<$ 0.001 providing strong evidence for the significance of the model's explanatory variables. The percent of correctly predicted observations (i.e., counties predicted to have coal-fired power plants) was 76%.

Electricity price was marginally significant with a negative sign suggesting that counties with no coal-fired power plants exhibited higher electricity prices than the average. This effect might be the result of higher distribution costs for counties that have to import energy through the grid instead of generating it locally. County area, urban area, and road × rail × stream presence were all statistically significant explanatory variables indicating the importance of electricity demand and infrastructural factors on the occurrence of coal-fired power plants by county (Muller and Mendelsohn, 2007; Nicholls et al., 2006). This is expected as counties hosting coal-fired power plants would generally require the presence of all three infrastructural characteristics to ease the transportation of energy feedstocks.

Table 4 shows regression coefficient estimates as well as summary statistics and marginal effects for the final models evaluating the presence of biomass cofiring facilities within a county. The second-stage model that utilized the expected probability of coal-fired power plants yielded a log likelihood ratio test statistic with a $p$-value $<$ 0.001. The single-stage model which utilized the observed number of coal-fired power plants and the internal proxy of technical feasibility per county also yielded a log-likelihood ratio test statistic with a $p$-value $<$ 0.001. The percent of correctly predicted observations (i.e., counties correctly predicted to have coal and biomass co-fired electric plants) for both models was 96%. Note that there were 62 counties with no information for technical cofiring feasibility. Consequently, these counties had to be dropped from the analysis for the final models.

The expected probability of coal-fired power plants was significant for the second-stage model. This result indicated that not only is the probability of biomass co-firing contingent upon coal-fired power plants, it is also highly correlated with factors that cause certain counties to be poised for hosting coal-fired power plants. Technical feasibility was also a highly significant variable in both models, indicating that a consideration of technical limitations for the coal-fired plants themselves is just as important as frequency or expected probability of their presence. Both models indicated a positive correlation between cofiring and electricity price, though this was only a significant effect for the second-stage model with an odds of cofiring of 1.804 for a 1 cent/kW h increase. Urban percentage of county area was significant for the second-stage model but not for the single-stage model. In contrast, road × rail × stream presence was significant for the single-stage model only. The disparity between the two models suggests that the two-stage model, after

**Table 3**
Coefficient, odds ratios and corresponding $p$-values for logistic model estimating coal-fired power plant presence in a county within the U.S. northern region (Eq. (2)).

| | Coefficient | Odds ratio | $p$-value |
|---|---|---|---|
| *External factors* | | | |
| Electricity price | −0.090 | 0.914 | 0.058 |
| County area | $0.2\times10^{-3}$ | 1.000 | 0.009 |
| Urban area | 0.030 | 1.031 | <0.001 |
| Land value | −0.001 | 0.999 | 0.594 |
| *Location-specific factors* | | | |
| Road × rail × stream presence | 0.705 | 2.023 | <0.001 |
| Coal price | −0.011 | 0.989 | 0.341 |
| EIA region 1 | −0.810 | 0.445 | 0.093 |
| EIA region 2 | −0.242 | 0.785 | 0.522 |
| EIA region 3 | 0.035 | 1.035 | 0.93 |
| EIA region 4 | −0.355 | 0.701 | 0.553 |
| Intercept | −0.318 | | 0.655 |
| Percent correctly predicted observations | 76% | | |

$n=1037$, log-likelihood = −524.78.

controlling for coal-fired power location factors, is more dependent on electricity demand; while the single-stage model places more importance on infrastructure. Both cofiring models show total mill residues as a significant variable. The importance of technical feasibility, infrastructure and biomass supply has a substantial impact on the probability of cofiring adoption.

Evaluation of marginal effects using odd ratios provides a better interpretation of the effect of explanatory variables on the probability of cofiring. The largest odds ratio value corresponds to technical feasibility in the second-stage model which shows an increase of 42.2 in the odd of cofiring when technical feasibility = '1'. Most noticeable differences in odd ratios coincided with a stark contrast in significance between the two models for the variable capturing road × rail × stream presence. However, the majority of variables had odds ratios close to one, indicating an approximate one-to-one change in odds of cofiring for a one unit change in the covariate.

Although assessment of the model fit statistics and significance of individual coefficients is useful for comparing the overall performance of the models, it is somewhat uninformative as to the ability of each estimation method to identify individual counties with a high potential for biomass cofiring. Predicted cofiring probabilities from both final models were assessed to determine which counties in the northern region currently lacking cofiring facilities were predicted to have a high probability of cofiring ($y_{\text{diff}}$). The numbers of counties identified as having high potential for biomass cofiring were 6 and 4 for the single-stage model and the second-stage model, respectively. Fig. 2 shows the locations of counties that currently do not have cofiring facilities but have a relatively high estimated probability for cofiring based on the results of both final models.

Note that the counties with a high estimated potential for cofiring indicated by both final models greatly reside in the U.S. Great Lakes region. All of the counties indicated by the single-stage model contain at least two existing coal-fired power plants. This is not surprising given the high significance of the number of existing plants as an explanatory variable in the model ($p<0.001$) (Table 4). Most of these counties have significantly developed road, rail, and waterway infrastructure as well as considerable amounts of wood mill residue produced by the wood products industry. Also, most of the indicated counties had values higher than the regional average for urban area, which was correlated with the presence of multiple coal-fired power plants.

Each of the counties indicated as having high potential for cofiring based on the second-stage model were also indicated by the single-stage model. For both models, every county identified had a high level of technical feasibility, denoting the importance of this variable regardless of which coal-fired power plant variable was used. Interestingly, the only counties highlighted in Fig. 2 with road × rail × stream presence were counties indicated as having high probability of co-firing by both models. The two counties that were indicated as having high probability of co-firing only by the single-stage model did not have road × rail × stream presence. This is somewhat unintuitive given the low statistical significance of road × rail × stream presence in the second-stage model. However, the lack of statistical significance of this variable in the second-stage model was largely due to its prominence in the estimation of expected probability of coal-fired power plants. In other words, the second-stage model provides information about counties that appear to have high potential for coal-fired electricity as well as a high potential for biomass cofiring.

**Table 4**
Coefficients, marginal effects and $p$-values for logit model estimation of cofiring in a county in the U.S. northern region.

| | Second-stage model (Eq. (3)) | | | Single-stage cofiring model (Eq. (4)) | | |
|---|---|---|---|---|---|---|
| | Coefficient | Odds ratio | $p$-value | Coefficient | Odds ratio | $p$-value |
| *Internal factors* | | | | | | |
| Estimated probability coal-fired Plants | 27.467 | $8.5\times10^{11}$ | 0.037 | – | – | – |
| Number coal-fired plants | – | – | – | 1.154 | 3.169 | <0.001 |
| Technical feasibility | 3.744 | 42.249 | <0.001 | 1.948 | 7.016 | 0.002 |
| *External factors* | | | | | | |
| Electricity price | 0.590 | 1.804 | 0.037 | 0.130 | 1.138 | 0.384 |
| County area | −0.001 | 0.999 | 0.136 | $0.1\times10^{-3}$ | 1.000 | 0.314 |
| Urban area | −0.175 | 0.840 | 0.039 | −0.013 | 0.987 | 0.495 |
| Land value | 0.007 | 1.007 | 0.217 | 0.005 | 1.005 | 0.395 |
| RPS as of 2001 | 1.152 | 3.164 | 0.102 | 1.000 | 2.719 | 0.175 |
| *Location specific factors* | | | | | | |
| Road × rail × stream presence | −1.939 | 0.144 | 0.259 | 1.480 | 4.392 | 0.025 |
| Coal price | −0.036 | 0.965 | 0.543 | −0.051 | 0.950 | 0.389 |
| Corn yield | 0.001 | 1.001 | 0.604 | 0.000 | 1.000 | 0.724 |
| Total mill residue | 0.009 | 1.009 | 0.018 | 0.008 | 1.008 | 0.044 |
| Region 1 | −1.690 | 0.185 | 0.520 | −3.832 | 0.022 | 0.080 |
| Region 2 | −3.791 | 0.023 | 0.023 | −3.738 | 0.024 | 0.024 |
| Region 3 | −1.924 | 0.146 | 0.053 | −1.794 | 0.166 | 0.072 |
| Region 4 | −0.876 | 0.417 | 0.690 | −2.005 | 0.135 | 0.340 |
| Intercept | −11.459 | | 0.044 | −3.485 | | 0.278 |
| Percent correctly predicted observations | 96% | | | 96% | | |

$n=975$, log-likelihood (second-stage model) = −62.1; log-likelihood (single-stage model) = −56.9.

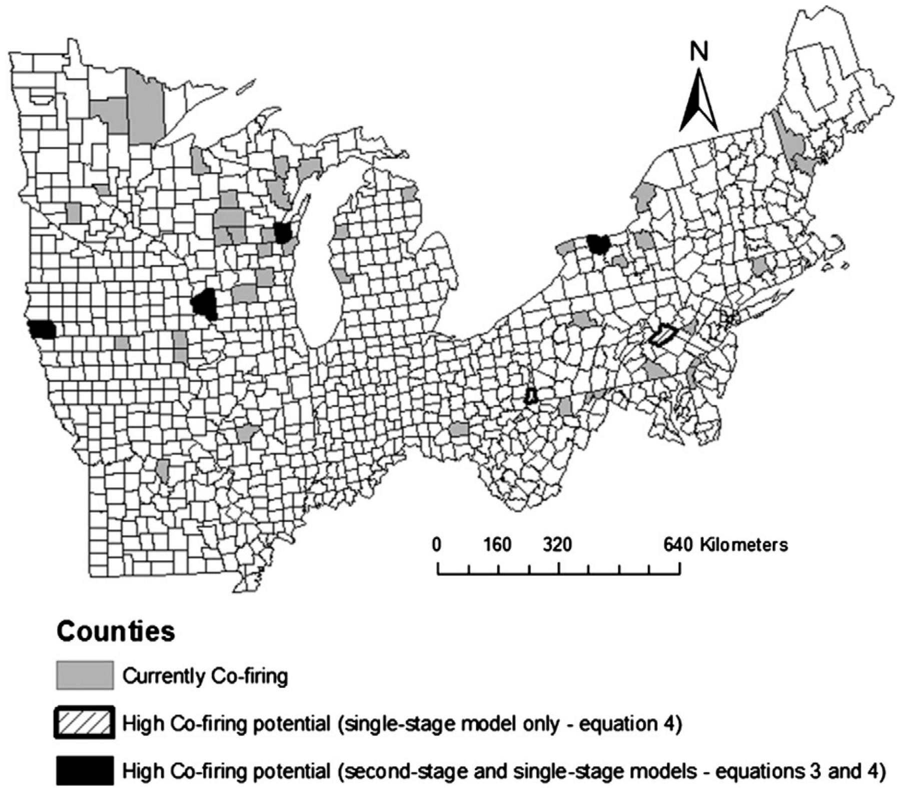


**Fig. 2.** Map showing location of counties poised for cofiring developments based on final models.

## 5. Discussion

Proxies for internal, external and location-specific factors were found to be significant in estimating the presence of biomass cofiring in both final models. The effect of each of these factors on the cofiring dependent variable provides valuable information as to the opportunities and challenges that future implementation of biomass cofiring may face and merit further discussion. The most important difference between the two final models pertained to the inclusion of internal factors in the econometric analysis. The second-stage model benefited statistically from the inclusion of expected probability of coal-fired power plants and technical feasibility. Similarly, both the number of coal-fired power plants and technical feasibility were highly significant for the single-stage model. The significance of technical feasibility was somewhat unexpected for the single-stage model given that this model had already accounted for the location of existing coal-fired power plants. Additionally, it was found that the introduction of a technical feasibility explanatory variable into both final models coincided with a drop in significance of some external proxies (e.g. adoption of RPS). This implies that much of the information provided by adoption of RPS to have an effect on cofiring actually pertained to the inherent characteristics of individual power plants between the different states and not to the adoption of state-level mandates. Similarly, the second-stage model does not show the probability of coal-fired power plants as a significant variable without the inclusion of the variable for technical feasibility.

Recall that the indicator variable for technical feasibility was calculated by assessing the difference between pulverized coal boilers and other boilers that are considered more suitable for cofiring of biomass. This is a very important issue, as the maximum particle size of biomass that can be fed to and burned in a given pulverized coal boiler can limit the suitability of certain types of biomass for cofiring (Sami et al., 2001). This was the primary motivation for indicating presence of other boiler types that can accommodate larger particle sizes such as stoker, cyclone, and fluidized bed boilers (Sami et al. (2001); Baxter, 2005). The adoption of cofiring brings about numerous technical challenges, and inclusion of boiler type addresses many of them (Sami et al., 2001).

The one external proxy that was at least marginally significant for the second-stage model was electricity price. A similar effect was observed for the first-stage model estimating the presence of coal-fired power plants per county. In each case, electricity price had a positive coefficient indicating that an increase in electricity price corresponds to an increase in probability of cofiring. The fact that electricity price is significant for the second-stage model but not for the single-stage model suggests that the importance of this variable is not simply a correlation with the expected probability of coal-fired power plants. The findings from a sensitivity analysis conducted by De and Assadi (2009) indicate that as the market price of electricity increases the additional costs of biomass cofiring would also increase. Therefore, the significant positive effects of electricity price may not hold if prices rise significantly in the future unless there are additional incentives for both producers and suppliers (De and Assadi, 2009).

The proxy for adoption of RPS by 2001 was only significant if the proxy for technical feasibility was left out of the models. This implies that in the absence of known industry internal variables (i.e. technical cofiring feasibility), there is a strong correlation between past renewable energy policy and present use of biomass for co-firing. Therefore, even though adoption of RPS by 2001 was not statistically significant in the final models, past public policy for renewable energy can have an effect on the use of biomass for coal-fired power plants while controlling for other explanatory factors. The variability in statistical significant effect off RPS is possibly associated to the influence technical feasibility has on public policy. In other words, capacity of existing biomass-using facilities and technical feasibility of existing power plants to incorporate bio-feedstocks are factors often taken into account in the policy-making process before any new regulation is adopted (Corey and Swezey, 2007).

The significance of supply infrastructure for the single-stage model was not surprising as close proximity of roadways, railways, and waterways is instrumental for most coal-fired power plant and cofiring operations. In fact, presence of waterways can fulfill multiple roles in a cofiring operation as both a potential feedstock transport mechanism and a source of water needed for cooling. Roadways are also of particular importance for cofiring facilities as a primary method for transport of biomass feedstock (Baxter, 2005; Nicholls et al., 2006; Voivontas et al., 2001). Combining all three infrastructural factors into a single interaction term (road × rail × stream presence) was useful in estimating the combined effect of a comprehensive transportation system on coal-fired power plant presence and biomass cofiring presence. Although rail presence will often not play a vital role in biomass supply and transport for cofiring, all three infrastructural factors are central to operation of a power plant by providing access to coal.

Primary processing mills produce about 87 million dry tons of residue per year (Smith et al., 2009). Although this is a considerable amount, very little of the residue produced in the U.S. northern region is currently unused (i.e. most residues are already used by the wood products industry to produce steam of contracted out to others). For coarse residue which is much of the residue produced by primary wood mills, about 13% is already used for fuel, while about 86% is used for fiber products and other applications (U.S. Department of Energy, 2011). Much of the significant correlation between cofiring probability and mill residues may pertain to this 13%. Fig. 1 illustrates this situation by showing the clustering of current cofiring facilities in the Great Lake states where numerous pulp and paper mills are located. This means that although location of past and present cofiring operations coincide with high quantities of mill residues, this trend may not hold into the future unless production of mill residues increases dramatically to meet greater energy demand. As discussed by Aguilar et al. (2011) the production of residues from the wood products industry will not be driven by energy demand but as derived demand for wood products. Hence, it is likely that other biomass residues with limited current use such as timber harvest material, crop residues and even dedicated energy plantations may have a greater role to play supplying biomass for cofiring in the future.

## 6. Conclusions

This study assessed various econometric models for estimating the potential of individual counties in the U.S. northern region for cofiring coal and woody biomass for electricity generation. In the first stage of the analysis we estimated the county-level probability for coal-fired electricity generation with a logistic regression model using several independent factors represented by proxies describing infrastructural, supply, and economical characteristics. The final stage of the analysis resulted in the development of two logistic regressions that incorporated both the known number of coal-fired power plants per county and the expected probability of coal-fired electricity generation per county obtained in the first-stage analysis, as well as infrastructural variables and wood mill residue information.

The location of existing coal-fired power plants and technical feasibility were highly significant variables for estimating the probability of cofiring. However, it was shown that the second-stage model performed similarly in terms of overall predictive capability. Additionally, this model was able to identify four counties with a high potential for cofiring. These counties are locations that are characterized by established infrastructure and available biomass. There was a statistically significant to marginally significant positive correlation between electricity price and cofiring probability, implying a moderate importance of electricity demand on cofiring potential. Supply and operational infrastructure, including bio-physical characteristics such as stream presence, was significant for the single-stage model, implying that infrastructure is a vital component for cofiring potential regardless of current presence of coal-fired power plants. Finally, biomass supply from mill residues was significant for both final models, implying a high dependency of cofiring operations on residues derived from wood mills. As such, further developments of cofiring in the U.S. northern region are most likely to take place in the Great Lakes area as shown in Fig. 2.

The results of this analysis provide a coarse screen for identifying counties in the U.S. northern region with a high potential for cofiring based on infrastructure, biomass supply, economic considerations, and current existence or potential of coal-fired electricity generation. A logical future direction for this research would incorporate additional technical and social factors such as power plant manager preferences regarding conversion technologies, feedstock supply, and operational procedures as well as public opinion towards cofiring and benefits for forest landowners at a local-scale. Such an assessment can supplement the bio-physical factors analyzed in this study for a more detailed and robust analysis indicating locations where cofiring coal and biomass may be most feasible.

## Acknowledgments

The authors thank Gregg Coffin for the technical assistance throughout the development of this study. This research was supported in part by the Northern Research Station under U.S. Forest Service Agreement 09-PA-11242305-143.

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